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Extension of the operating parameters of the two stage light gas gun to velocities below 2 km/sec.

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Disclaimer

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ABSTRACT

The Joint Actinide Shock Physics Experimental Facility (JASPER) located in area 27 at the Nevada Test Site has been tasked with providing high accuracy information on the Equation Of State (EOS) and other dynamic properties of weapons grade plutonium and other actinides important to the stockpile stewardship program. In the past 5 years this facility has provided dozens of experimental data points for the accurate determination of pressure density relationship for these materials over a broad pressure range. In order to complete this survey it is necessary to extend the low pressure region to include projectile velocities below 2 km/s.

For most gas gun facilities this would present not too great a difficulty, one could simply decrease the amount of propellant along with a decrease in the strength of the petal valve, However JASPER requires that the piston be securely embedded in the Acceleration Reservoir (AR) as part of the containment system. The projectile must remain flat and undistorted. This requirement makes the attainment of slow velocities problematic.

This talk will discuss the JASPER Facility, A finite difference code developed to give predictive capability for two stage gas guns, and a set of experiments performed to demonstrate this capability.

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INTRODUCTION

The Joint Actinide Shock Physics Experimental Facility (JASPER) located in area 27 at the Nevada Test Site (the old α device assembly area) has the primary task of obtaining the highest quality EOS and other dynamical properties of pure and weapons grade plutonium and other highly controlled Special Nuclear Materials (SNM). It is a two stage light gas gun with a 28 mm bore launch tube and a pump tube of 89 mm. The pump tube is approximately 11.8 m long and the launch tube is approximately 8.7 m long. It was designed and built by Thiot Ingenierie. It was meant to be as similar as possible to the two stage gun located at our laboratory in Livermore. It should have the capability of launching metal flyers weighing up to 27 gm with velocities ranging from 1.75 to 8 km/s while guaranteeing complete containment of the SNM The reasoning behind this engineering design is that the fielding of experiments done with these SNM was so expensive that any diagnostics, containment, or other experimental development would need to be done here at Livermore. It was understood that the release of any SNM from the site would probably result in the permanent closure of the facility.

Its first couple of shots, occurring in March and April of 2001 looked primarily at gun performance. Containment, diagnostics development, and gun performance were the objectives of the next 18 shots leading to the first plutonium shot in July of 2003. Since then we have succeeded in doing over 70 shots more than 20 of which were done on SNM. In all these shots there has never been a measurable release of SNM.

Figure 1 is an aerial photograph of the site. The gas gun itself is located in the uppermost white structure; the targets are built in the dome shaped building to the lower left within the fenced area. During SNM operations the fenced area is placed under heavy security and the entire area 27 is also place under armed guard.

Figure 2 is a cartoon of the gun along with the containment measures. The containment is divided into primary and secondary types. Primary containment is accomplished through the use of the Primary Target Chamber (PTC) shown shaded in pink. Secondary containment is shaded in yellow and consists of the piston, petal valve, sabot, and the Secondary Containment Chamber (SCC). Under normal operations the PTC and its contents are discarded after each shot. Should a containment breach occur in the PTC the SCC and launch tube would be sacrificed.

The target resides within the PTC in what is known as the Target Plug Assembly (TPA). During shipment the target resides in its own chamber behind a large gate valve. The entire TPA is mounted behind an Ultra-fast Closure Valve System (UCVS). This consists of a thick walled aluminum tube surrounded by high explosives. At shot time this explosive crushes the aluminum forming a gas tight seal. Figures 3, 4, and 5 are pictures of the gun and target chamber. Figures 6a and 6b show drawings of the PTC.

Figure 7 is a picture of a typical TPA (upper left). This entire assembly is deployed remotely just prior (minutes) to shot time and must maintain alignment to the tolerance of the target typically less than two microns in flatness and parallelism. This is accomplished by having the TPA kinematically locate three spheres in three ‘V’ blocks as shown in the lower left. The lower right is a set of pictures showing how the tolerancing is monitored during the target build which of course is done in a glove box. These pictures were taken of an actual target build.

The tolerancing is established by the accuracy needed in the measurements of shock velocities. This typically needs to be on the order of 0.5% or less to obtain P-ρ values that are accurate to less than 1%. The left side of figure 8 is a plot of the pin arrival times from a typical shot. The corresponding fit has a scatter of only a few hundred ps. This gives a standard deviation of about 0.5 ns. On this shot the uncertainty in the shock arrival time was about .03 km/s for a measured shock speed of 6.73 km/s . When systematic errors were added in along with errors in initial densities etc the error in P was 1.3% and ρ was 1.1%.

After a number of Pu shots had been done it was noticed that the data appeared to not always be of this quality. In particular it was observed that with aluminum flyers at about 5 km/s the time of arrival data appeared to be poorly modeled with standard fits to tilt (a sine wave) plus simple bowing (parabolic distortion). In an effort to understand these data the simple 13 pin top hat design was traded for a 19 pin flat plate target (non-SNM) and this target was shot with the objective of measuring the shape of the flyer. The left side of figure 8 shows the results of this measurement. Figure 9 is a surface constructed from the arrival times obtained from figure 8. Clearly the flyers were being deformed to and unacceptable degree.

CODE DEVELOPMENT

I had been re-writing a code that I had obtained from a colleague originally written by Charters and Sangster[1]. The original code was quite general in that it modeled the ballistics of single stage powder, or gas breech, as well as two stage guns. I was interested only in multi-stage guns and was also interested in a code that was more user friendly and could easily be run dozens of times in an hour, thereby allowing the user to do parameter studies easily and quickly. In addition there were a number of deficiencies to the code that I had obtained. Among them were: The petal valve opening time algorithm was incorrect. The code had an iterative routine that tried to match the piston velocity with a input piston velocity. This was extremely inconvenient to use. I was primarily interested in being able to predict the flyer velocity. I also wanted a program that was easier to understand and whose output was easy to interpret.

The code renamed GGUN was re-written for a windows environment and most of it was recoded to FORTRAN 95. It now includes the following: It provides a GUI with all the user input data, Gun dimensions, projectile weights, pump tub pressure, propellant type and mass etc. These parameters are displayed in edit boxes so that the user can easily change them as desired. The final input parameters are written out to a text file which has the same structure as the input file but with the problem name appended to it. By renaming this file to 'gunfile.txt ' . This file can be used as an input file to another problem. This makes running a series of problems where only one or two parameters are changed extremely simple. The code provides plots as well as text files of all the important quantities. In addition to the standard plots output by the Charter and Sangster the new version gives the stress on the projectile. Finally, new EOS and burn models were put in as drop down boxes. Standard propellants are M-6, WC-890 and HP-95. Their burn model parameters are built into the code. Standard drive gases are H_2, He, Ne, N_2 ,and CH_4. In addition the EOS for some of these gases was changed from Ideal gas law to Van der Waals gas law. Other EOS forms are included but not yet utilized. Simulations using this code were compared to actual shot data as well as the simulations obtained from Cesar3.1 which was provided by Thiot. The results were accurate in most cases to 5% in flyer velocity. Using both these codes it was discovered that the stress on the projectile could be reduced and still maintain containment by reducing the pump tube pressure from 15 bar to 10 bar. Subsequent experiments performed on 19 pin flat plates confirmed these predictions

EXPERIMENTS

By the year 2007 the Hugoniot measurements were progressing well and the only points left were the ones at the extreme limits of the guns range - below 3 km /s and 8 km/s. In order to proceed with these low pressure measurements a series of surrogate shots were made using WC-890 instead of M6, also for the lowest pressures we intended to substitute nitrogen for the helium drive gas. During one of the low pressure He shots the piston didn't succeed in rupturing the petal valve. This left us with a fully deployed target and an unloaded gun with the only containment being the projectile. It was decided to increase the powder charge to an amount where we knew the gun would perform as predicted and shoot as soon as possible. This experience brought about the need to start a research program back at LLNL to better understand how we might achieve low velocities without increasing the risk of a containment breach; we were particularly concerned that with low propellant loads the piston would not be wedged sufficiently far into the AR.

