SAND2016-3516C

EDS Containment Vessel Explosive Test and Analysis

ABSTRACT

This report documents the results of two of tests that were performed on an explosive containment vessel at Sandia National Laboratories in Albuquerque, New Mexico in July 2013 to provide some deeper understanding of the effects of charge geometry on the vessel response [1]. The vessel was fabricated under Code Case 2564 of the ASME Boiler and Pressure Vessel Code, which provides rules for the design of impulsively loaded vessels [2]. The explosive rating for the vessel, based on the Code Case, is nine (9) pounds TNT-equivalent. One explosive tests consisted of a single, centrally located, 7.2 pound bare charge of Composition C-4 (equivalent to 9 pounds TNT). The other test used six each 1.2 pound charges of Composition C-4 (7.2 pounds total) distributed in two bays of three.

INTRODUCTION

The Explosive Destruction System (EDS), which was developed at Sandia National Laboratories, is used by the US Army to destroy recovered chemical munitions. The apparatus treats chemical munitions through explosive access using shaped charges followed by chemical neutralization of the agents. The process is conducted inside a stainless steel vessel which both contains the detonation and serves as a chemical reactor.

The vessel was fabricated per Section VIII Division 3 of the ASME Boiler and Pressure Vessel Code and Code Case 2564 [1]. The Vessel Design Specification required by the ASME Code Case specifies a quantity and location of explosives to be used as the design basis impulse for the vessel. To provide the maximum flexibility to treat a variety of recovered munitions in the EDS, the vessel was designed and tested for the maximum explosive loading from a centrally-located charge.

Hydrocode analyses were performed on this vessel for several configurations and charge loads. The initial intent was to provide predictions for vessel loads and subsequent strains in order to retroactively develop a load limit for the system per the ASME Code Case – previous, like vessels, had been already designed and built. Analyses for unitary TNT charge weights between 5lbs and 50lbs were performed in order to bound the ASME criteria. Once this process provided for the 9lb TNT limit, additional analyses were conducted to determine the effect of a distributed load of six smaller charges on the vessel at the 9lb design limit. This configuration was chosen based on the intended use of the EDS to process up to six, explosively configured chemical munitions at one time.

By analysis, equivalent net explosive loads distributed in the vessel are predicted to deliver lower peak strains to the vessel. However, there had been no experimental results to validate the hydrocode analysis of this (or similar) distributed charge configuration. This paper documents the results of a six-distributed-charge experiment configuration and compares the results with a unitary charge of the same explosive weight, and then relates the results with earlier hydrocode analysis of similar configurations.

VESSEL

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 gasket. 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. The closure clamps are secured with four 17-4 PH steel threaded rods with 4140 alloy steel threaded-nuts on one end and hydraulic nuts on the other. Pertinent vessel dimensions are provided below in Table 1.

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

Table 1: Dimensional properties for vessel components.

HYDROCODE RESULTS

For each explosive charge configuration, an Eularian shock wave code was used to calculate the detonation pressures inside the vessel. The detonation velocity was set to 6.93 km/sec, typical for TNT. The JWL (Jones-Wilkins-Lee) equation of state, which is an empirical mathematical expression relating the pressure to volume and energy of the detonation products during the detonation process, was used. Material properties for the analysis are listed below in Table 2.

	Density	Young's modulus	Poisson's ratio	Yield stress	Hardening modulus
	$\frac{klb\text{-}s^2/in}{in^3}$	ksi	ksi		ksi
Vessel body and door (316 SS)	7.21e-7	30.0e+3	0.3	40.4	-
Seal ring (17-4 PH SS)	7.21e-7	30.0e+3	0.3	119.0	145.0
Clamps (steel)	7.21e-7	29.0e+3	0.285	-	-

Table 2: Material properties for vessel components.

This one-way coupled simulation was performed for different explosive loads for a unitary charge of TNT and a distributed 6-pack charge of TNT. The equivalent plastic strains were extracted at pertinent and critical locations, such as the waist center of the vessel and the center of the aft end, and were used to assess the performance of the vessel.

