LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-TR-236063

Isentropic Compression Experiments Performed By LLNL On Energetic Material Samples Using The Z Accelerator

K. S. Vandersall, D. B. Reisman, J. W. Forbes, D. E. Hare, F. Garcia, T. M. Uphaus, A. J. Elsholz, C. M. Tarver, J. H. Eggert

November 1, 2007

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

ISENTROPIC COMPRESSION EXPERIMENTS PERFORMED BY LLNL ON ENERGETIC MATERIAL SAMPLES USING THE Z ACCELERATOR

Kevin S. Vandersall, David B. Reisman, Jerry W. Forbes, David E. Hare, Frank Garcia, Timothy M. Uphaus, Allen J. Elsholz, Craig M. Tarver, and Jon H. Eggert

Lawrence Livermore National Laboratory, Livermore, CA 94550

Campaign 2 Milestone Report

September 30, 2007

EXECUTIVE SUMMARY

Several experiments have been conducted by LLNL researchers using isentropic compression experiments (ICE) on energetic materials as samples from Fiscal Year 2001 (FY01) to Fiscal Year 2005 (FY05). Over this span of time, advancements of the experimental techniques and modeling of the results have evolved to produce improved results. This report documents the experiments that have been performed, provides details of the results generated, and modeling and analysis advances to fully understand the results. Publications on the topics by the various principal investigators (PI's) are detailed in the Appendices for quick reference for the work as it progressed.

INTRODUCTION

The overall objective from these experiments is to obtain the un-reacted isentrope (and thus the Hugoniot that can be calculated from the isentrope) on several High Explosive (HE) (also known as energetic material) formulations. The main motivation of performing isentropic compression on explosive samples is that it allows an un-reacted isentrope of explosive material to be obtained to a higher pressure than with shock waves due to the shock wave causing the explosive to react and detonate rapidly at the higher pressures. Ongoing experiments have been performed using the Z Machine at Sandia National Labs (SNL), Albuquerque. The Z accelerator facility offers a viable tool for performing "Isentropic Compression Experiments" (ICE) [1-3].

Isentropic Compression is accomplished on the machine by using a large-amplitude, short-duration current pulse delivered into a metal panel "floor" which backs the sample and creates a ramp compression wave from the magnetic pressure. The Z-machine provides ramp wave loading with ~300 ns rise time to peak pressure in the range of 5-35 GPa for these experiments (with the machine capable of generating 100's of GPa (Megabar) pressures). The diagnostic of choice for these experiments is VISAR laser interferometry [4] and the data is obtained at the sample rear surface. From the VISAR signals of particle motion, generally at the interface of the sample and a backing window material, the sound speed as a function of pressure can be obtained.

Several explosive materials have been selected in this study to help understand the response of the different explosive molecules and also the binder effects in the different formulations. Several publications have been published during this project [5-11] and materials tested include LX-04 (HMX / Viton), Ultra fine TATB, LX-17 (TATB / Kel-F), single crystal HMX, Viton Binder, LX-10 (HMX / Viton), LX-14 (HMX / Estane), PBX9502 (TATB / Kel-F), RX-55-AE5 (LLM-105 / Viton), LX-16 (PETN / VCTFE), LX-19 (CL-20 / Estane), and RSI-007 (CL-20 / binder). The various publications are listed in the appendix for quick reference.

As mentioned above, the ultimate result for each experiment is a complete isentrope on each material tested, although some of the data sets did not provide data with enough quality to get this information from every experiment. In the earlier experiments, "shocking-up" was a problem that occurs when the ramp transforms to a shock in the material. This is due to the loading ramp being too short for ramp loading in the material to be sustained. Over the course of improving the experiments, the "shocking-up" problem was improved upon, but not completely remedied due to the longer ramps pushing the limits of the machine design combined with the low density of the samples requiring longer ramps.

Future work is also being conducted as a follow on to this project using additional explosive formulations, binder materials, and possibly temperature effects (both heated and cooled). These tests are being conducted on the "small pulser facility" at Sandia National Laboratories, Albuquerque. This "small pulser facility" (also named Veloce) will allow a quicker turn around of the experiments, hopefully with a comparable pressure range as was achieved in these experiments. Data from these experiments will be forthcoming.

This report will discuss: the motivation for the work, procedure used, analysis techniques utilized, results obtained in the experiments, and analysis of the results followed by a summary, acknowledgements, references and appendices.

MOTIVATION FOR ICE ON ENERGETIC MATERIAL SAMPLES

The motivation for doing isentropic compression experiments on energetic material samples comes from detonation theory [12]. The un-reacted isentrope (obtained without reaction) is then used to calculate the un-reacted Hugoniot for the energetic material. As depicted below in Figure 1, the un-reacted Hugoniot will allow the determination of the theoretical explosive detonation parameters based on CJ (Chapman Jouget) and ZND (Zeldovich, von Neumann, Doering) theory. This is accomplished, first by plotting the un-reacted and reacted Hugoniots for the energetic material and plotting them on a pressure-volume plot and drawing a "Rayleigh line" from the initial volume and tangent to the reacted Hugoniot. The point that intersects the tangent to the reacted Hugoniot is known as the Chapman-Jouget state, and is the equilibrated pressure after the initial pressure spike in the detonation of an energetic material. The point where the Rayleigh line intersects the un-reacted Hugoniot is known as the peak pressure in the detonation, also known as the von Neumann spike.

While estimates of the CJ and von Neaumann spike pressure have been estimated for some time for most energetic materials and those values have been used with reasonable accuracy, an experimentally calculated value with improved accuracy will allow us to utilize an improve un-reacted EOS in high-fidelity simulations. This will, therefore, improve the accuracy of the calculations since the von Neumann spike and CJ pressures are used in code simulations. Naturally, the use of a ramp wave is key to determining the un-reacted insentrope (and thus Hugoniot) at the very high pressures where the peak detonation pressure is observed because a shock wave would rapidly cause reaction and subsequent detonation in the energetic material.