We went back over the shot logs of our facility for the past 30 years and found scores of records of shots that resulted in velocities of 2 km/s or less. Most of them had the following in common: They used nitrogen for a drive gas and they used a much heavier projectile. However, these results were of limited use in that for most of these shots the projectile was a long rod penatrator, we found no cases where the planarity of the flyer was diagnosed, and finally there was no record of the penetration of the piston into the AR.

The first attempts at producing slow velocities involved simply using a fast burning propellant and decreasing the powder loads. Tests at Livermore showed that small loads (less than 400 gm) of WC-890 failed to burn the whole charge. However, a change in the type of propellant (blue dot) did produce complete burn but still failed to imbed the piston deeply in the AR

Simulations carried out using GGUN gave us several solutions. In order to achieve low launch velocities and still have the piston deeply embedded in the AR the energy on the piston could be increased without increasing its speed by using a heavier piston. The pump tube pressure could be increased. This would allow the petal valve to rupture sooner while the piston was still moving slowly. The petal valve could be made so that it ruptured at a lower pressure. And finally the projectile could be heavier.
The use of a heavier piston not only increased its energy bit also would require larger powder loads which in turn meant that the burn would be more reliable. We calculated that going from an 8 lb piston to a 15 lb piston would necessitate going from a 400gm powder charge to over a kilo-gram charge for the same launch velocity. The effect could be further enhanced by going from a 0.036 in web thickness petal valve which breaks at an estimated 30 ksi to a 0.01 in thick petal valve which breaks at an estimated 10 ksi.

In order to quantitatively test these simulations some experiments were carried out that would directly measure the trajectory of the projectile in the launch tube. These experiments were similar to a set of experiments carried out by Karl Konrad[2,3,4] and his colleagues at Sandia National Laboratory. In our experiments a laser beam was delivered though an optical fiber to the focal spot of a camera lens where it was directed up the launch tube and subsequently impinged on the surface of a flyer which had been lightly polished. The retro reflected beam was then collected by the camera lens and focused onto a return fiber. Light from this beam was then introduced into a VISAR interferometer. Figures 10 and 11 show a diagram of how this was done at Sandia as well as a 'target' used by us for our measurements. The use of a highly reflective surface and fiber optics allowed this to be carried out with a minimum of disruption to the facility since the beam would be completely enclosed and only required a few milli-Watts of laser power to work.

The first shot was a low velocity shot using nitrogen for a drive gas, a 15 lb piston and standard .035 in petal valve. This shot was predicted to go 1.7 km/s but only went 1.1 km/s. The reason for this gross discrepancy is apparently in the petal valve opening time. These times were obtained by adjusting the opening time to give the best fit to launch velocities as a function of powder load for a wide variety of powder loads. The top graph in figure 14 shows this fit. This was done for hydrogen drive gas. For this shot this curve was extrapolated to 400 gm of propellant which gave an opening time of 8 ms. The opening time that gave the best fit to launch velocity for this shot was 2 ms.

Figures 12 and 13 show the results and compare them to some simulations. In these and subsequent shots, the petal valve opening time was adjusted to give the best agreement to the flyer speed at the muzzle. As mentioned above this turned out to be 2 ms. What is noticed is that the acceleration of the projectile starts out very high and slows to a small fraction of its initial value by the time it reaches the muzzle. It is counterintuitive that decreasing the PV opening time would decrease the launch speed, but an opening time of 2 ms not only gives the correct launch velocity but also gives a much better acceleration profile. This demonstrates the danger in trying to adjust parameters when only the final velocity is known. There are probably many ways to arrive at the final velocity.

There is also a substantial difference in modeling with an ideal gas vs. Van der Waals gas. The Van der Waals EOS seems to at least predict the initial acceleration

It was decided that the rest of the shots would all use He for a drive gas. This was decided for two reasons. Helium was predicted to give a smoother acceleration and therefore less stress on the projectile. Helium also put less stress on the AR. The next shots used a thinner petal valve and heavier projectile. The first two shots used a petal valve with web thickness of 0.010 and 0.028 in respectively. In both cases the shots went very slow. When the gun was taken apart it was discovered that in both cases the petal valve only opened about half way. When we tried using a .035 in petal valve it failed to break at all. We finally settled on a 0.030 in web which seemed to be reliable. The results of this series of shots are shown in figure 15.

In summery the results are:

1 Using a 15 lb piston allowed the use of powder loads of nearly one kg which gives reliable, predictable results.
2 Using a petal valve of less than 0.030 in web gives unreliable results.
3 Using sabots weighing 45 grams also helps slow down the projectile.
4 At these low pressures small variations in the petal valve cause large variations in the launch velocity see figure 14.
5 Nitrogen puts large stresses on the projectile and AR.
6 Helium gives almost constant accelerations at these speeds.
7 For poly-atomic drive gases a Van der Walls EOS should be used.
8 These parameters provide for good secondary containment.

Figures 16 and 17 are photographs of the piston in the AR at both Livermore and JASPER. In all cases the piston was extruded into the AR by over one foot which would give highly reliably secondary containment.

REFERENCES

1 Charters A. C., and Sangster, D. K., Computer program for the Interior Ballistic Analyses of Light Gas Guns. Unpublished Manual to CFD code , 1973

2 Karl Konrad private communication.

3 Charley Enis, Roy Hendrix, Karl Konrad, and David Cox "Radar and VISAR Measurements of Interior Ballistics in AEDC's Upgraded Ballistic Range Facility", AIAA 94-0234, 33rd Aerospace Sciences Meeting and Exhibit, Jan 9-12/ Reno Nv.

4 Clint Hall and Karl Konrad. " New Projectile Design for Dynamic Inbore Projectile Velocity Measurements' 45th meeting of the Aeroballistic Range Asssociation, Huntsville Alabama.

FIGURE CAPTIONS

Figure 1 An aerial photograph of the JASPER site.

Figure 2 A drawing of the JASPER light gas gun along with the primary and secondary containment components.

Figure 3 A photograph of the JASPER two stage light gas gun as seen from the breech

Figure 4 A photograph of the JASPER gun as seen from the AR looking toward the target chamber

Figure 5 A photograph of the primary target chamber as it sits inside the secondary target chamber. The launch tubs muzzle is visible near the center of the chamber. The white tank below the PTC is used to catch gases from the explosively driven UCVS

Figure 6a A sketch of the PTC
Figure 6b A cutaway sketch of the PTC showing the main components.

Figure 7 A collage taken from a "hot" target. The Target Plug Assembly is shown in the upper right, the lower right shows how the TPA kinimatically locates itself to the three spheres located in the PTC. To the right are a series of pictures made during the actual assembly of the target. The interference fringes give an indication of how flat the surface of the target remains as the build progresses.

Figure 8 Pin arrival times along with their fit to the function $a+b\cos(\theta+\varphi)+cR^{2}$. Where a is the difference between the timing mark and the average arrival time. B is a measure of the tilt angle, φ is an arbitrary phase angle and c is the amount of bowing. Each pin is located at position (R,θ), The left hand plots are from a 19 pin flat plate target from JASPER shot 30. The right hand plots are for 13 pin tophat shot where the fit is good to better than one nanosecond.

Fig 9 The results of arrival times and fits for shot 30. This shot was made to determine how flat the flyer remained during acceleration. This surface plot obtained by fitting the arrival times shown in the left side of figure 8. This much distortion clearly cannot be allowed and provided motivation for us to develop an accurate predictive capability.

Figure 10 Method used by Sandia group to measure the internal ballistics of the flyer. On the right is a diagram of the system. To the left is a profile of the projectiles acceleration.

Figure 11 Target used for this set of experiments. Launch and collection fibers were mounted side by side at the focus of a camera lens which has been pre-focused at infinity. This light beam is directed up the launch tube where is is incident upon the police flyer in the sabot. Reflected light is collected and fed into a VISAR.

Figure 12 Results from the first measurement. To the right is the lissajjous to the left is the measured velocity profile.

