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AFRL's "HP3" 60mm Powder Gun

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The Air Force Research Laboratory at Eglin Air Force Base has invested in a new facility, called the High Pressure Particulate Physics (HP3) Facility, to study materials at conditions comparable to those occurring in or near a detonation or high speed impact event. The primary research tool of the new facility is a 60mm bore, single stage powder gun capable of accelerating projectiles to 2.3 km/sec and creating controlled (parallel-plate) impacts. The system is configured to allow for a variety of diagnostics, and to date, single point velocity interferometry has been demonstrated. This report discusses the gun and it's capabilities, the method by which the diagnostic data is interpreted, the design of the projectiles and targets, and the setup of the experiments.

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AFRL's "HP3" 60mm Powder Gun

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Summary

The Air Force Research Laboratory at Eglin Air Force Base has invested in a new facility, called the High Pressure Particulate Physics (HP3) Facility, to study materials at conditions comparable to those occurring in or near a detonation or high speed impact event. The primary research tool of the new facility is a 60mm bore, single stage powder gun capable of accelerating projectiles to 2.3 km/sec and creating controlled (parallel-plate) impacts. The system is configured to allow for a variety of diagnostics, and to date, single point velocity interferometry has been demonstrated. This report discusses the gun and it's capabilities, the method by which the diagnostic data is interpreted, the design of the projectiles and targets, and the setup of the experiments.

Chapter 1

Introduction

The use of precision research guns to investigate material properties at high pressures dates back to World War II, with most of the basic launch techniques for single-stage guns established in the following decade. The diagnostics applied to the guns, as well as the data analysis and interpretation, are still evolving, with an especially concentrated flurry of new analysis techniques accompanying a new diagnostic or experimental technique. Typically these guns are used in the parallel plate impact configuration, where the projectile, faced with a flat plate, impacts a target consisting of a stationary flat plate at a controlled impact velocity. The faces of both plates are perpendicular to the direction of travel, so that a one dimensional strain state is achieved in both plates. This 1D strain condition persists until disrupted by release waves travelling in from the boundary of the plates (assuming no non-parallel interfaces within the boundaries of the plates). These parallel plate experiments are well documented in the literature and other publications, and will hereafter be called "impact experiments", "experiments", or "shots" for brevity. The experiments conducted using the technique are used to determine parameters related to material equation of state (EOS), strength, and detonation at conditions representative of those encountered during high speed impact and in the vicinity of a detonation, when dynamic shock waves are produced.

The Air Force Research Laboratory (AFRL) has recently built the High Pressure Particulate Physics (HP3) Facility at Eglin Air Force Base in order to do impact experiments. Currently, the primary tool is a 60mm single stage powder gun. This paper describes the gun, projectiles, and targets typically employed, as well as the common experimental setups, diagnostics, and capabilities. Issues as of summer 2012 are also discussed. This report builds upon a previous report, AFRL-RW-EG-TM-2011-048. In that report, plans for the facility are described. In this report, the actual results of the first ∼16 months of operations are described.

Chapter 2

Physical Description

2.1 Gun

The 60mm gun had been in storage at AFRL prior to being de-mothballed in 2008 and refurbished by Physics Applications Inc of Dayton, OH. The refurbishment consisted of refacing and honing the barrels (originally an installed barrel and a spare) and creating a completely new breech assembly and support structure. In the fall of 2010 it was installed in the HP3 facility at Eglin, and the first shot was in May 2011. A picture of the gun is shown in Figure 2.1. As shown, the gun consists of the breech, barrel (now consisting of both barrel tubes coupled together), and catch tank. The breech is constructed of 4340 steel at Rc 36-40 with an inner diameter of 4.25" and an outer diameter of 12", and is sealed by an acme-threaded breech plug. The length of the powder chamber is adjustable by inserting cylindrical breech plates of various lengths, with a maximum length of 17". The transition from the powder chamber to the barrel is governed by the forcing cone, termed the "orifice plate". A cut-away diagram of the breech is shown in Figure 2.2.

The ignition system consists of a .300 H&H brass cartridge with a standard primer installed. The cartridge case is filled with 2-3 grams of FFFG black powder, followed by a small amount tissue paper for wadding. The primer is activated via a solenoid-driven firing pin. Once ignited, the black powder travels down the igniter tube, which is partially filled by 10-20 grams of benite strands. The igniter tube is extensively cross-drilled and is surrounded by the main powder charge, so that the benite ignites the main powder charge. The main powder charge is packed such that the charge extends the length of the igniter tube regardless of the amount of powder used. For example, with very small charges, the charge is rolled into a paper tube 30mm in diameter around the igniter tube. With large charges, a larger diameter paper tube is created, but the length remains constant. The forcing cone increases the efficiency of the powder, as well as provides a vacuum seal to the barrel and projectile boot (discussed later).

The 46 foot, 10 inch barrel consists of two joined 272 inch long main tubes, plus an 18 inch long replaceable muzzle tube, all made of 4340 steel at Rc 36-40. The tubes are joined together via reverse threaded couplers and alignment rings. The downrange tube has a 1/8"

Figure 2.1: The HP3 60mm gun

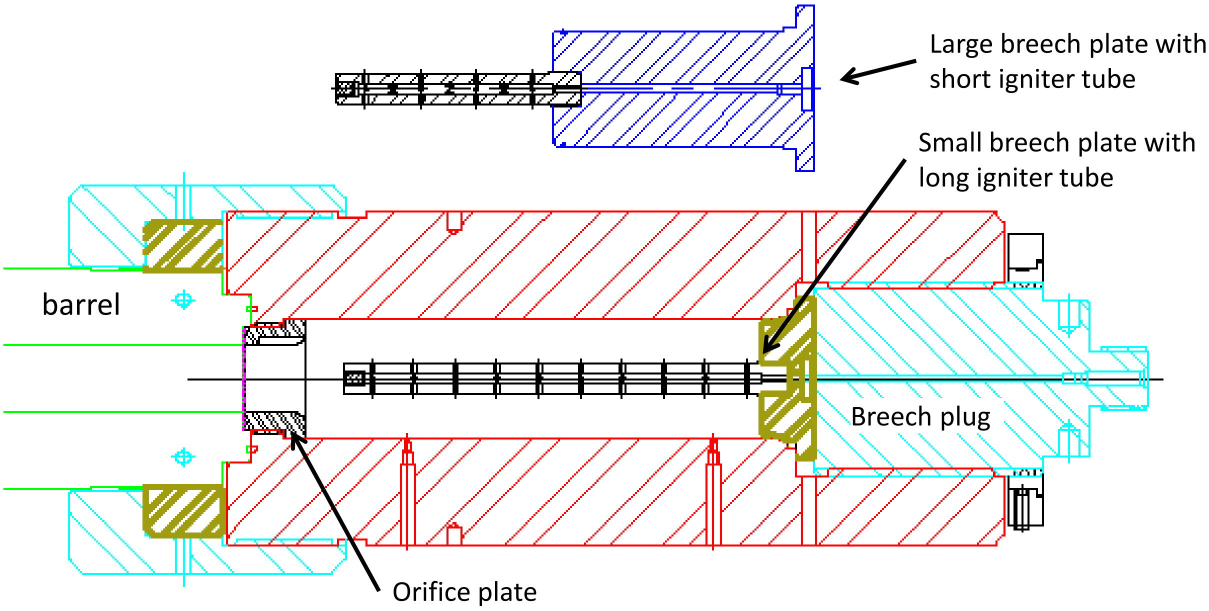


Figure 2.2: A cutaway of the assembled breech. Downrange is to the left in this schematic. The cyan plug on the right is the acme-threaded breech plug. The breech is shown with the small breech plate installed to yield a large breech volume. The large breech plate assembly is shown floating above the assembly- if it were installed instead the breech volume would be less. The orifice plate is shown in black and provides an angled seat for the projectile (not shown) to seal against.

chamfer on the leading edge to eliminate binding due to slight misalignment and the tubes were honed after assembly to further reduce that possibility. The breech and barrel are supported by a series of rollers which are mounted onto a rigid i-beam substructure which is mounted onto concrete footings. The rollers are precisely positioned by jacking bolts to support the barrel in alignment and then clamped in position. The rollers facilitate recoil, as well as barrel positioning within the catch tank.

