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Characterization of Gas Dynamic Effects in Baffled Tube Ram Accelerators

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**Abstract**

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The ram accelerator is a hypervelocity launch technology which uses a ramjet-like propulsion cycle to accelerate payloads to velocities in the kilometers-per-second range. The smooth bore ram accelerator (SBRA) has shown impressive performance at high velocities, drawing attention for its potential as an orbital launch device, as well as defense, emergency response, and mining possibilities. Recent developments have extended the capability of the system in the low-velocity regime. The most novel development is the inclusion of baffles within the launch tube, creating the baffled tube ram accelerator (BTRA). These baffles serve to isolate combustion regions within the launch environment, and have been proven to allow stable operation with propellants of higher energy densities. This work investigates secondary effects which arise from the more complicated gasdynamic environment of the BTRA.

Testing of the BTRA system has confirmed that predictions from quasi-one-dimensional SBRA theory are not always accurate in this more complicated geometry. In conjunction with computational efforts from other works, this study characterizes the impact of varying baffle dimensions

in inert gas and combusive environments. Inert gas phenomena were investigated pertaining to spacing between baffles, baffle wall thickness, and projectile-to-bore variation, and using a novel shadowgraph imaging technique. Performance phenomena were characterized by variation of baffle inserts within the BTRA test system, with projectile velocity and thrust or drag measured for both inert and non-combustive configurations.

The discovery of starting capabilities below established minimum limits permitted easier injection of projectiles into BTRA systems, with profound implications on large-scale implementation of the technology. Additionally, gasdynamic environments were imaged for projectiles of differing bore occlusion, suggesting the development of a distinct operating mode at high occlusion percentages which explains previous difficulties and inconsistencies in experiments with near-full-bore projectiles. Finally, it was found that both the spacing between baffles and the baffle chamber radius had direct effects on projectile thrust environment, permitting increased performance at the expense of energy density tolerance, and suggesting that optimization of the BTRA design may be a multi-dimensional effort with promising potential.

*“The Creator had a lot of remarkably good ideas when he put the world together,  
but making it understandable hadn’t been one of them.”*

Sir Terry Pratchett, *Mort*

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# List of Symbols

|               |                                    |                                   |
|---------------|------------------------------------|-----------------------------------|
| $a$           | speed of sound                     | $\text{m s}^{-1}$                 |
| $A$           | area                               | $\text{m}^2$                      |
| $c_p$         | specific heat at constant pressure | $\text{J kg}^{-1} \text{K}^{-1}$  |
| $c_d$         | coefficient of drag                |                                   |
| $C$           | contrast                           |                                   |
| $d$           | diameter or thickness              | $\text{m}$                        |
| $D$           | baffle drag force                  | $\text{N}$                        |
| $F$           | thrust force                       | $\text{N}$                        |
| $g$           | distance (optical)                 | $\text{m}$                        |
| $h$           | enthalpy                           | $\text{J kg}^{-1}$                |
| $I$           | non-dimensional thrust             |                                   |
| $k$           | Gladstone-Dale coefficient         | $\text{m}^3/\text{kg}$            |
| $L$           | length                             | $\text{m}$                        |
| $n$           | index of refraction                |                                   |
| $M$           | Mach number                        |                                   |
| $p$           | pressure                           | psi or Pa                         |
| $q$           | heat                               | $\text{J}$                        |
| $Q$           | non-dimensional heat release       |                                   |
| $R$           | gas constant                       | $\text{J K}^{-1} \text{mol}^{-1}$ |
| $t$           | time                               | $\text{s}$                        |
| $T$           | temperature                        | $\text{K}$                        |
| $u$           | velocity                           | $\text{m s}^{-1}$                 |
| $V$           | volume                             | $\text{m}^3$                      |
| $\beta$       | volume void ratio                  |                                   |
| $\gamma$      | specific heat ratio                |                                   |
| $\varepsilon$ | deflection angle                   |                                   |
| $\lambda$     | wavelength                         | $\text{m}$                        |
| $\rho$        | density                            | $\text{kg m}^{-3}$                |
| $\phi$        | equivalence ratio                  |                                   |

# List of Abbreviations

## Abbreviations

|      |                                                                     |
|------|---------------------------------------------------------------------|
| BTRA | <b>B</b> affled <b>T</b> ube <b>R</b> am <b>A</b> ccelerator        |
| CFD  | <b>C</b> omputational <b>F</b> luid <b>D</b> ynamics                |
| CJ   | <b>C</b> hapman- <b>J</b> ouguet                                    |
| MCRA | <b>M</b> echanically <b>C</b> hoked <b>R</b> am <b>A</b> ccelerator |
| PID  | <b>P</b> iping and <b>I</b> nstrumentation <b>D</b> igram           |
| RTRA | <b>R</b> ailed <b>T</b> ube <b>R</b> am <b>A</b> ccelerator         |
| SBRA | <b>S</b> mooth <b>B</b> ore <b>R</b> am <b>A</b> ccelerator         |
| TCRA | <b>T</b> hermally <b>C</b> hoked <b>R</b> am <b>A</b> ccelerator    |

## Subscripts

|        |                                           |
|--------|-------------------------------------------|
| 1      | entrance state                            |
| 2      | exit state                                |
| $b$    | smooth tube bore, baffle perforation bore |
| $b$    | blurring (optics)                         |
| $baff$ | baffle (typically baffle wall)            |
| $c$    | baffle chamber                            |
| $eff$  | effective                                 |
| $lab$  | lab or external frame of reference        |
| $p$    | projectile                                |

## Superscripts

|   |                          |
|---|--------------------------|
| * | critical throat property |
|---|--------------------------|

## *Acknowledgements*

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# Chapter 1

## Introduction

### 1.1 The Need for the Ram Accelerator

The age-old adage "what goes up must come down" is unshakable truth to many, but to two groups it is a challenge: investors and aerospace engineers. Both groups have challenged it effectively; investors in Apple or General Dynamics (or, more recently, Bitcoin) are likely very wealthy today, and the Voyager probes won't be coming home. But as time passes once monumental and revolutionary efforts become mundane, venture efforts become maintenance, and, perhaps most importantly, the appeal of the challenge wears off.

In the 1950s radios all over the world heard the first faint beeps of Sputnik. Two decades later the US Congress decided there was no reason to go back to the Moon, as the public was no longer interested. And in 2024 alone there were 2719 publicly acknowledged objects launched into space, an average of one every three hours [1]. In short, space launch has become something few ever thought it could be: boring.

But therein lies a new and exciting challenge! Space launch must be brought in line with demand in a manner and cost which is acceptable to customers, and so rockets must go the way of the galleon and paddleboat. As powerful as rockets are, they still suffer from slow turnaround times and the fundamental limits imposed by Tsiolkovsky's rocket equation [2].

By employing mechanisms more closely related to propulsion devices used in aviation, the ram accelerator is able to bypass many of the common limitations of rocketry, offering time between

single-site launches on the order of minutes instead of days, and much lower ratios of fuel to payload mass. This work serves to further develop the capabilities of ram accelerator technology by studying the gas dynamic effects of varying system geometries, as well as by investigating the effects of these geometric changes on propellant combustion and projectile performance.

## 1.2 Ram Basic Principles

In its simplest implementation, the Smooth Bore Ram Accelerator (SBRA) consists of a projectile traveling at super- or hyper-sonic velocities through a propellant mixture, confined within a smooth tube. As the propellant is compressed around the projectile body and energized by the resultant shock train it begins to combust, releasing chemical energy from the propellant in the form of heat, which in turn creates a more energized flow behind the projectile (Fig. 1.1). In this way an SBRA acts on a similar propulsive cycle to a ramjet engine [3], with the projectile acting as the ramjet centerbody and the tube acting as the engine cowling.

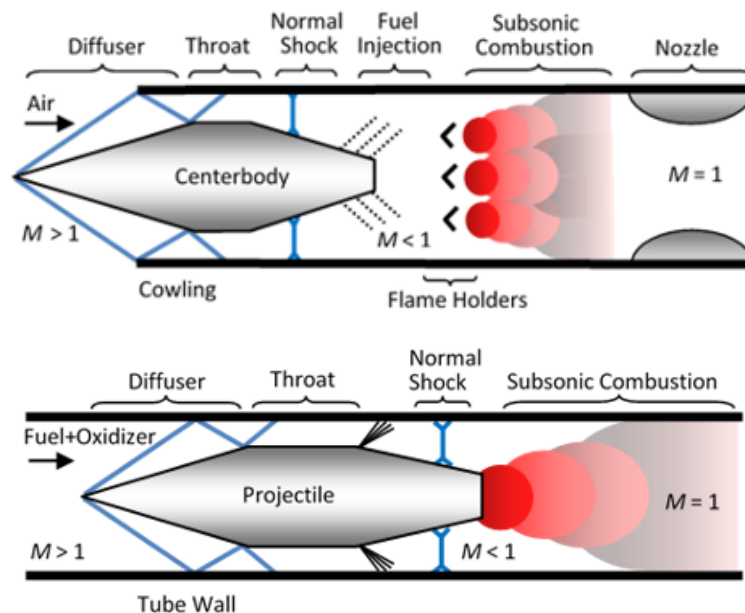


FIGURE 1.1: Comparison between a ramjet (top) and a ram accelerator (bottom).

Once flow is established and the projectile is moving supersonically, no external energy or moving parts are required to continue operation. With proper propellant staging, a ram projectile might reach velocities of greater than 11 km/s, permitting direct-to-space launches [4] [5].

For its first two decades ram accelerator testing was primarily limited to the SBRA. Significant progress was made in fundamental understanding and modeling [6], proof of operation [7], propellant chemistries and projectile geometries [8], and expanding system limits [9] for the SBRA system. Study of a Railed Tube Ram Accelerator (RTRA) system was conducted by the French-German Research Institute of Saint-Loius (ISL) starting in the 1990's, focusing on similar principles to the SBRA and operating in the superdetonative (above the Chapman-Jouget detonation velocity) regime [10, 11]. It wasn't until 2005 that significant work began on altering the geometry of the ram tube itself [12], leading to the creation of the Baffled Tube Ram Accelerator (BTRA)[13].

The major problem addressed by the BTRA is a phenomenon called an unstart. An unstart occurs when a ram system, whether ramjet, scramjet, or ram accelerator, is unable to fully trap combustion in the desired region behind the centerbody/projectile. This results in the combustion front moving forward over the narrow shoulder and in front of the projectile. When this occurs in a ram accelerator system the projectile will experience a rapid, violent deceleration, preventing a successful shot and potentially damaging the system. Unstarts commonly occur when the propellant mixture in a system is too energetic.

The innovation of the BTRA is the inclusion of baffled walls placed along the ram tube. These baffles act as one-way valves, keeping the combustion from driving too far up the projectile shoulder, thereby preventing a runaway unstart (Fig. 1.2). The BTRA system also has proven to be operable with more volatile propellants, with projectiles of simpler geometries, and at lower starting velocities [14–19].

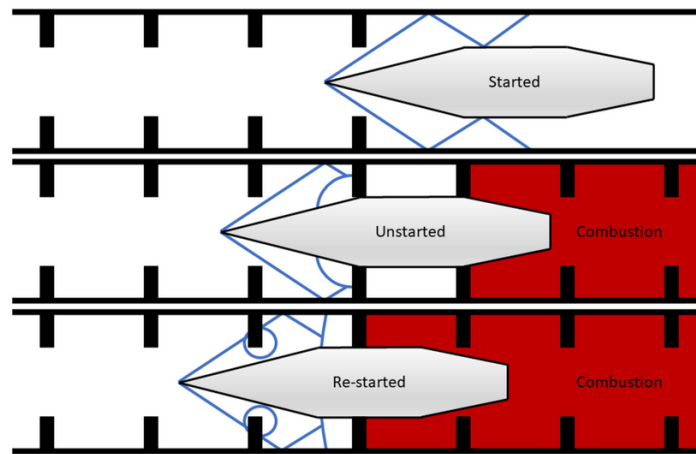


FIGURE 1.2: Visualization of BTRA baffles preventing an unstart [20].

## 1.2.1 Modes of Operation

### Subdetonative Operation

The model of the ram accelerator presented in Fig. 1.1 is accurate to the testing that will be described in this work, but does not fully encompass ram accelerator operations. It is known as the Thermally Choked Ram Accelerator (TCRA) model, in which the projectile conical diffuser decelerates the flow through its area constriction to a lower supersonic value, and thermal choking from combustion maintains high pressure on the projectile base. An alternate design, known as the Mechanically Choked Ram Accelerator (MCRA), consists of a projectile with a profile which widens, narrows, and then widens again. In this mode of operation the projectile operates more similarly to a ramjet engine, with subsonic combustion occurring between the diffuser and nozzle. This mode of operation is shown in Fig. 1.3, with the first and second throats at stations 2 and 7, respectively.

Both of these modes of operation are considered to be in the subdetonative ram accelerator regime, as energy is released via combustion (as opposed to detonation) [3]. The TCRA model is discussed in further detail in Chapter 2. For further information on the MCRA model see [21].

### Superdetonative Operation

Above the CJ velocity the projectile is moving too quickly to maintain a large combustion

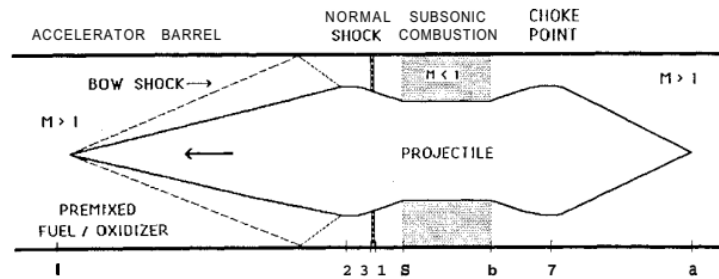


FIGURE 1.3: Location of combustion on a mechanically choked ram projectile [3].

region, instead becoming more similar to a scramjet engine. In this superdetonative mode of operation, combustion instead occurs on the projectile shoulder. At this point one of three variations can occur: first, if the projectile is of similar shape to a mechanically choked body, an overdriven detonation wave can be established behind the diffuser throat that renders the flow subsonic before it is accelerated and choked at the nozzle throat (Fig. 1.4). In this mode a projectile is expected to be able to reach velocities up to 5 km/s.