Figure 13 Comparison of the data in figure 12 with simulations using an ideal gas EOS and Van der Walls EOS.

Figure 14 Shot 4016, the first He shot. In this shot and the next the petal valve did not fully open. Note how much more uniform the acceleration is using helium for the drive gas than using nitrogen.. While the simulation do not quantitatively match the measurements the qualitative behavior is quite good.

Figure 15 Shot 4019 He drive gas and a .030 " web thickness on the petal valve. This appears to be the thinnest web thickness that would allow the petal valve to open fully.

Figure 16 The projectile velocity is affected by several unknowns including friction, piston release pressure, petal valve opening time, and opening pressure. The top graph is a plot of the 'best' fit to velocities verses petal valve opening time vs powder load. The bottom plot is a graph of the simulated projectile velocity vs petal valve opening pressure. This shows that at slow launch velocities the burst pressure can have a significant effect since at high velocities high burst pressures are almost always used.

Figure 17   Shot summery. The shots 4016 and 4017 were the shots where the petal valve failed to open all the way. The plots below depict burst pressure as a function of petal valve web thickness. The source of these curves are unknown.

Figure 18 A collage of showing the amount of extrusion of the 15 lb piston into the AR for one of these test shots.

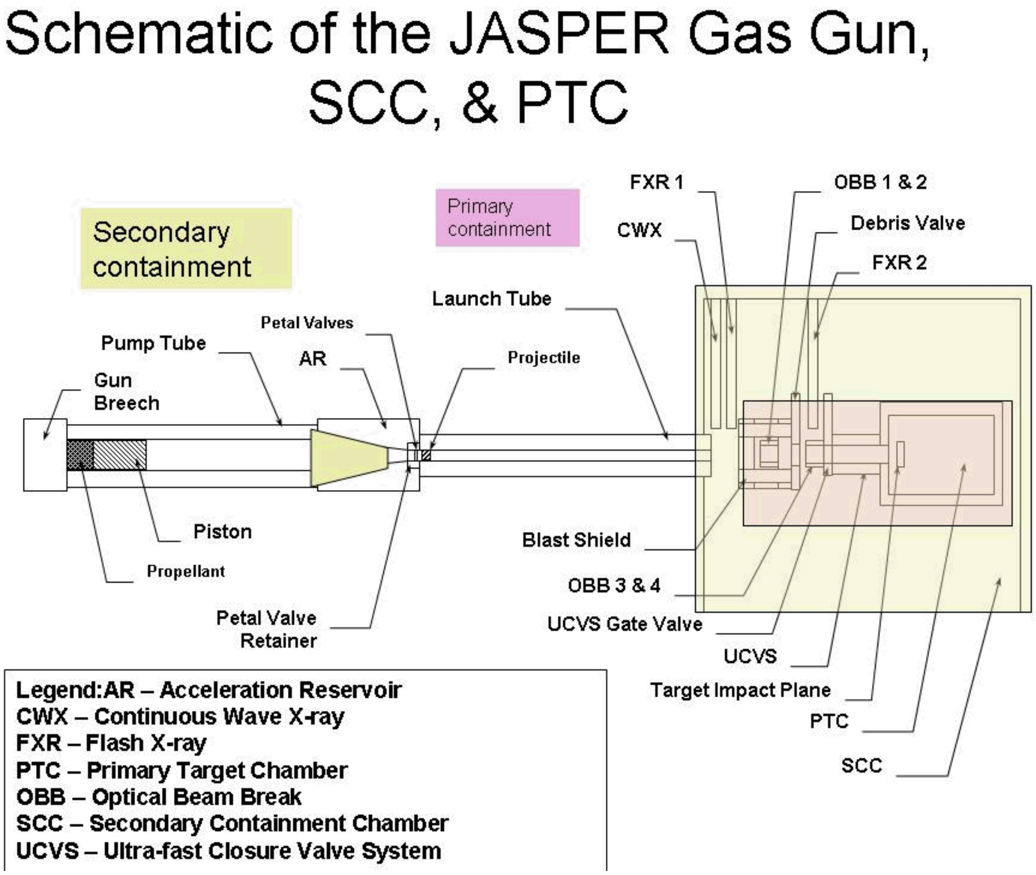
Figure 19 Similar to figure 16 but for the test shot at JASPER.

The JASPER Compound

- The Joint Actinide Shock Performance Experimental Research Facility (JASPER) is a two stage light gas gun located in Area 27 at the Nevada Test Site (NTS)
  - Impact actinide targets (primarily Pu) with high velocity projectiles (2 km/s to 8 km/s) to improve equation of state models

Aerial view of the JASPER Facility site.

Figure 1



Schematic of the JASPER Gas Gun, SCC, & PTC

Legend:AR – Acceleration Reservoir
CWX – Continuous Wave X-ray
FXR – Flash X-ray
PTC – Primary Target Chamber
OBB – Optical Beam Break
SCC – Secondary Containment Chamber
UCVS – Ultra-fast Closure Valve System