For the unitary charge, the explosive was simulated as a single, centrally-located, cylindrically-shaped, bare charge of TNT with the same aspect ratio as the vessel. The detonation was initiated at both ends of the cylinder along the axis. Figure 1 shows the evolution of pressure inside the vessel. The black region at time zero is the TNT. The grey dots along the walls are pressure tracers, where the pressure histories were recorded. A typical pressure-time history near the waist center is shown in Figure 1. For these calculations, the walls were specified to be rigid.

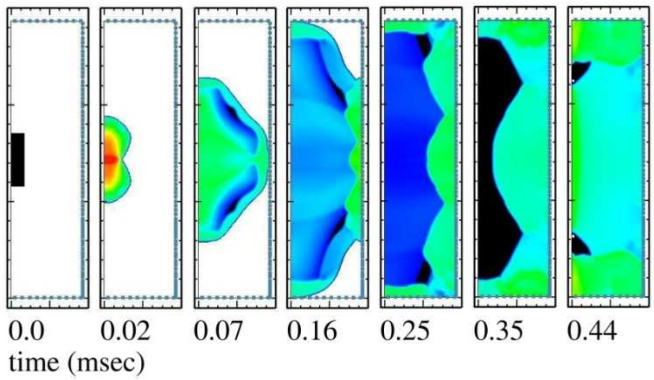

Figure 1: Pressure time history for unitary 7.2lb charge.

For the distributed charge, the explosive was simulated as six, distributed, cylindrically-shaped bare charges of TNT identical in size, each having the same aspect ratio as the vessel. The detonation was initiated at both ends of the each cylinder along the axis. Two groups of three charges at were located on two planes perpendicular to the vessel ends and parallel to the vessel axis at 7.250 inch center-to-center on an 8.372 inch diameter circles. The forward three charges were rotated so that one of the charges was top-dead-center. The rear three charges were rotated 60 degrees from the front three so that the rear set had one charge at bottom-dead-center and two, equally spaced, 60 degrees from top-dead-center. The two sets of charges were spaced 8 inches apart, about 12.25 inches center-to-center. This positioning is slightly closer than that for the subsequent experiment. Figure 2 shows the evolution of pressure inside the vessel.

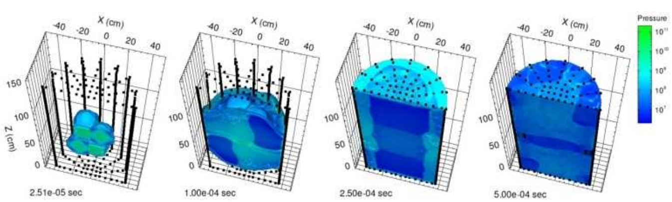

Figure 2: Pressure time history for distributed 7.2lb charge.

The pressure histories were transferred to an explicit finite element code as input loads to perform the structural analysis of the vessel under impulsive loadings. Here, the vessel parts were treated as deformable. A material model native to the code was used for both the vessel body and door, which are made from 316 stainless steel.

The pertinent results of the analyses are shown in Table 3.

CHARGE	EPS (%) INTERIOR	EPS (%) CENTER	EPS (%) EXTERIOR	AFT END BENDING (%)
Unitary	0.260	0.070	0.013	0.49
Distributed	0.168	0.035	0.012	0.85
Ratio dist./unitary	0.646	0.5	0.923	1.755

Table 3: Comparative results from hydrocode analysis.

A graphic showing the relative peak strains for the distributed charges (left) and the unitary charge (right) is shown below.

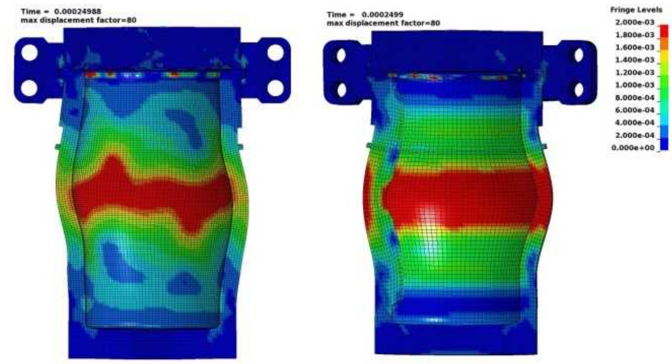

Figure 3: Amplified vessel deformation at peak strain.