The catch tank is composed of an A70 steel tank, approximately 80 inches inside diameter and 120 inches long, with 2 inch thick walls. The rear door is composed of two 1 inch thick low-carbon steel plates, and bolts onto the catch tank flange via 27 1-1/4 inch bolts. A vacuum seal is provided by a 70-durometer Buna-N gasket with an "L" cross section. Each "leg" is .75 inches long, with one leg slightly thicker than the other (0.42 and 0.38 inches thick). One of the legs fits into an o-ring groove in the flange. The bolts are tightened to 100 ft lbs each and compress the gasket. The muzzle of the barrel extends into the tank and is sealed via an o-ring arrangement. The tank has numerous ports to allow for future diagnostics and controls. Several of the ports are currently employed to support feedthroughs for the existing diagnostic systems. The tank also contains ports for vents and vacuum lines. The vacuum system consists of a three in-line vacuum pumps, supplied as a complete package. The first pump, which outlets to atmosphere, is an oil-lubricated rotary vane pump from Elmo-Rietscle. The first and second boosters are oil-free, 3-lobe positive displacement rotary blowers from Aerzen USA. The system is capable of pumping the tank and barrel down from atmosphere to better than 100 mtorr in approximately 1.5 hours.

2.2 Projectile

There are two standard projectile designs- the "high speed" and the "low speed" design. The low speed design is heavier and therefore allows the gun to obtain lower velocities. If the high speed design is used with low velocities, then below about 700 m/sec the projectile is decelerating at impact. The deceleration causes the flier plate to separate from the sabot, with disastrous consequences for tilt. The high speed projectile is shown in the top of 2.3. It is composed of five main components (from right to left in the figure): the boot, rear aluminum plate, phenolic body, front aluminum cup, and sample, although the sample may consist of several parts. The boot is made of HDPE, machined with a 9°(total included angle) taper to match the angle of the forcing cone. It has two o-ring grooves machined into it and fitted with o-rings, which provide a vacuum seal to the forcing cone. The boot serves as a vacuum seal and catch prior to launch (it prevents the projectile from being pulled down the barrel during pump-down), and also provides a mechanism for pressure build-up in the breech during ignition, and then a gas seal during launch. From interior ballistics simulations, we predict that the pressure required to force the boot through the cone (to "launch") is 2.5 ksi. In the front of the boot, there is a 1/2 inch deep, tapped blind hole. A threaded stud is screwed into the hole until it bottoms out. The portion of the stud extending from the boot is screwed into the next piece of the projectile, the rear aluminum plate, via a tapped hole extending through the center of the plate. The rear aluminum plate serves to attach the boot to the phenolic body, which is a hollow tube of grade LE linen-phenolic for the high speed projectile, with an inner diameter of 1.5 inches. During assembly, the plate is bolted onto the body via three screws that thread into the phenolic body. After assembling the plate to the body, then the boot is attached via the threaded stud. The phenolic body serves to align the projectile with the axis of the barrel and provide the bearing surface during projectile motion. It is precisely machined so that it is a slip fit in the bore of the barrel with no discernible play, which corresponds to a diameter of 2.387 inches (indicating that the bore is actually slightly oversize). Although the body is 4 inches long, the bearing surface is approximately 3.8 inches long. The front aluminum cup is attached to the front of the phenolic body using 5-minute epoxy, and alignment is achieved using carefully machined mating surfaces on both parts. The sample, also known as the "flyer" or "impactor", is contained within the cup, and protrudes slightly beyond it. It may be a single layer or multiple layers of materials, depending on the experimental objectives. The "standard" impactor diameter is 55 mm. The layers are lapped and polished to be flat within 5 Na fringes/inch and parallel within $\sim$0.0001 inches (as measured by the variation in thickness of the polished disc). They are epoxied together using unfilled Hysol®epoxy (RE2038 and HD3475) and clamped for 24 hours while the epoxy is curing. Typical epoxy bond thicknesses are a few microns, and are sometimes difficult to measure because they are near the uncertainty in our thickness measurements. The low speed projectile, shown in the bottom of Figure 2.3, is similar but distinctly different. The low speed projectile is fabricated from a solid (as opposed to hollow) rod of grade LE linen phenolic. The rear is drilled and tapped to directly accept the stud from the boot, so no aluminum rear plate is necessary. Also, the front is machined to include the cup to accept the sample materials, eliminating the the need for the front aluminum cup. Finally, the HDPE boot for the low speed projectile is smaller than it's high speed cousin to allow for launch at lower pressures, and also to allow for less drag in the barrel (and therefore less deceleration). It should be noted that although the high and low speed projectiles use grade LE linen phenolic bodies, the material is qualitatively different. For the high speed body, which is hollow, the linen is wrapped around a mandrel during layup, such that the linen layers make concentric rings. In the low speed projectiles, the linen is laid in flat layers, giving the turned surface a look reminiscent of wood-grain. It is unknown what effect the different construction techniques will have on the material's suitability as a projectile body.

2.3 Target

The standard target assembly is shown in Figure 2.4. The target itself is composed of various sample materials, and may consist of many layers of materials as required by the experimental objectives. All components of the target stack (not already supplied with an optically flat surface) will be lapped and/or polished on a double sided lapping/polishing machine so that the surfaces are flat to within 5 fringes of Na light per inch, and the part surfaces are parallel to within $\sim$0.0001 inches (as measured by the variation in thickness of the polished disc). When assembling a target composed of multiple layers, the Hysol epoxy

