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EDS V25 Containment Vessel Explosive Qualification Test Report

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ABSTRACT

The V25 containment vessel was procured by the Project Manager, Non-Stockpile Chemical Materiel (PMNSCM) as a replacement vessel for use on the P2 Explosive Destruction Systems. It is the first 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 limit is an increase from the 4.8 pounds TNT-equivalency rating for previous vessels. This report describes the explosive qualification tests that were performed in the vessel as part of the process for qualifying the vessel for explosive use. The tests consisted of a 11.25 pound TNT equivalent bare charge detonation followed by a 9 pound TNT equivalent detonation.

ACKNOWLEDGMENTS

This work was performed for the US Army Project Manager for Non-Stockpile Chemical Materiel.

CONTENTS

FIGURES

1. BACKGROUND

EDS Background

The Explosive Destruction System (EDS), which was developed at Sandia National Laboratories, is designed to neutralize recovered chemical munitions. The apparatus neutralizes chemical munitions through explosive access and chemical reaction. The entire process, including accessing the munition using explosive devices and chemical neutralization, is conducted inside the enclosed EDS vessel. Considering the extreme physical environments imposed on the EDS vessel, both from high explosive pressures and corrosive chemical reagents, and the absolute necessity of maintaining operational and occupational safety, an accurate knowledge of the vessels response to explosive loads is required for safe and efficient operation.

EDS Vessel Specification

A new EDS vessel (S/N: JH2830801, P/N: H90063-119-3), owned by the Project Manager, Non-Stockpile Chemical Materiel (PMNSCM), was to be tested as part of the process for qualifying the vessel for explosive use. The proposed explosive rating for the vessel, shown in Figure 1, was nine (9) lbs. TNT-equivalent for up to 637 detonations. This limit is an increase from 4.8 lbs. TNT-equivalency rating from previous vessels. The increase in the rating is based on ASME Code Case 2564 and recent tests and structural analysis. EDS vessel dimensions and further specifications can be found in the test plan.

Figure 1: This image shows the EDS vessel mounted in the shipping fixture.

2. TEST OVERVIEW

Test Goals

The primary goals of this test series were to satisfy the DoD Explosive Safety Board requirement for a 1.25X qualification test, experimentally confirm predicted maximum strain limits on the vessel, and validate the fidelity of various vessel seals and fittings. Two individual tests were planned for this test series. The first test used 125% of the design basis load (11.25 lbs. TNT-equivalent). The second tested the vessel at 100% of the design basis load (9 lbs. TNT-equivalent). The first test provided the required overtest while the second test served to demonstrate shakedown and the absence of additional plastic deformation.

Diagnostics

To validate predicted strain data, dynamic strain gauges (Vishay EP-08-250BG-120) were installed on the EDS vessel in the configuration shown in Figure 2. These gauges were used to record dynamic strain behavior at specified points on the vessel in order to be compared to calculated values from simulations. In addition, plastic strain, or permanent vessel deformation, was measured by taking nine (9) individual outer diameter measurements around the circumference of the EDS vessel main body using a stainless steel π-tape.

In addition to static and dynamic strain measurements, leakage measurements of the vessel were taken before and after each test to validate acceptable leak rate. Leakage measurements were taken around the edge of the door, flange, electrical feed-through, and around various valves and fittings installed on the front face of the EDS vessel. Although not specified in the test plan, digital image correlation (DIC) was conducted on high-speed images recorded during each test of the long edge of the EDS vessel.

To verify that no transient gas leaks were present during the detonation, latex balloons were attached to the vacuum port on the EDS vessel door. These balloons and the front face of the EDS vessel were monitored during each test by a high-speed digital camera, which could image both the balloon's movement (inflation due to leakage) and general vessel response during the test event.

Visual inspections of the EDS vessel, surroundings, and diagnostics were completed before and after each test event. This visual inspection included analyzing the seals, fittings, and interior surfaces of the EDS vessel following each test and documenting any abnormalities or damages. Photographs were used to visually document vessel conditions and findings both before and after each test event. All tests were conducted according to the proposed test plan and all appropriate site-specific safety procedures were followed.

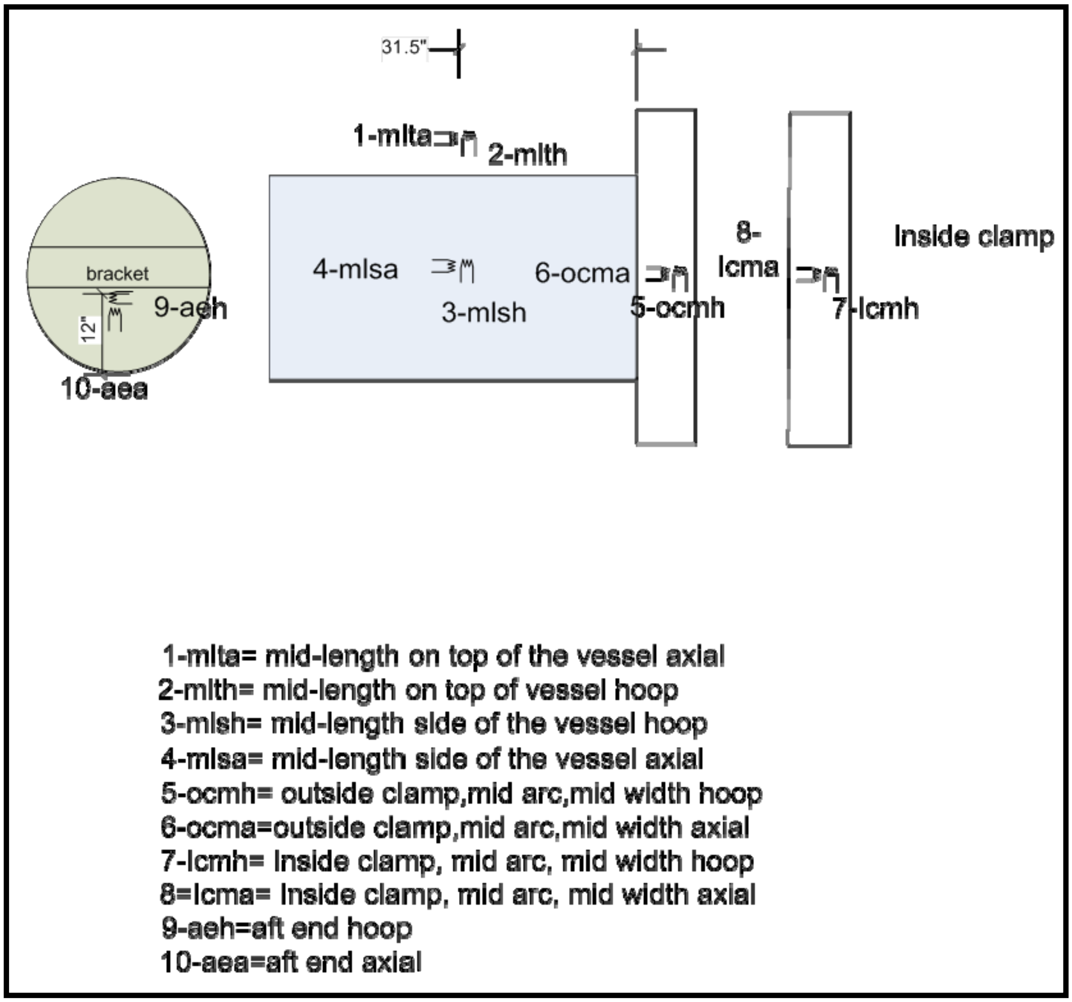

Figure 2: This image depicts the locations of strain gauges installed on the EDS vessel for these tests. The description of each gauge's nomenclature is also described in this figure. For the aft end gauges, hoop (9-AEH) refers to Y-direction strain (parallel to aft end bracket) and axial refers to X-direction strain (perpendicular to aft end bracket).

Explosives

The design basis for the vessel was a cylindrical, 9 pound TNT charge located at the center of the vessel and simultaneously detonated at both ends. In an actual EDS operation, there can be multiple explosive charges dispersed around the vessel. There are also obstacles such as munition housings and the fragment suppression system (FSS) that can dissipate or redirect the pressure shocks. Modeling and testing have shown that a bare charge produces higher peak loads than the distributed, partially confined charges in an actual operation, making the design impulse conservative. For example, Figure 3 shows the ratio of time integrated hoop strain at the vessel body center from a previous EDS test comparing the detonation of a mock GTR and the detonation of a 17 pound charge. The hoop strain with the munition was about 80 percent of the strain with the bare charge. Axial strain was about 60 percent while the strain in the clamps was only about 20 percent.