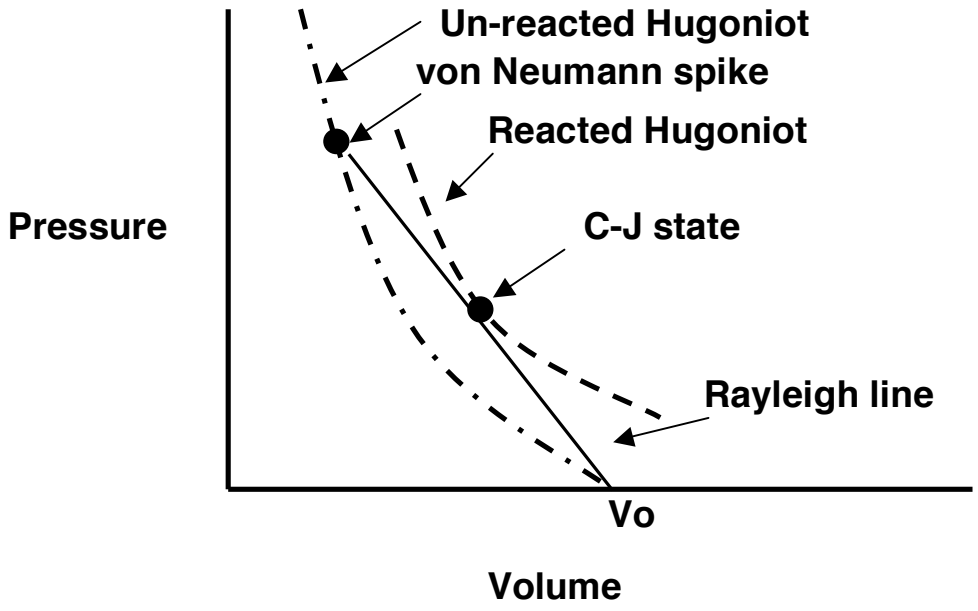

Figure 1. Detail of Detonation Theory utilizing the un-reacted and reacted Hugoniot for an explosive. The un-reacted Hugoniot can be obtained from an un-reacted isentrope generated from an isentropic compression experiment (ICE).

PROCEDURE

The first step in the process is deciding what materials to test and the peak pressures desired in the test. After that, the basic procedure for performing an experiment involves placing samples on test panels, having the panels installed on the machine, firing the machine, and collecting the data. However, due to the scale of the machine and experiment complexity, the start to finish time for the experiment is roughly 3-4 months (12-16 weeks). A "kick-off" meeting is first conducted at Sandia National Laboratories, where the desired samples, sample thicknesses, pressure ramp, peak pressure, and panel and machine parameters (if known) are discussed with the group at Z. During the following weeks, the unanswered questions at the kick-off are answered, the hardware is made, the samples are mounted on the panels, the panels are shipped to Sandia (LLNL does the panel assembly due the presence of energetic materials), and the experiment is assembled and fired.

Two different panel designs were predominantly used in the experiments, one being used for "low-pressure" (up to 20 GPa) and the other for "high-pressure" (up to 35-40 GPa). The "low-pressure" panel used a 20 mm by 20 mm cathode stalk, a gap of 3 mm between the stalk and panels, and panels 26 mm wide. The "high-pressure" panels used a 11 mm by 11 mm stalk, a gap of 2 mm between the stalk and panels, and panels 15 mm wide. Keep in mind that the "low-pressure" panel uses a larger stalk with wider panel and a bigger gap than the "high-pressure" panel. Because the pressure obtained is proportional to the current density, spreading the current over a larger area reduces the pressure achieved. The samples were all approximately 6 mm in diameter and 200-700 μm thick and mounted on the aluminum panels with a floor thickness of nominally 800 μm (although this was varied in development from roughly 500 μm to 1 mm). Photographs and a schematic of the basic panel design is shown in Figures 2 and 3, respectively. Figure 4 also shows a set of the "low-pressure" panels.

The samples were backed by windows that had a reflective surface (nominally 250 nm of silver) vapor deposited on the side in contact with the sample. The windows were either sodium chloride (NaCl) or lithium fluoride (LiF), depending on where the window was located as well as the peak pressure obtained in the experiment. The NaCl windows have a good acoustic impedance match to the energetic material sample, although it has a phase transition at about 25 GPa, so using this window at above this pressure is not advised.

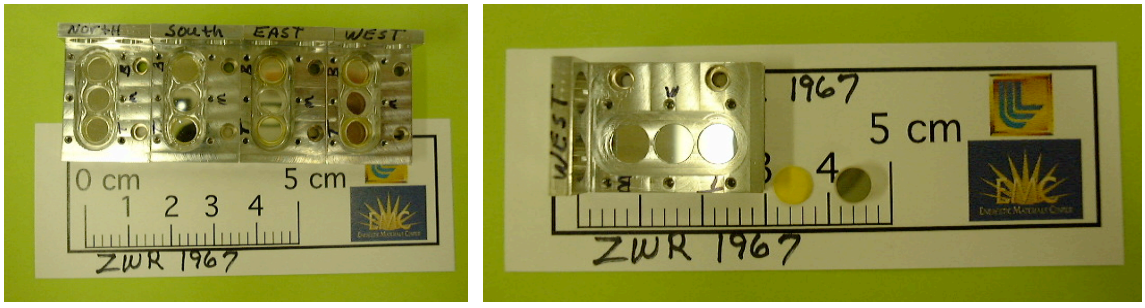

Figure 2. Photographs of the panels and samples used in Experiment ZWR1967. Panels used are the "high-pressure" (peak ~35 GPa) design and are narrower than the "low-pressure" panels (peak ~20 GPa).

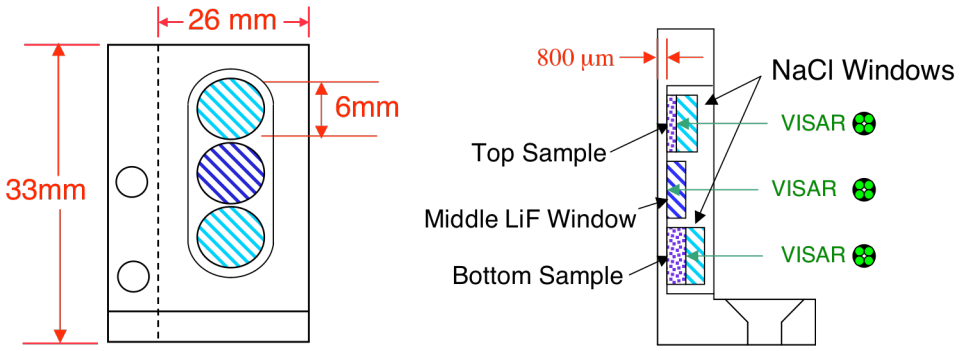

Figure 3. Schematic of the panels and sample locations for a typical experiment.

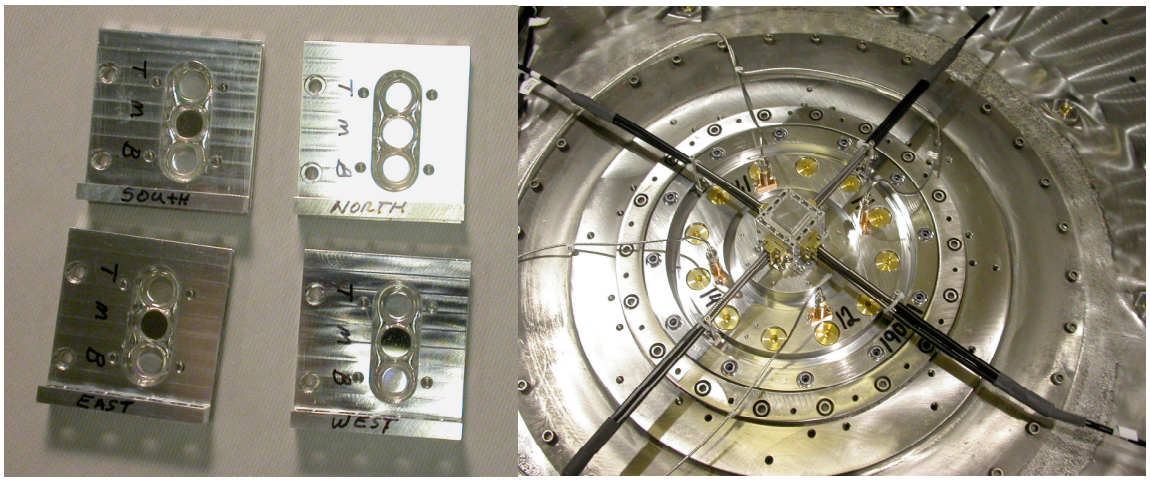

Figure 4. Photographs of the "low-pressure" (peak ~20 GPa) panel design and the panels mounted in the "square short" arrangement in the center section of the Z-machine.