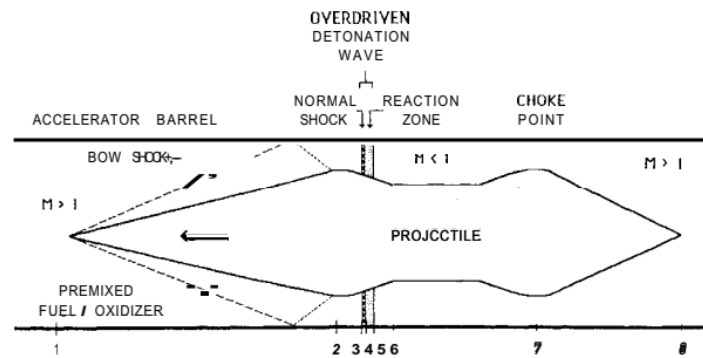


FIGURE 1.4: Location of the detonation wave on an overdriven ram projectile [3].

Second and third, in the case of a projectile shaped more like the classic TCRA projectile, one of two oblique detonation modes (known as Type 1 and Type 2) is instead predicted. In a Type 1 oblique detonation mode the detonation wave is coupled to the reflection of the projectile's oblique shock from the wall (Fig. 1.5). In a Type 2 oblique detonation mode the wave occurs on an oblique shock reflection from the projectile shoulder. Which mode occurs is controlled by slight differences in projectile nose angle and shoulder geometry (Fig. 1.6). Under ideal circumstances

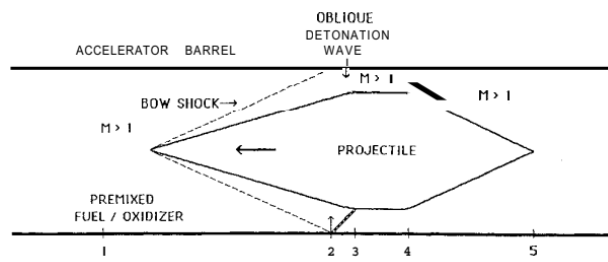


FIGURE 1.5: Location of the detonation wave in the Type 1 oblique detonation mode [3].

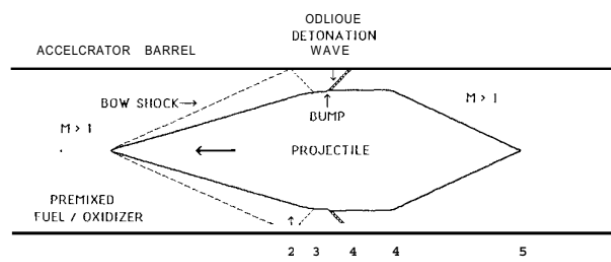


FIGURE 1.6: Location of the detonation wave in the Type 2 oblique detonation mode [3].

the oblique detonation modes could accelerate a projectile in excess of 15 km/s, but when heat and projectile survival are taken into account these estimates drop to 6-10 km/s.

Superdetonative operating modes have not been extensively studied but have been experimentally demonstrated to align with theoretical predictions [7, 22]. Additional superdetonative modes, such as the shock-induced scram combustion mode, have also been proposed and studied in a limited capacity [22, 23].

### 1.3 Applications

The ram accelerator is an appealing technology for direct-to-space launch, with predictions of launch payloads in excess of 2000 kg reaching orbit without the need for conventional rocketry [5], and with others even suggesting it may be fit for low-acceleration manned launches [20]. Another major application is the use of a ram accelerator as a hypervelocity impactor [24]. As a mining device, a ram accelerated projectile has been shown to be highly effective in rock-breaking, expected to remove material more quickly than conventional tunnel boring or drill-and-blast techniques over a variety of conditions [25]. Further possible applications are as a mechanism for high-velocity impact testing [26] or rapid response supply delivery. It has also been proposed as competition to naval railguns or other long-range defense devices.

## 1.4 Contribution of Research

The present work serves to extend ram accelerator development beyond established parameters and towards a more fully characterized system. More specifically, this work further characterizes the effects of baffled tube geometry as it pertains to gasdynamic effects, starting conditions, and reaction timing.

An in-depth review of fundamental ram accelerator theory is covered in Chapter 2. Chapter 3 reviews both pre-existing and new experimental infrastructure. Chapter 4 presents new results which serve to better characterize BTRA operations. Chapter 5 reviews the key findings, implications of results, and potential future investigations. Finally, Appendices A-C offer additional insights into the technical aspects of the ram accelerator facility and other aspects of this study, and Appendix D provides a representative summary of the new data used in this study.



## Chapter 2

# A Brief History of the Ram Accelerator

### 2.1 Theoretical Ram Accelerator Model

The fundamental model of the ram accelerator, regardless of operating mode, is generalized as a one-dimensional, quasi-steady, inviscid supersonic flow. In this scheme a black-box approach is taken, with a control volume established around a projectile of arbitrary geometry and which is set in the projectile's reference frame. This control volume is bounded with an entry sufficiently upstream on the projectile so as not to be perturbed by shocks, an exit downstream of the projectile at a post-combustion distance, with volume edges on the inner surface of the surrounding ram tube. The incoming propellant mixture is assumed to react before exiting the volume, modeled as an increase in heat  $\Delta q$ . The only remaining unknown, after applying known chemical constants and isentropic flow conditions, is the force  $F$  exerted on the projectile. A visualization of this scheme is shown in Fig. 2.1 [27, 28]. The derivation and calculation of this resultant force, which is effectively the net projectile thrust, follows.

The derivation of projectile thrust begins from the standard flow one-dimensional conservation equations of mass, momentum, and energy

$$\rho_1 u_1 = \rho_2 u_2 \tag{2.1}$$

and

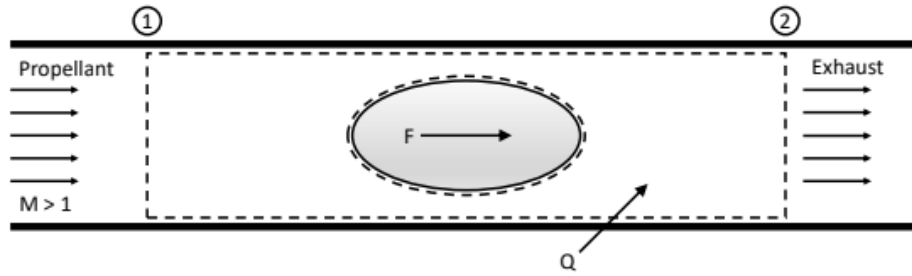


FIGURE 2.1: Control volume for the general ram accelerator model [20].

$$\rho_1 u_1^2 + p_1 + \frac{F}{A} = \rho_2 u_2^2 + p_2 \quad (2.2)$$

and

$$h_1 + \frac{u_1^2}{2} + \Delta q = h_2 + \frac{u_2^2}{2} \quad (2.3)$$

where  $A$  is the cross-sectional tube area and  $h$  is the sensible enthalpy. Enthalpies of formation are included as part of  $\Delta q$  ( $\Delta q = h_{f1} - h_{f2}$ ). Further useful relations are the ideal-gas equation of state

$$p = \rho RT \quad (2.4)$$

as well as the definitions of sound velocity  $a$ , Mach number  $M$ , and the non-dimensional heat release parameter  $Q$

$$a = \sqrt{\gamma RT} \quad (2.5)$$

$$M = \frac{u}{a} \quad (2.6)$$

$$Q \equiv \frac{\Delta q}{c_{p1}T_1} \quad (2.7)$$

Utilizing these relations, Eqs. 2.1-2.3 may then be re-written non-dimensionally as

$$\frac{p_2}{p_1} = \frac{M_1}{M_2} \sqrt{\frac{\gamma_1 R_2 T_2}{\gamma_2 R_1 T_1}} \quad (2.8)$$

$$\frac{F}{p_1 A} = \frac{p_2}{p_1} (1 + \gamma_2 M_2^2) - (1 + \gamma_1 M_1^2) \quad (2.9)$$

and

$$\frac{h_1}{c_{p1}T_1} + \frac{\gamma_1 - 1}{2} M_1^2 = \left( \frac{h_2}{c_{p2}T_2} + \frac{\gamma_2 - 1}{2} M_2^2 \right) \left( \frac{c_{p2}T_2}{c_{p1}T_1} \right) \quad (2.10)$$

Finally, by solving Eq. 2.10 for the ratio  $T_2/T_1$ , it may be combined with Eq. 2.8 and then Eq. 2.9 to define the non-dimensional ram accelerator thrust  $I$

$$I \equiv \frac{F}{P_1 A_b} = \frac{\gamma_1 M_1}{\gamma_2 M_2} (1 + \gamma_2 M_2^2) \sqrt{\frac{\gamma_2 - 1}{\gamma_1 - 1} \left( \frac{\frac{h_1}{c_{p1}T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q}{\frac{h_2}{c_{p2}T_2} + \frac{\gamma_2 - 1}{2} M_2^2} \right)} - (1 + \gamma_1 M_1^2) \quad (2.11)$$

This model then gives non-dimensional ram thrust as a factor of only gas properties at the entrance and exit planes, as well as the flight Mach number and heat release. By using iterative methods, along with chemical kinetics modeling software, this method has been found to accurately predict projectile thrust in the smooth bore case.

### 2.1.1 The Thermally Choked Ram Accelerator

Equation 2.11 may be further simplified by placing the exit plane of the control volume at the point of thermal choking. Since a choked flow has a Mach number of 1, the non-dimensional

thrust equation may be simplified to

$$I_{\text{TCRA}} = \frac{F}{P_1 A_b} = M_1 \frac{\gamma_1}{\gamma_2} (1 + \gamma_2) \sqrt{\frac{\gamma_2 - 1}{\gamma_1 - 1} \left( \frac{\frac{h_1}{c_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + Q}{\frac{h_2}{c_{p2} T_2} + \frac{\gamma_2 - 1}{2}} \right)} - (1 + \gamma_1 M_1^2) \quad (2.12)$$

This simplified expression may be solved in the same manner as the general case equation, but is limited in scope. It is only accurate for the thermally choked ram accelerator case, and may not be used for super-detonative or mechanically choked ram operation. This simplification does allow some insight however. Most obvious is that, for a given operating Mach number, an increase in heat release will lead to direct increase in system thrust. An example of this effect, as well as the relationship between heat release and Mach number for a given propellant, is shown in Fig. 2.2.

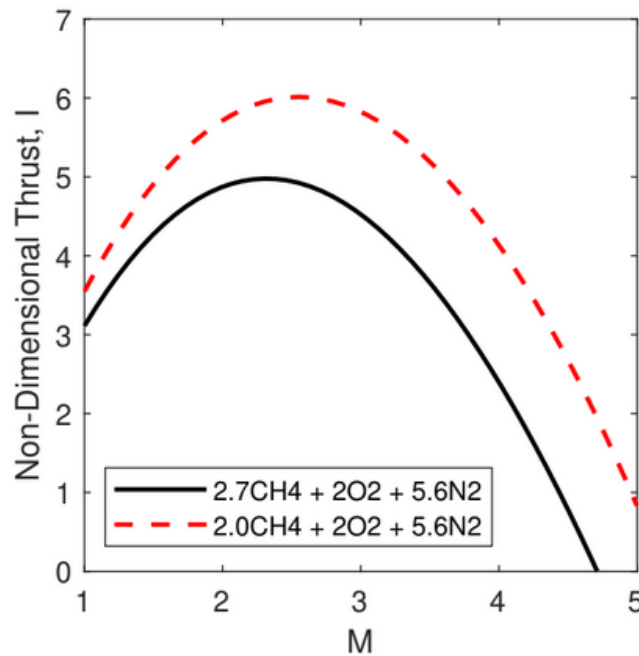


FIGURE 2.2: Non-dimensional thrust as a result of Mach number for methane-air-nitrogen propellant mixtures [20].

Thrust experienced by an SBRA projectile has shown remarkable alignment between theory and practice. As early as 1987, subdetonative and superdetonative testing was conducted on SBRA

models in a variety of mixtures, in which analytical predictions showed nearly perfect consistency with experimental observations (Fig. 2.3) [6]. In some cases early experimentation outperformed theory, such as in the transonic case shown in Fig. 2.4 in which a projectile may not have remained in the same propulsive mode through the entire experiment [7].

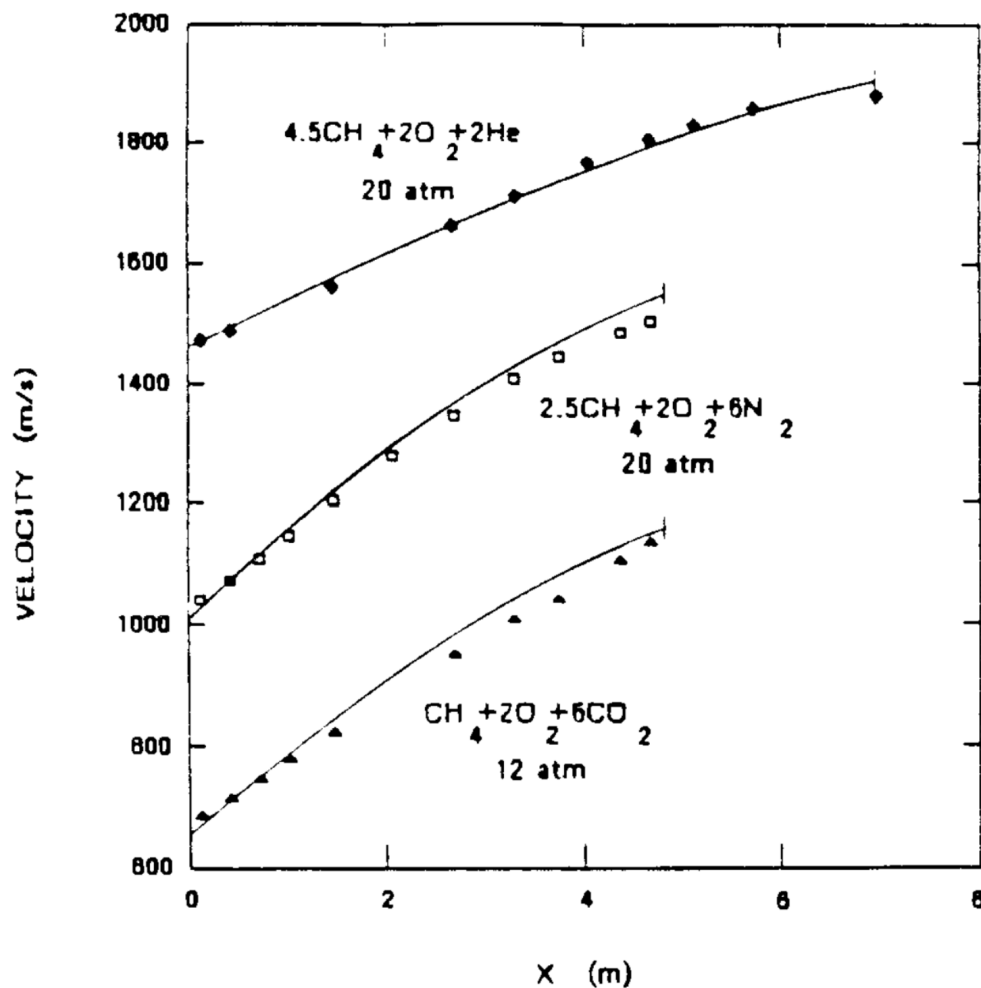


FIGURE 2.3: Comparison of experimental and theoretical velocity profiles in ram accelerator for  $\text{CH}_4 + 2\text{O}_2 + 6\text{CO}_2$ ,  $2.5\text{CH}_4 + 2\text{O}_2 + 6\text{N}_2$  and  $4.5\text{CH}_4 + 2\text{O}_2 + 2\text{He}$  propellant mixtures at 12, 20 and 20 atm, respectively. Projectile mass 75 g for the  $\text{CO}_2$  and  $\text{N}_2$  diluted mixtures and projectile mass 60 g for He diluent case [6].