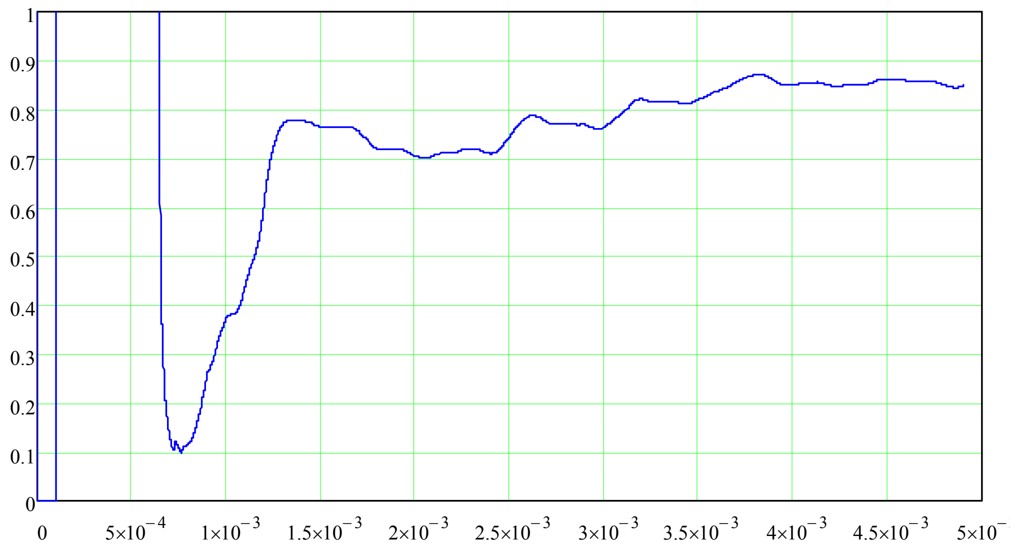

Figure 3: This image shows the ratio of time integrated hoop strain at vessel body center comparing a mock GTR and a 17 pound charge

All EDS munition configurations are evaluated and approved by the Army and operational procedures are implemented to ensure that the actual impulse loads will not exceed the design basis load.

Since C-4 explosive was used for both tests instead of TNT, the quantity of explosive was adjusted based on a TNT equivalency value of 1.25 for C-4. Therefore, the amount of C-4 used in the two tests was 9 lbs. and 7.2 lbs., respectively.

We used four methods to determine TNT equivalence: 1) peak pressure equivalency using empirical values of Composition C4 compared to historical data for pressure versus scaled distance (also empirical in nature); 2) positive impulse (pressure integrated over time to the first zero-pressure crossing) from the same data sets; 3) total energy available in the two explosives based on values for heat of detonation for both explosives; and 4) comparison of theoretical isentropic expansion curves/rates for detonation products of each explosive.

These multiple methods were used to capture a comparison for the entire detonation and gas expansion dynamic. The peak pressure provides a power comparison at the highest rates of the dynamic. The chemical energy provides a total energy comparison in a static sense (zero-rate). The impulse compares the power/energy relation without regard to rate (considers all frequencies equally), and the gas expansion isentrope provides a rate envelope comparison – indicating no crossover of the expansion curves at some mid-level rate.

This analysis is based on scaling of blast dynamics of the two explosives in a point symmetric configuration. It does not consider geometry or configurations that might alter a one-dimensional, or point symmetry analysis.

For the peak pressure and positive impulse comparison, we calculated the amount of TNT needed to produce the same peak pressure and impulse values as a reference amount of Composition C4. For the comparison of total chemical energy and gas product expansion rates, direct ratios were made for values obtained for the same amounts of explosives of each type.

The empirical values for Composition C4 were obtained through testing at Sandia National Laboratories on spheres of Composition C4 packed to a density of 1.58g/cc, providing data for peak pressure and impulse comparisons. Four pressure measurements were taken at scaled distances of 0.49m/kg$^{1/3}$, 0.90 m/kg$^{1/3}$, 2.37 m/kg$^{1/3}$, and 4.28 m/kg$^{1/3}$. Scaling to TNT was performed via comparison to empirically derived historical TNT values, reference: Explosive Shocks in Air, Gilbert Kinney and Kenneth Graham, Springer Verlag, 1985. These TNT data are normalized to standard temperature and pressure and are representative of cast TNT at a density of 1.63-1.64g/cc.

Averaging the values for TNT equivalency of Composition C4 at the four abovementioned locations using the peak pressure method resulted in an equivalency value of 1.3. There was some small spread in the values, but no monotonically varying trend.

Averaging the values for TNT equivalency of Composition C4 using the positive impulse method resulted in an equivalency value of 1.3 as well. Again, there was some small spread in the values, but no monotonically varying trend.

In the comparison of chemical energy, a density of 1.63g/cc for TNT was used, and a value for 90% RDX powder was used (Composition C4 is 90% RDX with 10% polyisobutylene). Taking the direct ratio for heats of detonation for these two explosives in their solid states resulted in a value of 1.25, reference: Explosives, Rudolf Meyer, Josef Kohler, Axel Homburg, Wiley-VCH, 2007.
It has been shown that the parameters (Chapman-Jouget pressure, Chapman-Jouget density, etc.) for isentropically expanding gases from a detonation state can be directly related to the square of detonation velocity, reference: Explosives Engineering, Paul W Cooper, VCH, 1997. We used this simple method to make the comparison of these parameters in the isentropic

expansion of these gases to completion. The ratio of the square of detonation velocities of the two explosives results in a value for equivalency of 1.25. Finding consistency in all four methods provides some confidence that the detonation, peak pressure formation and subsequent expansion of the detonation products are consistent throughout the entire shock formation and gas expansion process for both explosives. We therefore concluded that the value for TNT equivalency doesn't vary with time as these explosives perform work on a target. We conservatively chose a representative value of 1.25, as this is the lowest value of the four comparisons.

3. RESULTS

Simulation

Simulation data was provided by M. Yip from SNL/CA. The simulation data predicted the dynamic stress field in the EDS vessel walls and faces following detonation of the larger, 11.25 lbs. TNT-eq. charge. Based on the simulation, limiting strains occur at two locations designated as “aft” and “waist” on Figure 4. The maximum bending strain occurs at the “aft” location on the end of the vessel at the center. This location corresponds roughly to the locations of strain gauge positions 9 and 10, as shown in Figure 2, although the gauges were not quite at the center because the mounting bracket was in the way. The maximum membrane strain occurs at the “waist”, which is on the diameter of the vessel, roughly 34 inch from the vessel’s aft end. This position corresponds approximately with strain gauge locations 1, 2, 3, and 4, although the gauges were a few inches further back.

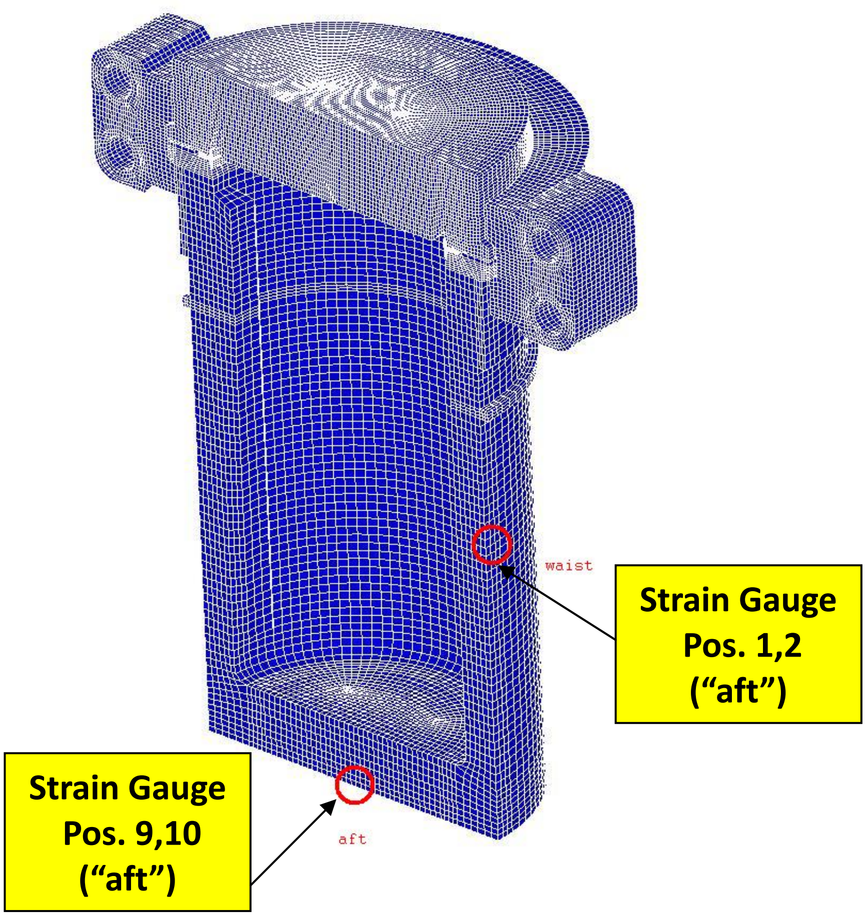

Figure 4: This image shows the locations on the EDS simulation model where strain data were recorded and the corresponding test strain gauge ID numbers used for comparison.