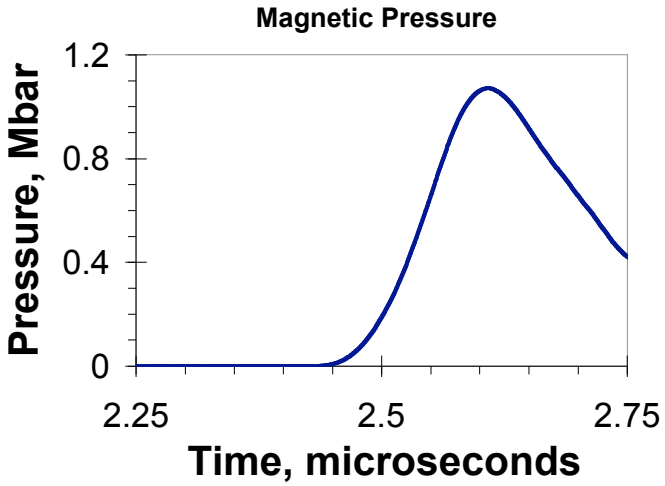

Figure 5. Graph showing a typical pressure pulse that can be obtained in an experiment at the Z-machine. The pressures utilized in this work were in the range of 15-40 GPa (150-400 kbar or 0.15-0.40 Mbar), and are at the low end of the pressure regime for the machine.

All 4 of the panels similar to that depicted in Figures 2 and 3 were assembled in a “square short” arrangement with each panel making up a side of the square. Note that in Figure 2, the panel is laying sideways with the top being toward the right and the bottom at the left. Figure 4 shows another photograph of 4 panels for an experiment after being assembled for the experiments in the center section of the machine before a shot. A typical pressure pulse for an experiment on the Z machine is shown in Figure 5. The pressures utilized in this work were in the range of 15-40 GPa (150-400 kbar or 0.15-0.40 Mbar), and are at the low end of the pressure regime for the machine.

It should be noted that the panel design evolved through the years. The first panels had only spots for two samples, and a third was added later. With the 3 locations for samples, it was common to use the top and bottom places for “thin” and “thick” samples each backed by windows and a measurement of the drive in the center location with a window mounted directly on the panel. This allowed three basic measurements, the first being the drive at the center location, the second being the interface between the “thin” sample and the window, and the third being the interface between the “thick” sample and the window. Figures 2-4 all show this typical sample arrangement.

Figure 6 shows a photograph of the Z-machine when firing. As depicted in Figure 6, the machine is an annular design and uses 36 capacitor banks and transmission lines. The capacitor banks are located in oil at the outer periphery of the machine and the transmission lines run through a water section on the way to the center section of the machine where the sample is placed. A typical charging voltage for the machine is 90 kilovolts. After the machine is fired, the VISAR data is collected by the technicians and provided electronically (usually on a CD) for the experimenters.

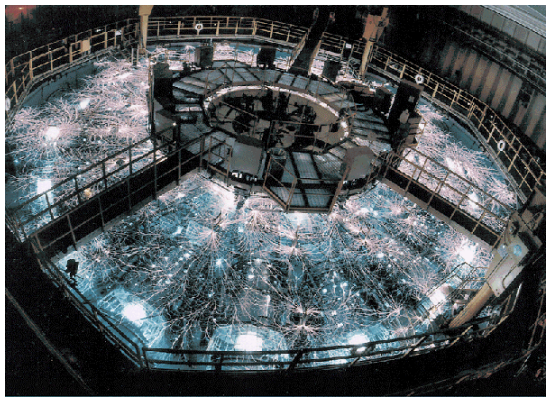

Figure 6. Photograph showing the firing of an experiment on the Z-machine. The diameter of the machine is approximately that of a baseball diamond (~30 meters or ~90 feet).

DATA ANALYSIS TECHNIQUES

Several data analysis techniques are available for analyzing isentropic compression experiment (ICE) data. The techniques have advanced through the years, mainly due to the inability of the simple analysis techniques to correctly compensate for the time dependent effects of the sample/window interface motion. At least 4 different analysis schemes have been utilized by different researchers to analyze isentropic compression experiment data. The first and least complex is the "Lagrangian" analysis and the rest involve using some sort of code to analyze. The

"Trac II code", a "Backward Integration" method, and the "Method of Characteristics" have all been used with codes. Each one of these is described below.

The least complex of the analysis techniques uses Lagrangian analysis to obtain an isentrope from the equation of state (EOS) "thick" and "thin" samples (also known as "EOS pairs") mounted on the panel and utilizes the sound speed transit times between the difference of thickness in the samples. This technique is depicted graphically in Figure 7 and shows the sample measurements resulting in two VISAR traces from the "thick" and "thin" samples followed by a "bootstrap" integration technique to provide the isentrope. The disadvantage of this technique is that it does not compensate for wave interaction affects that appear as a result of the long ramp loading affecting the reflection of the sound waves at pressure from the window and sample interface. This causes the measured velocity to vary from the actual velocity at moderate and higher pressures. In cases where the window material is a good impedance match to the sample (e.g. HE sample and NaCl window) it does a reasonable job, but does a poor job where there is not a good impedance match (e.g. HE sample and LiF window).