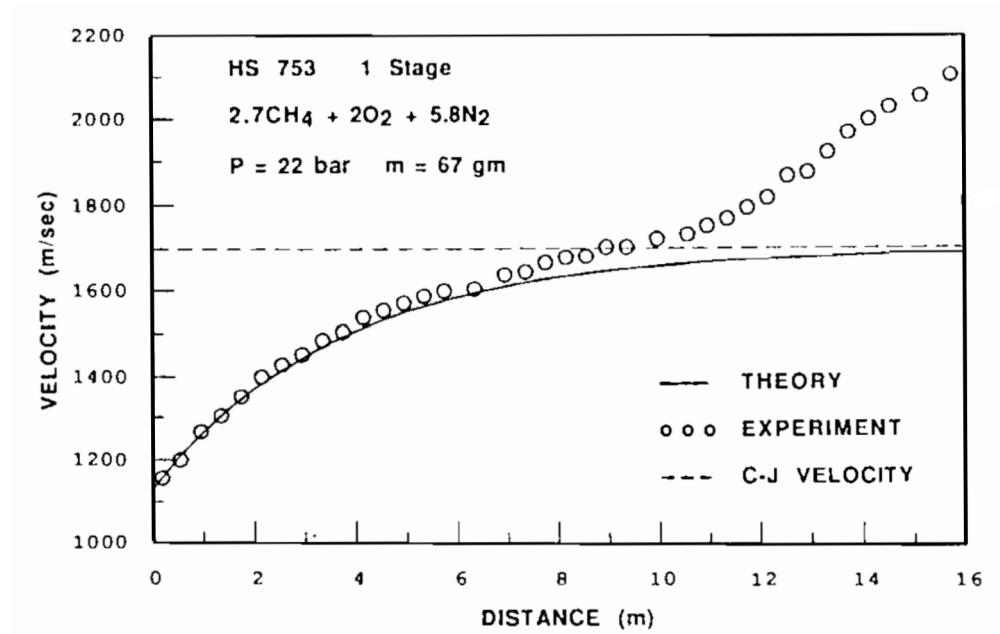


FIGURE 2.4: Velocity profile in transdetonative ram accelerator operation [7].

### 2.1.2 Smooth Bore Operating Limits

The non-dimensional thrust equations discussed thus far have assumed stable, steady-state operation. They do not take into account conditions that may push the projectile outside of its operation window. In the theoretical one-dimensional model there are three key limits which constrain operation [29]. The first is that the flow must gas-dynamically choke past the projectile throat. This is calculated through the standard relation between tube area, throat area, and flow Mach number, as given in Eq. 2.13 [30]. Satisfying this condition ensures that flow is sonic at the projectile throat.

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2} \left[ \frac{2}{\gamma+1} \left( 1 + \frac{\gamma-1}{2} M^2 \right) \right]^{\frac{\gamma+1}{\gamma-1}} \quad (2.13)$$

The other two critical operational limits require consideration of not only the Mach number but also the propellant heat release. First among these is the stipulation that the normal shock must occur past the throat of the projectile. This manifests as a heat release maximum for a given Mach number, above which the normal shock is pushed onto or ahead of the projectile throat, resulting

in combustion occurring ahead of the projectile and causing a drastic projectile deceleration, commonly known as an unstart. This, along with the sonic-at-throat condition, provide the lower Mach number limit for a given propellant mixture.

The final operation limit is the inverse of the second - the minimum heat release for a given Mach number. Should a mixture be too cool, there will not be enough energy to sustain combustion on the tail of the projectile. This phenomenon is known as wave falloff, where the projectile moves too fast for the combustion to keep up, resulting in a complete loss of thrust. Were a projectile tail to taper fully to a point, this Mach number is predicted to be the Chapman-Jouguet (CJ) detonation velocity, and is lower for projectiles with a flat base. This condition provides the upper Mach number limit for a given heat release. This operational envelope is shown in Fig. 2.5, although the limits may shift as a results of differences in propellant properties.

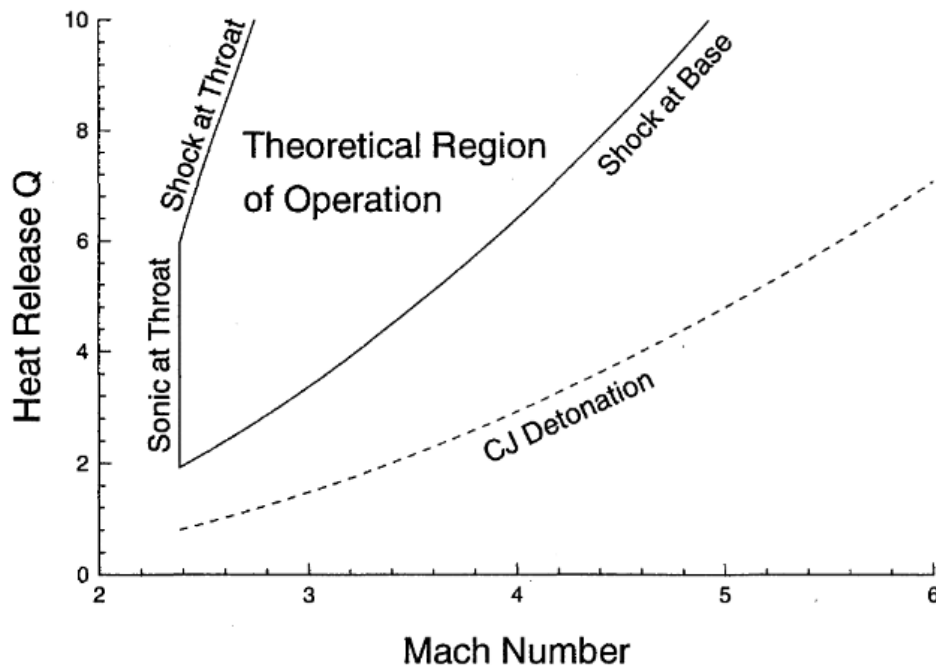


FIGURE 2.5: Theoretical operational envelope of the thermally choked ram accelerator [29].

In reality, however, the operating envelope of the ram accelerator does not typically align with

theoretical limits. Fig. 2.6 shows the experimentally-determined operating envelope for two different propellant mixtures, which extend to much higher Mach numbers beyond the shock-at-base limitation predicted by theory, or even the limit presented by the CJ velocity, as shown in Fig. 2.7. Starting with the top boundary in Fig. 2.7 and moving clockwise, these limits are thought to be as follows [9, 29]:

- a:** The projectile immediately unstated upon entering the ram experiment region. This effect can be prevented by reducing heat release and seems to indicate an upper  $Q$  limit.
- b:** The projectile initially started but unstated further downstream, and is believed to be the result of incorrect or failing assumptions relating to the flow field.
- c:** The projectile unstated beyond the CJ velocity, likely in the transdetonative or superdetonative regimes. These failures are thought to be the result of projectile structural failure.
- d:** These tests resulted in wave falloff instead of the strong unstateds of the other cases, indicating that the heat release is too low and the flow is being quenched or otherwise not sustained.



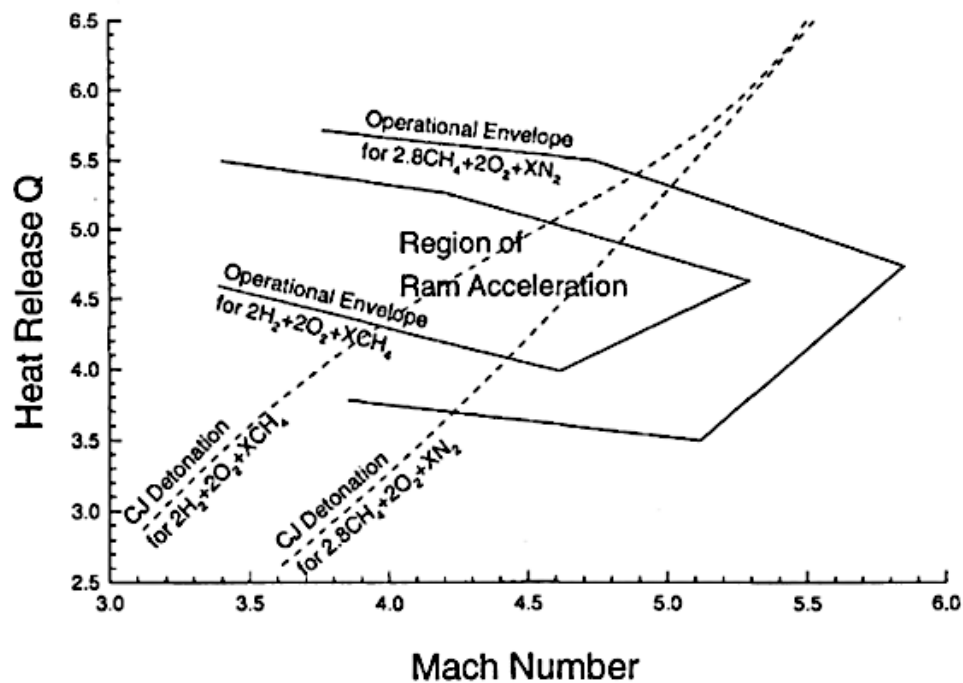


FIGURE 2.6: Operational envelopes for experiments in nitrogen- and methane-diluted mixtures [29]

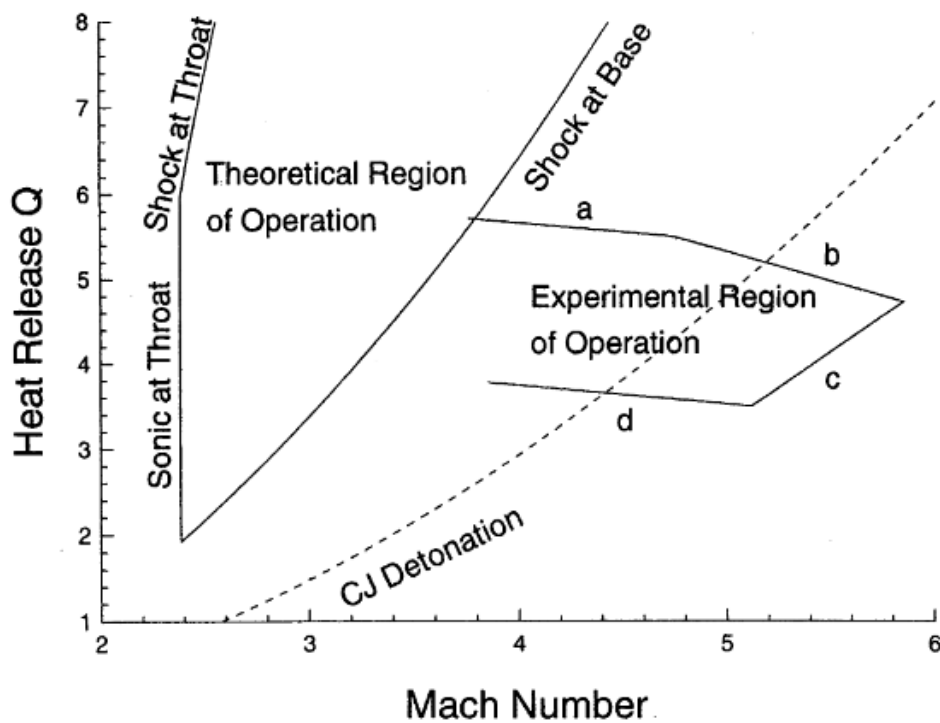


FIGURE 2.7: Combined theoretical and experimental ram accelerator operating limits [9]

Unlike a bullet or other conventional projectile, which must be nearly full-bore to minimize leakage of launch pressures around the projectile, a ram accelerator projectile must be sub-caliber to produce compression and flow around the projectile body, a limit imposed by Eq. 2.13. This means that the ideal ram projectile has no imposed dynamic stability or guidance while traveling through the tube, leaving it free to bounce or cant during operation. Additionally, this sub-caliber requirement allows gas from the injection system<sup>1</sup> to leak around the ram accelerator projectile during its initial acceleration. The SBRA design has historically incorporated two methods for solving these problems [31].

Initially SBRA projectiles were designed with a number of full-bore fins which would ride along the edges of the tube and prevent non-axial motion. The number of fins varied by design, but four or five were common numbers. A representative SBRA projectile of this type may be seen in Fig. 2.8.

To solve the injection system issue, an obturator (or sabot) was affixed to the base of the projectile. This obturator would prevent launch gun leakage around the projectile body and would be broken off by the pressure of the ram accelerator section. Obturators came in varying designs, but were always full-bore and designed in such a way as to seal against tube walls. The obturator was also thought to assist in the initial ignition of the ram accelerator [31]. Early and modern obturator designs are shown in Fig. 2.9.

The fins and obturators on SBRA projectiles permitted successful, stable operation of ram accelerator experiments, but came with problems of their own. Notably, the addition of fins increased per-projectile manufacturing costs immensely when compared to the idea axisymmetric projectile. The obturators had a tendency to become stuck in the ram tube after a shot, thereby blocking or damaging subsequent shots if not removed. Both of these factors, in addition to the aforementioned heat limits, led researchers to seek more robust designs than the SBRA could offer.

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<sup>1</sup>In most cases a light gas gun, see Chapter 3.