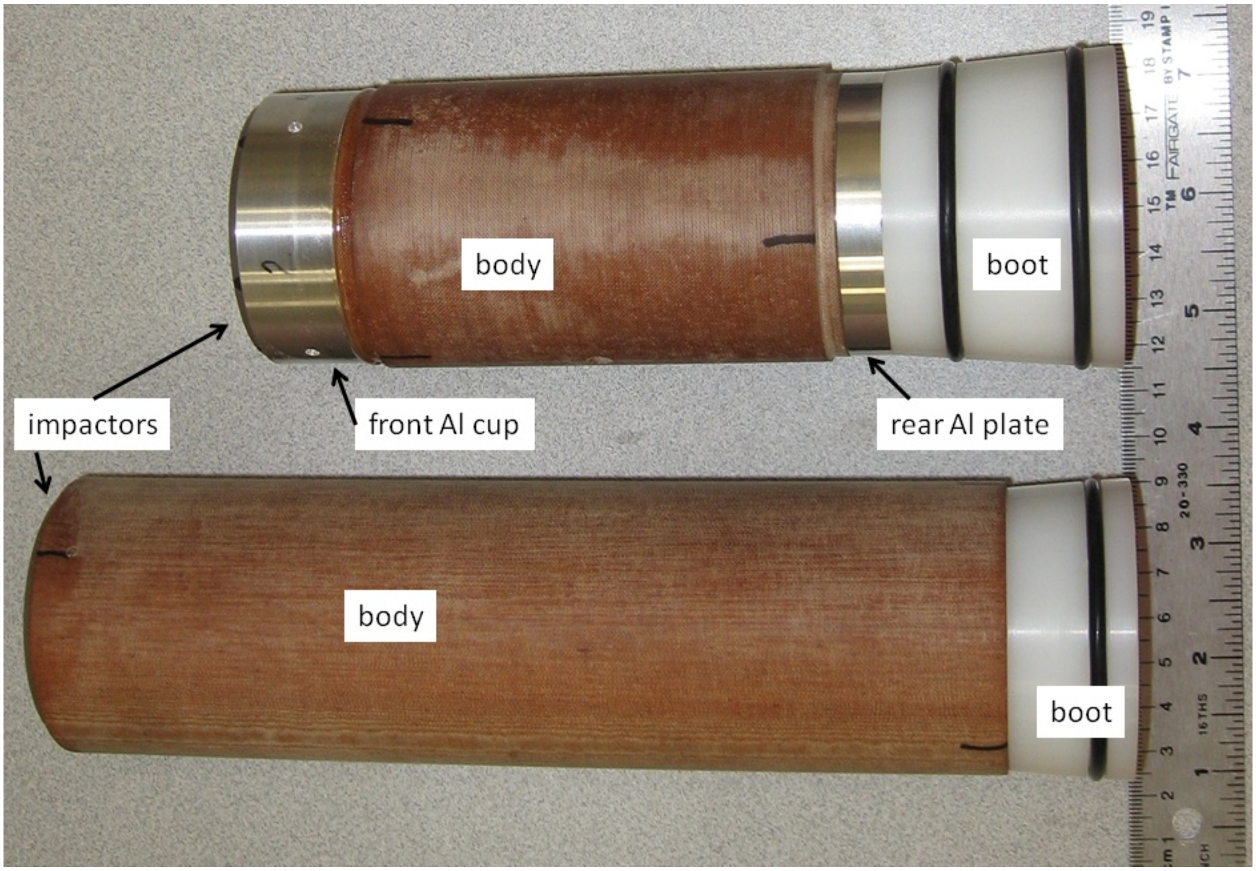


Figure 2.3: High speed projectile on top, and low speed version on bottom. Note that the low speed projectile is solid, and so does not require the front and rear aluminum plates seen on the high speed projectile. Due to solid body and longer length, the low speed projectile weighs some 400g more than the high velocity projectile.

will be used to achieve thin bonds. Regardless of the complexity of the target, it is mounted into an aluminum target mount as shown in the figure. The aluminum target mount is also lapped and polished on both sides to the same specs as the target or sample materials. When setting the target into the mount, the target and mount are each independently pressed onto a granite datum plane while 5-minute epoxy is mixed and applied to the interface between them. The epoxy is allowed to set with the parts so clamped in place for at least 15 minutes. After removing from the clamps, an optical flat is used to ensure co-planarity between the target and target mount by ensuring that fringes can be seen over both surfaces. Figure 2.4 also shows the self-shorting pins installed. The use of the pins is described more fully it the 3 section, but their basic purpose is to determine velocity and tilt at impact. The pins are installed into threaded holes arranged as shown. The pins are carefully set such that they are proud from the impact face by predetermined amounts- the "height" of the pins is the distance they are proud. The heights are measured using a high-precision micrometer mounted on a jig, as well as a multimeter to determine when the pin makes contact. The normal targeted heights for the tilt pins are 75 μm, and for the three velocity pins the heights are set so that they are shorted at 3, 6, and 9 μsec prior to impact. Thus, the targeted heights depend on the anticipated impact velocity. The pin heights are set using the threads and jam nuts, and then epoxied in place with quick setting epoxy. After the epoxy is cured they are measured. The measured heights generally agree with the targeted heights to within 20 μm. During the measurement operation the height of the target is also checked again to ensure alignment between the target and mount. The heights are generally within 5 μm, which is near the measurement uncertainty of 2-3 μm. The variation in the height of the sample is taken into account in the tilt calculation. The "standard" target assembly can accommodate up to a 46 mm diameter sample.

The standard target is mounted onto a set of linen-phenolic plate mounts, which are mounted to brackets on either side of the muzzle (they do not connect directly to the muzzle, but instead connect to a semi-permanent table mounted to the tank). The standard target is shown, after attaching to the linen-phenolic plate mounts and mounting in the target chamber, in Figure 2.5. From the images in the figure, it can be seen that the two mounting plates are separated from each other. The separation is accomplished using three screws. The bottom-most screw has a standoff spacer to tighten against, whereas the top two screws tighten against springs. The standoff screw on the bottom accomplishes two things. It provides a consistent standoff distance, and it prevents a very large target assembly from deforming a bottom spring and therefore tilting under it's own weight.

In order to minimize tilt, the target must be aligned to the bore prior to each shot. This is accomplished by using an alignment jig. The jig consists of a linen-phenolic tube, machined to a diameter which provides a close slip fit to the bore, approximately .5 m long, which is inserted into the muzzle of the gun. On the front of the tube a mirror has been glued so that it is perpendicular to the tube to a fraction of a milliradian. To do the alignment, the jig is inserted into the muzzle and then the standard target is replaced with an optical flat, which has been drilled so that it can mount to the alignment plates in the same manner as the standard target. The jig is lightly spring loaded against the muzzle to maintain a light