Figure 2

View of JASPER target chamber as seen from the breech

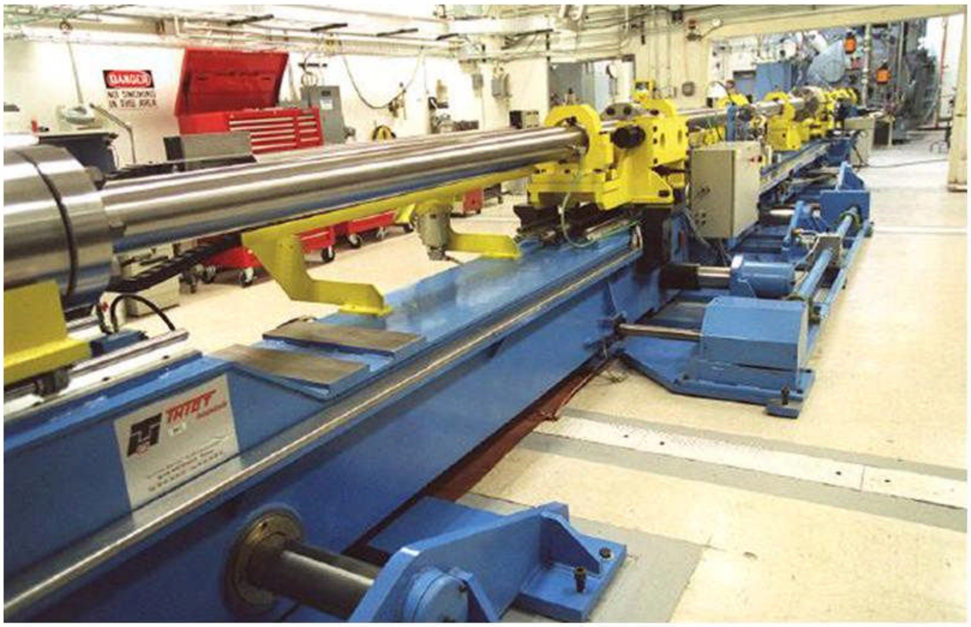


Figure 3

JASPER AR and target chamber

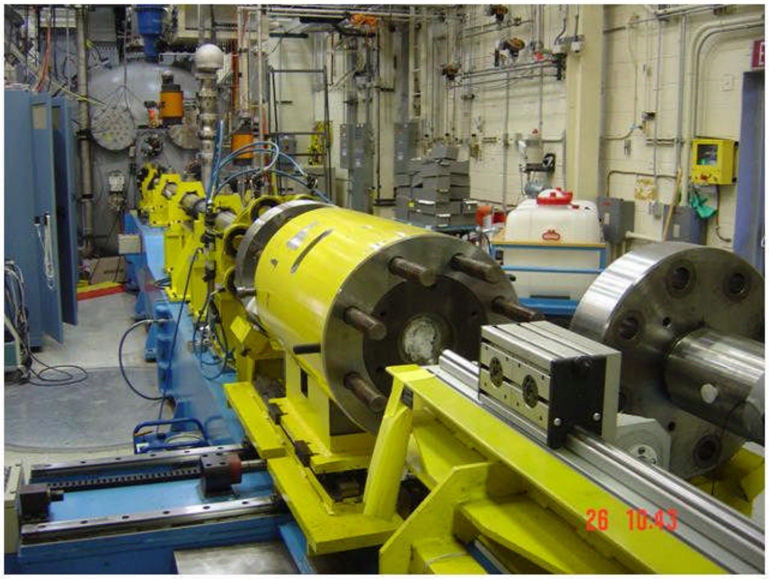


Figure 4

SCC with PTC being installed

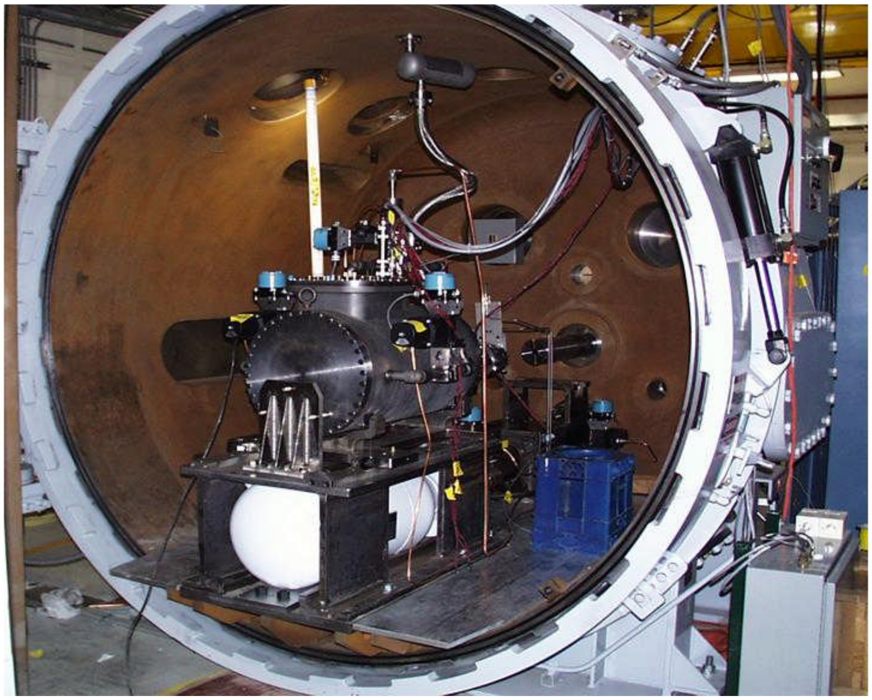


Figure 5

The Primary Target Chamber contains the Target impact load and debris

- Pu targets will be installed and contained in a Primary Target Chamber (PTC)
- The PTC will be installed in a Secondary Containment Chamber (SCC)
- Expended PTCs are placed in a standard waste box for eventual disposal

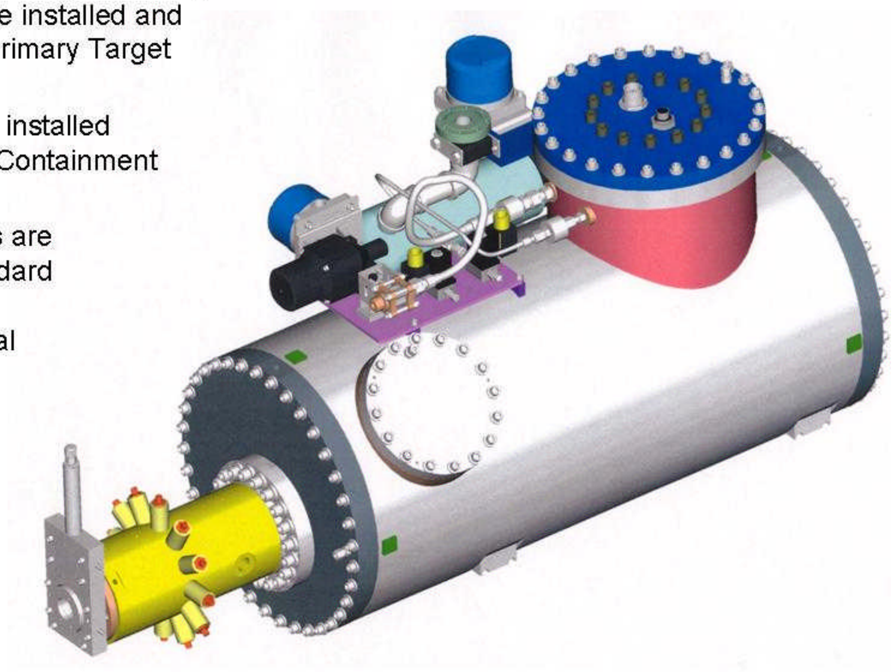
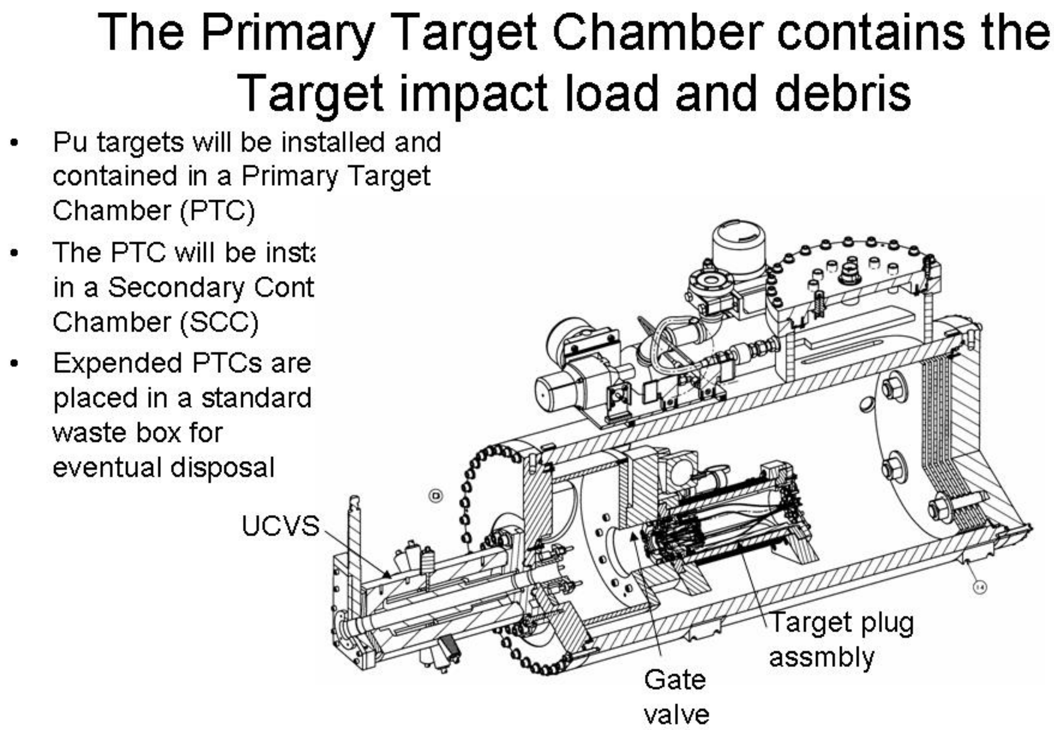