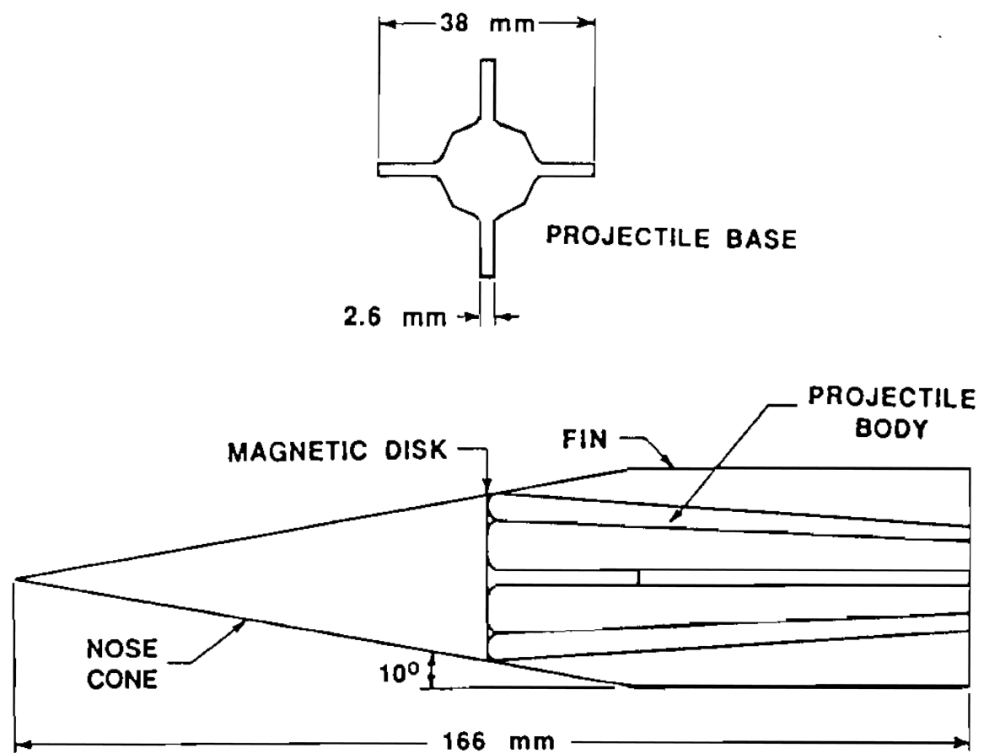


FIGURE 2.8: A typical SBRA projectile drawing [31].

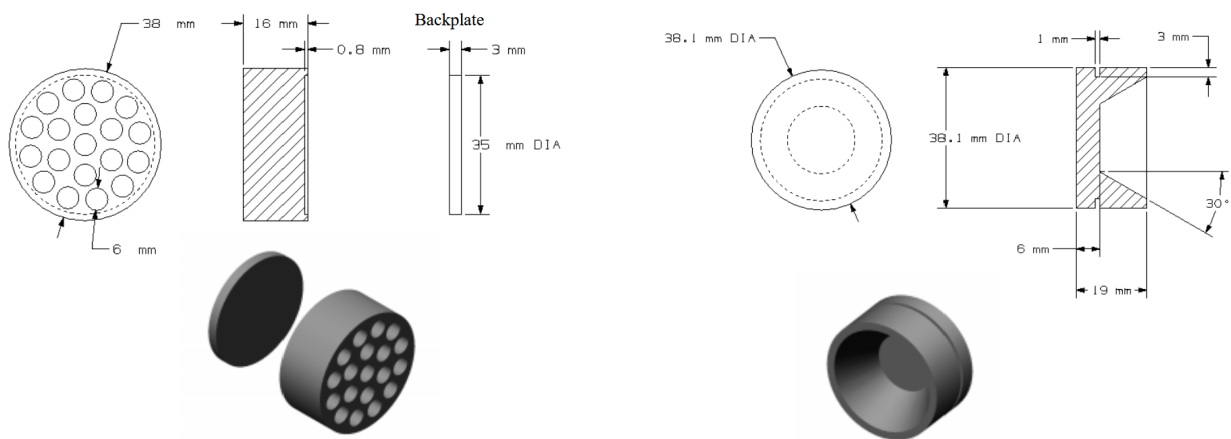


FIGURE 2.9: Early perforated (left) and modern solid (right) obturator designs [31].

## 2.2 Baffled Tube Ram Accelerator Model

In order to address both the heat and stability concerns, a more complicated in-tube geometry was developed, called the Baffled Tube Ram Accelerator (BTRA). As discussed in Chapter 1, the BTRA enhances the SBRA by operating in effect as a series of one-way valves to prevent unstarts from traveling over the projectile shoulder [13]. A tube cross-section with a projectile in a BTRA system may be seen in Fig. 2.10. In terms of non-dimensional heat release ( $Q$ ), SBRA systems typically unstart at a  $Q$  of around five or six [32]. BTRA systems, however, regularly operate with  $Q$  in excess of 10 [20]. Additionally, the more elaborate tube geometry can incorporate space for stabilizing rails, which make projectile fins unnecessary and permit operation with more easily produced axisymmetric projectiles.

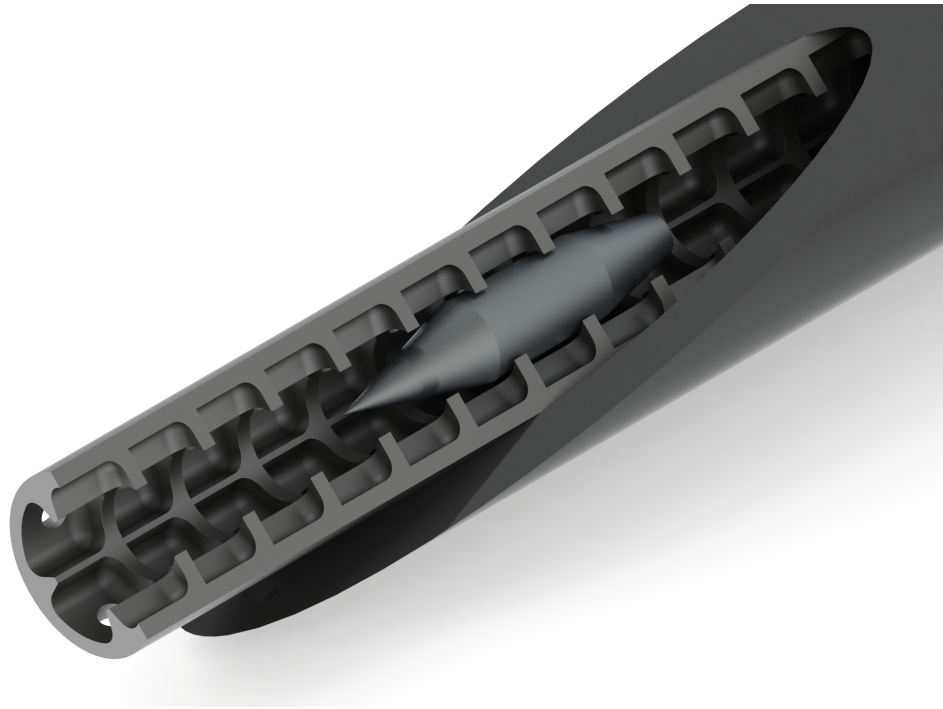


FIGURE 2.10: Tube cross-section showing an axisymmetric ram projectile in a BTRA system.

### 2.2.1 BTRA Performance Modeling

Historically, modeling of the non-dimensional thrust of the BTRA has been conducted similarly to that of the SBRA system, with a few notable modification. The first is that baffle drag ( $D$ ) must now be included. This is different from the projectile drag, which is already included in the black-box net-thrust calculation.  $D$  in these equations instead refers to the force exerted on the flow by the baffles, since the baffles are moving in the reference frame of the projectile. More specifically, these baffles generate force which opposes the gas pulled along with the projectile during transit. The updated control volume may be seen in Fig. 2.11.

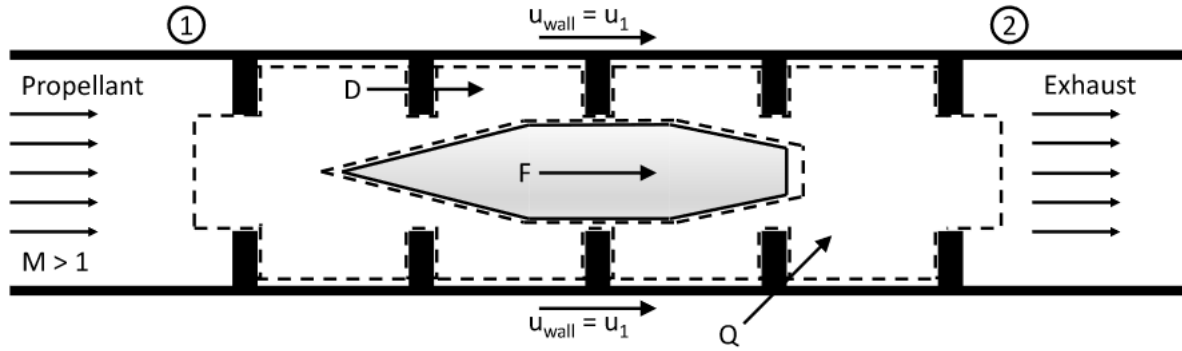


FIGURE 2.11: Control volume for the baffled tube ram accelerator model [20].

The derivation of Eq. 2.12 for a baffled system must take  $D$  into account within the conservation of momentum and energy relations, as detailed by Yancey [33]. The updated non-dimensional thrust equation then becomes

$$I_{\text{TCRA}} = \frac{F}{P_1 A_b} = M_1 \frac{\gamma_1}{\gamma_2} (1 + \gamma_2) \sqrt{\frac{\gamma_2 - 1}{\gamma_1 - 1} \left( \frac{Q + \frac{h_1}{c_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2 + \frac{D(\gamma_1 - 1)}{P_1 A_b \gamma_1}}{\frac{h_2}{c_{p2} T_2} + \frac{\gamma_2 - 1}{2}} \right)} - (1 + \gamma_1 M_1^2) - \frac{D}{P_1 A_b} \quad (2.14)$$

Determination of a precise model for the baffle drag  $D$  is ongoing. Various models have been proposed, to varying degrees of accuracy. An initial model, proposed by Knowlen et al., claimed

that the thermally choked plane should itself experience drag and decelerate relative to the projectile [14]. In this manner the baffle drag  $D$  should take a similar form to aerodynamic drag, resulting in Eq. 2.15.

$$D = \frac{1}{2}c_d\rho_2u_{2,lab}^2A_{eff} = \frac{1}{2}c_d\rho_2(u_1 - u_2)_{2,lab}^2A_b\beta \quad (2.15)$$

This model failed to take into account the full reality of the flow field. It assumed that the baffle drag can be measured solely by its effect on the thermally choked plane. In reality there are times, such as during peak thrust (relative to Mach number), when the thermally choked plane is stationary. At this moment the drag, according to Eq. 2.15, must be zero, which cannot be the case as the moving baffle walls still act on other parts of the flow field.

Knowlen et al. later introduced a more refined drag model, believing that it could more accurately model the observed phenomena [16]. This model was modified to include the free-stream gas properties, a more accurate baffle area, and a more accurate directional term. This new model, given in Eq. 2.16, was thought to be more accurate than Eq. 2.15 during lower Mach number operation.

$$D = \frac{1}{2}c_d\rho_1|u_1 - u_2|(u_1 - u_2)(A_c - A_b) \quad (2.16)$$

This second model takes steps in the correct direction, but again falls short of providing an accurate model of baffle drag across varying  $Q$  [20]. Yancey attempted to correct these discrepancies, as well as provide a model which took both the inlet and thermally choked zones into account, but even then a unified model was unable to be determined with confidence [33]. Further, recent work has shown that the assumptions in these drag models may not hold up to experimental scrutiny. The idea of the thermally choked plane experiencing drag was based on work by Gu et al., in which it was suggested that a detonation wave in a baffled system traveled at significantly lower velocities than its smooth-tube equivalent [34]. This result, however, has been called into question by Bernhard on shock propagation in baffled tubes [35], as well as by results of detonation tests in

the current study. In summary, while baffle drag is demonstrably acting on the system, a means of modeling it that is compatible with existing ram accelerator theory has not yet been determined.

A second modification to Eq. 2.12 comes as a result of the baffle chambers. This change is less intrusive to the equation and may be included as compensation factor applied to the bore area normalization. This is accomplished by defining an alternate cylindrical bore with equivalent volume to the baffle chamber and using this cross-sectional area instead. This is, in essence, averaging the BTRA into a similarly-sized SBRA model so that the analytical schema described in Section 2.1.1 may be used. This volume approximation may be seen in Fig. 2.12 and the derivation and use of the volume void ratio  $\beta$  is shown in Eq. 2.17 [36].

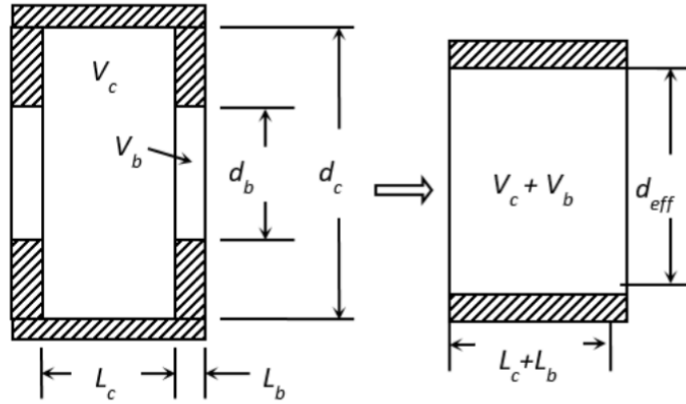


FIGURE 2.12: Effective diameter geometry for BTRA chamber volume.

$$\beta = \frac{A_{eff}}{A_b} = \frac{V_c + V_b - V_{solid}}{V_b(1 + L_c/L_b)} = \frac{d_{eff}^2}{d_b^2} \rightarrow I_{BTRA} = \frac{I_{TCRA}}{\beta} \quad (2.17)$$

With these modifications, a one-dimensional model of the BTRA system is produced.

### 2.2.2 BTRA Performance

Since 2005, significant experimental testing of the BTRA system has been conducted [12]. In general, while the theory aligns well with trends of BTRA performance, actual thrust values are considerably below theoretical predictions, in some cases performing at less than 50% expected

thrust [17]. Various explanations for this discrepancy have been suggested, ranging from a simple misinterpretation of which area  $A_b$  to use in Eq. 2.17 to the suggestion of low combustion efficiency (shown in Fig. 4.18) [33]. Regardless of cause, BTRA experimentation matches the **trends** predicted by theory, but theory can not yet match observed experimental **values**. This section serves to review key findings of these characterization tests and to discuss unsolved variations between theory and experiment.