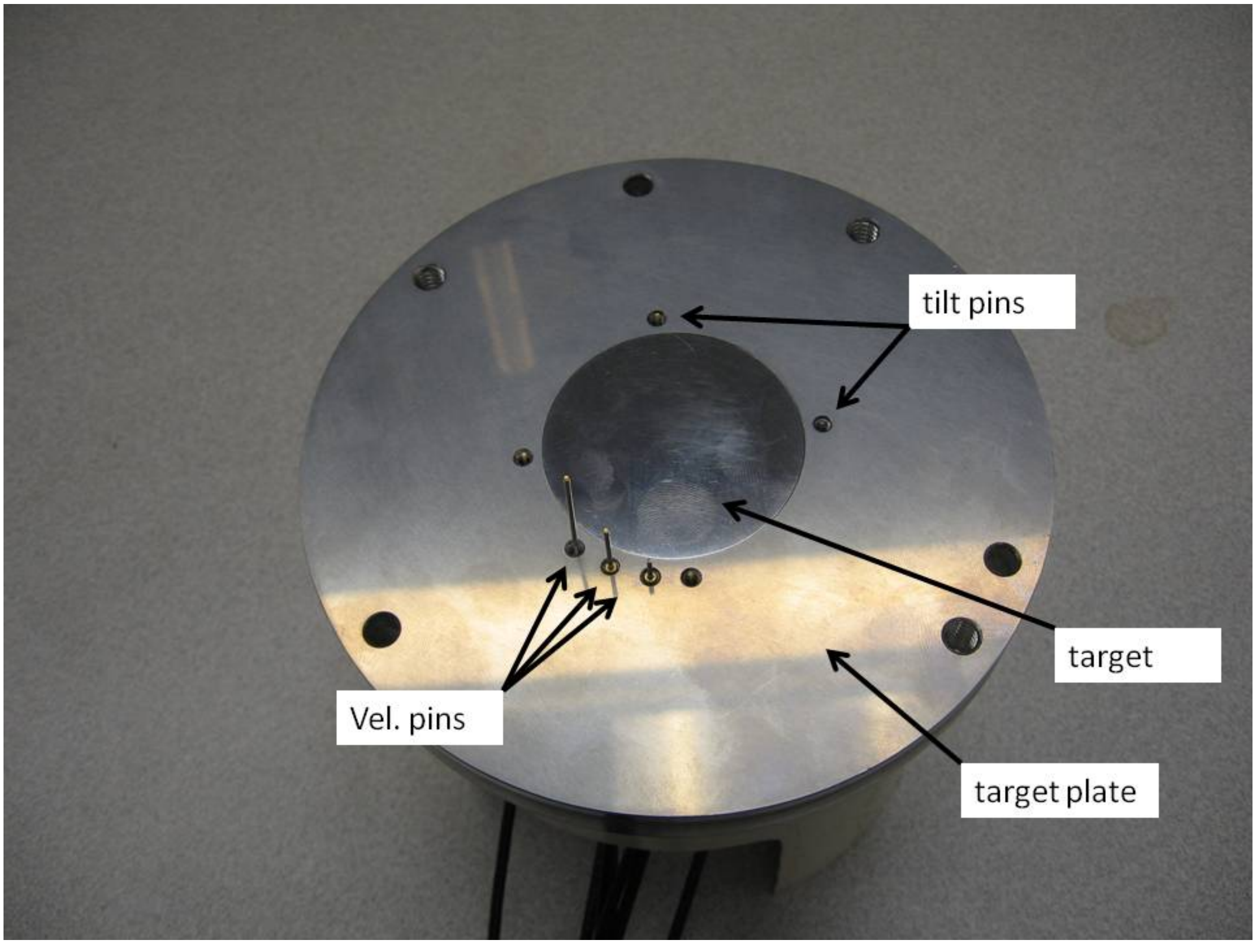
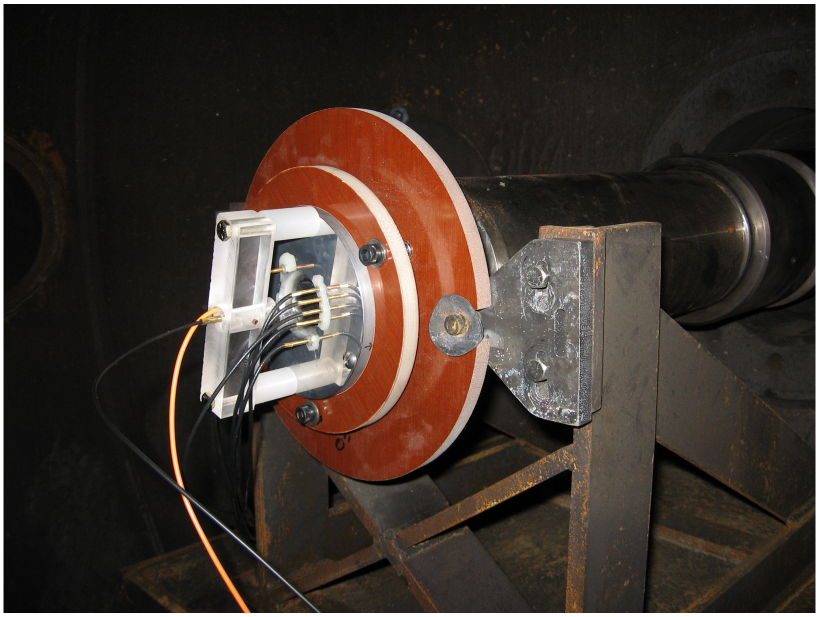
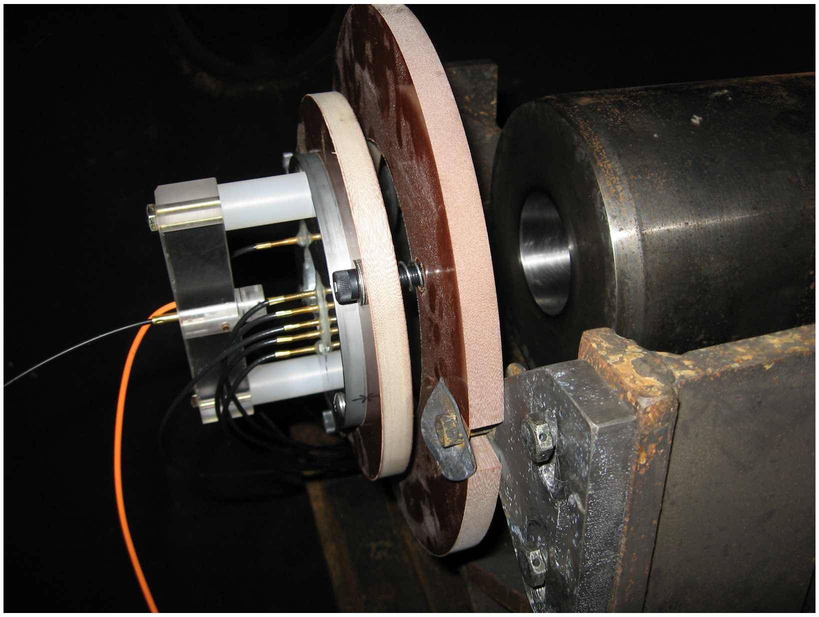


Figure 2.4: Standard target, viewed from the impact face. Only two of the four tilt pins are labelled. The tilt and velocity pins are all self-shorting pins; they are merely called “tilt” or “velocity” pins depending on their function. In either case- they create a short when the tip is “crushed” by a few thousandths of an inch. The holes around the edge of the target plate are use to affix diagnostics and to mount the target plate into the phenolic mounts.



(a) From rear quarter. Notice that the tilt and velocity pins have been epoxied in place, and the standard target has been mounted onto the linen phenolic positioning mounts.



(b) From side. Here the muzzle is visible, as well as the gap between the two positioning plates and one of the springs used in the angular alignment scheme.

Figure 2.5: Target mounted and ready to shoot. The large plastic bar and mounts on the rear of the target plate are the interferometry probe holder (and probe).

pressure between the mirror and the optical flat. A monochromatic light is used to illuminate the mirror and the optical flat, and the two spring-loaded screws are adjusted until fringes are found and optimized, a process known as the “Newton’s rings method”. Generally the target mount can be aligned to produce a bullseye about an inch in diameter, with only a few additional rings towards the edge of the alignment jig. After alignment, the optical flat and jig are removed, and the target is installed, as shown in Figure 2.5. The alignment is maintained even when the target is carefully removed and reinstalled several times.

Chapter 3

Diagnostics

Several diagnostic systems have been deployed with the gun. The initial systems monitor the breech pressure, impact velocity, tilt at impact, and material velocity. Each of the systems will be discussed separately, but all of the systems feed into a National Instruments PXI chassis containing several data acquisition cards. The effect is that of a single, large oscilloscope monitoring all the various data channels. The system is controlled by custom software written in Labview. Collectively, the cards, chassis, and software are referred to as the data acquisition system (DAS).

The breech pressure transducers are PCB Piezotronics Model 109C12 piezoelectric pressure sensors whose signals are conditioned through a PCB Piezotronics Model482C signal conditioner before being recorded by the DAS using a 12-bit, 150 MHz bandwidth digitizer running at approximately 900kS/sec. There are two breech pressure sensors- one located near the muzzle and the other near the rear of the powder chamber. They typically yield pressure traces that agree to within a few percent. Initially the pressure traces are used to ensure we are not overpressurizing the breech and to develop the interior ballistics simulation parameters while we do not have a powder curve (or velocity curve). We expect the breech pressure traces to become less important as the gun is used routinely, and only closely examined in the event of an abnormal firing or when operating the gun very near max pressures. Representative breech pressure traces are shown in 3.1.