EXPERIMENTAL RESULTS

Dynamic strain gauges (Vishay EP-08-250BG-120, 120 ohm, biaxial) were installed on the EDS vessel. In addition, 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 and validated through post-test signal processing techniques. Strain gage location and orientation are shown in Table 4. The bulk of this comparison focuses on gage 2-H and 4-H, highlighted in Table 4. Cursory analysis is performed on gages 1-H and 3-A.

Gauge	Hoop/Axial	Location
1	H	Aft center
1	A	Aft center
2	H	Vessel body 1/3 from aft
3	A	Vessel body 2/3 from aft
4	H	Vessel body mid-point
5	H	Clamp outside
5	A	Clamp outside
6	H	Clamp inside
6	A	Clamp inside
7	H	Door center

Table 4: Strain gage location and orientation.

The complete test series consisted of a hydrostatic pressure test, and four explosive tests in the vessel. A hydrostatic test was conducted prior to the dynamic testing in order to calibrate the strain gauges and validate the response of the vessel to static loads. The first explosive test provided the required over-test, while the second explosive test served to demonstrate shakedown and the absence of additional plastic deformation. The third explosive test used cast TNT machined to the same diameter and mass as the C-4 charge at the design rating. In the final explosive test, 7.2 pounds of C-4 was separated into 6 discrete, identical charges (of the same aspect ratio as the 7.2 pound unitary charge of the second test) and distributed in the vessel. Table 5 shows the complete series of experiments, with the tests for this comparison highlighted.

Test	Description
Hydrostatic pressure	Static pressurization to 2850 psi

9 lb. Composition C-4	1.25 X over-test, 11.25 lb. TNT eq.
7.2 lb. Composition C-4	1 X test, 9 lb. TNT equivalent
9 lb. TNT	Comparison of TNT and Comp C-4
Six 1.2 lb. Comp C-4	9 lb. TNT equivalent distributed

Table 5: Complete vessel test series.

The 7.2lb explosive test consisted of explosive packed into a 5-inch inside diameter cardboard shipping tube to a density of 1.6g/cc. Two EBW detonators were used, one placed in each end. The two detonators were detonated simultaneously (within tens of nanoseconds). A 1/4 inch thick disk of 10lb/ft^3 polyurethane was placed at the midpoint of the cylinder. The intent of the disk was to prevent radial jetting that occurs when detonation fronts from both ends of the cylinder meet. The total length of the explosive and disk was 6.6 inches. The thickness of the cardboard tube was 1/8 inch. The charge was located at dead center along the length and diameter and held with 2-inch thick sheets of Styrofoam insulation board. Figure 4 shows the unitary charge positioned in the vessel just prior to detonation.

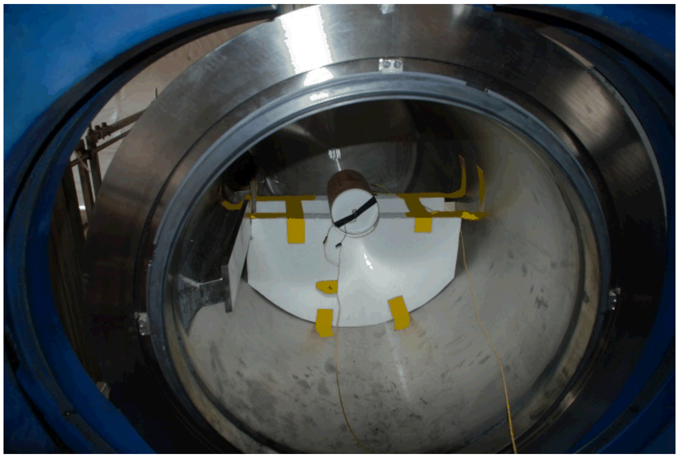

Figure 4: Unitary 7.2lb charge in vessel.