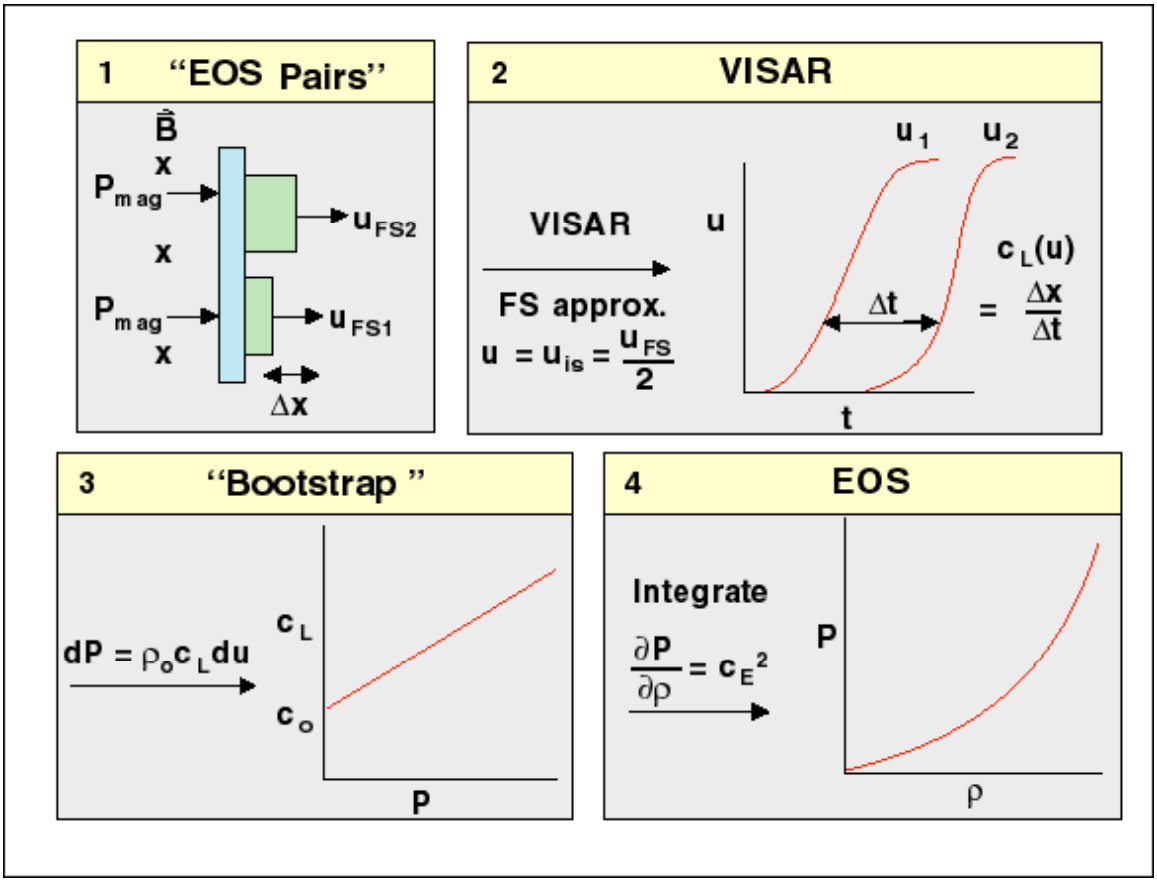

Figure 7. Flow chart showing a straightforward analysis technique for creating an equation of state from isentropic compression experiment data from two different thickness samples.Note that this technique assumes that "shock-up" is not observed in the samples.

This analysis technique assumes that no "shock-up" is observed in either of the samples, since an Equation of State (EOS) must be specified as your start state at the top of the shock to complete the analysis for the remainder of the ramp after the shock. Unfortunately, "shock-up" does occur in the experiments due to the relatively lower density and higher compressibility of the energetic

material samples (as compared to a metal) which push the limits of the pulse shape capability of the machine.

The "Trac II code" (3) is a forward technique that takes the machine current measurement and applies this to the panel material (aluminum in this case) and sends that pressure (induced by the current) forward (hence a forward technique) through the aluminum and then through the sample material to extract the isentrope. This code requires that the planar current be adjusted to a spherical current problem by using geometrical factors for the arrangement. Often when running the current through the panel the drive does not match and requires multiple iterations to tweak until the final runs through the sample are performed. Because the material parameters are tweaked to get a good fit of the measured VISAR traces to the calculated velocity versus time profiles, it does not necessarily offer a unique solution, which is a limitation to the technique.

The "Backward Integration" method [13] was developed by Dennis Hayes and takes the experimental velocity traces and moves them back in space by using the equations of motion. In going back in space it corrects the experimental velocity traces for the wave interaction effect. This technique is the basis of the new INVICE code [14] put out by Sandia. Because the material parameters are tweaked to get a good fit of the measured VISAR traces to the calculated velocity versus time profiles, it does not necessarily offer a unique solution, which is a limitation to the technique.

The "Method of Characteristics" [15] has been used by researchers at AWE, LLNL and is the basis for the CHARICE inverse analysis code [16] by Sandia National Labs. In this method, it takes the experimental velocity traces and moves them along a characteristic sound velocity curve. By doing this, it corrects for the wave interaction effects described above. Once it does this it performs the Lagrangian analysis to define the EOS. It has an iterative feature to allow it to continue through the cycle again until any errors are minimized. This technique has the advantage of offering a unique solution of the equation of state. This technique was used to analyze some of the data for an LX-04 ICE experiment and see how it compares to a modified simple "Lagrangian Technique" and the results were promising. Further analysis is in progress.

RESULTS AND DISCUSSION

Over the course of this project, several different energetic materials have been tested under the direction of different principal investigators (PI's). Table I lists the Z shot numbers, the ZWR (Z Work Request) numbers that are assigned before the experiment to track hardware, the date fired, the materials used, the main PI, and the notes that detail which references contained the published results.

Details are included on each experiment listed in Table I in this section. More detail is included on the later experiments due to the information being readily available. Since the earlier work is documented in publications, the sparse details are sufficient because the publications are listed in the Appendices for quick reference. It should be noted that the last three experiments remain unpublished, mainly due to waiting for the analysis techniques to get improved to allow for the most to be learned from this data and to enhance improvement of any further experiments.

TABLE I. Listing of shot numbers and energetic materials tested using the Z machine from FY01 to FY07.

SHOT #	ZWR #	DATE FIRED	MATERIALS	PI	NOTES
679		12/18/00	LX-04	Reisman	Ref. 6
754		5/29/01	LX-04	Reisman	Ref. 6
755		5/30/01	UF TATB	Reisman	
844		12/19/01	LX-17	Reisman	Ref. 7
896		4/9/02	HMX X-tal	Reisman	Ref. 7
949		8/2/02	HMX X-tal	Forbes	Ref. 9
1067	1329	3/19/03	LX-04	Forbes	Ref. 8
1146	1415	8/5/03	Viton-A and LX-17	Hare	
1221	1537	12/9/03	LX-17	Hare	
1265	1650	3/16/04	Hot LX-04	Hare	Ref. 10
1289	1697	4/23/04	HMX X-tal	Hare	Ref. 11
1408	1906	11/16/04	LX-10 and LX-14	Vandersall	
1443	1967	2/22/05	PBX 9502 and RX-55-AE5	Vandersall	
1505	2025	6/27/05	LX-16, LX-19, and RSI-007	Vandersall	

Experiments Z679 and Z754

These two experiments were the first to be conducted with energetic materials and used LX-04 (85% HMX and 15% Viton A by weight) with thicknesses in the range of 200-600 μm thick using lithium fluoride (LiF) windows. This used the earlier panel design with a faster ramp wave as compared to later experiments where the ramp loading was improved. Therefore, shock-up in the samples was present to a high degree. It was also desired to determine if there would be any reaction in the samples in the ramp loading, but the presence of shock-up in the samples did not provide this information based solely on a ramp loading. Modeling of this experiment using the TRAC II code compared well to the velocity vs. time VISAR records. Details on these experiments were published in an earlier paper [6] that is included in the Appendix for reference.