The tilt pin system utilizes four self-shorting pins (Dynasen CA-1039-C) evenly arranged around the target to precisely determine the angle, at impact, between the impactor and target. Although the pins are arranged just outside the target, they are just within the edge of the impactor. Because the height of each pin in relation to the plane of the target is measured, and the impact velocity is known from the velocity pins, the tilt at impact is easily computed. The circuit for the tilt pins is shown in 3.2(a), and the physical location of the circuitry is immediately outside the catch tank. Cables are run from the circuitry to the recorders. All cable lengths are matched as closely as possible, both from the tilt pins to the circuitry and from the circuitry to the control room (LMR-400 50-ohm cable with measured lengths are 69'8", 69'8.75", 69'8.625", and 69'8.75"), and when shorted simultaneously, all signal show up on the DAS within one nanosecond of the others. The tilt pins are typically

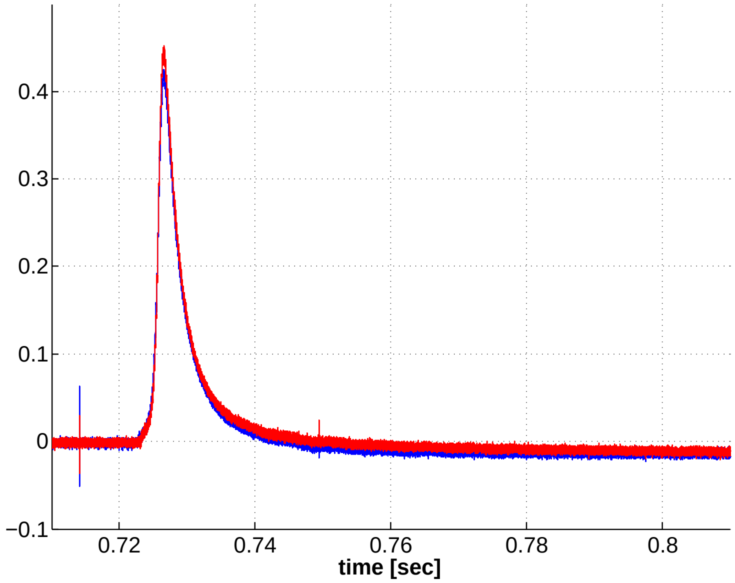


Figure 3.1: Breech pressure plots for shot 6. The ordinate axis is in units of volts. The two probes have calibration values of .0732 and .0746 V/ksi. Therefore, it can be easily computed that the max breech pressure for shot 6 was ∼ 5.9 ksi.

set so that they are 75 μm proud, although in practice the measured heights vary from 60-90 μm. The pins are set proud, rather than flush, to account for the small air gap before the short is made. It was desirable that the air gap would close just prior to, or at the instant of, impact. Since the gaps range from 20-80 μm, the pin are set to a "'target"' height of the upper end of the air gap range. Although it would be possible to set each pin proud by the amount of the air gap, the initial process does not include such compensation. An example of tilt-pin data is shown in Figure 3.3(a). Tilt calculation for each experiment relies on knowing the height of the tilt pins above the sample at the four locations. These heights are measured, as described previously, and are corrected by the gap distance and by the distance that the sample is proud or recessed from the target plate in the location adjacent to the tilt pin in question. These corrected heights, in conjunction with the gap closure times (see Figure 3.3(a)), are use to compute tilt by two different methods. The first method, given the impact velocity, computes the height of the impactor above the target plate at each tilt pin location at a reference time. The reference time is the time the first tilt pin closes (generally within a few tens of nanoseconds of impact). Then, for each combination of two pins (1&2, 1&3, 1&4, 2&3, etc), the distance between the pin pair (either 50 mm or $50/\sqrt{2}$) and the difference in heights at the reference time immediately yields the tilt for that pin pair. The tilt for the shot is taken as the maximum of the results for the six pairs. This method is more conservative than some other methods employed elsewhere, which assume that the impactor is planar. The second method uses equations for computing the angle between two planes, or the dihedral angle. First, a plane is fit to each group of three tilt pin points ("points" being the corrected heights at the common reference time just prior to impact). This is accomplished by defining two vectors and taking the cross product to obtain the plane normal P. The reference plane normal (taken as parallel to the barrel), is R. Then the dihedral angle ϕ_{PR} between the two planes is given as shown in Equation (3.1).

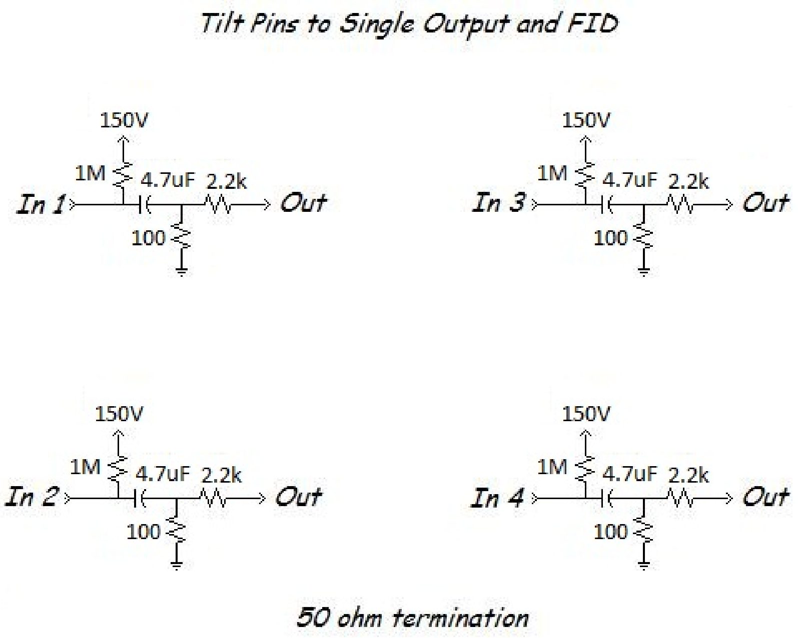
$$\phi_{PR} = \arccos\left(\frac{|P \bullet R|}{|P|\,|R|}\right) \tag{3.1}$$

This is performed for each of the four sets of three pins. Results generally cover a similar range to the tilt calculated by the first method. If the impactor is planar, all four normals will closely coincide. If they do not, it indicates a warped impactor. Also, because the orientation of the tilt pins is known with respect to the catch tank, the direction of the normals can be conveniently plotted as a projection to indicate both the direction and magnitude of tilt. In this way the tilt direction and magnitude can be easily plotted from shot to shot to look for and diagnose systematic problems that can be addressed. Both tilt calculations assume a constant impactor velocity.

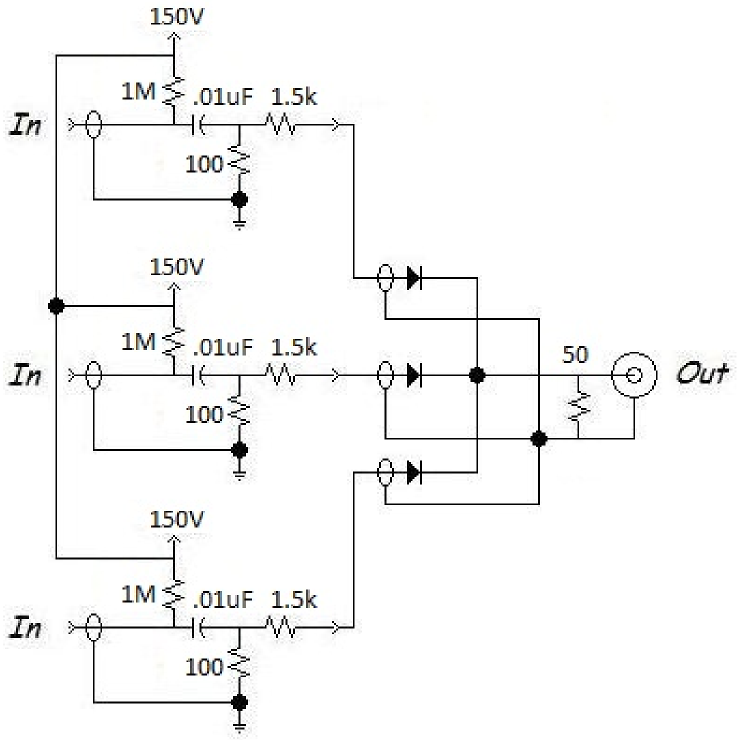
The velocity pin system is similar to the tilt pin system in that it utilizes the same self shorting pins, except that the pin lengths may vary. The velocity pins are positioned at the same radial position as the tilt pins ($25mm$), such that they contact the impactor near the outer edge. However, rather than being evenly spaced, they are located as closely together as possible so as to minimize the effect of tilt on the velocity reading. (The velocity calculation assumes zero tilt.) In addition, they are arranged so that one of the tilt pins can function as both a tilt pin and as the shortest velocity pin. The pin heights are set, with prior knowledge of the approximate experimental velocity, so that the three velocity pins close at 3, 6, and 9 μsec prior to impact. Obviously, the aforementioned neighboring tilt pin closes at approximately 0 μsec before impact, and so the three spans are used to compute three velocities and then averaged for the reported velocity. The velocity pins are multiplexed together onto one single data line so as to minimize the total number of analog digitizer channel required. The velocity pin circuit is shown in 3.2(b). As with the tilt pins, the circuit is physically located just outside the catch tank, and the cable lengths from the individual pins to the circuit are matched. Furthermore, the long cable from the circuitry to the DAS is 69'9" of LMR-400 50-ohm cable to match the tilt pin signal transit time. The tilt and velocity pin signals are both monitored by data acquisition cards operating at 1 Gs/sec sample rate with 300 MHz bandwidth and 8-bit resolution. An example of velocity pin data is shown in Figure 3.3(b).