General Test Setup

The EDS vessel was mounted in its shipping cradle at testing site 9920 at Sandia National Labs, Albuquerque, NM. The vessel was bolted to the shipping cradle at the aft end in the same locations that it will be bolted to the rotating shaft on the trailer. The vessel waist is unconstrained in both configurations. Consequently, the cradle should not alter the vessel response compared to normal operational conditions. A custom frame, designed and fabricated by the 9920 team, was used to support the large door clamps during pre- and post-test operations. The EDS vessel, cradle, and door clamp frame are shown in Figure 5.

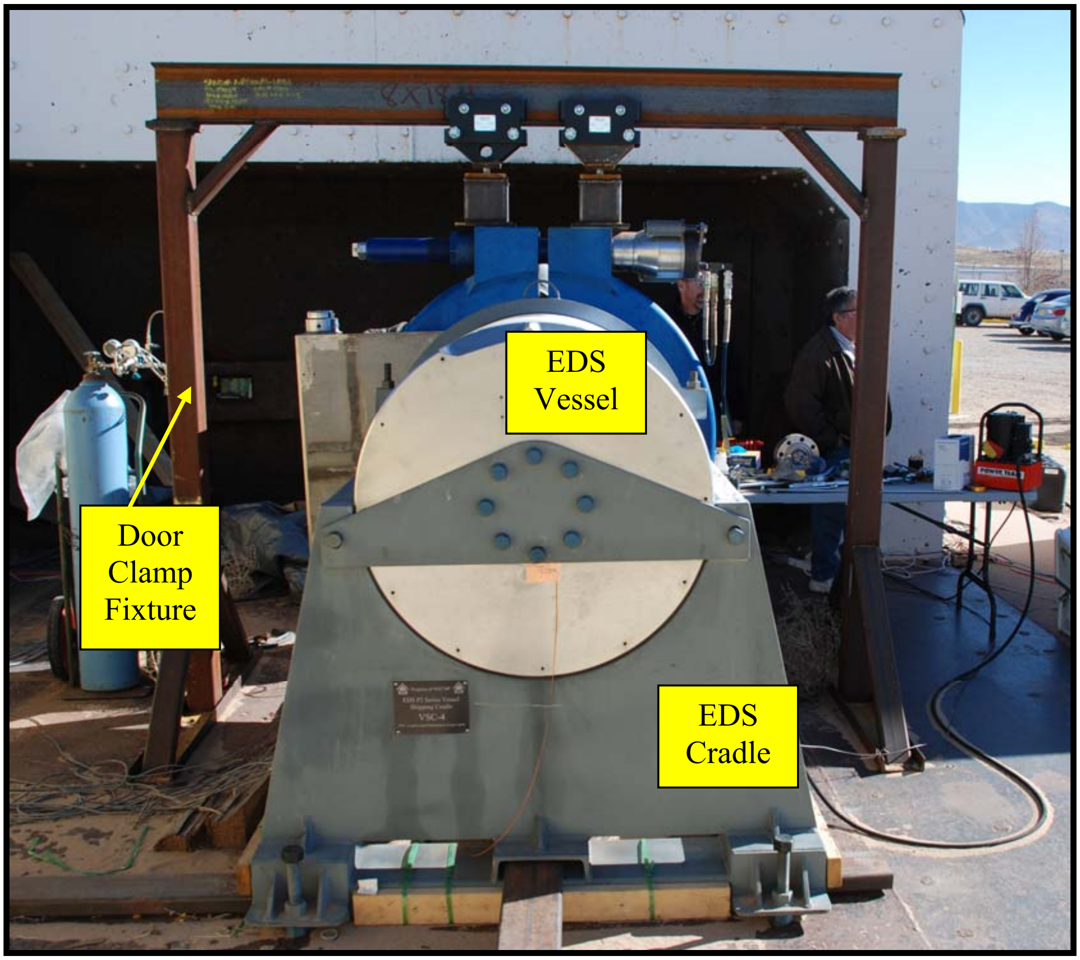

Figure 5: This image illustrates the setup of the EDS vessel for explosives testing at site 9920, Sandia National Laboratories. Note the custom door clamp frame and EDS cradle. View of EDS is from the aft end (opposite end is door).

As mentioned previously, ten (10) separate strain gauges were installed on the exterior surfaces of the EDS vessel and on the clamp surfaces. Data from only two strain gauge positions were compared to simulation data. These positions are shown in Figure 4. Figure 6 below shows the actual installed strain gauges at positions 1, 2, 9, and 10 (waist and aft, respectively). The name of each respective gauge is also given.

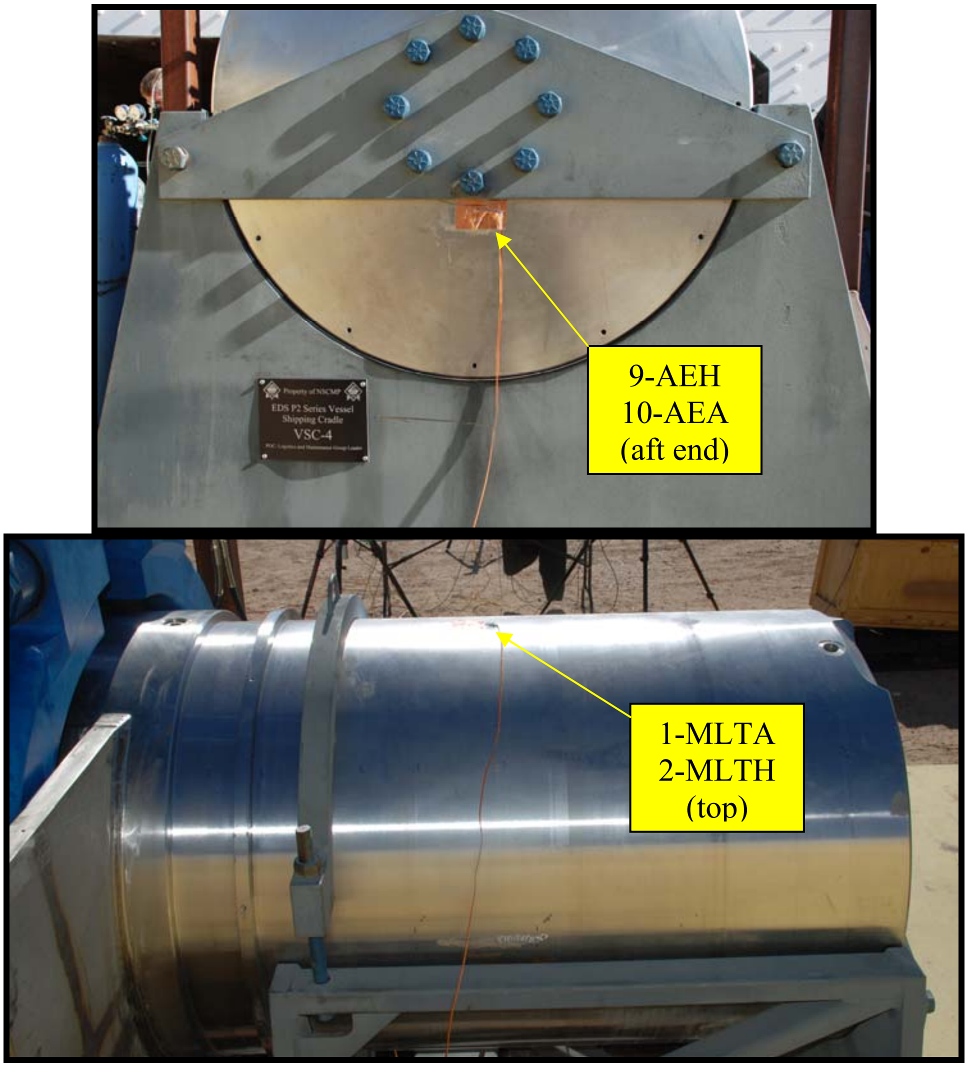

Figure 6: These images illustrate the locations of strain gauges on the EDS vessel. Data from these positions were compared to modeling data. The name of each gauge indicates the position and strain direction measured. For example, "MLTA" indicates Mid-Length Top Axial. An "H" following the position indicates hoop strain measurement.