Figure 6a



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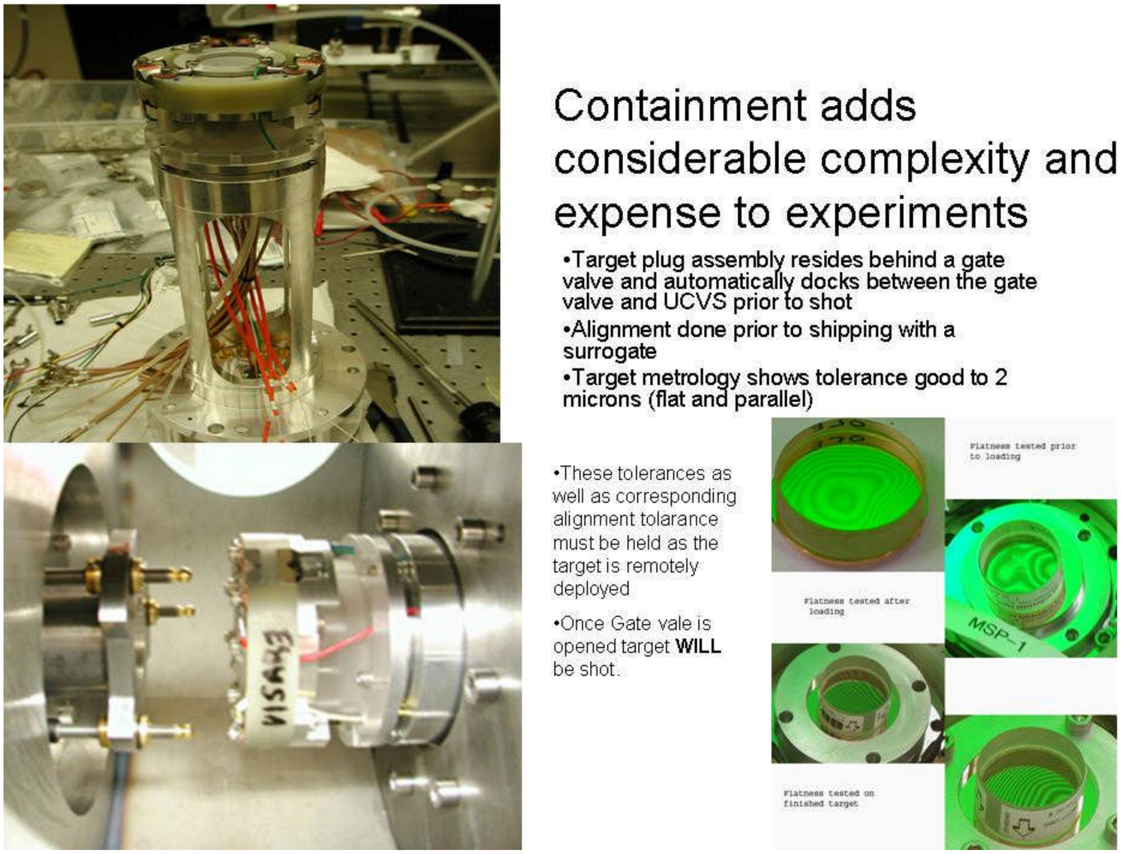
- The PTC will be insta in a Secondary Cont Chamber (SCC)
- Expended PTCs are placed in a standard waste box for eventual disposal

Figure 6b



Containment adds considerable complexity and expense to experiments

- Target plug assembly resides behind a gate valve and automatically docks between the gate valve and UCVS prior to shot
- Alignment done prior to shipping with a surrogate
- Target metrology shows tolerance good to 2 microns (flat and parallel)

- These tolerances as well as corresponding alignment tolarance must be held as the target is remotely deployed
- Once Gate vale is opened target **WILL** be shot.

Flatness tested prior to loading

Flatness tested after loading

Flatness tested on finished target

Figure 7

Incorrect gun operating parameters can cause flyer distortion

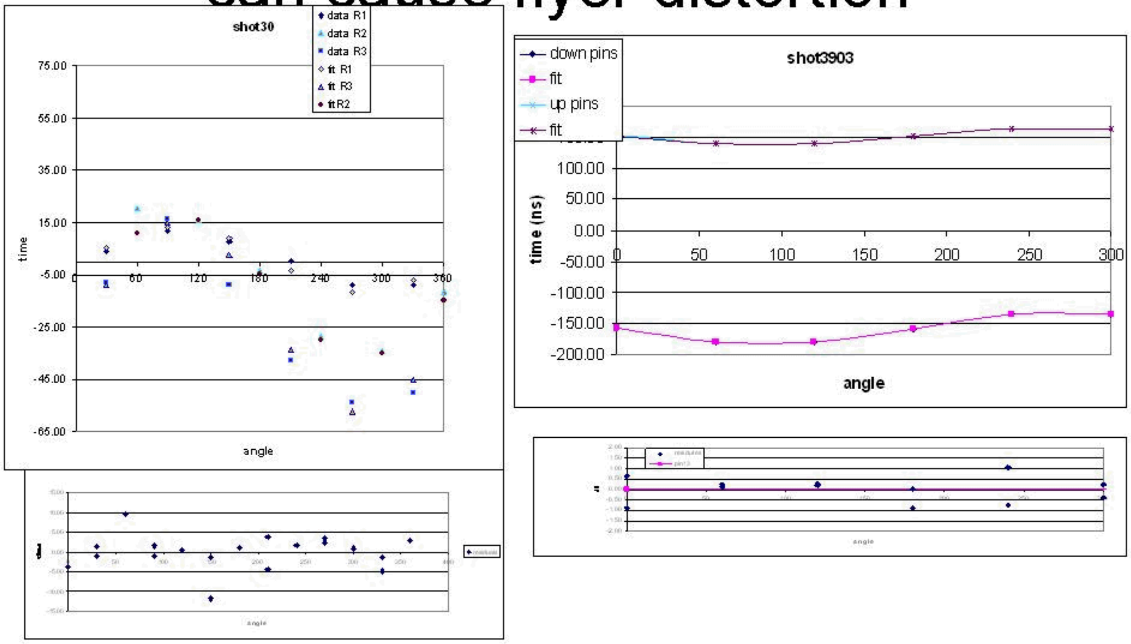
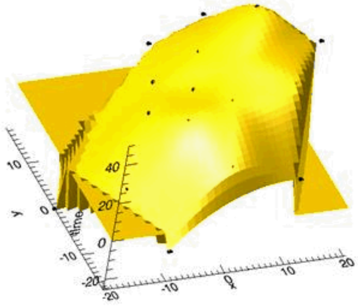


Figure 8

Incorrect gun operating parameters can cause flyer distortion

- Surface measured from shot 30
- 19 pin –Al flyer-Al plate
- 5.6 km/s



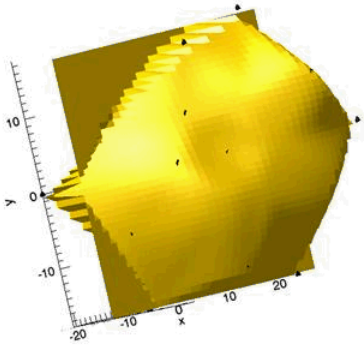


Figure 9

Used technology developed at SNL[2]

This method required several watts of light in open beams, When we tried it we had very little light returned

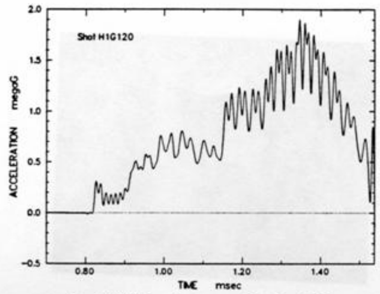


Fig. 6. VISAR acceleration record for shot #H-120.

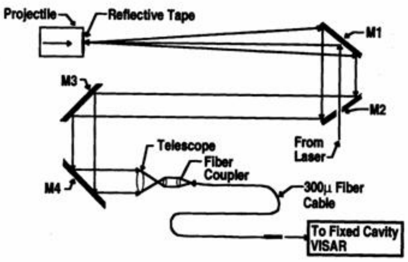


Fig. 4. Experimental VISAR setup configuration.

2 Konrad, Cox, Asay, and Hall “Radar and VISAR Measurements of Interior Ballistics in AEDC’s Upgraded Ballistic Range Facility”, AIAA 94-0234, 33rd Aerospace Sciences Meeting and Exhibit, Jan 9-12/ Reno Nv.