The six distributed charge test consisted of six 1.2-pound charges of Composition C-4 with three of charges nearer the aft and three nearer the door. Each charge was 2.5 inches in diameter and 4.25 inches long so as to maintain a comparable aspect ratio to the unitary test charge, and to the vessel itself. Two feet of detonating cord were used to initiate each end of each charge. The detonating cord adds about 0.17lb of explosives to the charge and was ignored for this analysis. Each group of three charges was located on a plane perpendicular to the vessel ends and parallel to the vessel axis at 7.250 inch center-to-center on an 8.372 inch diameter circle. The forward three charges were rotated so that one of the charges was top-dead-center (directly under gage 3-A). The rear three charges were rotated 60 degrees from the front three so that the back set had one charge on the bottom and two, equally spaced, 60 degrees from top-dead-center (directly under gage 2-H). The planer locations of each group of three charges was not exactly the same as for the hydrocode analysis. The charge center planes were separated by 12.25 inches in the hydrocode analysis, as opposed to 19 inches for the experiment. The allowed the charges to be located directly below strain gages.

Strain gages were located along top-dead-center of the exterior of the vessel at one-third of the vessel interior length (gage 2-H), at two-thirds of the interior vessel length (gage 3-A) and above the center point of the vessel interior (gage 4-H). Other gages were attached to the vessel aft (gages 1-A and 1-H), door (gage 7-H) and various locations around the clamping system (biaxial gages 5 and 6). Gage 2-H, located at one-third of the interior vessel length, at 25 inches from the exterior aft (19 inches from the interior aft), had only an active hoop element. Gage 3-A, located two-thirds along the interior body length, at 44 inches from the exterior aft end of the vessel (38 inches from the interior aft end), had only an active axial strain element. And gage 4-H, located at the center of the vessel body, 35 inches from the aft (29 inches from the interior aft of the vessel, had a hoop strain element, but no axial strain element. This gage is positioned so that it is equidistant from the planes containing each group of three charges. This location records both the un-clocked group and the clocked group equally, with initial blast coming from a top-dead-center charge from the forward group and the shock collision from two charges from the rear group. Figure 5 shows the six distributed charges positioned in the vessel just prior to detonation.

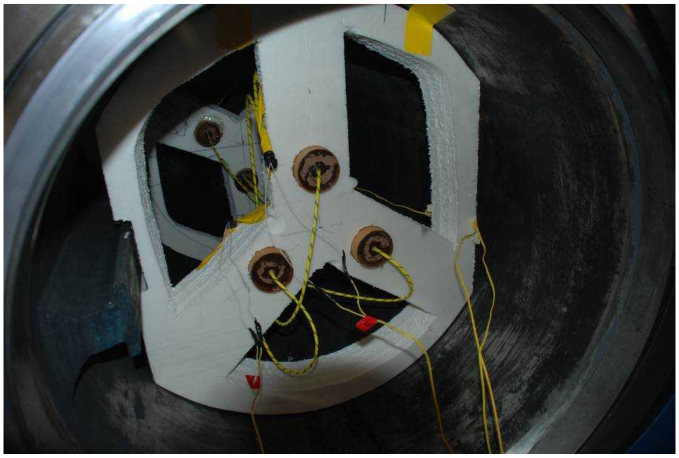

Figure 5: Six distributed 1.2lb charges in vessel.

The 1.25X over-test conducted in this vessel prior to these tests resulted in a permanent strain of about 580$\mu\varepsilon$. In each subsequent test, there was a very small (almost immeasurable) amount of additional permanent strain noted. Therefore, this additional, very small shift was ignored in this comparison.

Figure 6 shows the comparison of the unitary 7.2lb charge with the distributed 7.2lb (6 X 1.2lb) charge for the strain gage 4-H (Table 4), located above the center point of the interior of the vessel. The extent of the entire measurement is 20ms. However, for clarity, only the initial 2ms of signal is shown.

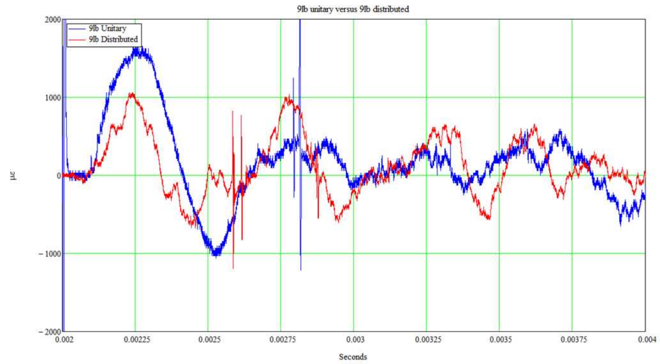

Figure 6: Comparison of unitary and distributed charges for strain gage 4-H (center-body-hoop).