High-speed imaging was used both to monitor dynamic leakage through ports on the EDS vessel front edge and also to gather data for DIC analysis. Figure 7 below depicts the DIC setup, which consisted of two Phantom high-speed digital cameras mounted to view the side of the EDS vessel. It was necessary to create a random pattern of dots on the EDS vessel for the DIC to properly function. This pattern was created by applying a series of random black dots onto a painted (white) side of the EDS vessel. The random pattern applied to the EDS vessel and the camera setup are shown in Figure 7.

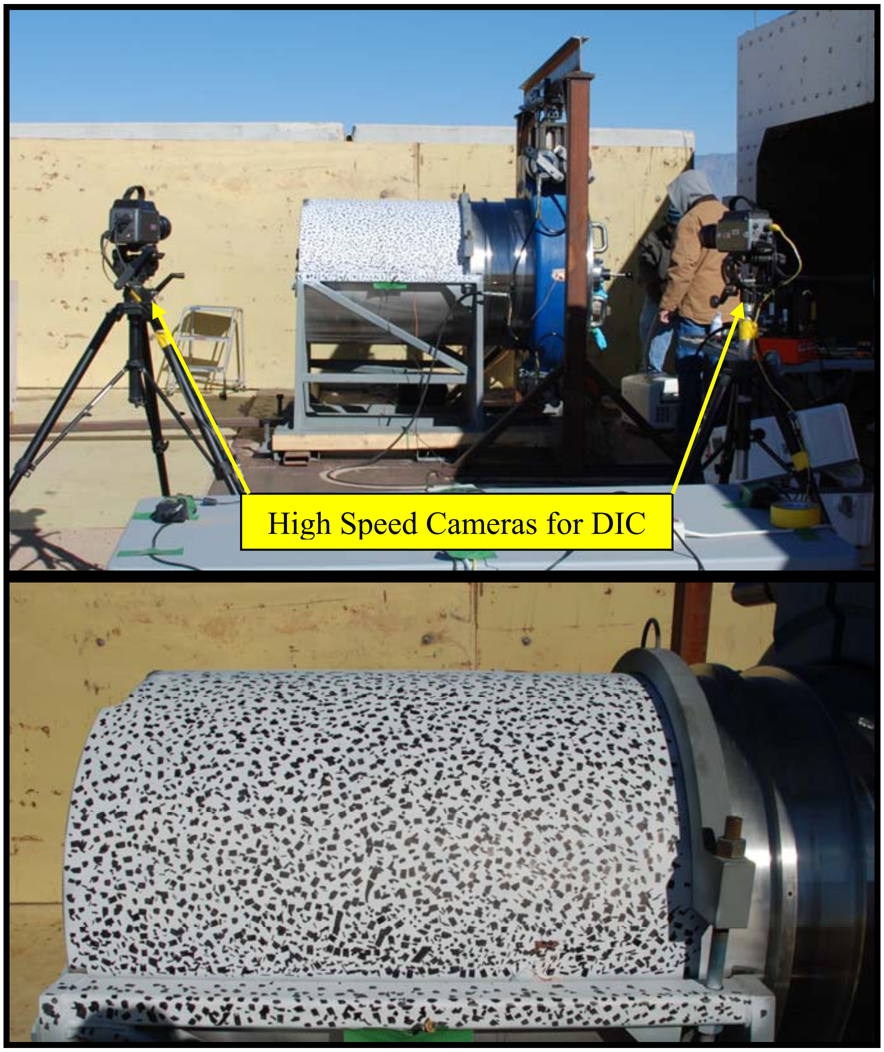

Figure 7: This figure illustrates the locations of the high-speed digital cameras used for DIC analysis. Also shown is the random dot or "speckle" pattern applied to a section of the EDS vessel. DIC analysis was not specified in the test plan; however, these tests presented the opportunity to conduct this analysis without interfering with the original test goals.

To document the permanent (plastic) strain on the EDS vessel outer diameter, a series of measurements were taken at specified locations along the EDS vessel. These measurements were taken using a π-tape both before and after each detonation. The locations were referenced from the aft end of the EDS vessel. Marks were made on the non-speckled portion of the EDS vessel so that measurements could be made at the same location. Figure 8 indicates the locations of the reference marks on the EDS vessel. Exact distances and measurements are given in the next section.

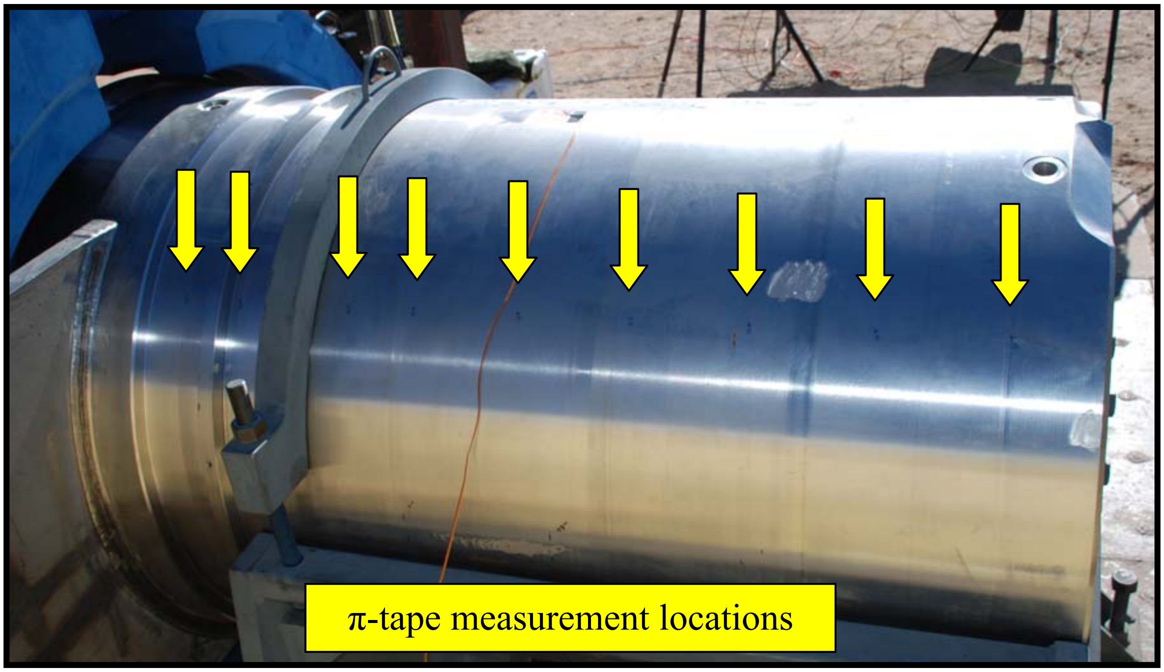

Figure 8: The positions where before and after EDS vessel diameter measurements were taken are shown in this figure. Nine (9) total diameters were measured.

The explosive charge was formed into a cylinder of identical aspect ratio (L:D ≈ 1.925:1) to the cylindrical section of the EDS vessel. Cylindrical charge dimensions were approximately 2.5 in. radius and 9.7 in. length. For each test, the cylindrical charge, with installed detonators (2 per charge), was mounted inside the EDS vessel and supported by an appropriately oriented cardboard box. Charges were oriented at the center of the hollow portion of the EDS vessel (28 in. along inside length of vessel) and aligned concentrically with the EDS vessel center axis (14.5 in. height). Each charge was initiated with two (2) RP-83 detonators. For the first test, the detonators were not completely inserted into each flat end of the cylindrical charge. However, for the second test, the detonators were pressed into the charge's center and completely enclosed inside the charge. The as-installed charge is depicted in Figure 9.