Figure 10

Our VISAR experiment used a single pair of fibers with a standard camera lens

1. Required only a few mW of light to get strong return.
2. Intensity would sometimes vary strongly but not enough to hurt the data

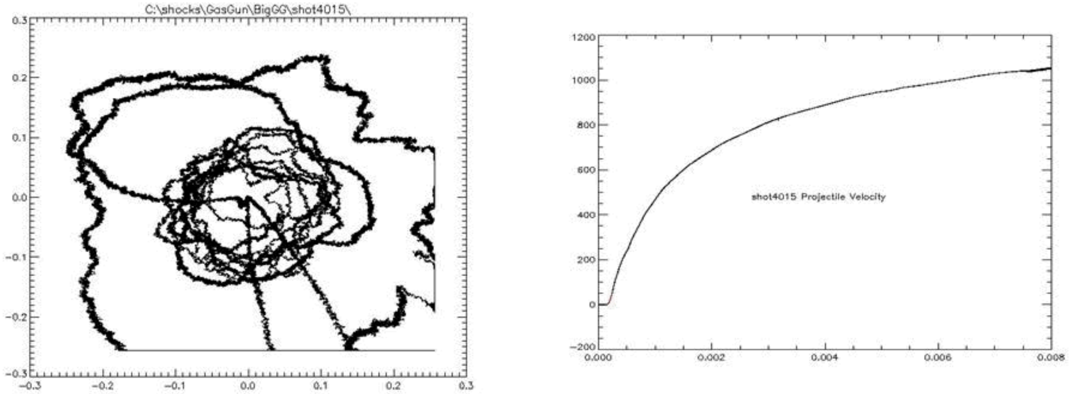
Figure 11

Shot 4015

8 bar N_2,   15 lb piston, PV opening time =2 ms, burst pressure 3.5ksi

650 gm of M6,

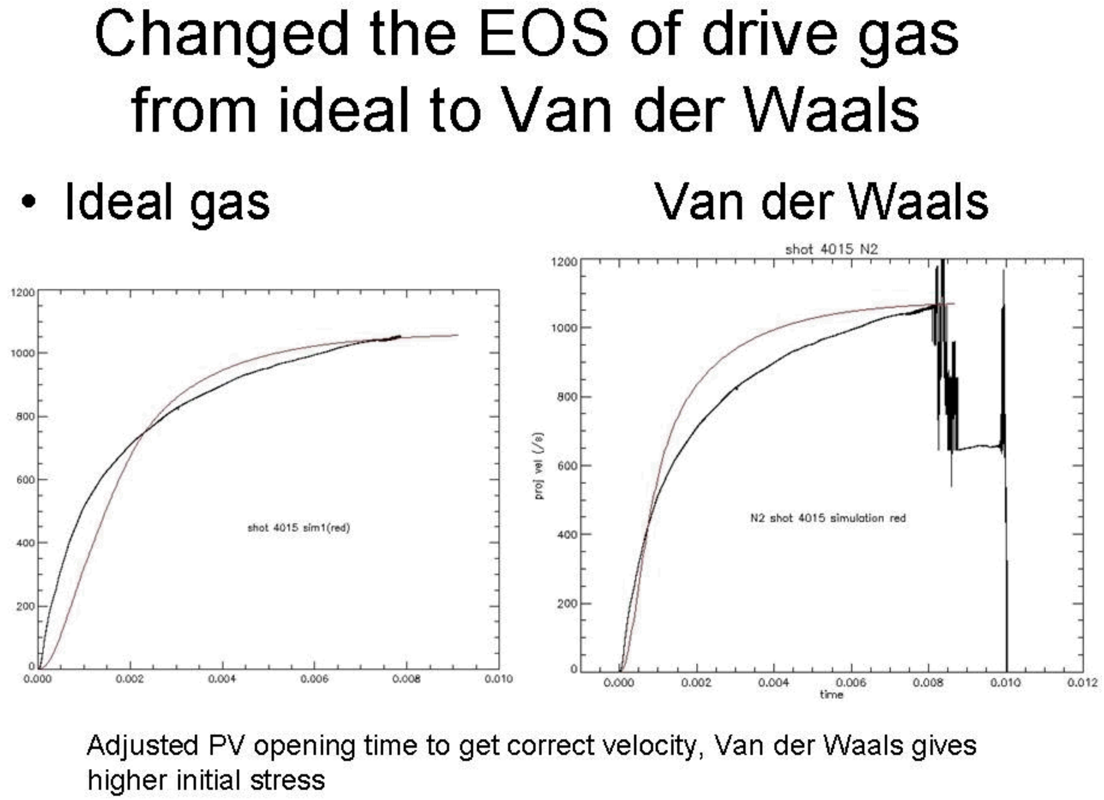
Vflyer = 1.18 km/s



Lissajous

Velocity profile of projectile

Figure 12



Changed the EOS of drive gas from ideal to Van der Waals

- Ideal gas

Van der Waals

Adjusted PV opening time to get correct velocity, Van der Waals gives higher initial stress

Figure 13

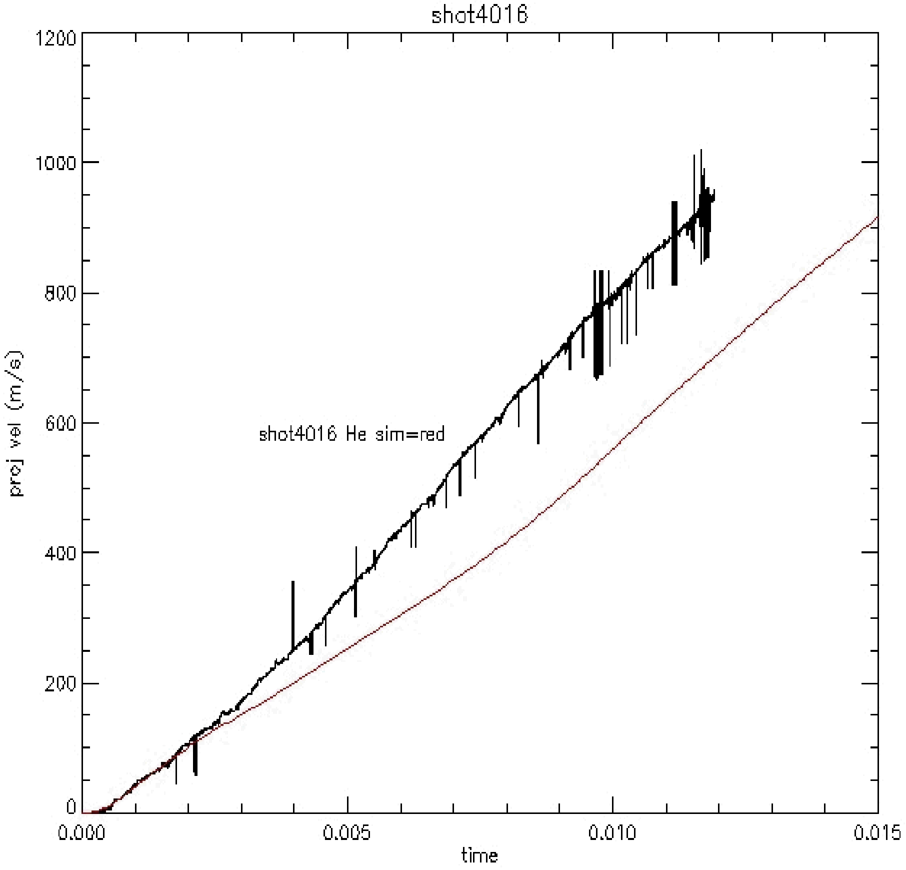

shot4016
1200
1000
800
600
400
200
0
proj vel (m/s)
shot4016 He sim=red
0.000
0.005
0.010
0.015
time