### Exploration of BTRA Heat Release

The BTRA has been shown to operate at high  $Q$ , fulfilling the goal of its initial design [17, 37, 38]. This is demonstrated in Fig. 2.13, which shows the velocity-position data of four projectiles in mixtures varying between  $Q$  of 8.8 and 11 [38]. While the thrust measured is still quite high, the measured non-dimensional thrust is well below that expected by theory, with some estimates suggesting discrepancies of 70% or more (Fig. 2.14) [37].

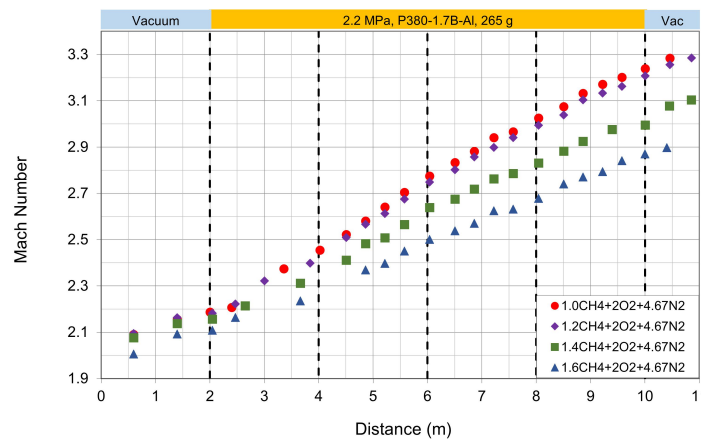


FIGURE 2.13: Mach number-distance data from BTRA experiments having excess methane as diluent. Tests used projectiles with a shoulder diameter of 1.38 inches and length of 1.7 baffle lengths, nose and tail angles of  $15^\circ$  and  $12^\circ$ , respectively, fill pressure of 2.2 MPa, and  $\phi\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  propellant [38]



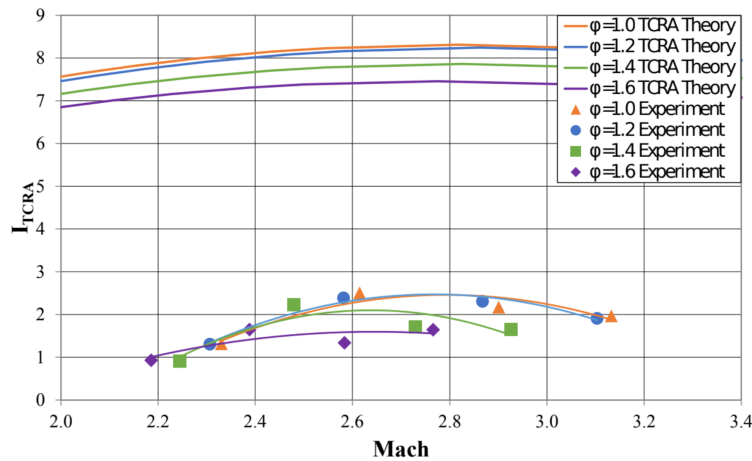


FIGURE 2.14: Experimental BTRA and theoretical TCRA non-dimensional thrust versus Mach number at equivalence ratios of 1.0 to 1.6. Tests used projectiles with a shoulder diameter of 1.38 inches and length of 1.7 baffle lengths, nose and tail angles of  $15^\circ$  and  $12^\circ$ , respectively, fill pressure of 21 atm, and  $\phi\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  propellant [37].

### Exploration of BTRA Fill Pressure

Pressure scaling, as opposed to  $Q$  scaling, has shown to be remarkably consistent with Eq. 2.17. This has been demonstrated over a variety of studies and baffle configurations [12, 16, 17, 37, 39]. A simple example may be seen in Fig. 2.15 [38].

### BTRA Chamber Diameter Exploration

Multiple baffled tube configurations have been investigated, but in general inserts have fallen into three categories: 3" normal baffles, 2.5" normal baffles, and inclined baffles.<sup>2</sup> Studies comparing baffle chambers with diameters of 2.5" and 3" (corresponding to an area increase of 44%), found that acceleration experienced by the projectile scaled as expected when compared to the  $\beta$  factor described in Eq. 2.17. Testing by Leege et al. in methane-air propellant mixtures showed an increase in ballistic efficiency by a factor of two between the designs [15], but further testing is necessary for full characterization.

<sup>2</sup>Designs of normal baffles are discussed in more detail in Chapter 3, and inclined baffle designs are discussed in other works [19, 40, 41].

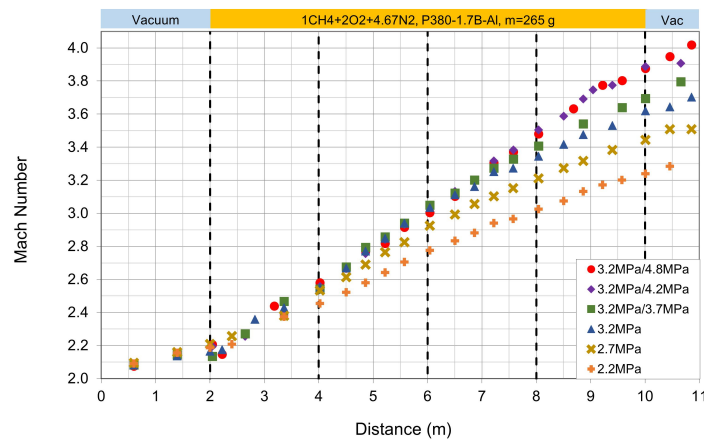


FIGURE 2.15: Mach number-distance data from BTRA experiments at various fill pressures using same propellant. projectiles with a shoulder diameter of 1.38 inches and length of 1.7 baffle lengths, nose and tail angles of  $15^\circ$  and  $12^\circ$ , respectively, and  $\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  propellant [38].

### BTRA Chamber Shape Exploration

While the prior results compared BTRA performance in normal baffles of varying diameter, additional work has been completed which investigated alternate shapes of BTRA chambers [41, 42]. These investigations began through computational fluid dynamics (CFD) modeling, which suggested that significant improvements could be made to thrust for baffles at shallow inclination angles (Fig. 2.16, as well as reduced drag on the projectile.

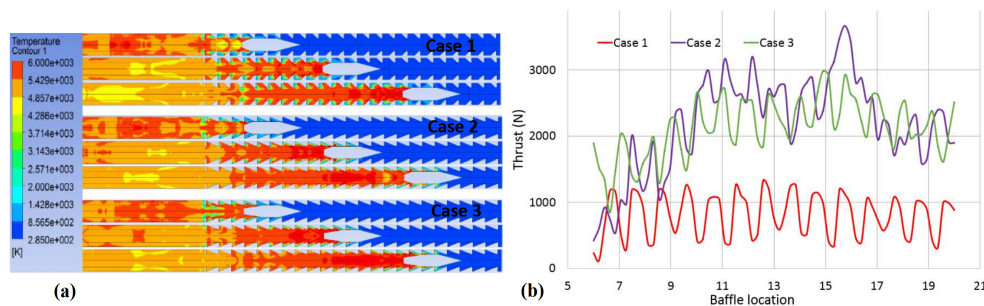


FIGURE 2.16: (a) Temperature contours on center-plane of BTRA at  $M = 2.86$  for three different cases. (b) Thrust profiles of these cases at  $M = 2.86$  from the sixth to twentieth baffle chambers forward of the BTRA entrance [19].

From these simulations, an angle of  $31^\circ$  was chosen for practical experimentation. Fig. 2.17 shows the results of this experimental campaign, with the triangular-marker points not on the curve

reflecting the configuration used in Case 3 of Fig. 2.16a. It was found that, although CFD predicted higher thrust, the inclined baffles resulted in both lower acceleration and more limited operational envelopes than the standard  $90^\circ$  baffles [40]. Reversing the orientation of the inclined baffles, such that the slopes rise upstream instead of downstream, did show some thrust improvement over the normal baffles, but still required a more limited operational envelope [18, 19].

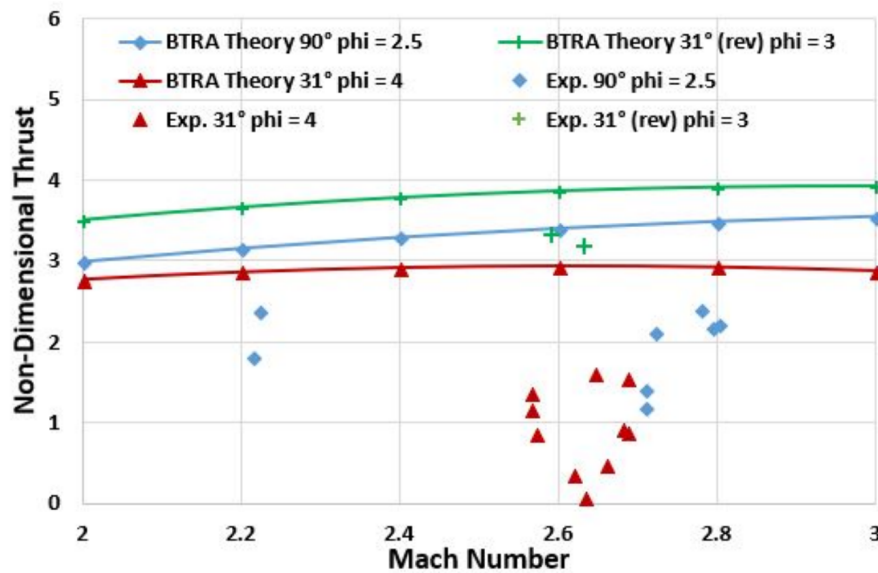


FIGURE 2.17: Comparison of methane-oxygen mixture class in three baffle configurations [40].

These results suggest that, while the inclined baffles may not offer the precise benefits researchers expected, nonstandard baffle configurations may be of use in certain operational regimes.

### 2.2.3 Revised BTRA Performance Modeling

As shown in Section 2.2.2, while the BTRA is able to achieve high performance, it does not reach the maximum performance predicted by theory. Additionally, experimental testing has shown that the baffles themselves experience significant force during operation, which is not fully accounted for in the baffle drag  $D$ . This force may cause simple shifting of the baffles along the tube during

operation, or outright warping and buckling of BTRA assemblies [40]. As such, an alternate interpretation of Eq. 2.17 has been proposed [43].

While the analytical schema proposed in Section 2.2.1 folds its control volume around the baffles, treating them as immutable walls, the new technique includes them in the analysis as discrete bodies that may experience a force. This leads to a modification of Eq. 2.14 in the form of

$$I_{TCRA} = \frac{F_p + F_{baff}}{P_1 A_{eff}} = M_1 \frac{\gamma_1}{\gamma_2} (1 + \gamma_2) \sqrt{\frac{\gamma_2 - 1}{\gamma_1 - 1} \left( \frac{Q + \frac{h_1}{c_{p1} T_1} + \frac{\gamma_1 - 1}{2} M_1^2}{\frac{h_2}{c_{p2} T_2} + \frac{\gamma_2 - 1}{2}} \right)} - (1 + \gamma_1 M_1^2) \quad (2.18)$$

where  $F_p$  represents the force experienced by the projectile, and  $F_b$  represents the force experienced by the baffle. Through the definition of the  $\beta$  term, these values may be further related as

$$I_{TCRA} = \frac{F_p + F_{baff}}{P_1 A_{eff}} = \frac{I_{TCRA}}{\beta} + \frac{I_{TCRA}(\beta - 1)}{\beta} = I_p + I_{baff} \quad (2.19)$$

While this equation cannot capture certain phenomena which arise as a result of baffle geometry (such as from the inclined baffles discussed in Section 2.2.2), it does provide more accuracy in predicting performance of the BTRA system [43]. The work presented this study is done in an effort to better understand the transient and multi-dimensional phenomena of the BTRA.

## 2.3 Railed Tube Ram Accelerator

An alternative to the BTRA has been investigated which enables the acceleration of axisymmetric projectiles. This concept, dubbed the Railed Tube Ram Accelerator (RTRA), operates on similar principles to the SBRA system, but contains rails which run the length of the tube (Fig. 2.18). These rails guide the projectile body and stabilize it, making fins unnecessary and allowing axisymmetric operation.

The RTRA system, developed in the 1990s by the French-German Research Institute at Saint-Louis (ISL) found good success in RTRA operation in the superdetonative velocity regime, making it an appealing option for high-velocity ram accelerator operation [10, 11, 44]. Additionally, ISL reported two experiments which were partially successful in the subdetonative regime, though both unstated after three meters of operation. These experiments showed that TCRA operation was possible with axisymmetric projectiles. It was not until the early 2020s that subdetonative RTRA operation began to be investigated at the University of Washington [15, 20].

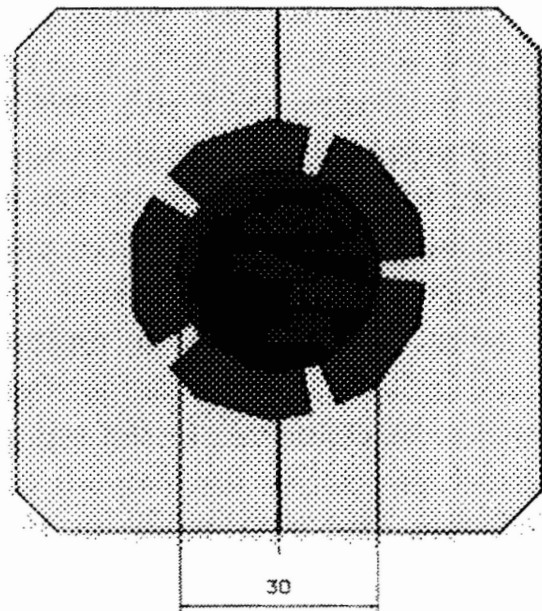


FIGURE 2.18: Cross-section view of a five-rail RTRA design from ISL [11].

On a theoretical modeling level the RTRA is taken to operate in the TCRA propulsive mode just as does in the SBRA. The quasi-one-dimensional analysis from Eq. 2.12 remains in place, and thrust is scaled with the same  $\beta$  factor as the BTRA system, although in the RTRA case  $\beta$  is determined without the need to compensate for the baffle wall's volume, as no baffle wall is present. The TCRA propulsive mode prediction holds much better for RTRA thrust than in the case of the BTRA, only slightly overpredicting performance [15, 20].