It is noticeble in the distributed charge waveform that there are two distinct peaks in the initial rise of the waveform. This is an effect of the two sets of three charges being clocked differently at the planes equidistant from this gage. The peak strain from the unitary charge is about 1580με, while the maximum peak strain from the distributed charges is about 1040με, approximately 66 percent of that of the unitary charge. The waveform for the distributed charge has been shifted left by 0.2ms for this comparison. While the signals were started from detonator initiation, the distributed charge strains commenced slightly later in time because of the extra time required to propagate the 24 inches of detonating cord and the difference in distances to this gage from the clocked charges. The amplitudes of the two waveforms are similar after about the third cycle (not shown in the plot).

A running integration of strain for each signal was calculated over 10ms in order to compare intermediate-time loads on the vessel. These results are shown Figure 7, again, with one waveform shifted 0.2ms for alignment purposes.

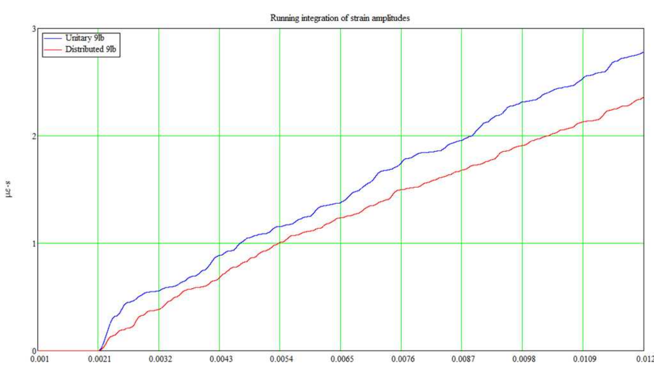

Figure 7: Comparison of unitary and distributed charges for running strain integrals for gage 4-H.

The ratio of running integration of strain is a measure used in this analysis to provide a comparison of intermediate-time loads on the vessel from the two charges. For this technique to work adequately, the waveforms must be aligned to start at the same point, and so the distributed charge waveform was shifted left exactly 0.2ms (as in figures 6 and 7) prior to the ratio being taken. This ratio of distributed charge versus unitary charge results in about 0.84:1 throughout the measurement beyond the first two cycles, and remains consistent throughout the entire 20ms measurement. This ratio is shown in figure 8. These results indicate that the distributed charge imposes a hoop strain energy/impulse that is only about 84 percent of that of a unitary charge of the same weight at the center location along the waist of the vessel. Because of fluctuations in the signals and bit-noise, this running integration ratio process is somewhat uncertain for the initial 3ms, but converges nicely, and remains constant after that point.

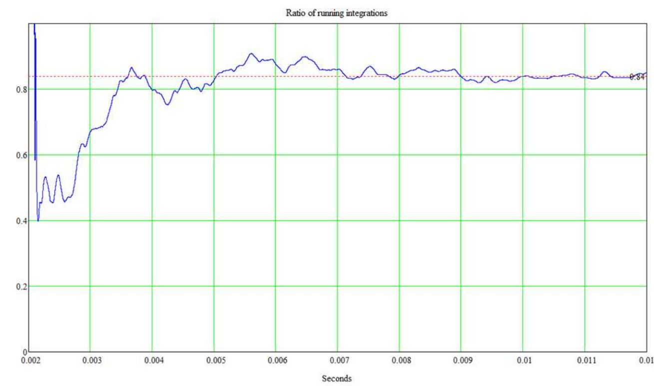

Figure 8: Ratio of distributed to unitary charge running strain integrals for gage 4-H.

Gage 2-H (Table 4), located at one-third of the interior length of the vessel, was located directly under the charge plane containing the three charges that were clocked 60 degrees from top dead center. This gage then was not located directly under one of the three charges in that plane but equidistant from two charges each clocked 60 degrees left and right. This location is interesting because it measures the shock collision from these two charges. Gage 2-H, located directly under the plane containing the front set of three charges, did not have an active hoop element. The hoop component of this gage failed prior to these tests and only axial strain was measured.