Figure 14

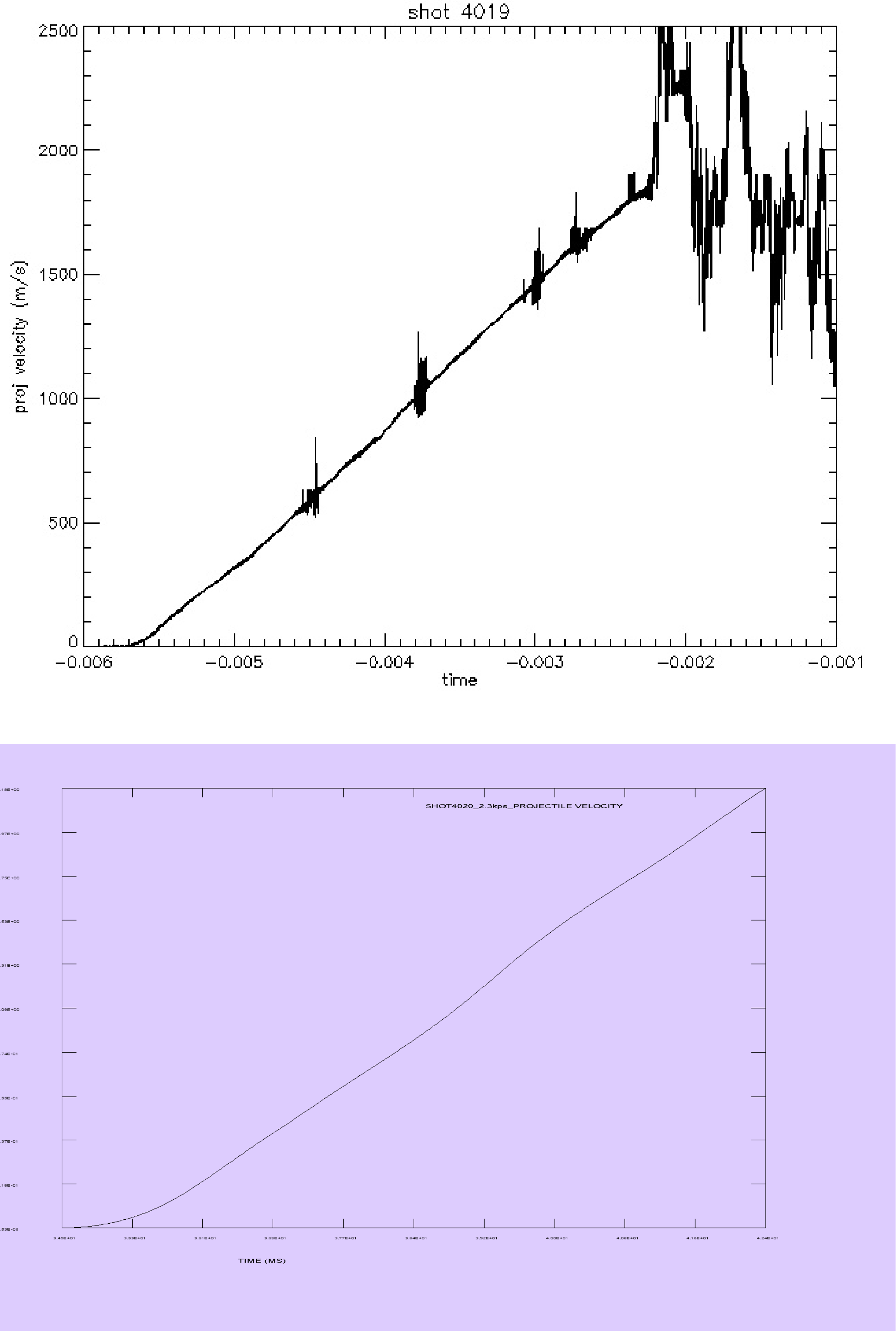
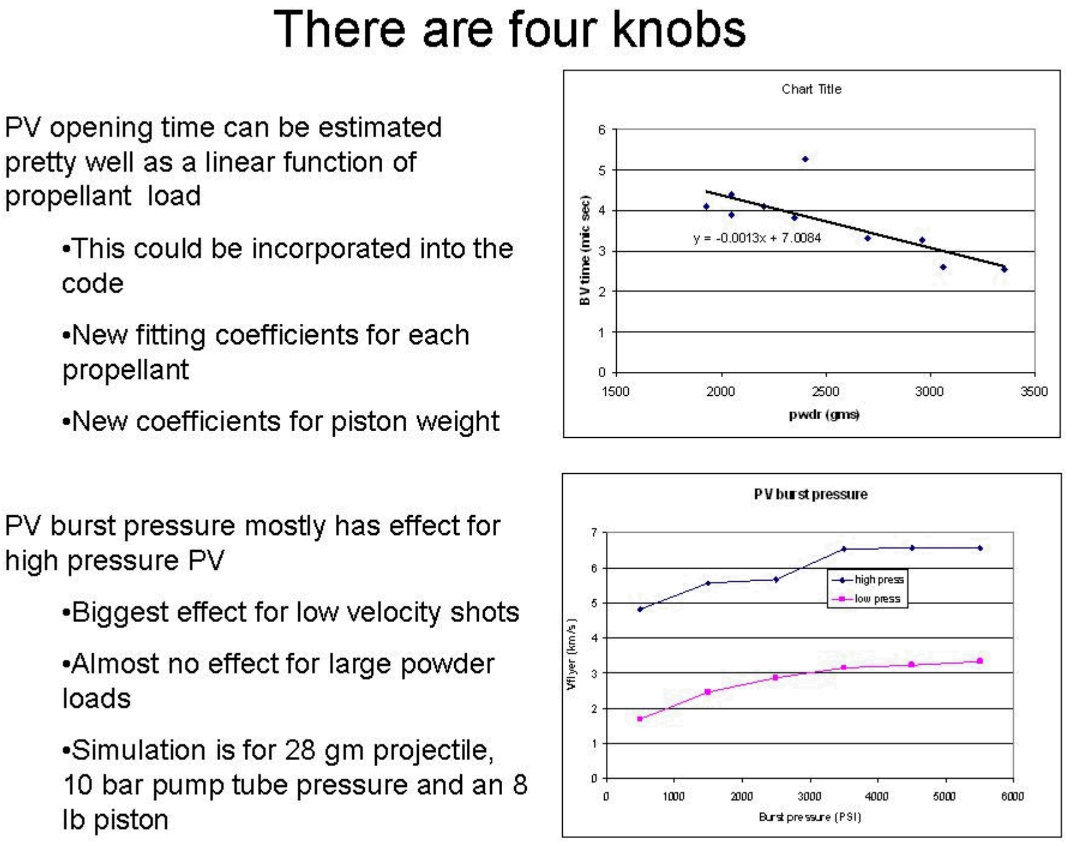

shot 4019
proj velocity (m/s)
2500
2000
1500
1000
500
0
−0.006
−0.005
−0.004
−0.003
−0.002
−0.001
time
SHOT4020_2.3kps_PROJECTILE VELOCITY
V (KM/S)
2.18E+00
1.97E+00
1.75E+00
1.53E+00
1.31E+00
1.09E+00
8.74E-01
6.55E-01
4.37E-01
2.18E-01
3.53E-06
3.45E+01
3.53E+01
3.61E+01
3.69E+01
3.77E+01
3.84E+01
3.92E+01
4.00E+01
4.08E+01
4.16E+01
4.24E+01
TIME (MS)

Figure 15



There are four knobs

PV opening time can be estimated pretty well as a linear function of propellant load

- This could be incorporated into the code
- New fitting coefficients for each propellant
- New coefficients for piston weight

PV burst pressure mostly has effect for high pressure PV

- Biggest effect for low velocity shots
- Almost no effect for large powder loads
- Simulation is for 28 gm projectile, 10 bar pump tube pressure and an 8 lb piston

Figure 16

Numerous shots all gave results to within a few percent

shot	F_vel	projectile	PV	PVP	pwdr	pwdr wt	gas	gas_press	piston	proj stress
4015	1.116	17.2	35/62	3500	M6	650	N2	125	15	0.26
4016	1.11	38.5	10//62	400	M6	750	He	125	15	0.04
4017	1.232	45.29	28/62	650	M6	550	He	145	15	
4018	bounced	45.3	35/62	6500	M6	550	He	145	15	0
4019	1.837	45.35	30/62	1150	M6	900	He	145	15	0.1
4020	2.55	45.6	30/62	2000	M6	1400	He	145	15	0.25
4021	1.88	45.6	30/62	1250	M6	950	He	145	15	0.123
4022	2.15	45.413	30/62	1535	M6	1100	He	145	15	0.15
4023	1.98	45.5	30/62	1350	M6	1000	He	145	15	0.135