### 2.3.1 Rail Sweepers

Unfortunately, the RTRA is subject to similar limitations on heat release, minimum velocity, and unstarts as the SBRA, meaning that the RTRA can never operate in the TCRA mode with the high  $Q$  propellants of the BTRA. This limit has been long discussed, with the idea of "resetting" the flow in some way being proposed. To this end, a novel idea was tested by Leege: operate in an RTRA, interspersed with BTRA inserts to mitigate unstarts [20]. These inserts, called "rail sweepers," were successful, allowing for subdetonative RTRA operation in more energetic mixtures than would otherwise be stable in a pure RTRA system (although operation in the highly energetic mixtures used in the BTRA has yet to be achieved). These tests ran successfully though the test section up to a heat release of  $Q = 6.75$ , as shown in Fig. 2.19. A proposed rail sweeper design is shown in Fig. 2.20.

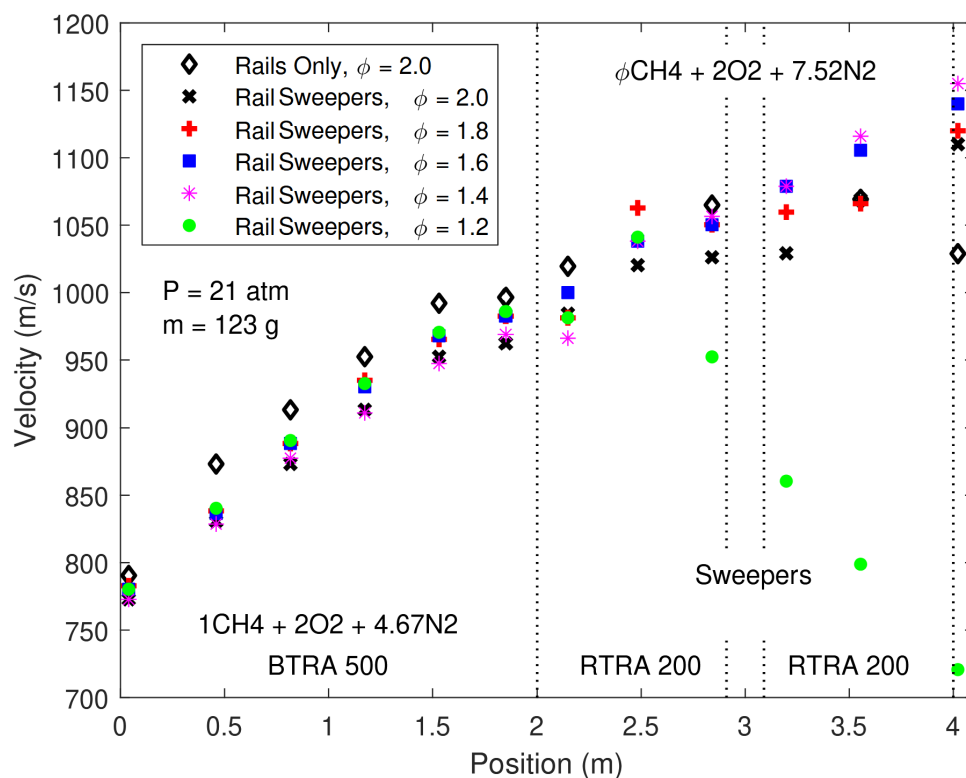


FIGURE 2.19: Experimental velocity versus position curves for the RTRA with rail sweeper and varying propellant mixtures [20].



FIGURE 2.20: Schematic of a proposed rail sweeper design [45].

Leege's testing showed that the concept of the rail sweepers was feasible, but was not able to determine a complete relationship between a given propellant mixture and the necessary sweeper configuration. Moreover, it introduced several key questions, among them:

1. Is there a simple relationship between sweeper spacing and propellant heat release, or are other factors involved (sound speed, projectile velocity, projectile length, etc?)
2. How many baffles are necessary to reset the RTRA flowfield?
3. Does the diameter of the sweeper chambers affect sweeper spacing?

## 2.4 Justification of Study

Experimental performance measurements and theory have been found to be largely in agreement within the SBRA system, for both the subdetonative and superdetonative regimes [7, 23]. The BTRA theoretical predictions, however, do not align with experimental observations along several metrics. In the quasi-steady one-dimensional black box model (as described in Sections 2.2.1 and

2.2.3) there is no mechanism, aside from the  $\beta$  factor, by which unique baffle geometries may affect performance, despite experimental results showing otherwise [46]. Further, testing has suggested that the operational limits of the SBRA system, as suggested by the theoretical model, may simply be inapplicable to the BTRA, as described in the following section.

### 2.4.1 Low Mach Number Starting

Aside from limited computational fluid dynamics modeling [18, 19, 41], past ram accelerator analysis has been limited to the one-dimensional approximation discussed earlier in Section 2.1. Experimentation with the BTRA system, using the aforementioned  $\beta$  factor, has followed this practice, but often fails to accurately predict performance. The reasonableness of this simplifying assumption was called into question by work conducted by Ginos [47]. During a study of projectile geometry<sup>3</sup> an anomalous shot failed to immediately ignite in what should have been safe operation (as described in Section 2.1.2). This experiment, shown in Fig. 2.21, saw the projectile fail to start upon entry, decelerate due to drag to a velocity of Mach 1.68, then successfully ignite and operate through the rest of the experimental section. Even allowing for the most generous error measurements, the minimum operating Mach number predicted by Eq. 2.13 was 1.77.

This result lent support to the long-standing suspicion that quasi-one-dimensional operational limits are inadequate for predicting the operational limits of the BTRA system. As such, two-dimensional analysis must be investigated.

### 2.4.2 Study of Full Design Parameters

In addition to the lack of concrete understanding about low-velocity gas dynamics in the BTRA, studies of scaling and geometry have been limited. In terms of baffle shape, most experimentation has consisted of normal baffles, entirely radial to the axis of projectile motion. Angled baffles have been studied to a limited extent, but real-world testing has not shown the performance benefits

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<sup>3</sup>Work not inherently related to the BTRA design.



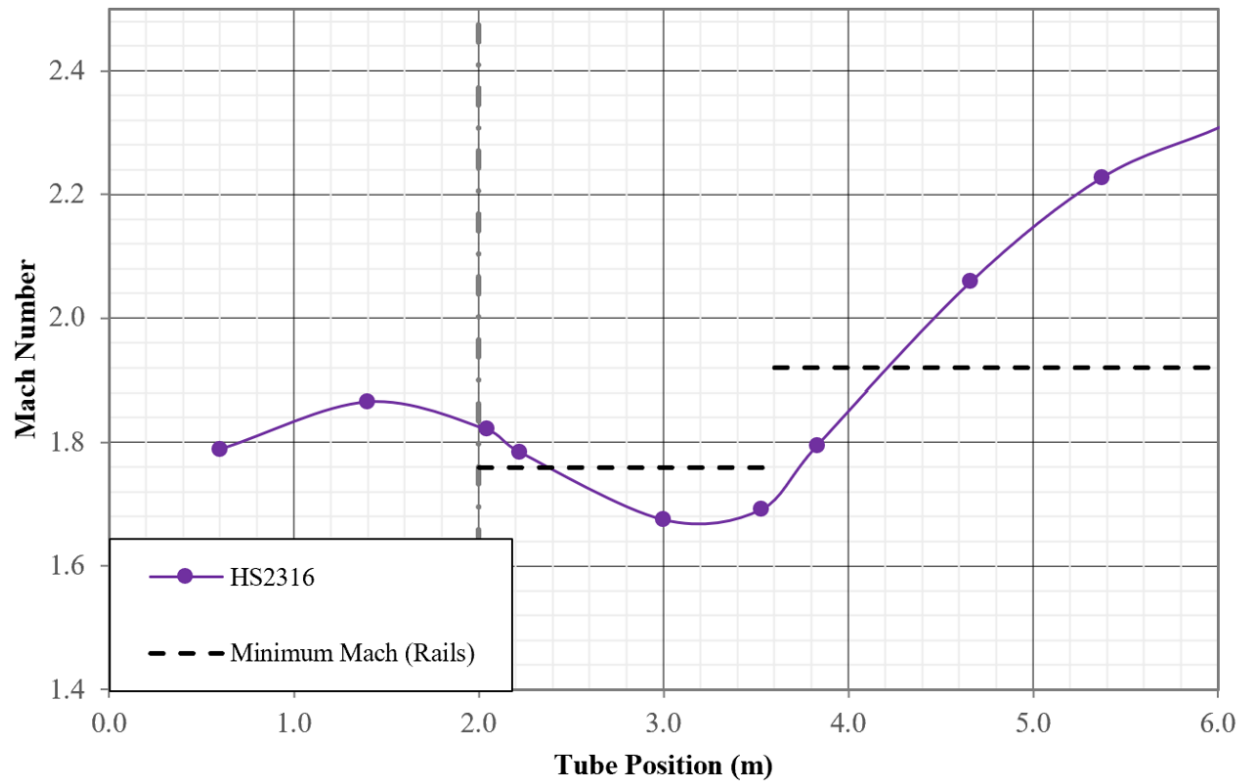


FIGURE 2.21: Velocity-position data of a ram accelerator projectile experiencing a delayed start which dropped its velocity below the one-dimensional minimum Area-Mach limit.

predicted by CFD [16, 18, 19, 46]. Within the bounds of normal baffle geometry, the only parameter that has been experimentally examined is the radius of the baffle chamber, and even in this case, only within a handful of parameters [15, 17, 20, 37–39]. These experiments have confirmed certain theoretical trends (*i.e.* smaller chamber diameters have higher thrust, while larger chamber diameters permit lower-velocity operation), but as discussed in Sec. 2.4.1 these theories do not fully predict performance.

The effect of altering the spacing between baffles has never been the focus of an experimental study, despite the likely effects of stability and reaction dynamics. This is due to a number of factors, including cost, ease of maintenance, and time required. Still, the effects of altering the axial distance between baffles is likely to be of importance in a fully designed, industrial scale BTRA system.

### 2.4.3 Rail Sweeper Optimization

Consideration of geometric spacing leads to a final question: at what point does the line between rail sweepers and BTRA blur? It has been previously discussed that the BTRA system is not able to achieve the desired peak thrust seen in RTRA systems, but the RTRA system is not able to operate with the same high  $Q$  propellant mixtures. It is hoped that there may exist some optimal configuration in which sweepers are clustered tightly enough to allow the use of high  $Q$  propellants at a given Mach number while still maintaining high thrust operations (Figure 2.22).

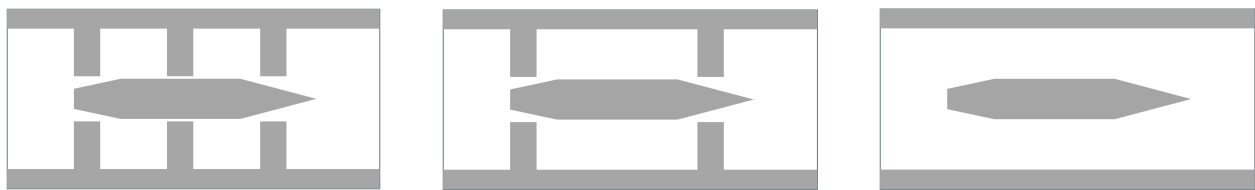


FIGURE 2.22: Comparison of BTRA (left), RTRA (middle), and rail sweepers (middle). Figure not to scale.

## 2.5 Imaging of Ram Accelerator Systems

To better understand the effects discussed in Sec. 2.4, a method has been devised in the current study to understand the gasdynamic structure evolving within the baffle chambers in an experimental environment, as numerical efforts have proven inadequate. Of particular interest is the implementation of an optical imaging system, permitting direct capture of phenomena in BTRA operation.

Imaging of gasdynamic structures, such as shock waves and expansion fans, is not a new science. It has been observed since before the dawn of human civilization in the shadow of air from a fire as light refracts differently through regions where the air is more or less dense. Study of this effect as a science is attributed to various individuals, but a few originators are generally accepted. Shadowgraph imaging, the simplest method of observing this effect, is commonly attributed to

Hooke in 1665 [48]. Shadowgraphs occur when light is bent via refraction, allowing a gas' structure to be observed via the patterns of light and dark regions. Further development occurred with schlieren photography, attributed to Toepler in 1864, making use of a better focusing scheme and a knife-edge to produce more sensitive measurements [49]. Further developments, such as interferometry, have taken gasdynamic imaging even further.

Imaging of ram accelerator in-tube phenomena is not new. Sasoh et al. used holographic interferometry to observe entrance effects as a projectile transited to a high-pressure region, and Yatsufusa et al. used shadowgraph imaging to observe combustion phenomena [50, 51]. Their techniques are summarized below.

### **2.5.1 Shadowgraph Imaging of Planar SBRA Operation**

Yatsufusa et al. in 2002 established a method in which the shock pattern around a ram accelerator projectile could be directly imaged by shadowgraphy [51]. This technique employed a planar ram accelerator, consisting of a flat dual-wedge projectile in a rectangular bore tube. The planar design enabled operation with flat walls, and preserved the collimation of light for shadowgraphy. This work demonstrated that shadowgraph imaging is a useful means of capturing ram accelerator flow fields, as shown in Fig. 2.23. The planar ram accelerator, however, is a distinctly different implementation than the axisymmetric ram accelerators more widely adopted. As such, a different method of imaging is required for BTRA investigations.