Figure 9 shows the comparison of the unitary 7.2lb charge with the distributed 7.2lb (6 X 1.2lb) charge for gage 2-H. The extent of the entire measurement is 20ms. However, again for clarity, only the initial 2ms of signal is shown below.

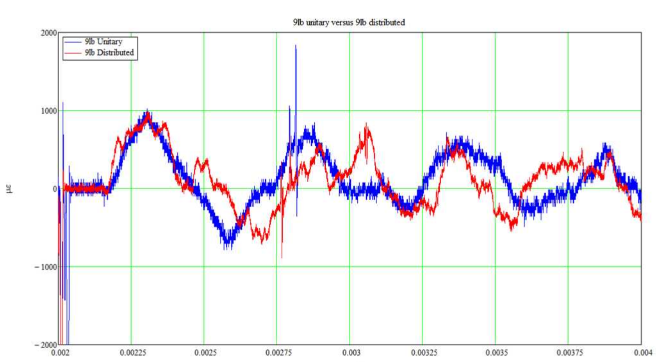

Figure 9: Comparison of unitary charge and distributed charge for strain gage 2-H (1/3-body-hoop).

The peak strains for both charges is about 900με. The waveform for the distributed charge has been shifted left by only 0.02ms for this comparison, almost coincident in time of arrival for the blast wave and about the extra time required for detonation of the 24 inches of detonating cord.

As for gage 4-H, a running integration of strain with time for each signal was calculated over 10ms in order to compare intermediate-time loads on the vessel. These results are shown in figure 10, again with one waveform shifted 0.02ms for alignment purposes.

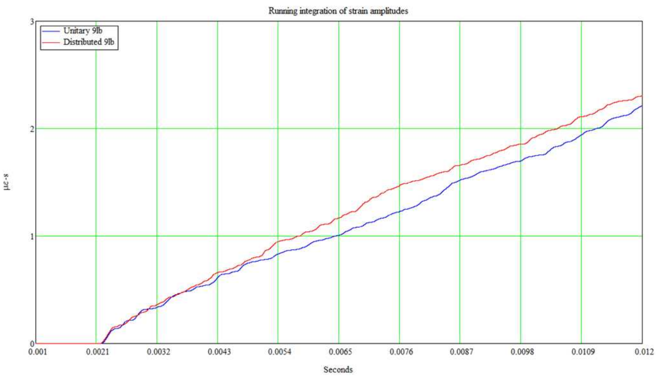

Figure 10: Comparison of unitary and distributed charges for running strain integrals for gage 2-H.

This ratio of distributed charge versus unitary charge for this gage location results in about 1.1:1 throughout the measurement beyond the first two cycles and remains consistent throughout the entire 20ms measurement. These results indicate that the distributed charge imposes a hoop strain energy/impulse that is about 110 percent of that of a unitary charge of the same weight at a location directly under the rear plane of three distributed charges. This ratio is shown in figure 11.

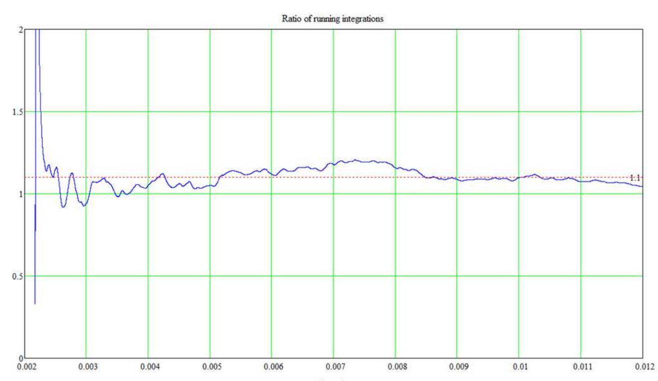

Figure 11: Ratio of distributed to unitary charge running strain integrals for gage 2-H.

In order to be complete, the axial gage located directly under the front group of charges (gage 3-A) was analyzed as well. All of the plots are not shown here however. The initial strain peaks for gage 3-A are noisy and difficult to discern exactly. However, the running integration converges to a ratio of distributed charges to unitary charge strain energy/impulse of about 0.75:1, lower than that for the gage 2-H, highlighting that shock interactions between charges are very much important when designing a representative impulsive load through the use of multiple, distributed charges.