As previously mentioned, the tilt pin neighboring the the velocity pins is used as a velocity pin as well as a tilt pin. Because the two circuits are separate, it is possible that a systematic timing error could cause the velocity measurement between the tilt pin and velocity pin give an incorrect reading. We assume, due to the matched cable lengths, that there is no systematic error. As of the time of writing, there have been several dozen experiments performed on the gun where velocity and tilt were measured accuratly enough to assess the validity of this assumption. The velocity from the span including the tilt pin is always very close (within 1%) of the velocities from the other two spans, and is sometimes slightly greater and sometimes slightly less. Therefore the three spans represent valid, independent measurements, and the total range of the three measurements is generally about 1% of the average. The velocity uncertainty is reported as the maximum deviation of the three measurements from the average, and is generally 0.5% or better, but occassionally is near 1%.

Particle velocity (also known as material velocity) in the target is measured by either VISAR [1] or PDV [3]. Currently there are two single point Valyn VISAR systems used at the HP3 facility. Both VISARs share a single Coherent Verdi (532 nm) 6 Watt Laser as the light source. The light is transmitted from the laser to the sample by means of a fiber and optical probe positioned 20-100 mm behind the sample. The current probes have dedicated illumination and collection fibers, which, respectively, are 50/125 and 1000/1035 micron fused silica multimode fibers. The probe lens focuses returned light onto the collection fiber for input into one or both VISARs. The VISARs are push-pull style [2], where each of the four optical signals is fed into a photomultiplier tube (PMT). The output of each pair of PMT (a "'pair"' here refers to the two PMT sampling the same polarization) is input into a differential amplifier, and the output of both differential amplifiers is monitored by the DAS using 8 bit, 1 GHz cards sampling at 2 GS/sec. The PDV system uses a dedicated 12.5 GHz, 25 GS/sec recording oscilloscope monitoring 8 GHz analog detectors. Representative data traces from both VISAR and PDV can be seen in Figure 3.4.

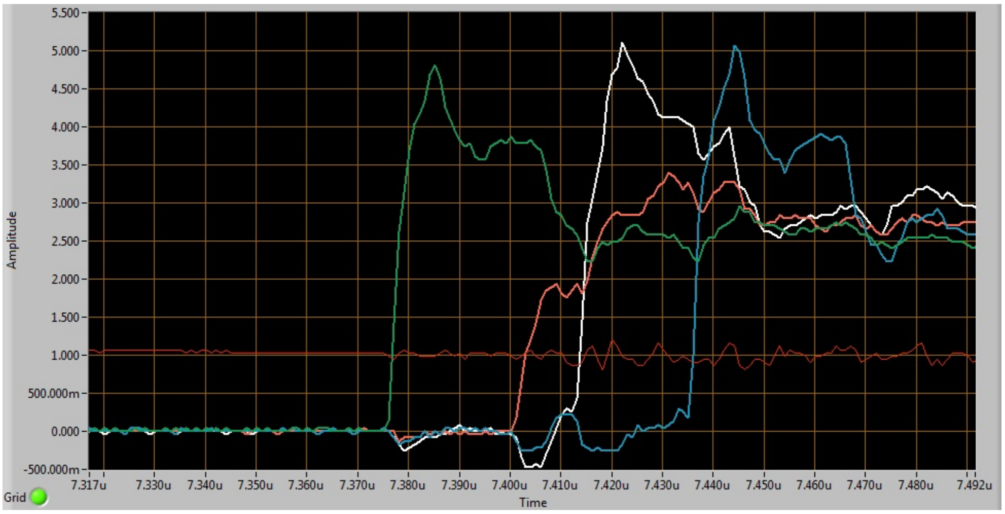


(a) Tilt pin circuits.

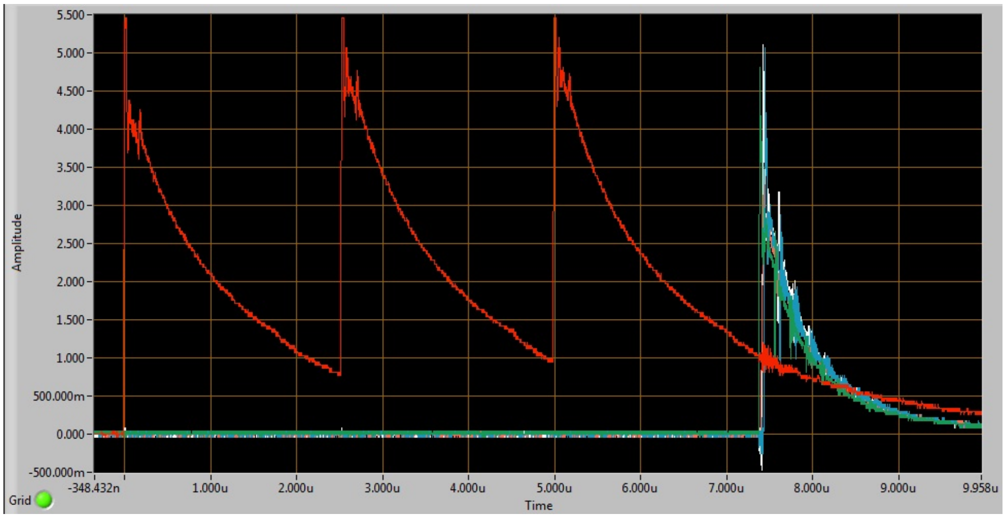


(b) Velocity pin circuit.

Figure 3.2: Tilt and velocity pin circuit diagrams.



(a) Tilt pin data from shot 11. Because the data comes in on different DAS channels, it is easy to assign each trace to a specific tilt pin. Since the position of the tilt pin is known, the tilt at impact can be computed.



(b) Velocity pin data from shot 11. The red line with the three spikes is the velocity pin data, and the jumble of lines afterwards is the tilt pin data.