Experiment Z755

For this experiment, a different energetic material, ultra-fine (UF) TATB, was used to see how it would compare to earlier experiments on LX-04. Because UF TATB does not have any binder and is simply pressed TATB powder with a fine particle size, it has inter-dispersed pores. During the ramp loading, these samples shocked-up severely as a direct result of the porous samples and showed that is does not compare well with an energetic material that is plastically bonded such as LX-04. This experiment provided education for future experiments on energetic materials.

Experiment Z844

This experiment used LX-17 (92.5% TATB, 7.5% Kel-F) to try and extend the knowledge learned on the early formulations to a different formulation. As in the earlier experiments, this exhibited some shocking-up of the samples but provided some preliminary data that was used for

modeling with the TRAC II code. These findings were published in the 12th International Detonation Symposium [7].

Experiments Z896 and Z949

Both of these experiments utilized HMX single crystals as samples and were provided by Jerry Dick at Los Alamos National Laboratory. A motivation of this work, other than obtaining an isentrope for single crystal HMX, was to observe a phase transition in HMX that is predicted to occur at 27 GPa. In some of these experiments, sodium chloride (NaCl) windows were used, which added some ambiguity to the results since NaCl also has a phase transition at approximately 25 GPa. It was found that the results were inconclusive to determine if the phase transition was occurring and it was thought that the phase transition might be time dependent and therefore not observed in the time scale of the ramp loading. This work was included in two different publications [7, 9] and they highlighted the need to use a different window than NaCl due to a phase transition occurring in the window at approximately the same pressure as in HMX.

Experiment Z1067

Experiment Z1067 tested LX-04 and NaCl window samples to 17 GPa (170 kbar) and was published in an earlier report [8]. A slightly modified Lagrangian technique was first used to analyze the data followed by analysis using the method of characteristics. In the first analysis, a spreadsheet was used to calculate the isentrope by utilizing the transit times from the arrival in "thick" and "thin" samples at the same measured particle velocity. It should be noted that since shocks were present in the data a modified Lagrangian technique was used by taking the equation of state based on earlier shock and diamond anvil cell work to use as a starting point at the top of the shock to calculate the upper limit of the isentrope. Although this is not the ideally rigorous solution, it does work as an extrapolation of sorts using a known equation of state and extending it to a higher pressure region. Figure 8 shows the isentrope and Hugoniot obtained from this calculation on the experiment compared to prior work using shock compression and a diamond anvil cell. There is a good match to the data, but this is not too unexpected since this data was used in this analysis.

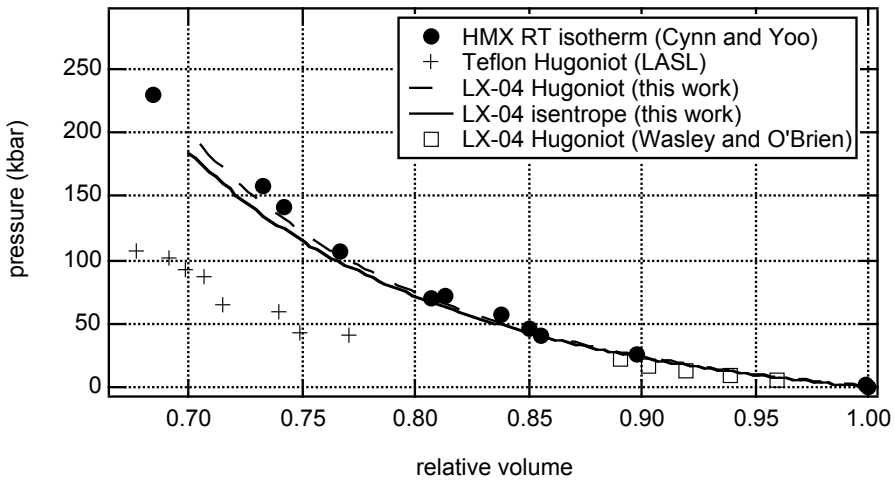

Figure 8. Results of the isentrope of LX-04 obtained from using a Lagrangian technique [8].

An analysis using the "method of characteristics" was also performed by Jon Eggert at LLNL. As a first step, an average drive measurement and the different VISAR waveforms were plotted

together on one plot and are shown below in Figure 9. It appears that all of the waveforms had some steepness and possible shock-up in the region up to 0.5 km/s.

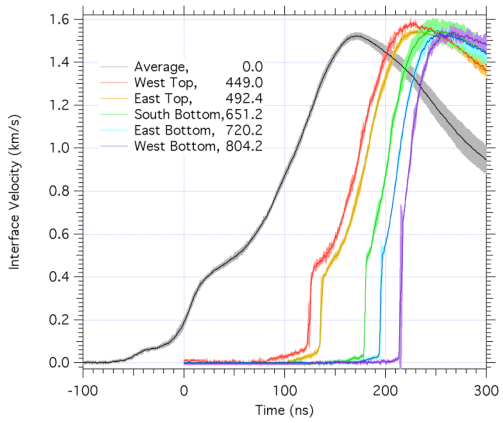

Figure 9. Velocity vs. time VISAR traces for a drive measurement and LX-04 samples with 5 different thicknesses. A standard deviation band plotted around them, which at earlier times it appears that the standard deviation is slightly thicker than the line width.

For the analysis, 300 characteristics were used and using the analysis using all of the combined data (i.e. more than one panel used in the analysis) provided good results. Figure 10 shows the Lagrangian sound speed as a function of particle velocity (left) and the isentrope (right) for LX-04 compared to the earlier results. The black sound speeds show the results of the 0/449/492 panels where it is assumed are not shocked. The red sound speeds use the three un-shocked panels below 0.5 km/s, but above 0.5 km/s all six panels were used to determine the sound speed. Note that this analysis uses the maximum number of panels possible, which reduces the uncertainties to the maximum possible extent. This analysis is in excellent agreement with the previous stress-strain analysis [8]. To analyze the uncertainties the standard deviations were considered for the average velocities as well as a 1 ns timing error. A 3 µm uncertainty in panel thickness was also used.