### **2.5.2 Holographic Interferometry of Cylindrical SBRA Operation**

In 1999, Sasoh et al. developed an alternative method of seeing into a ram accelerator with a cylindrical bore [50]. By selecting a non-cylindrical outer surface, Sasoh et al. were able to maintain collimation of light through the test section, thereby capturing images of non-planar phenomena. This was achieved via an aspherical lens geometry in the tube design, as described by Takayama (Fig. 2.24) [52]. Sasoh et al.'s work was conducted using holographic interferometry instead

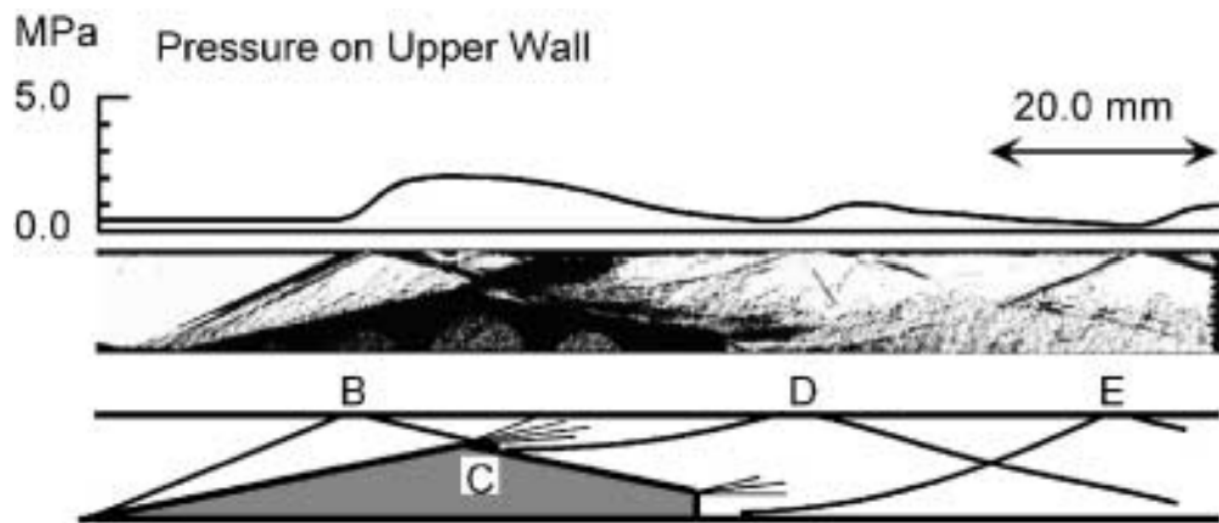


FIGURE 2.23: Shadowgraph image and pressure history along top wall in a planar ram accelerator.  $M = 4.08$ , mixture:  $\text{CH}_4 + 2\text{O}_2 + 4.8\text{CO}_2$  [51]

of shadowgraph imaging, producing more detailed images, but the operational requirements were similar. The results, shown in Fig. 2.25, were used to analyze shock patterns around a ram projectile entering a high pressure non-combustive region. Though this work was conducted with the goal of understanding how the projectile interacts with a thin diaphragm, the imaging technique and the results bode well for BTRA experiments.

### 2.5.3 Imaging in Rounded Tubes

As a precursor to imaging of BTRA flowfields, options for capturing images of gasdynamic phenomena within the UW Ram Accelerator facility were explored. Discussed fully by Hlavsa, this work was conducted in smooth cylindrical tubes, with the goal of verifying that sizing, experimental setup, and recording equipment were robust enough to capture information with sufficient resolution [53].

Hlavsa was able to measure the transit velocity of a piston-driven normal shock to within 2% agreement between embedded pressure transducers and visual shock from the optical system, using twelve frames of shock transit. The system was also sensitive enough to detect weaker

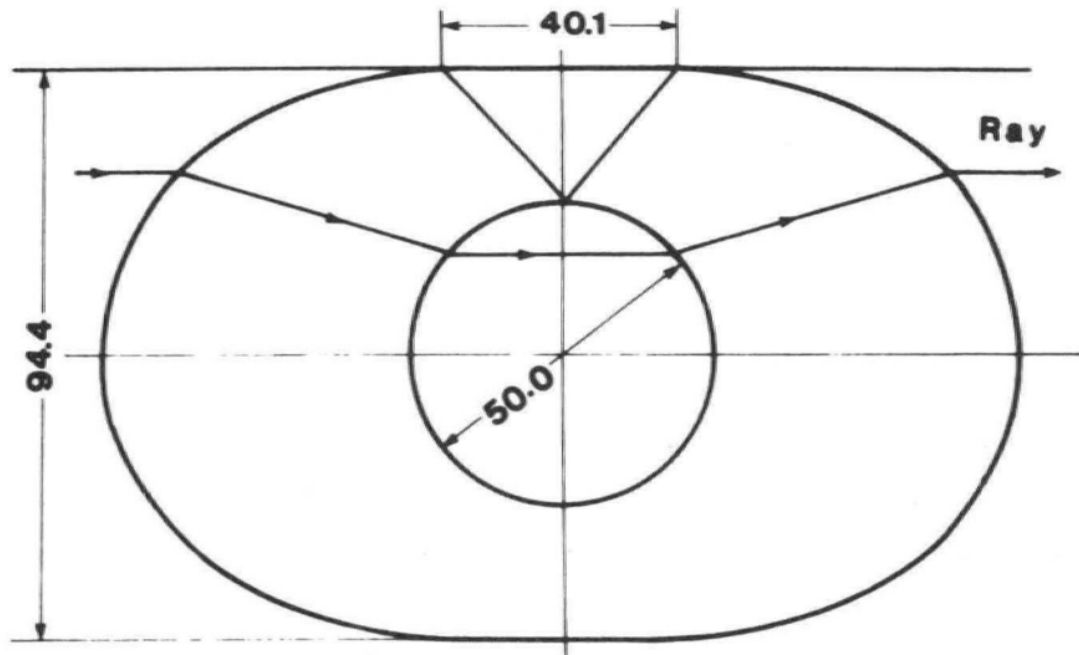


FIGURE 2.24: Cross-sectional design of the acylindrical tube proposed by Takayama [52].

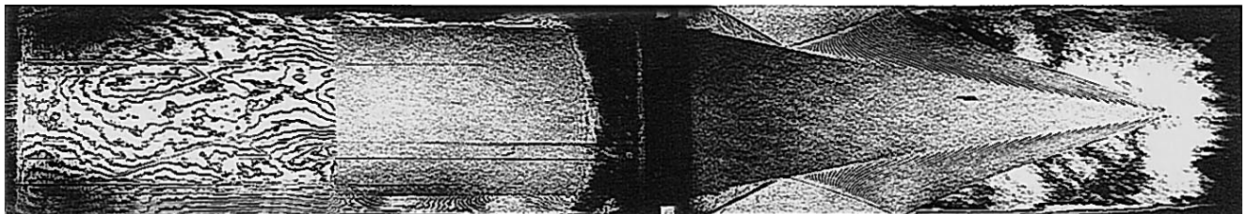


FIGURE 2.25: Reconstructed interferogram of projectile entry process by piercing Mylar diaphragm,  $p_2 = 0.1$  MPa,  $p_3 = 1.0$  MPa, two-layer diaphragm (thickness = 188  $\mu\text{m}$ ),  $U_p = 1105$  m/s [50].

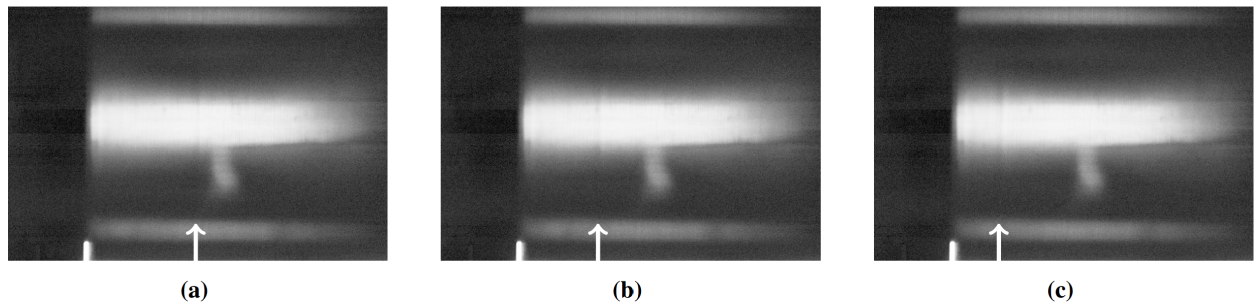


FIGURE 2.26: Sequential shadowgrams of a piston-driven normal shock wave [53].

reflected shocks coming from downstream as they transited the instrumented area from the opposite direction.

The accuracy and simplicity of the system presented by Hlavsa was determined to be sufficiently sensitive to detect phenomena in BTRA systems, and thus a simple shadowgraph photography system (with the potential for upgrade to shleiren photography) was selected for further study.

## 2.6 Shadowgraph Imaging and Optics

As discussed in the preceding section, shadowgraph imaging is based upon capturing images which are darkened due to density variations in a gas. First characterized by Gladstone and Dale, the eponymous Gladstone-Dale relation provides a fluid's index of refraction ( $n$ ) as a function of its density ( $\rho$ ) and the Gladstone-Dale coefficient ( $k$ ) [54].

$$n - 1 = k\rho \quad (2.20)$$

It follows then that a fluid with a density gradient would have a corresponding refractive index gradient, which may be calculated from the Gladstone-Dale relation. If light is shined through such a gradient, its resultant paths would disperse due to the different refractive indices, creating gradients of illumination when captured downstream [55]. If light is considered to be initially traveling parallel to the Z axis of a space, the displacement of a given ray may be found as

$$\frac{\partial^2 x}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial x}, \frac{\partial^2 y}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial y} \quad (2.21)$$

Using the small angle assumption, for a fluid of refractive index  $n_0$  and a gradient with extent  $L$  along the  $Z$  axis, the deflection angles may be found as

$$\epsilon_x = \frac{L}{n_0} \frac{\partial n}{\partial x}, \epsilon_y = \frac{L}{n_0} \frac{\partial n}{\partial y}, \quad (2.22)$$

In naturally occurring (or merely everyday) shadowgram and schlieren phenomena, such as the shimmering of air above hot pavement, the scattering produced is noticeable but difficult to quantify. In a controlled environment, however, optical pathways may be precise enough to permit quantifiable measurements of fluid properties. This is the basis of focused shadowgraphy, where traditional optical methods are used to enhance the effects of refractive gradients in a sample region.

A typical focused shadowgraphy apparatus consists of three focusing lenses, which take a point light source, collimate it through a test section, then focus it onto an imaging surface (Fig. 2.27). From source to image, the scattered light is collimated through a first field lens, transits the sample region, is re-focused through a second field lens, then finally focused onto the viewing plane. When properly established, this viewing plane will recreate the light patterns produced at a plane in the sample region, in a position determined by the focal distances of the lenses. In this manner any refraction due to density differences may be directly imaged externally and the shadowgram may be captured accurately. Real-world effects, such as the specific design of the light source and lenses, can place limitations on the quality of captured shadowgrams [55].

In simple analysis, the contrast  $C$  of a region, defined as the ratio between the differential illuminance  $\Delta E$  and the background illuminance  $E_0$ , is used to quantify a sample's properties. This contrast term is related to the deflection angle of the light  $\epsilon$ , the separation between the refractive gradient and the focal zone of the lens (defined as  $g$ ), and the extent of the refractive index gradient ( $d$ ) [55].

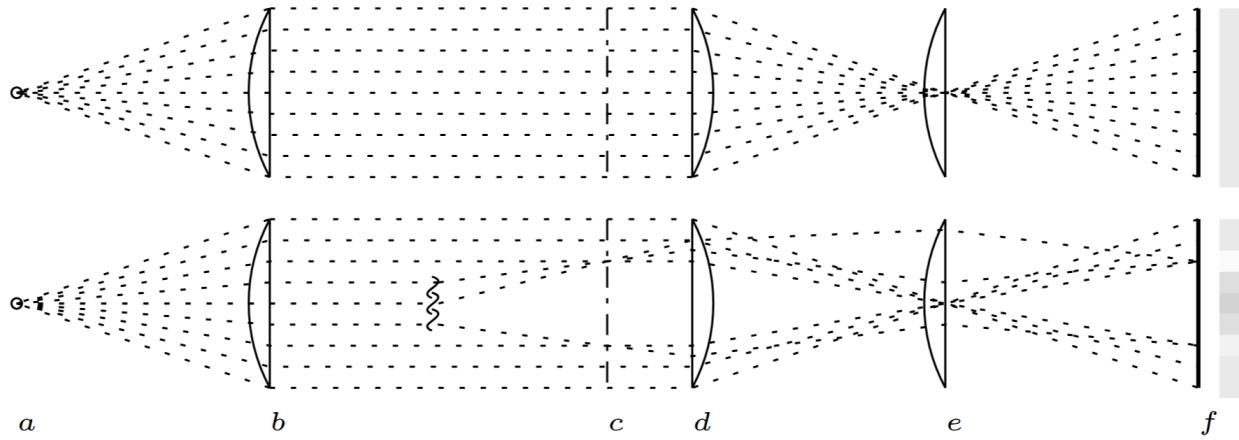


FIGURE 2.27: Ray tracing diagram illustrating the difference in illuminance produced by introducing a refractive index gradient into the test area of a focused shadowgraph apparatus: (a) light source (b) first field lens (c) focal zone of focusing lens (d) second field lens (e) focusing lens (f) viewing plane [53].

$$C = \frac{\Delta E}{E_0} = \frac{\varepsilon g}{d} \quad (2.23)$$

In imaging of large-scale flows this analysis of contrast may prove sufficient. However, the shock waves generated in super- or hypersonic flows are so thin that the wave nature of light must be considered. Along thin phenomena (or around the sharp edges of larger phenomena), refracted light is blurred [56]. The thickness of this blurring is defined as  $d_b$ , and, assuming collimated light through the refraction gradient, is given as

$$d_b = \sqrt{\lambda g} \quad (2.24)$$

where  $\lambda$  is the wavelength of the light and  $g$  is once again the distance between the region being imaged and the focal point of the lens.

The relevant shock waves, typically being only a few mean-free-paths in thickness, are thin enough to cause a noticeable blurring effect. They also produce a high enough density gradient to cause significant deflection angles, resulting in images that resolve their shadowgrams as orders of



magnitude greater than their actual thickness [57]. The present work, however, is concerned primarily with imaging of shock structures and patterns than with actual quantitative measurements, so further analysis was deemed out-of-scope.

## Chapter 3

# Experimental Facility

The UW ram accelerator facility is made up of three key systems, as shown in Fig. 3.1. The first, in order of operation, is the 6.4-m-long, 38-mm bore light gas gun, capable of accelerating projectiles of mass up to 300 g to velocities approaching 1 km/s. For specific velocities see Appendix C.1.