Figure 3.3: Data from shot 11. Both figures show the same data traces, but image 3.3(a) is zoomed in on the tilt pin data, which appears as a jumble in 3.3(b)

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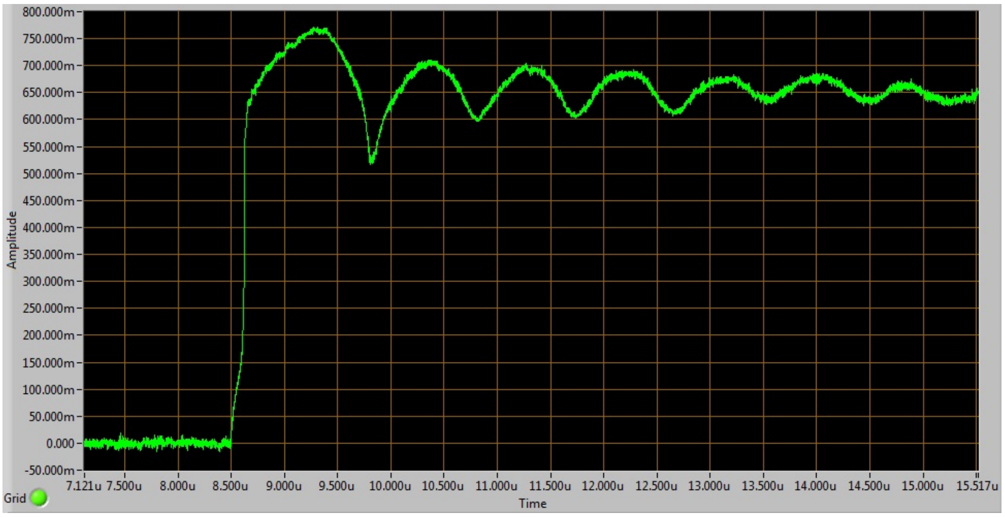
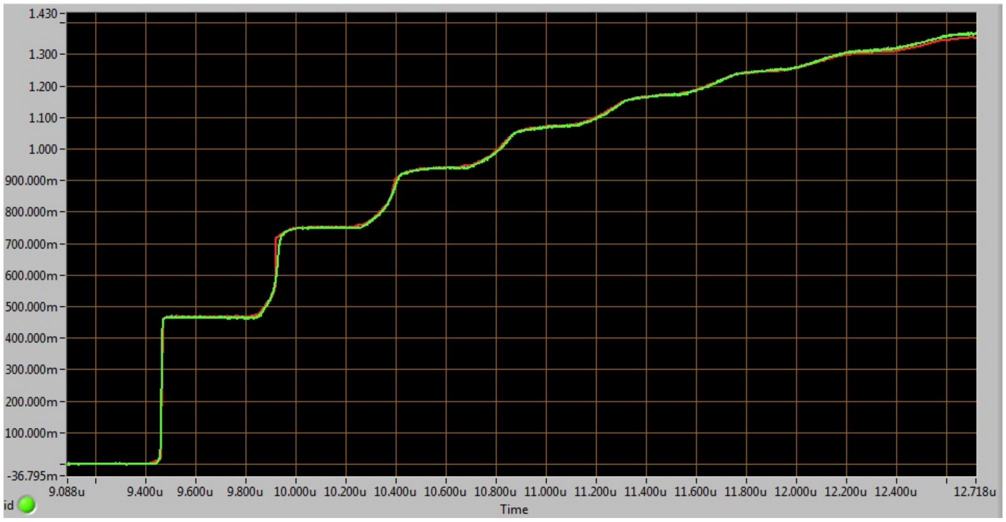


(a) VISAR trace from shot 11. This was a spall experiment where the VISAR sampled the free surface and the spall signal (and subsequent reverberations) are analyzed. The ordinate here is velocity with units of km/sec.



(b) VISAR and PDV traces from shot 38, where the two probes were positioned side by side. The PDV trace is red, and the VISAR trace is plotted on top in green. Note the close agreement (the underlying red trace is difficult to see). This experiment sampled a free surface as it "rung up" to a final velocity in multiple steps. Also note the improvement in VISAR noise between shot 11 and 38. The ordinate is velocity in units of km/sec.

Figure 3.4: Velocity and Pressure Curves

Chapter 4

Capabilities

The velocity capabilities of the gun are limited by safety considerations and mechanical limits. The breech is rated from the manufacturer to 90 ksi. However, based upon experience at different labs, we have decided to limit the breech pressure to 50ksi in order to avoid crushing the projectile at launch. This obviously limits our maximum velocity capability. However, the velocity, in addition to maximum breech pressure, also depends on the pressure required to extrude the tapered boot through the tapering cone of the orifice plate, the breech pressure pulse shape (how long the high pressures are maintained once the projectile begins to accelerate), the mass of the projectile, and the friction drag between the extruded boot and the bore. At the low end of the velocity spectrum, we are limited by the desire for consistent and predictable velocities, which becomes increasingly difficult as the powder charge decreases due to the need for consistent, 100% powder burn and the drag of the boot. With some powders, a minimum impulse is needed to get near 100% of the powder to burn, and without 100% burn, velocity reproducibility is degraded. Originally the gun was to be used with only one powder. However, once the experiments commenced and an interior ballistic model was applied and tuned, it became apparent that in order access the desired range of velocities, powders with different characteristics were needed. For low velocities, a very fast-burning powder was needed so that small amounts of it could be used, generating very small impulses, while still maintaining near 100% burn. Red-dot, a commercially available reloading powder from Alliant, is ideal. It burns very quickly, and the burn is nearly independent of pressure. However, for high velocities, a slower burning powder is desirable to keep as much pressure on the projectile as possible as it accelerates down the barell. Therefore, GAU-8 powder was chosen to access the high velocity regime of the gun.

Several dozen shots have been performed on the gun as of this writing (summer 2012). In order to access as wide a range of impact velocities as possible, the two projectile designs previously described are used in conjunction with three different powder and breech configurations. The breech for the gun can be configured as the "small breech" (with the large breech plug to occupy volume within the breech) or the "large breech" (utilizing the small breech plug to provide more space for powder). See Figure 2.2 for a schematic showing both

Table 4.1: Experimental configurations to access entire velocity range.

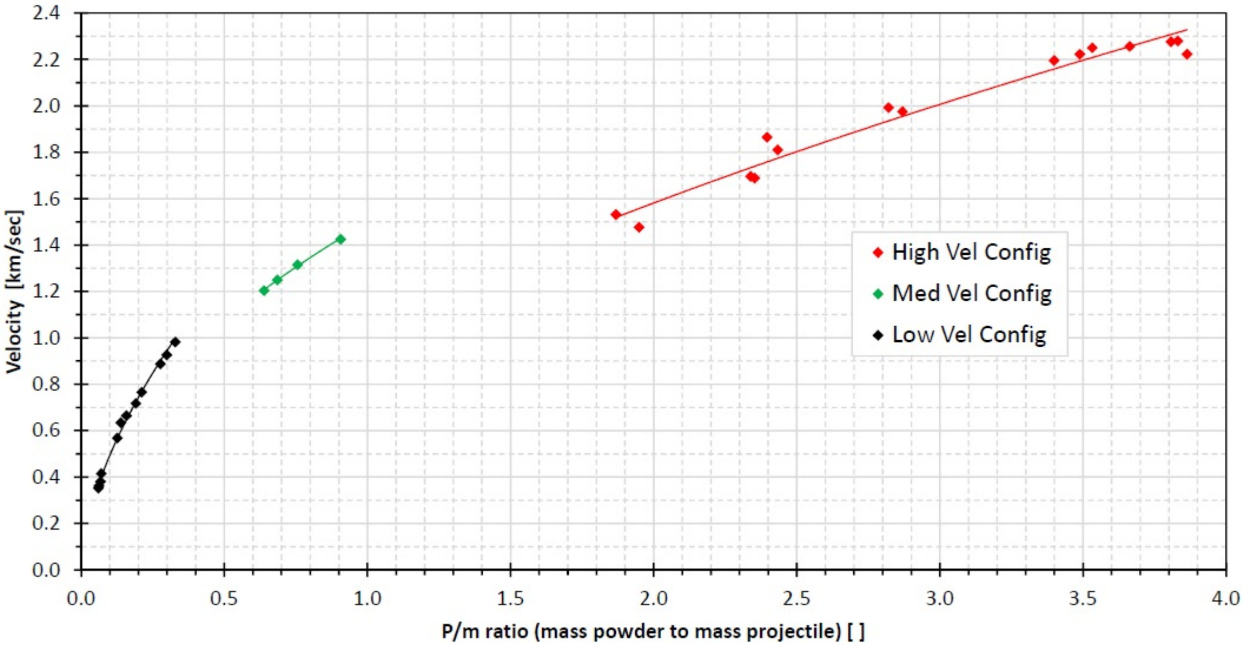
Config	Vel [km/s]	breech [ ]	powder [ ]	Projectile [ ]
low	<1	small	red dot	heavy
med	1-1.4	large	red dot	lightweight
high	>1.4	large	GAU 8	lightweight