In normal operations, fragment suppression devices are used to prevent impact and damage on the interior surface of the vessel from munition fragments. Since the bare charge does not produce fragments, no suppression was used. In terms of the impulsive load on the vessel, this represent a "worst-case scenario" since the fragment suppression system also provides some mitigation of the shock loads by disrupting the pressure waves.

Once the charge was installed, the EDS vessel door was closed after ensuring that proper cable connections remained intact from the detonator to the wire feed-through. The clamps and sealing surfaces were lubricated with Loctite N-7000 anti-seize. N7000 is being evaluated as an alternative to the Permaslik that has historically been used in EDS operations because it appears to produce a better and more repeatable seal.

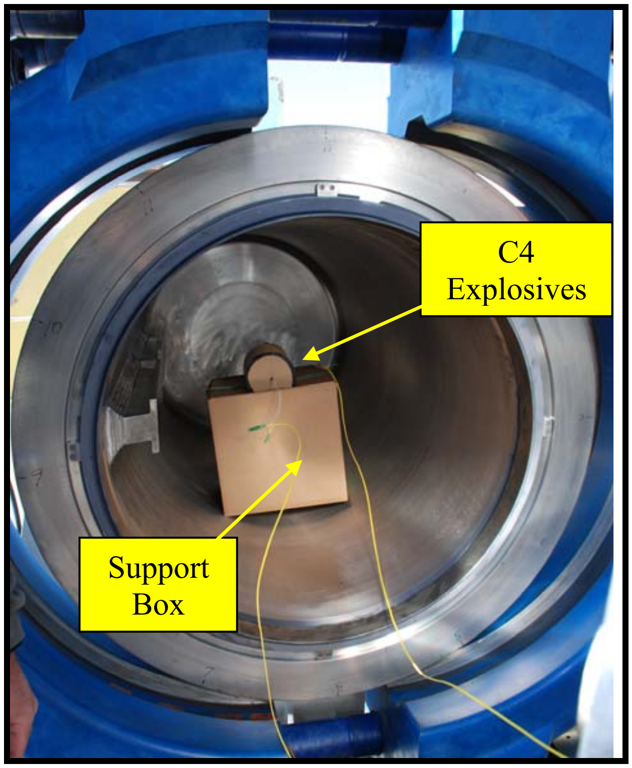

Figure 9: This image shows the installed high explosives charge in the proper orientation inside the EDS vessel.

The large clamps surrounding the door were hydraulically drawn together to a pressure of 5000 psi, as indicated on the pump pressure gauge. The gaps between the two clamps at the top and bottom were measured before each test for consistency. For Test 1 (11.25 lbs. TNT-eq.), the top gap measured 1.375 in. and the bottom gap measured 0.6875 in. Those measurements were 1.375 in. and 1.0 in., respectively, for Test 2 (9 lbs. TNT-eq.). These measurements did not change following each respective test's detonation. Gap locations and the sealed, pre-test configuration of the EDS vessel are shown in Figure 10.

Once the vessel was properly sealed and the charge installed, a leak test was performed to measure leakage around the door seal, wire feed-through, and other fittings. The vessel was pressurized through the drain valve using helium gas to a pressure of 5 – 10 psi. An acceptable, pre-test leak rate was defined in the test plan as being no greater than 1.0 x 10^{-2} std cc/s (1.01 mbar l/s).

Leakage was measured around the large door seal and small manifold seal. A sniffer detector was used to measure leakage around the drain manifold and voltage feed-through.

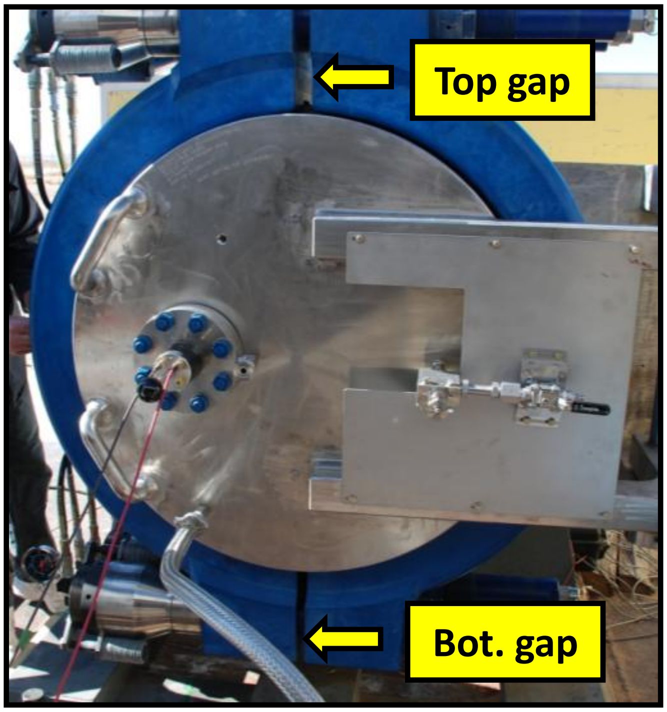

Figure 10: Door gap locations are shown in this figure. This view indicates the pre-test firing condition of the EDS vessel.

Pre-detonation and post-detonation leak rates and detection positions are summarized as follows (all rates in mbar l/s):

1. Test 1 (11.25 lbs.)
    a. Large door seal – 8.0×10^{-6} (before), 6.0×10^{-2} – 3.9×10^{-3} (after)
    b. Small flange seal – 6.8×10^{-8} (before), 4.3×10^{-7} (after)
    c. Drain manifold – none (before and after)
    d. Voltage feed-through – none (before and after)
    e. Ball valve – none (after)
2. Test 2 (9.0 lbs.)
    a. Large door seal – 8.9×10^{-9} (before), 3.4×10^{-4} – 3.0×10^{-5} (after)
    b. Small flange seal – 3.0×10^{-7} (before), 1.0×10^{-6} (after)
    c. Drain manifold – 5.2×10^{-5} (before), 5.5×10^{-5} (after)
    d. Voltage feed-through – 5.2×10^{-5} (before), 5.8×10^{-4} – 1.0×10^{-3} (after)
    e. Ball valve – 5.5×10^{-5} (before), 5.5×10^{-5} (after)

The pretest leak rates were good compared to normal EDS operations. This is notable considering the adverse conditions under which the tests were conducted. There were high winds that caused dirt and grit to accumulate on the sealing surfaces as the door was closed. These leak rates are consistent with other data that show the N7000 is a more effective seal lubricant.

Posttest leak rates are not measured in normal EDS operations, but are monitored during explosive testing to observe if the seal is damaged or impaired by the detonation. Between the times when the leak detector is removed following the pretest measurement and when it is reconnected following the detonation, helium accumulates in the volume around the seal based on the initial leak rate. Consequently, when the leak detector is reconnected, there is an initial high reading which decreases as the volume is evacuated and the accumulated helium is removed. In these tests, the operators did not wait for the system to re-equilibrate, but terminated the posttest leak rate measurements once they established that the seal met the requirements and the measured rate was continuing to decrease.

In addition to the leak rate measurements taken before and after the detonation, a latex glove was placed over the drain manifold and sealed using tape. A high-speed digital camera was used to monitor any inflation in the glove during each test. Inflation would indicate transient leakage from the drain manifold. High-speed images indicate that no leakage was experienced from the drain manifold during both tests. These high-speed images also show that no gross deformation was caused during the detonation of each charge or that other damage occurred.

A thorough physical inspection of the EDS vessel before and after each test was conducted. The purpose of this inspection was to note any damage or unexpected behavior caused by the detonation and blast effects. Typical post-detonation views of the EDS vessel interior are shown below in Figure 11.

Following Test 1, several (2-3) small divots were observed on the interior surface of the EDS vessel near the center of the charge (and vessel interior). The deepest of these divots was estimated to measure around 0.050 in. deep. It appeared that the damage was caused by high-velocity fragments from the explosive's packaging, box support, or detonator wires. A detail of the divot features is shown in Figure 12. Damage of this magnitude is not unusual in EDS operations and these divots are not expected to affect EDS vessel performance. No additional damage was noticed following Test 2. No damage to the exterior of the EDS vessel was noted for any tests.