Shots 4016,4017 PV didn't open all the way

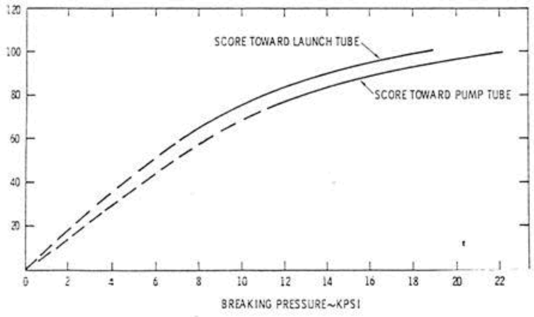


Figure 11 Relationship of Breaking Pressure to Web Thickness for Two 0.060" Thick Petal Valves — 1-1/8 Inch Petal Valve Retainer

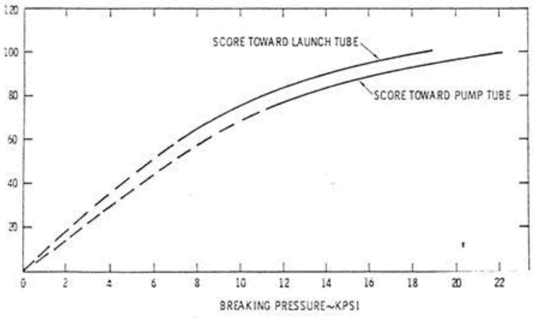
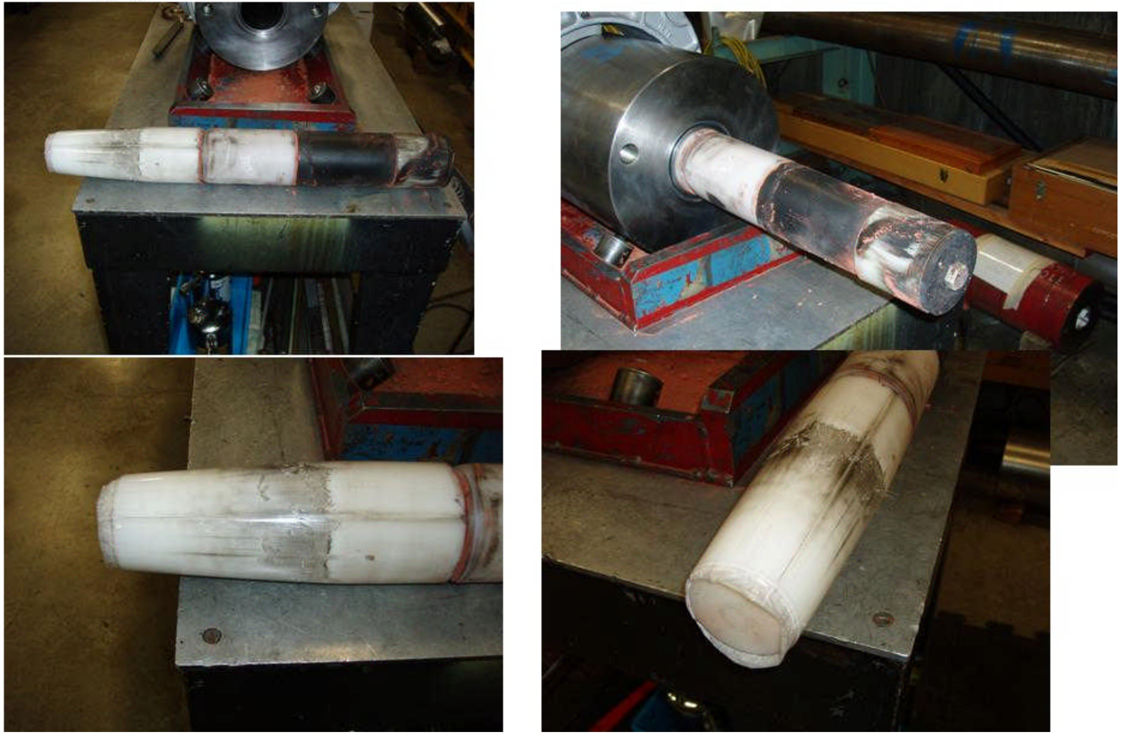


Figure 11 Relationship of Breaking Pressure to Web Thickness for Two 0.060" Thick Petal Valves — 1-1/8 Inch Petal Valve Retainer

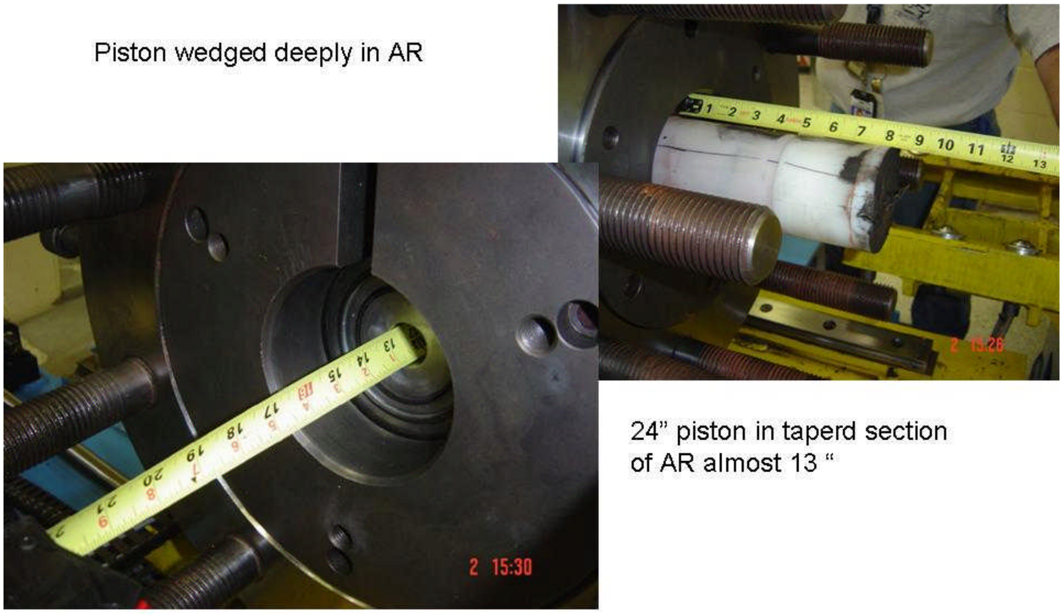
Figure 17



Typical result of Livermore shot

Figure 18

Results of shot JAS71



Piston wedged deeply in AR

24” piston in taperd section of AR almost 13 “

Jasper shot 71 Piston

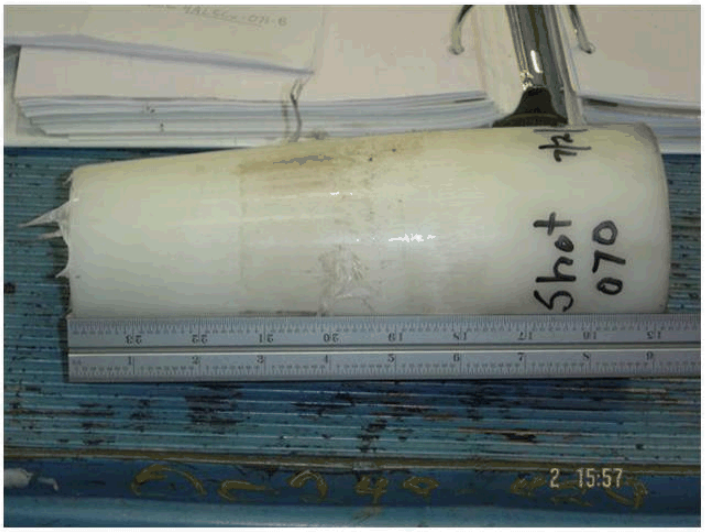


Figure 19