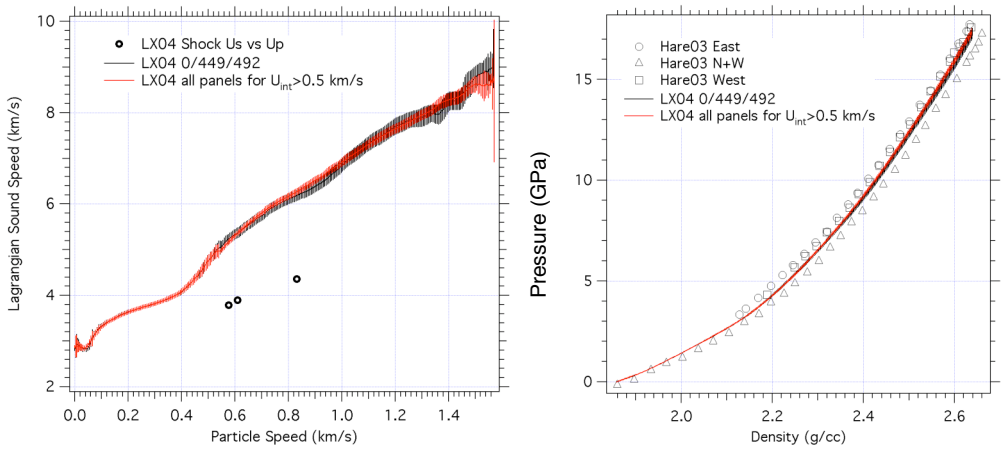

Figure 10. Shown is the Lagrangian sound speed as a function of particle velocity (left) and the isentrope (right) for LX-04 compared to the earlier results showing good agreement.

One final question that came up was whether the shocks observed correlate with the EOS results. Figure 11 shows the timing of the characteristic lines compared to the Lagrangian position showing shocks form at about 540 µm which compares well with the shock-up not being observed in the 492 µm thick sample and seen in the 652 µm thick sample. This example shows the viability of this technique to analyze isentropic compression experiment data.

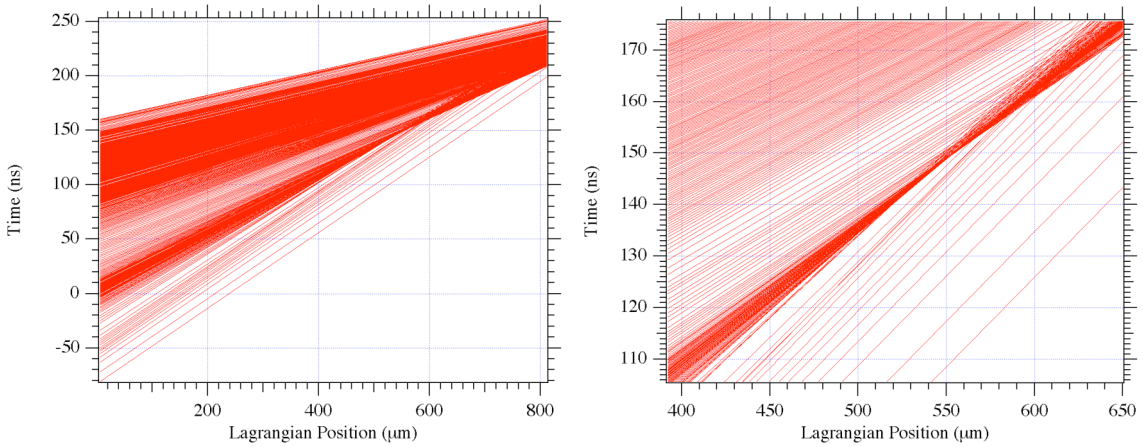

Figure 11. Graphs showing the timing of the characteristic lines compared to the Lagrangian position showing shocks form at about 540 µm which compares well with the shock-up not being observed in the 492 µm thick sample and seen in the 652 µm thick sample.

Experiment Z1146

This experiment had panels containing LX-17 and Viton A binder materials. In the case of Viton A, it was found to be difficult to get an accurate measurement for the thickness of the material since it was highly deformable. Measurement of the thickness before the assembly and the thickness after the assembly where a constant force is applied during the glue-up of the epoxy found a considerable discrepancy of thickness indicating deformation of the sample. Some of the LX-17 data showed shock-up although to a lesser degree as earlier experiments due to enhanced capability of the machine to extend the ramp load.

Experiment Z1221

Experiment 1221 was an experiment that followed Z1146 with slightly different sample thicknesses, a different pulse shape, and possibly a different panel design. Not much information was available for this experiment in the archive, but it looks like it would warrant another look and further analysis.

Experiment Z1265

Experiment Z1265 was unique since it involved heating the LX-04 samples before the ramp was applied. The heater control of the temperature was not optimal, so a slight overshoot in temperature was observed. A loss in the VISAR signal due to the reflector layer on the windows degrading at temperature was also seen. However some of the panels did provide some viable data with some shock-up of the samples. One challenge for this experiment was not being able to

determine the thickness of the samples at temperature, since the samples expand upon heating and were not confined or did not contain a way to measure the expansion. This experiment was published in an earlier work [10] and is listed in the Appendix for further reference.

Experiment Z1289

The experiment Z1289 was similar to earlier HMX experiments and utilized lithium fluoride (LiF) windows to clear up any ambiguity due to a phase transition in sodium chloride (NaCl) windows. Several different crystal orientations were used and the data was analyzed using the "backward integration" technique. The data from this experiment was published with collaborators at Los Alamos [11] with no conclusive evidence of seeing phase transition under ramp loading.

Experiment Z1408

Experiment Z1408 was performed using LX-10 (HMX with Viton binder) and LX-14 (HMX with Estane binder) explosives. Each panel had two different thickness explosive samples backed by Sodium Chloride windows and a measurement of the drive (panel floor) with a lithium fluoride window. Shown below in Figure 12 are the particle-velocity time histories for the North (LX-10, 95%HMX / 5% Viton) and East (LX-14, 95.5% HMX / 4.5% Estane) panels. Each sample had two different VISAR (velocity interferometry) measurements for redundancy. Figure 12 shows the plot of the North panel data which shows the drive measurements in red, the thin LX-10 sample in green, and the thick LX-10 sample in blue. Note that for this panel the agreement between the two different VISAR measurements is very good. Also shown in Figure 12 is the plot of the East panel data which also shows the drive measurement in red, the thin LX-14 measurement in green, and the thick LX-14 sample in blue. Note that the agreement on the thin LX-14 sample is good (other redundant measurements unsuccessfully obtained). Further analysis of this experiment is in progress.