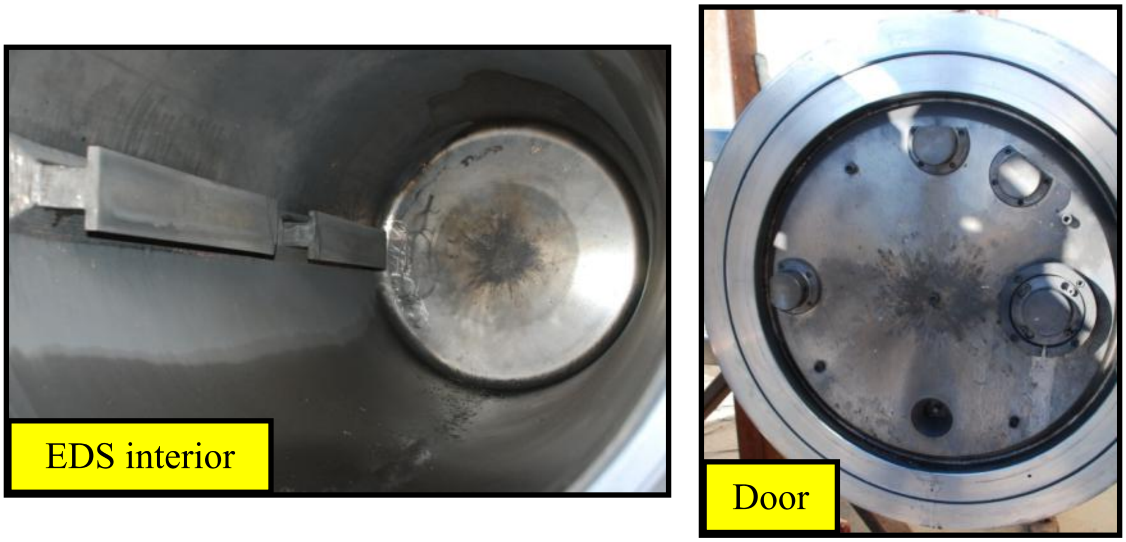

Figure 11: Representative condition of EDS vessel interior surfaces following detonation and de-pressurization. Blast marks (non-damaging) are evident on flat door and end (aft) surfaces.

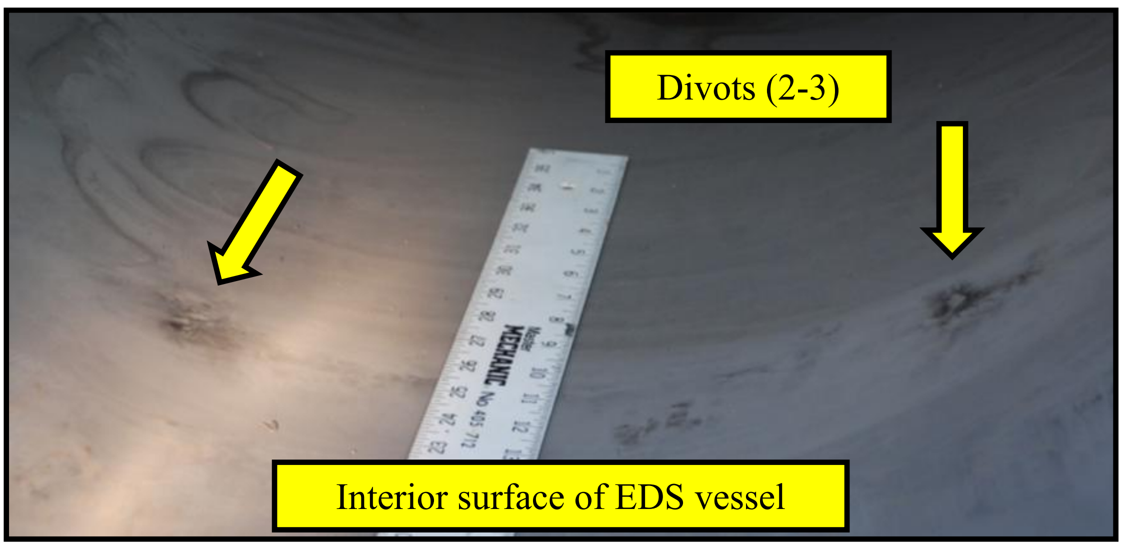

Figure 12: Detailed view of damage to interior surface of EDS vessel following Test 1 (11.25 lbs.). The maximum depth for each divot was determined to be no greater than 0.050".

4. ANALYSIS

High-Speed Imaging

As mentioned above, no significant deviation from expected behavior or leakage from the vessel was noted from high-speed imaging data. Compared to strain gauge data, DIC data gave much lower numbers. This is most likely due to less than optimum resolution and fidelity from the DIC analysis.

Strain Gauge and Simulation Data Comparison

Predicted strain data were compared to actual strain gauge data from the 11.25 lbs. TNT-eq. test (Test 1). The locations, which had corresponding data in both the simulation and test, were outlined previously. The following figures (Figures 13, 14, and 15) compare the predicted strain value to the actual measured value. Note that these figures are of dynamic strain and not permanent (plastic) strain.

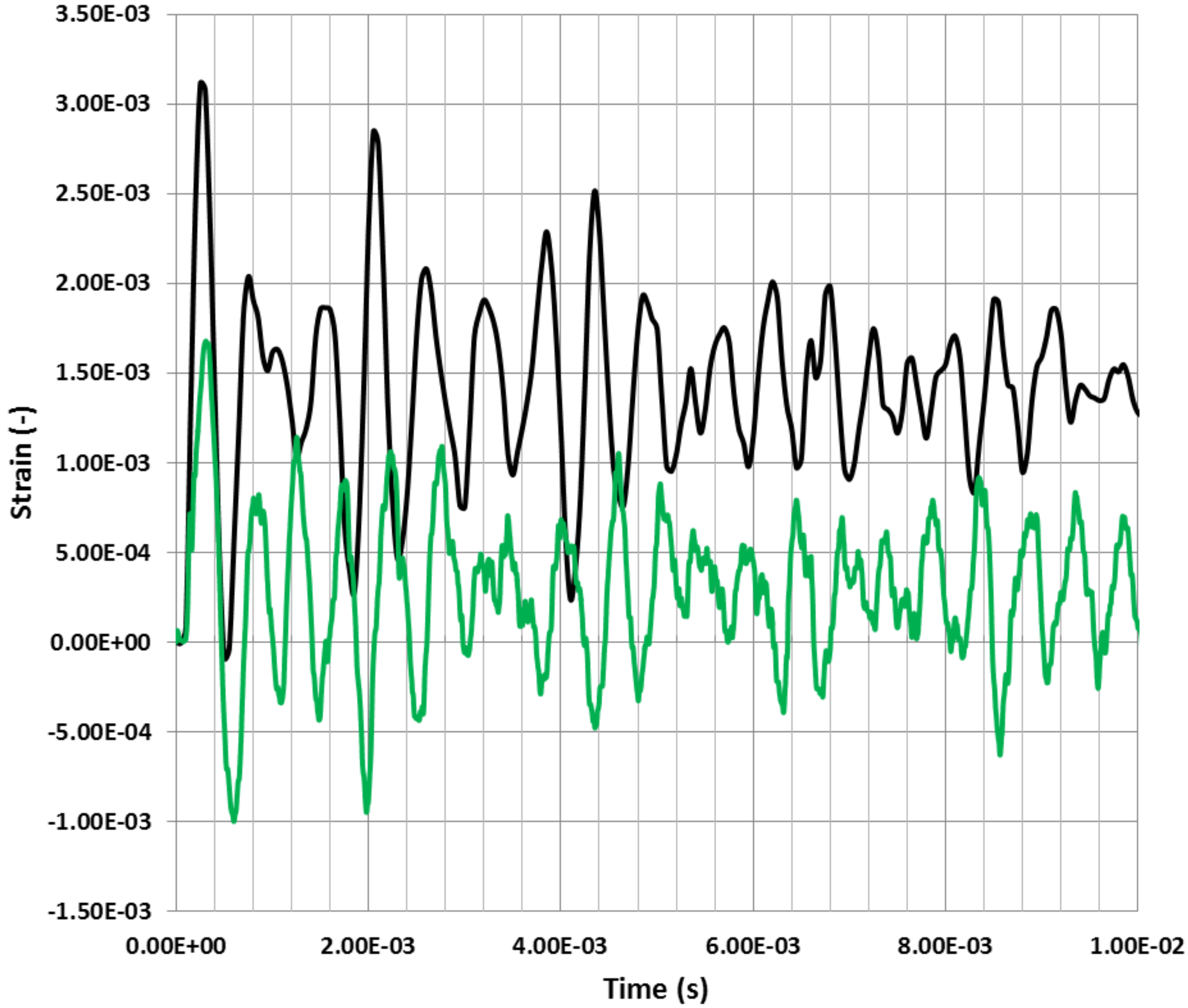

Figure 13: Predicted (black) and measured (green) mid-length dynamic hoop strain data for 11.25 lbs. TNT-eq. test (Test 1) are shown above. Measured data are from strain gauge 3-MLSH because 2-MLTH was unusable.