assemblies. The powder chamber volumes for the small and large breech are approximately 2296 and 3873 cm^3, respectively. For the lowest velocity configuration, we require a heavy projectile and red-dot powder which will completely burn at low confinement pressures. For efficiency with small powder loads (ranging down to a few dozen grams of red-dot) the large breech plug (resulting in the small breech volume) is employed. When the highest velocities are required, slower-burning GAU-8 powder is used with the small breech plug and lightweight projectile to achieve higher velocities. For intermediate velocities, a third, hybrid configuration is used. Table 4.1 gives the three configurations, along with the applicable velocity ranges.

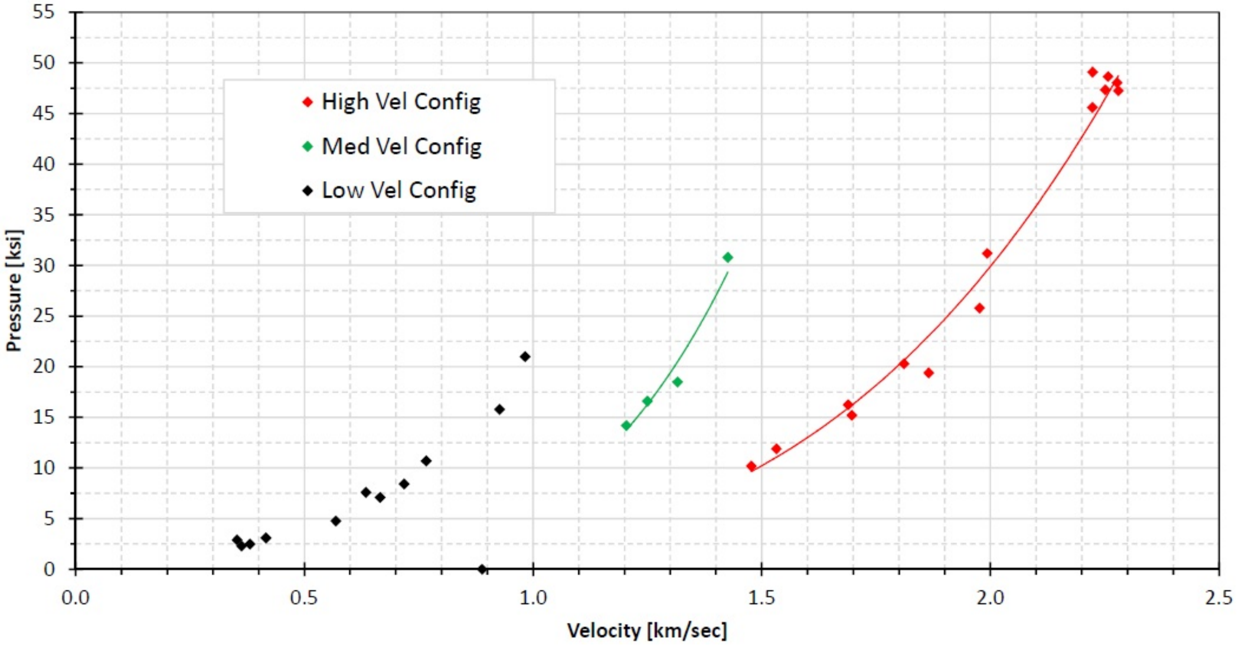
These three configurations currently allow velocities from 350 - 2300 m/sec to be reliably accessed. The velocity and pressure curves for the three configurations are shown in Figure 4.1. It can be seen in the figure that the velocities are well behaved for the low and medium velocity configuration, but that there is much more scatter for the high velocity configuration. The reason for this is unknown. However, it may be due to powder variations beyond our control and we may simply have to accept 5% uncertainty in our velocity predictions with the high velocity configuration.

The tilt is an indicator that the experiment went as planned (no breakup of projectile, etc) and that key assumptions built into most analysis (such as one dimensional strain) are valid. For our low velocity configuration, with the exception of one outlier, we always have <2 mrad of tilt. However, for the med and high velocity configurations, the tilt is considerably worse. Most shots are around 5 mrad, with occasional outliers beyond 10 mrad. The reason for this unknown, but since both the med and high velocity configurations use the lightweight projectile, we are currently investigating alternate designs for the the projectile to address the issue. Thus far, other than the projectile, we have not identified a pattern with tilt when attempting to correlate it with a number of variables such as breech pressure or impact velocity. However, from our limited data, the tilt is *more likely* to be worse as impact velocity increases. There is also no clear spatial pattern; ie, the tilt is not always oriented in a certain direction. Since the lightweight projectile is both hollow and shorter than the heavy, low-speed projectile, the current theory is that the tilt is due either to the hollow projectile yielding during acceleration or to the shorter projectile having more freedom to pitch and yaw.

It is desirable to be able to correlate times taken from the various diagnostics. For



(a) Velocity curves for each of the three configurations. The lines are power-law fits to each dataset.



(b) Pressure curves for each of the three configurations.

Figure 4.1: Velocity and Pressure Curves for the three gun configurations.

instance, to determine wavespeed using the combination of the tilt pins and the VISAR to determine wave transit time over a known sample thickness. We have performed about twenty shots where we can calculate the impact time from the VISAR trace, due either to the presence of an elastic precursor, or due to sampling the impact surface directly with the VISAR. Since the time for the crush pin signals to propagate to the recorders is not matched to the time for the optical signals to reach the recorders, it is not expected that impact time, as reported by the tilt pins (and slightly corrected for the distance the pins are proud, gap, and tilt), will match the impact time reported by the optical interferometers. However, it is expected that a constant offset, corresponding to difference between the propagation times of the two systems, will be observed. In most shots, the offset is constant to within ~ 20 nsec, but it occasionally is much higher, and is off by 50 or even 80 nsec. While it is tempting to attribute the poor correlation to tilt, since poor tilt dramatically increases the corrections that must be made to assign an impact time from the tilt pins, the outliers did not have poor tilt. Impactor planarity, particularly a concave or convex shape, could also cause such a problem, though insufficient data exists to examine this potential cause. We hope that gradual improvements to the projectile design and to assembly methods will improve this correlation.

Chapter 5

Conclusion

The Air Force Research Laboratory at Eglin AFB, FL has commissioned and done initial experiments on a 60mm bore, single stage powder gun. The initial results indicate that, for a new facility still working out minor issues, the experiments performed at the facility are reliable and repeatable. Impact velocities from $\sim$ 0.35 - 2.3 km/sec have been demonstrated, and we hope to soon demonstrate impact planarity of $<$3 mrad across the full velocity range. In addition, single point VISAR interferometry and PDV have been demonstrated. Together, the results of this work represent a facility ready to begin simple research experimentation and gradually develop more complex techniques and diagnostics. These more advanced techniques and diagnostics are currently under development.

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