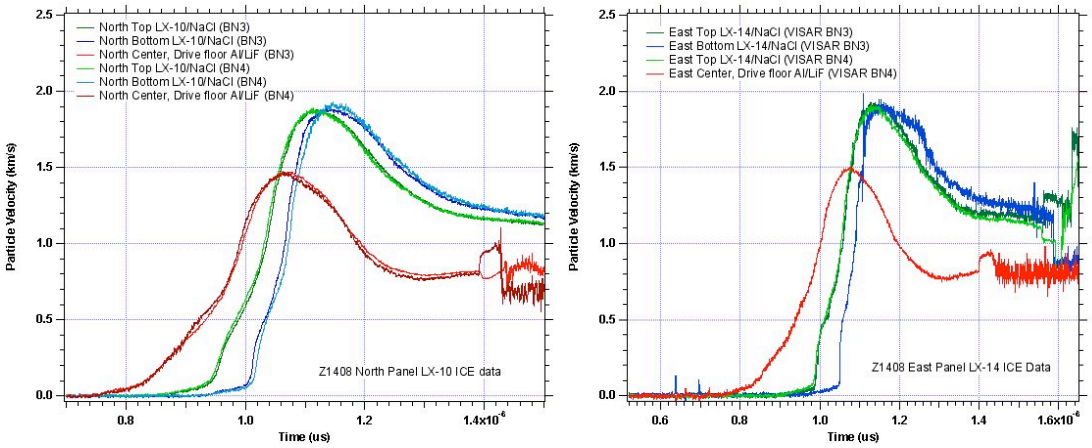

Figure 12. Graphs showing the LX-10 (left) and LX-14 (right) VISAR interface velocities for experiment Z1505. Note that the LX-10 samples do not show a clear shock-up, but the LX-14 samples exhibit this behavior indicating that the LX-14 is more compressible. The red curve is the drive measurement where the green and blue traces are the "thin" and "thick" sample measurements, respectively.

Experiment Z1443

Experiment Z1443 was performed using the TATB formulation PBX9502 and the LLM-105 based formulation RX-55-AE5 using the high-pressure panel design. Because of the high pressures achieved in the experiment, all of the sample windows and the drive measurements were made using LiF windows. All of the panels showed reasonably good data with the North and East panels showing the best data due to the use of thinner saples with some shock-up observed. Figure 13 displays graphs showing the PBX9502 and RX-55-AE5 VISAR interface velocities for experiment Z1443. Comparing these side by side reveals differences in their pressure loading and that some shock-up was observed. Further analysis of this experiment is in progress.

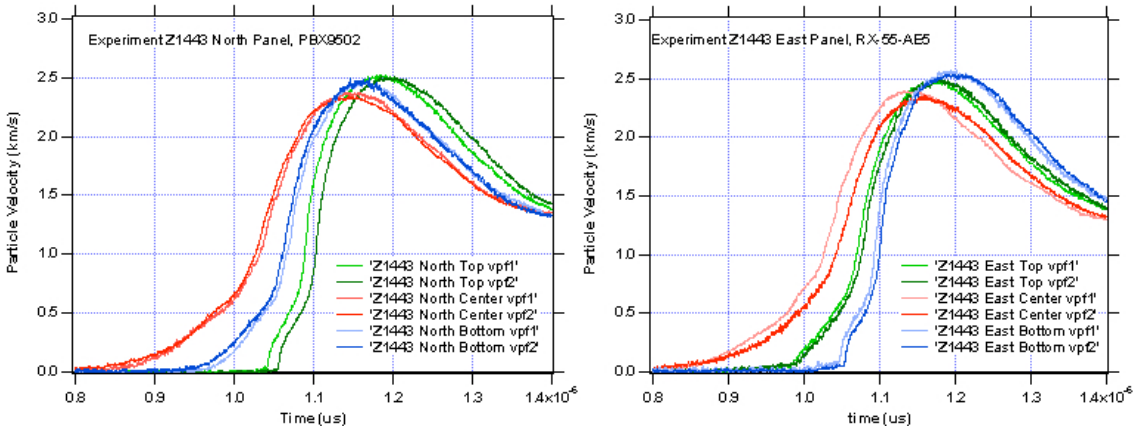

Figure 13. Graphs showing the PBX9502 (left) and RX-55-AE5 (right) VISAR interface velocities for experiment Z1505. The red curve is the drive measurement where the green and blue traces are the "thin" and "thick" sample measurements, respectively.

Experiment Z1505

The energetic materials LX-16 (PETN based), LX-19 and RSI-007 (CL-20 based) were chosen for experiment Z1505 to learn more about energetic formulations that are more energetic than HMX. The low-pressure panel design was used since it was not known whether the samples would react under the ramped loading. The samples were backed with NaCl windows and the drive measurement was made using a LiF window on the aluminum panel. Two of the panels (North and East) showed good data with some shock-up observed. The other two panels showed severe shock-up and missed VISAR fringes. Figure 14 displays graphs showing the LX-16 and LX-19 VISAR interface velocities for experiment Z1505. Comparing these side by side reveals differences in their low pressure loading that is a measure of the stiffness of the samples. Further analysis of this experiment is in progress.

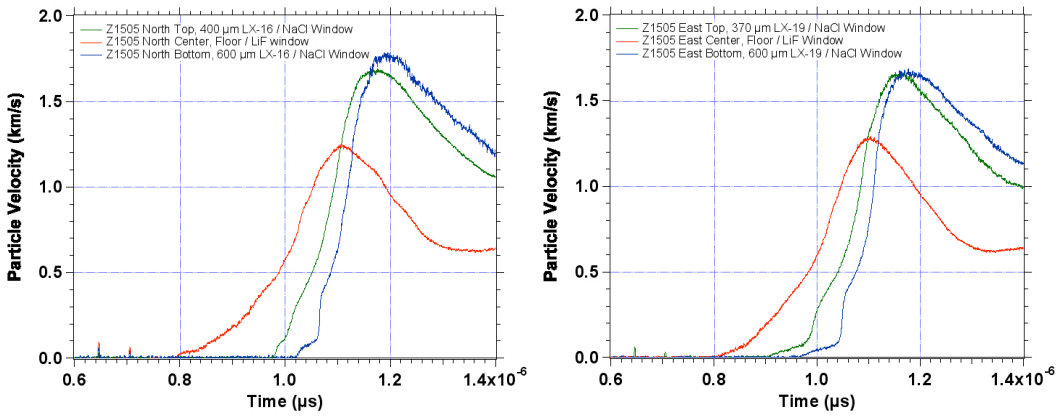

Figure 14. Graphs showing the LX-16 (left) and LX-19 (right) VISAR interface velocities for experiment Z1505. The early loading structure of the samples reveals differences in their dynamic response. The red curve is the drive measurement where the green and blue traces are the "thin" and "thick" sample measurements, respectively.

SUMMARY

Several experiments have been conducted by LLNL researchers using isentropic compression experiments (ICE) on energetic materials as samples from Fiscal Year 2001 (FY01) to Fiscal Year 2005 (FY05). Over this long span of time, advancements of the experimental techniques and modeling of the results have evolved to produce improved results. This report documents the experiments that have been performed, provides details of the results generated, and modeling and analysis advances to fully understand the results. Publications on the topics by the various principal investigators (PI's) are listed in the Appendix.

FUTURE WORK

The small pulser at Sandia will be used in the future to provide lower-cost, faster turnaround ICE experiments at the modest pressures needed for explosives and other related (e.g. binders) materials. The scope of this project is to begin experiments using the small pulser and to expand the dataset of isentropes for explosives and binders. This will initially involve running shakedown and verification tests, and then will progress to measuring new materials.