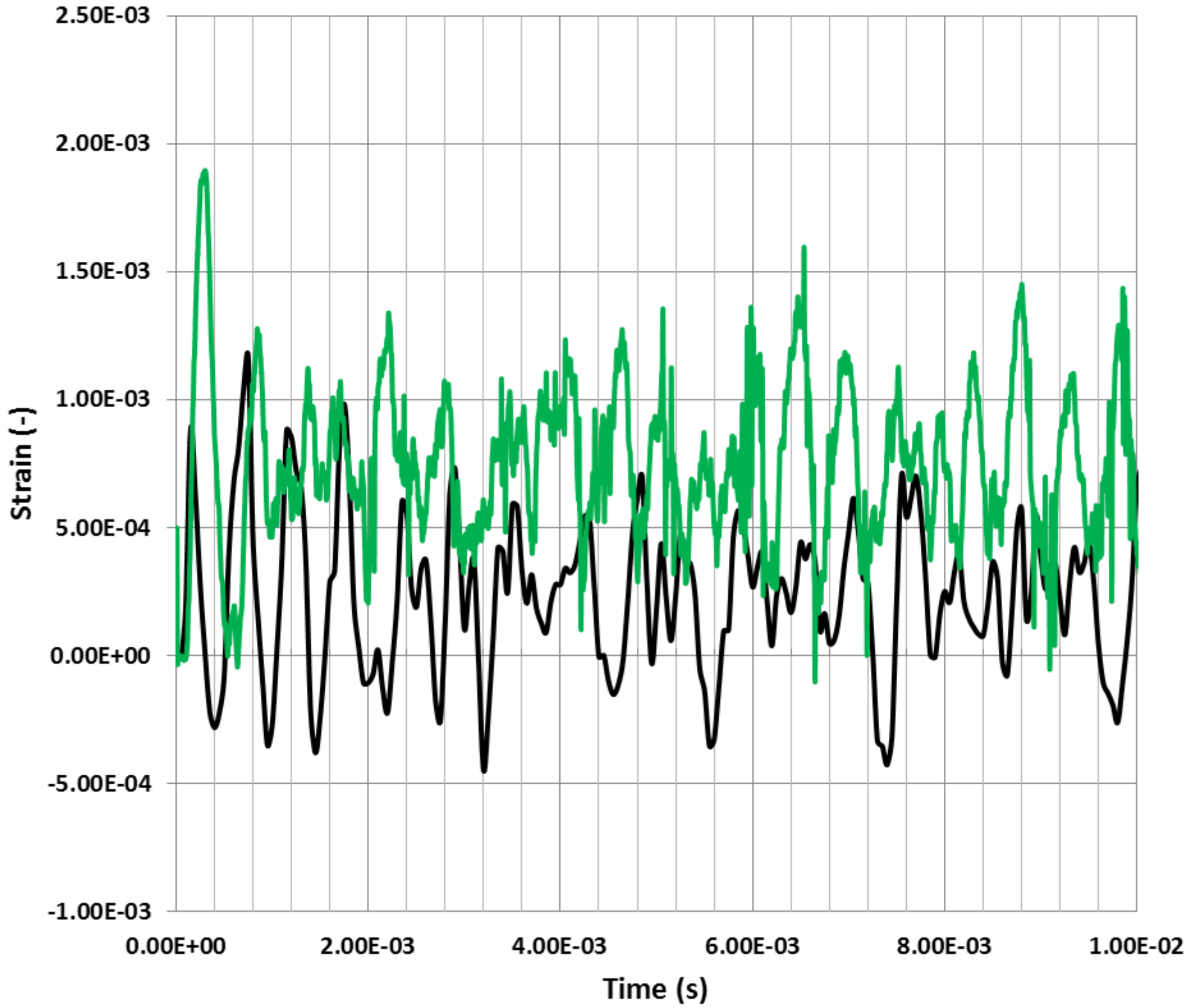

Figure 14: Predicted (black) and measured (green) mid-length dynamic axial strain data for Test 1 are shown above. The measured strain is from gauge 1-MLTA.

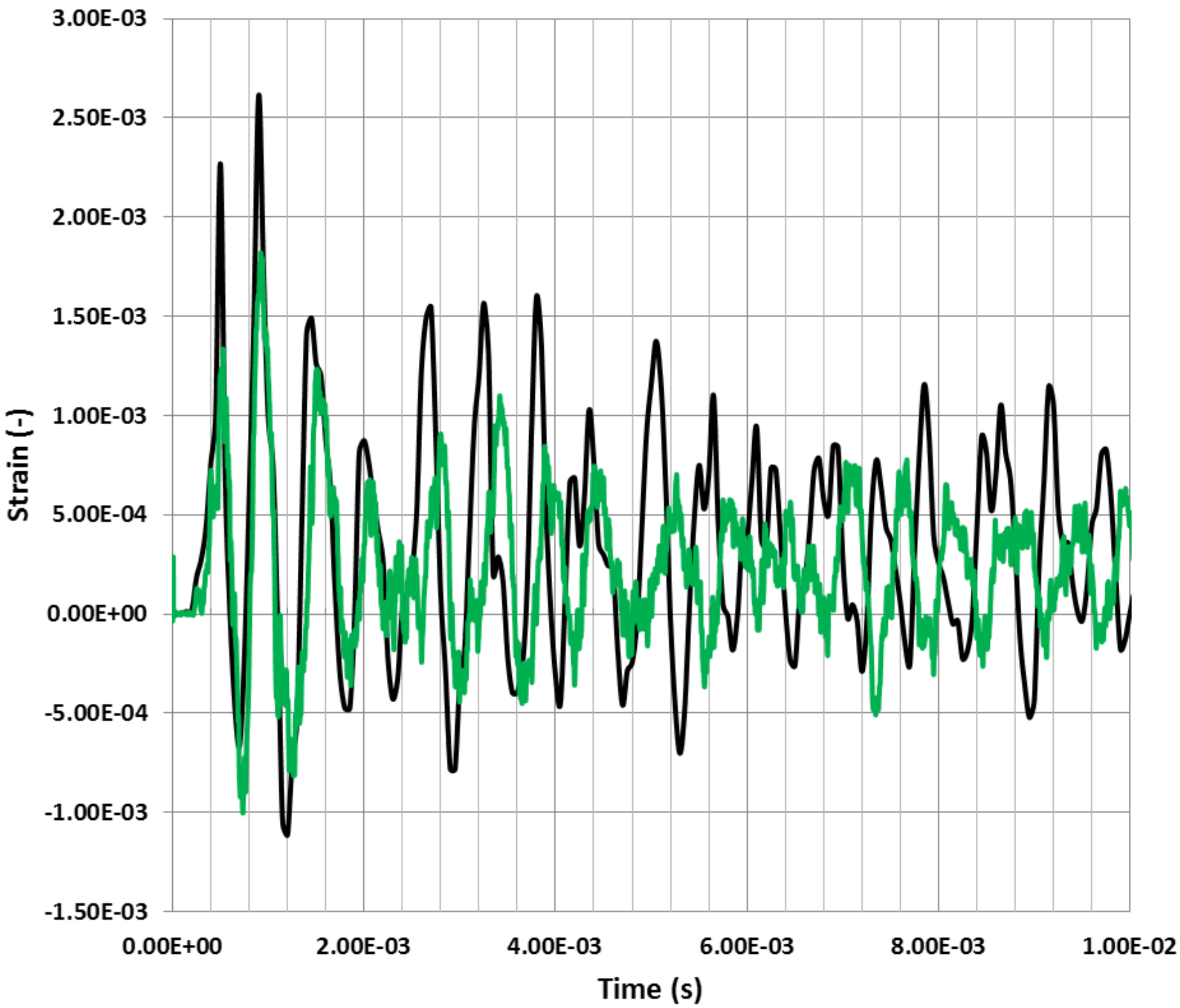

Figure 15: Measured (green) and predicted (black) aft end dynamic hoop strain data from Test 1 are plotted above. Test data was recorded from gauge 9-AEH.