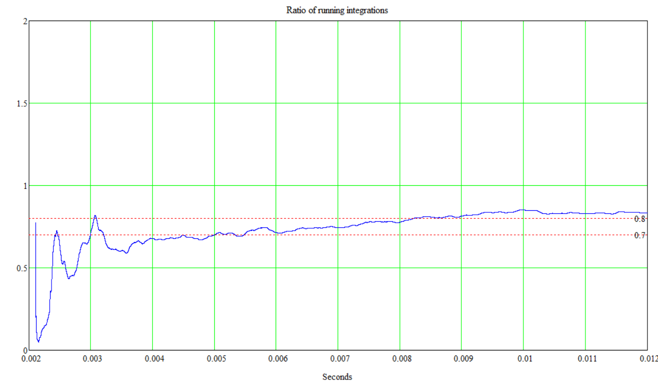

Figure 12: Ratio of distributed to unitary charge running axial strain integrals for aft end gage 3-A.

As well, a comparison of gage 1-A at the center of the aft end was analyzed. In both peak strain and integrated strain, there was approximately a 50 percent increase for the distributed charge geometry. For design purposes in this vessel, this increase is of little consequence, as the hoop strains at the waist of the vessel are the limiting factor.

Finally comparing the two gage locations 4-H and gage 2-H for each test individually, somewhat of a strain profile for each test may be gleaned for each configuration. As expected, the unitary charge produces a maximum peak hoop strain and integrated strain at the center point of the wall of the vessel. The waveforms in figure 13 have not been time shifted in the strain versus time plots. However, for the strain ratio plots, the off-center gage (2-H) waveforms for the unitary charge case and the distributed charge case have been shifted by 0.08ms in order to align the waveforms for strain-integral ratios.

For the unitary charge, the strain at gage 2-H is reduced to about 57 percent of the maximum peak strain at gage 4-H and about 74 percent of the integrated strain at gage 2-H from gage 4-H.

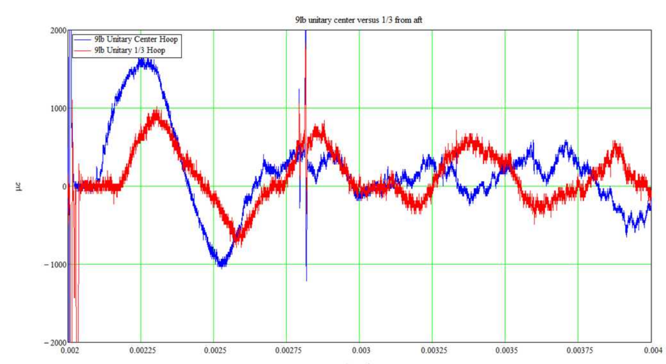

Figure 13: Comparison of unitary charge strains at gages 4-H (center) and 2-H (1/3 from aft end)

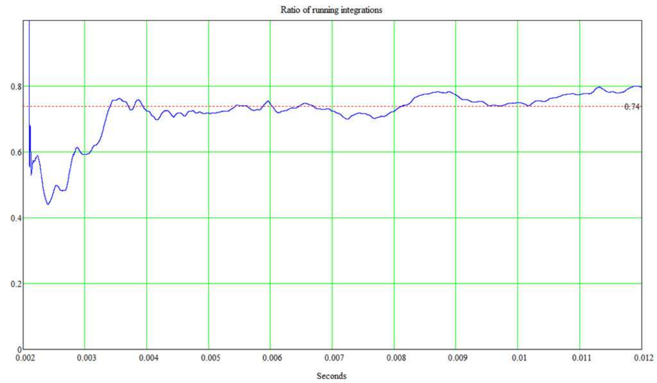

Figure 14: Ratio of unitary charge running strain integrals for gage 2-H (1/3 from aft end) to 4-H (center).

The distributed charge geometry results in a strain at gage 2-H that is reduced to about 90 percent of the maximum peak strain at gage 4-H and about the 93 percent for integrated strain at 2-H from gage 4-H.