Because some time was spent waiting for the analysis techniques to be improved to allow for the most to be learned from this data and to enhance improvement of any further experiments, doing further analysis of all of the prospective data sets to gain information that the latest techniques can offer is desired.

ACKNOWLEDGEMENTS

This work would not have been possible without the assistance with the sample preparation by LeRoy Green and Scott Humphery from LLNL, and from SNL the outstanding technical staff of the Z-machine facility. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

1. Hall, C.A., "Isentropic Compression Experiments on the Sandia Z Accelerator," Phys. Plasmas 7, 2069 (2000).
2. C. A. Hall, J. R. Asay, M. D. Knudson, W. A. Stygar, R. B. Spielman, T. D. Pointon, D. Reisman, A. Toor, and R. C. Cauble, Rev. Sci. Instrum. 72, 3587 2001 .
3. D. B. Reisman, A. Toor, R. C. Cauble, C. A. Hall, J. R. Asay, M. D. Knudson, and M. D. Furnish, "Magnetically driven isentropic compression experiments on the Z-accelerator," J. Appl. Phys. 89, 1625 (2001).
4. Barker, L. M., and Hollenbach, R. E., "Laser interferometer for measuring high velocities from any reflecting surface," J. Appl. Phys. 43, 4669-4675, (1972).
5. Reisman, D. B., Wolfer, W. G., Elsholz, A., "Isentropic compression of irradiated stainless steel on the Z accelerator", J. Appl. Phys. 93, 8592 (2003).
6. Reisman, D. B. et al., "Isentropic Compression of LX-04 on the Z accelerator," Shock Compression of Condensed Matter – 2001, edited by M. D. Furnish, N. N. Thadhani, and Y. Horie, AIP press, 2002, pp. 849-852.
7. Reisman, D. B., Forbes, J. W., Tarver, C. M., Garcia, F, Hayes, D. B., Furnish, M. D., Dick, J. J., "Isentropic Compression of High Explosives with the Z Accelerator," Proceedings of the 12th International Detonation Symposium, San Diego, CA, August, 2002, pp. 343-348.
8. Hare, D. E., Reisman, D. B., Garcia, F., Green, L. G., Forbes, J. W., Furnish, M. D., Hall, C., Hickman, R. J., "The Isentrope of Unreacted LX-04 to 170 kbar," Shock Compression of Condensed Matter – 2003, edited by M. D. Furnish, Y. M. Gupta, and J. W. Forbes, AIP press, 2004, pp. 145-148.
9. Hare, D. E., Forbes, J. W., Reisman, D. B., and Dick, J. J., "Isentropic compression loading of octahydro-1,3,4,7-tetranitro-1,3,5,7-tetrazocine (HMX) and the pressure induced phase transition at 27 GPa," Applied Physics Letters, Vol. 85, n 6, (2004).
10. Hare, D. E., Vandersall, K. S., Garcia, F., Davis, J-P, Hall, C., and Forbes, J. W., "Isentropic Compression Data on LX-04 Explosive at 150°C using the Z-accelerator," Shock Compression of Condensed Matter – 2005, edited by M. D. Furnish, M. Elert, T. P. Russell, and C. T. White, AIP press, 2006, pp. 1315-1318.
11. Hooks, D. E., Hayes, D. B., Hare, D. E., Reisman, D. B., Vandersall, K. S., Forbes, J. W., and Hall, C. A., "Isentropic Compression of cyclotetramethylene tetranitramine (HMX) single crystals to 50 GPa," J. Appl. Phys. 99, 124901 (2006).
12. Fickett, W. and Davis, W. C., "Detonation Theory and Experiment," Dover Publications, Inc., Mineola, NY, 2000.
13. D. B. Hayes, Backward Integration of the Equations of Motion to Correct for Free Surface Perturbations, Sandia National Laboratories Report SAND2001–1440, Albuquerque, NM, 2001.
14. J.-P. Davis, User Manual for INVICE 0.1-beta: A Computer Code for Inverse Analysis of Isentropic Compression Experiments, Sandia National Laboratories Report SAND2005–2068, Albuquerque, NM, 2005.
15. Maw, J. R., "A Characteristic Code for Analysis of Isentropic Compression Experiments," Shock Compression of Condensed Matter-2003, AIP Conf. Proc. 706, AIP Press, pp. 1217-1220 (2004).
16. J.-P. Davis, User Manual for CHARICE 1.0: An IDL Application for Characteristics-Based Inverse Analysis of Isentropic Compression Experiments, Sandia National Laboratories Report SAND2007–4984, Albuquerque, NM, 2007.

APPENDICES – Published Papers Detailing this work

APPENDIX A - D. B. Reisman, A. Toor, R. C. Cauble, C. A. Hall, J. R. Asay, M. D. Knudson, and M. D. Furnish, "Magnetically driven isentropic compression experiments on the Z-accelerator," J. Appl. Phys. 89, 1625 (2001).

APPENDIX B - Reisman, D. B. et al., "Isentropic Compression of LX-04 on the Z accelerator," Shock Compression of Condensed Matter – 2001, edited by M. D. Furnish, N. N. Thadhani, and Y. Horie, AIP press, 2002, pp. 849-852.

APPENDIX C - Reisman, D. B., Forbes, J. W., Tarver, C. M., Garcia, F, Hayes, D. B., Furnish, M. D., Dick, J. J., "Isentropic Compression of High Explosives with the Z Accelerator," Proceedings of the 12th International Detonation Symposium, San Diego, CA, August, 2002, pp. 343-348.

APPENDIX D - Hare, D. E., Reisman, D. B., Garcia, F., Green, L. G., Forbes, J. W., Furnish, M. D., Hall, C., Hickman, R. J., "The Isentrope of Unreacted LX-04 to 170 kbar," Shock Compression of Condensed Matter – 2003, edited by M. D. Furnish, Y. M. Gupta, and J. W. Forbes, AIP press, 2004, pp. 145-148.

APPENDIX E - Hare, D. E., Forbes, J. W., Reisman, D. B., and Dick, J. J., "Isentropic compression loading of octahydro-1,3,4,7-tetranitro-1,3,5,7-tetrazocine (HMX) and the pressure induced phase transition at 27 GPa," Applied Physics Letters, Vol. 85, n 6, (2004).

APPENDIX F - Hare, D. E., Vandersall, K. S., Garcia, F., Davis, J-P, Hall, C., and Forbes, J. W., "Isentropic Compression Data on LX-04 Explosive at 150°C using the Z-accelerator," Shock Compression of Condensed Matter – 2005, edited by M. D. Furnish, M. Elert, T. P. Russell, and C. T. White, AIP press, 2006, pp. 1315-1318.

APPENDIX G - Hooks, E. E., Hayes, D. B., Hare, D. E., Reisman, D. B., Vandersall, K. S., Forbes, J. W., and Hall, C. A., "Isentropic Compression of cyclotetramethylene tetranitramine (HMX) single crystals to 50 GPa," J. Appl. Phys. 99, 124901 (2006).