The initial deflection of the vessel results in minor plastic deformation with the result that the subsequent oscillation is not centered on zero, but on some positive value. Generally, the model overestimated the magnitude of this offset, but predicted the peak-to-peak magnitude of the subsequent oscillations reasonably well. There are several possible explanations. One is that the strain gauges were not located at the point of peak strain. Another is that the vessel material is stronger than what was assumed in the model so the amount of plastic deformation was less than predicted. Another possibility is that the model is conservative.

Plastic Strain Measurement (Vessel Diameter)

Pre- and post-detonation measurements of the EDS vessel outer diameter were made at nine (9) points along the outer surface. The locations of the points are referenced from the aft end of the EDS vessel. Using this datum, the center axis of the charge was at 34 in. The diameter measurement was accomplished through the use of a stainless steel π-tape. The readability of the tape yielded an error of ±0.001". The error due to accurate placement on the cylinder was estimated to be +0.000"/-0.002". In addition, an error associated with thermal expansion was calculated to be around +0.000"/-0.0015" for a 10°F change. For both tests, the pre-detonation measurement was made early in the morning before the vessel heated. Therefore, the measurement error associated with the pre-detonation measurements is +0.001"/-0.003". The error associated with the post-detonation measurement is +0.001"/-0.005". Temperature rise on the surface of the vessel was measured using an IR thermometer and confirmed to be between 5°F and 10°F from morning to afternoon. Pre- and post-detonation measurements are compiled in Figure 16.

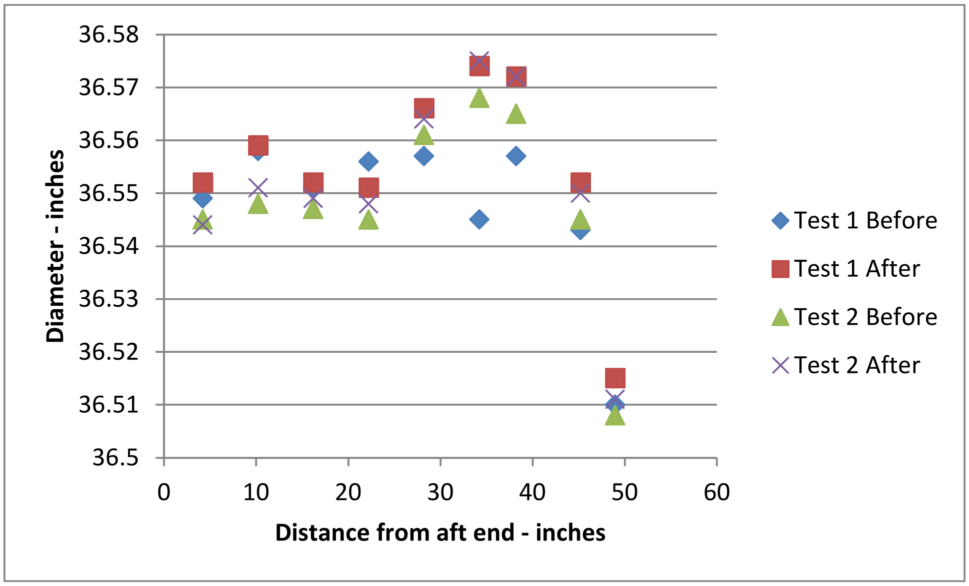

Figure 16: This image summarizes the before and after EDS vessel diameter measurements for Tests 1 and 2. The location of the center of the charge is around 34 in.

The change in diameter at each point for each test is shown in Figure 17. The maximum diametrical plastic expansion was 0.029 inch (Test 1 at 34.25 in.) which corresponded to a plastic strain of 0.079%. This is only about one-third of the predicted plastic strain of 0.084 inch. Taking into consideration the uncertainty in the measurement, the maximum strain possible was 0.090%. As expected, the largest plastic deformation at all points occurred on the first explosive test with only minimal deformation on the second test.

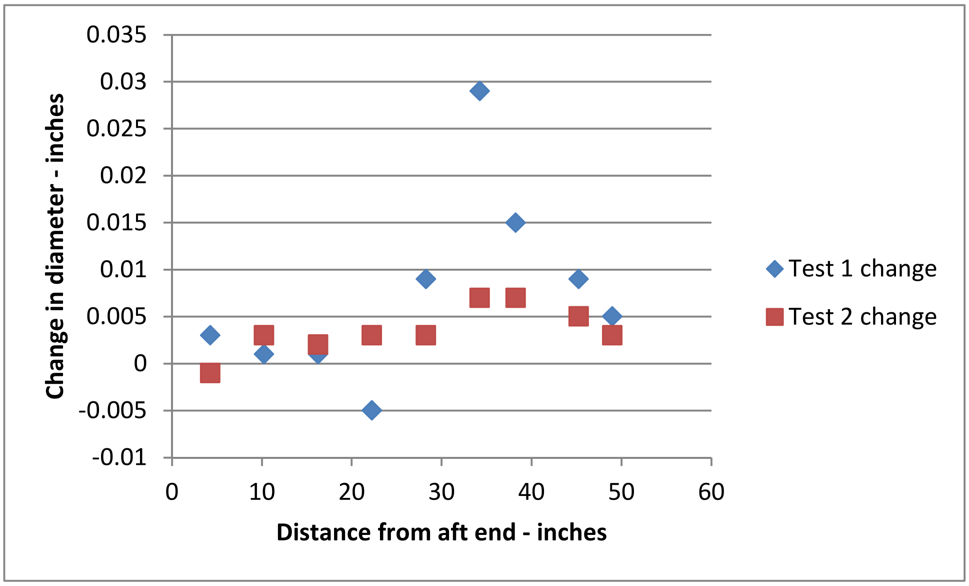

Figure 17: This image shows the difference between the before and after EDS vessel diameter measurements for Tests 1 and 2. The location of the center of the charge is around 34 in.

5. CONCLUSIONS

General Experiment

Two explosive tests were conducted on the newest EDS vessel at testing site 9920, Sandia National Laboratories, Albuquerque, NM as part of the process for qualifying the vessel for an explosive limit of 9 pounds TNT. Test 1 exposed the EDS vessel to 125% of its proposed rating (11.25 lbs. TNT-eq.) and Test 2 exposed it to 100%. Test data were compared to modeling results for the EDS vessel under these loads that was accomplished by SNL/CA. Measured dynamic strain and permanent deformation were less than predicted indicating that the model is conservative.

Acceptability Criteria

Outlined in the test plan was a list of acceptability criteria for successful EDS testing. These criteria and whether or not the individual criterion was satisfactorily achieved are discussed below (in order, as they appear in the test plan).

1. Maximum equivalent plastic strain
    a. Cylindrical wall
        i. Max. allowable limit: 0.17%
        ii. Measured value: 0.090%
    b. Aft end
        i. Max. allowable limit: 0.6%
        ii. Measured value: no measureable deformation
2. No deformation or damage was caused during EDS testing that would affect the form or fit of the vessel. There was superficial, interior damage to the EDS vessel (discussed above), but this minor damage is not expected to affect EDS functionality or safety.
3. No leakage was noted from each source:
    a. Leak tests both pre- and post-detonation confirm that maximum leakage rates around the Grayloc door seals were not surpassed.
    b. The vessel retained pressure following detonation.
    c. No leakage was observed from the drain port during and following the detonation as determined through high-speed imaging.
    d. No valves or fittings indicated leakage during the detonation as determined through high-speed imaging.
    e. No permanent distortion or damage to sealing surfaces was indicated.

f. Some fittings did become slightly loose following the tests, but were easily re-torqued to proper specifications. No damage to the sealing surfaces of the fittings occurred.
g. Acceptable leak rates were attained using the post-detonation vessel condition and the Grayloc seals. The EDS vessel sealed properly with an acceptable leak rate following each detonation.

The tests were successful in determining critical EDS vessel deformations and verifying its safe operation before and after critical design loads. Dynamic strain data and plastic strain measurements verified appropriate material response to loads of 125% and 100% of design load. All design criteria, for which data were collected, were successfully met.

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