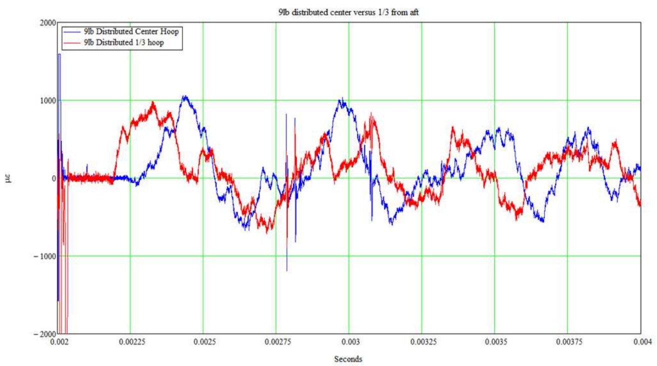

Figure 15: Comparison of distributed charge strains at gages 4-H (center) and 2-H (1/3 from aft end)

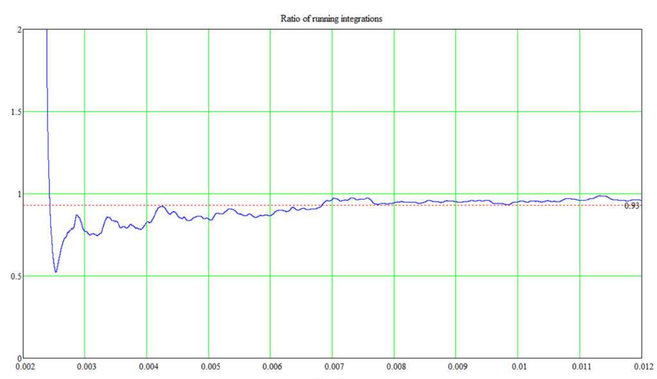

Figure 16: Ratio of distributed charge running strain integrals for gage 2-H (1/3 from aft end) to 4-H (center).

A comparison of the hoop strains at the center point along the waist of the vessel between the hydrocode results and the experimental results at gage 4-H shows very good agreement. The ratio of peak strain of the distributed charge versus the unitary charge predicted from the hydrocode is about 0.65, while the ratio of peak strain of the distributed charge versus the unitary charge from the experiments is 0.66. A comparison of the hydrocode results to the experimental results (gage 1-H) for the aft end strain are 1.8 and 1.5 respectively, indicating that while the strains on the body of the vessel are reduced by distributing the charge, the strains on the ends may be increased.

CONCLUSION

In general, there is good agreement between the hydrocode analyses and the experimental results. There have been several iterations of hydrocode analysis performed on this vessel, as well as many other vessels designed and used for similar applications by this team, enough to lend confidence in the efficacy of the analysis of the relatively simple dynamic phenomena of vessel deformation.

The experiments validate the results of the analysis for this comparison of a unitary versus distributed charge and provide insights into the advantages and disadvantages of both. At the center vessel hoop locations, the distributed charge results in lower peak strains (66%) and lower integrated strains (84%) over the unitary charge.

At a location one-third of the interior extent of the vessel, the distributed charge results in peak strains on the order of that of the unitary charge where the charges are positioned such that there is blast wave focusing, and a significantly lower strain where there is no blast wave focusing. At the location where there is no shock focusing (directly under one of the distributed charges), axial strain comparisons (no hoop data available) indicates a reduction of distributed charge strain to about 74% of that of the unitary charge strain.

The distributed charge then provides a more eccentric load on the vessel, but provides a load that is far lower in overall extent (less overall deformation). Lastly, the distributed charge seems to increase the loads on the ends of the vessel by a reasonable amount, again by shock focusing. However, for this design, the increase is of no consequence.

Some consideration was given to intentionally delaying the timing of each charge to further reduce the loads on the vessel by temporal smearing of the blast, but no analysis or experiments were conducted to bear this idea out.

ACKNOWLEDGMENTS

Put acknowledgments here.

REFERENCES

[1] Yip, M., and Haroldsen, B.L., 2013, "Design Basis of an Impulsively Loaded Vessel for Specific Loading Configurations," Proc. of the ASME 2013 Pressure Vessels and Piping Conference, Paris, France, 7 pages.

[2] Haroldsen, B., Yip, M., Stofleth, J., and Caplan, A., 2013, "Experience with Using Code Case 2564 To Design and Certify An Impulsively Loaded Vessel," Proc. of the ASME 2013 Pressure Vessels and Piping Conference, Paris, France, 7 pages.