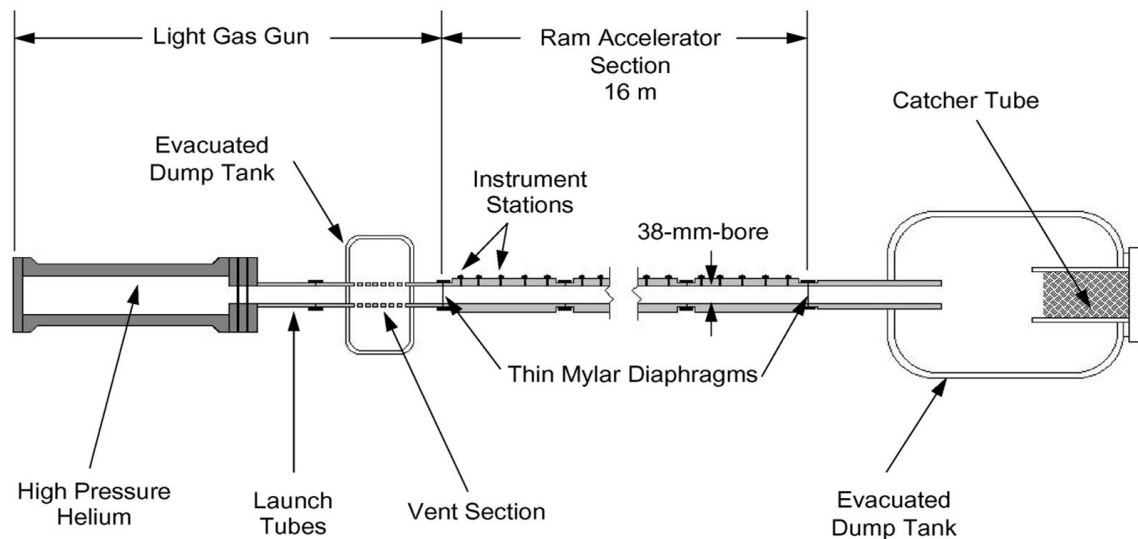


FIGURE 3.1: UW ram accelerator schematic.

The second key system is the ram accelerator test section. This section is made of eight two-meter-long tubes, with room for minor additions or modifications as needed. In the configuration

used in this study, four tubes have an increased internal bore diameter of 76 mm to accommodate baffle inserts, while the remaining tubes have smooth 38 mm bores. Each tube is designed with the capability to serve as its own discrete propellant stage which is typically achieved through the placement of a thin diaphragm at the tube joint. This, when combined with baffle insert modifications, allows the full customization of internal conditions in each ram tube.

The third key system, the deceleration section, consists of a catcher tube with decelerates projectiles kinetically and a dump tank which accommodates the expansion of gases trailing the projectile. The light gas gun, ram accelerator section, and deceleration section are all connected to two Welch Duo-Seal vacuum pumps to evacuate of ambient gasses before the experiment and dispose of residual gasses afterwards.

The ram accelerator facility uses a propellant flow control system to feed gaseous mixtures into each ram tube. Mass flow controllers for the fuel, oxidizer, and diluent have an uncertainty of  $\pm 1\%$ , resulting in equivalence ratio uncertainty of  $\pm 2\%$  and diluent-to-oxygen molar ratio uncertainty of  $\pm 2.3\%$  for the methane-air mixtures used in this work. During shot preparation each ram stage is first isolated from the gas system and evacuated to less than 30 torr, ensuring minimal contamination of gasses. Propellant is mixed as it flows within the tubing connecting the manifold to the desired ram stage(s). After each stage is filled, the individual flow rates are adjusted to change the propellant composition before routing the new mixture into the next stage [37]. A full piping and instrumentation diagram of the ram accelerator gas handling is shown in Figure 3.2.

### **3.1 Ram Tube Inserts**

As discussed in Section 2.2, the ram accelerator test section may be equipped with a variety of inserts to alter in-tube geometry. While inserts may vary in size and geometry, a few common factors were selected for each design. Each insert has an inner bore diameter of 1.502" to ensure proper fit and clearance with the transiting projectile. Additionally, each baffle insert has an outer

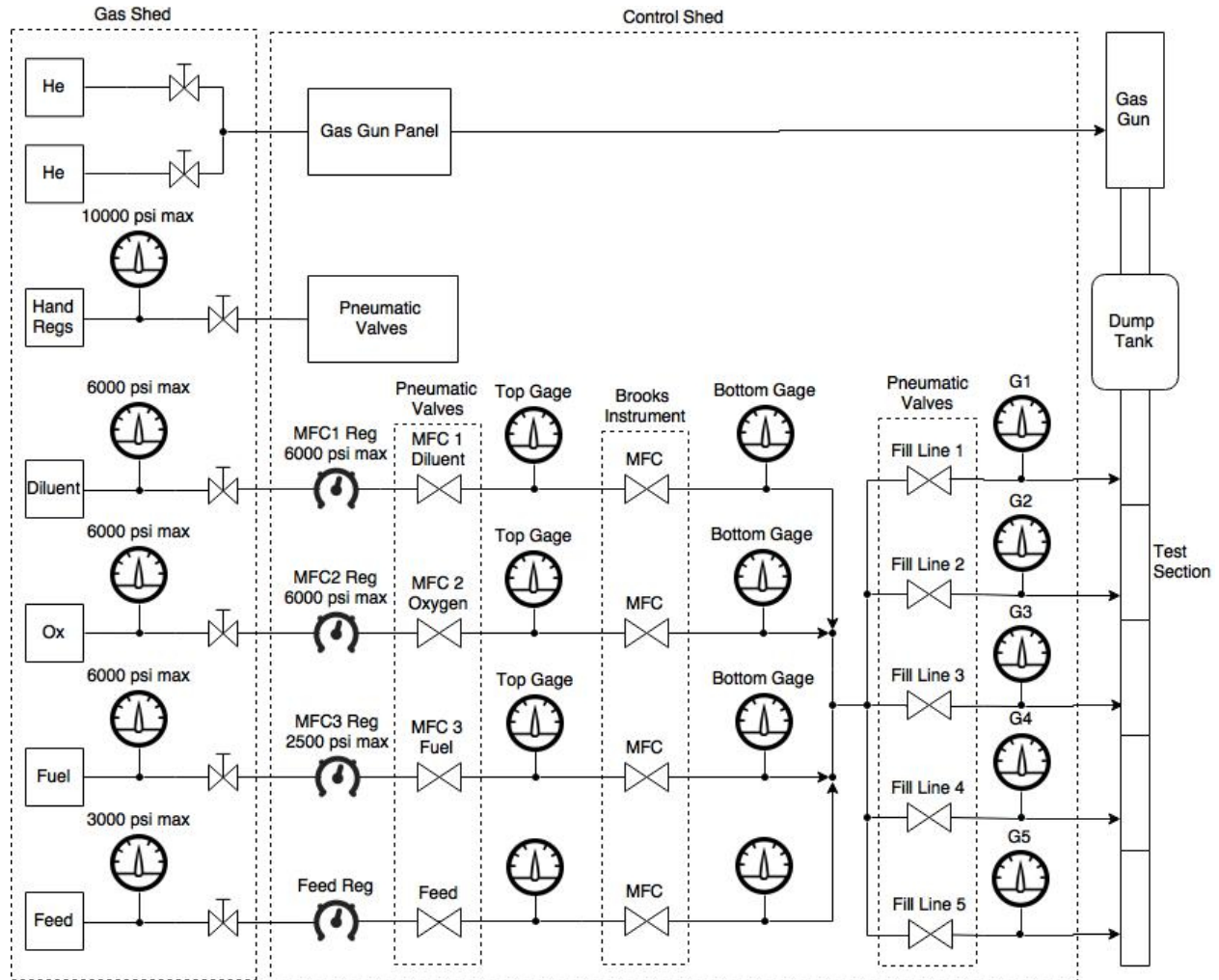


FIGURE 3.2: UW ram accelerator flow control PID [37].

diameter between 2.980 and 2.997", depending on desired diametric clearance with the shell tube bore, to ensure good alignment within the ram tubes.

The standard BTRA insert is also limited by a few geometric constraints. Each is limited to an axial length of 1.406" (defined as one standard baffle length), permitting 56 inserts to be placed into a given two-meter-long ram tube while maintaining clearance for instrumentation. Irrespective of chamber diameter, the baffle wall between chambers is held at 0.25". The standard insert design used in this investigation consists of four rails, placed at 90° increments, to ensure projectile stability.

Within these imposed standards, the primary geometric variation is the chamber diameter. A

| Insert Designation | Nominal Chamber Diameter, in | Fluid Volume, in <sup>3</sup> | $\beta$ |
|--------------------|------------------------------|-------------------------------|---------|
| BTRA 501           | 3.0 (full tube)              | 7.04                          | 2.83    |
| BTRA 601           | 2.5                          | 5.27                          | 2.12    |
| BTRA 751           | 2.0                          | 3.96                          | 1.59    |

TABLE 3.1: Critical design parameters for baffle tube inserts. All inserts used nominal outer diameters of 2.980-2.997", axial lengths of 1.406", and central bore diameters of 1.502".

pure SBRA tube at this scale would have a chamber diameter of 1.502", the same as the central bore, which would result in a  $\beta$  value of 1. For this test campaign three diameters were chosen, with nominally 3", 2.5", and 2" (not including fit tolerances). These inserts, once accounting for the volume taken up by the rails, resulted in  $\beta$  values of 2.83, 2.18, and 1.59, respectively. In this work baffles are labeled by the ratio of nominal chamber diameter to nominal bore diameter. As such, the 3" baffle insert is referred to as a 50X series insert ( $\frac{1.5}{3} = 0.500$ ), and the other two are 60X and 75X series inserts, respectively, with the final digit X representing how many standard insert lengths (each of 1.406") an insert occupies. Specific inserts had slightly different  $\beta$  values due to added holes or to allow for instrumentation access. The three standard insert designs are shown in Fig. 3.3 and their critical design parameters are listed in Table 3.1.

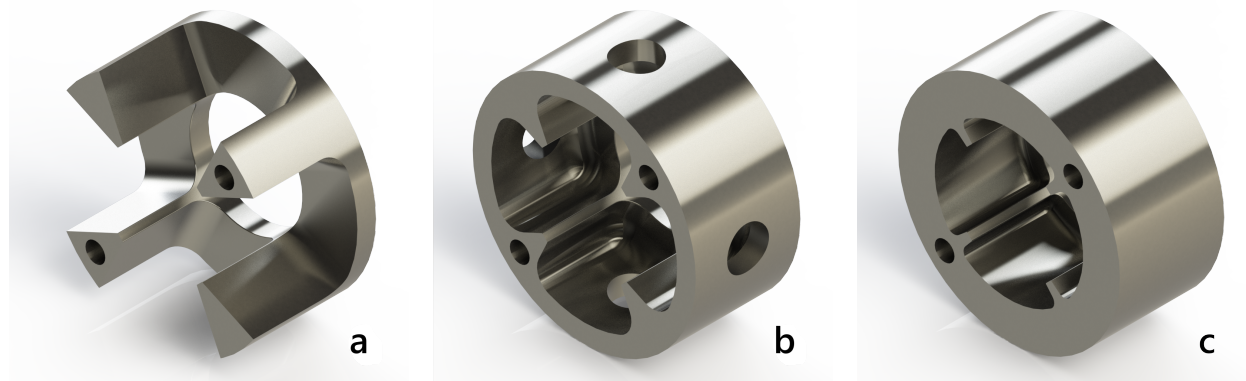


FIGURE 3.3: The BTRA 501 (a), BTRA 601 (b), and BTRA 751 (c) baffle insert designs. Drilling of instrument holes were standard for BTRA 601 inserts, but non-standard for BTRA 751 inserts.

BTRA inserts were rearranged as desired to suit experimental needs. The optimal baffle configuration was expected to be with the highest  $\beta$  inserts at the tube entrance, with downstream inserts

progressively decreasing in  $\beta$ . This configuration was chosen due to the lower minimum entrance velocity for high  $\beta$  baffles.

### 3.1.1 RTRA Inserts

In order to facilitate testing of the rail sweeper phenomenon (Sec. 2.3.1) a modified version of the BTRA 751 inserts was procured. This insert, dubbed the RTRA 751, is identical to the baffled insert in every key dimension with the exception of the removal of the baffle wall itself (Fig. 3.4). The RTRA 751 inserts could be assembled end-to-end to replicate the testing configurations of prior RTRA studies [20], or placed adjacent to a BTRA insert to create a BTRA system with increased chamber lengths.

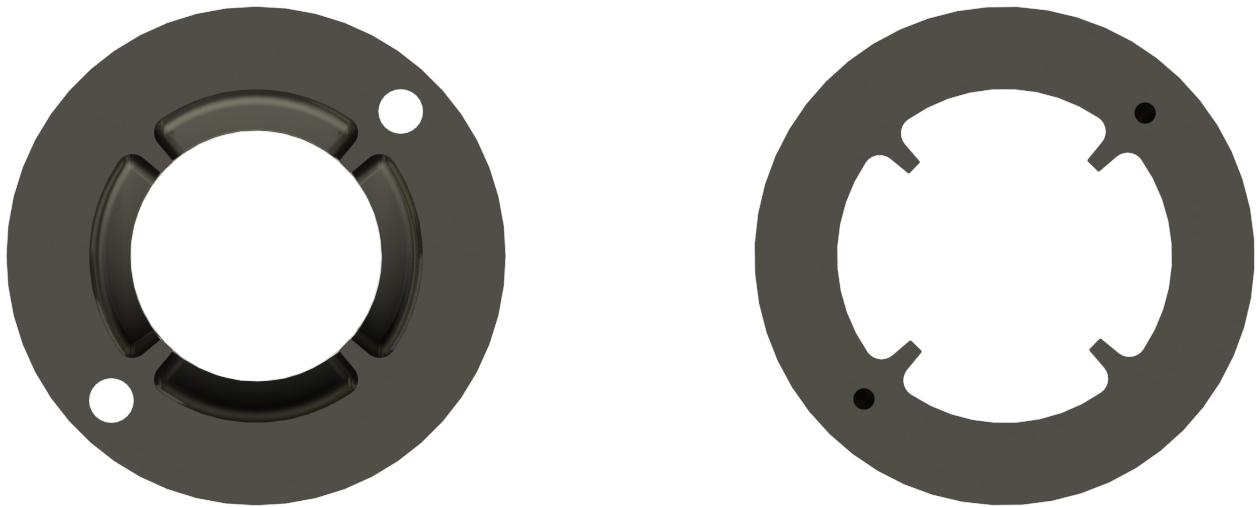


FIGURE 3.4: Comparison of the BTRA 751 and RTRA 751 inserts.

## 3.2 Projectile Designs

Projectiles in the BTRA or RTRA systems are typically axisymmetric with a conical nosecone and tail separated by a smooth shoulder. The standard polycarbonate P380 projectile, shown in Fig. 3.5, has a conical nosecone with an angle of  $15^\circ$  and a tail with an angle of  $12^\circ$ , which meet at a shoulder with diameter of 1.380" (hence P380). The tail is truncated to a base with diameter

of 0.710 inches" for obturator seating. The cylindrical shoulder is of varying length, which is typically parameterized as a multiple of the standard baffle-length (*e.g.* a P380-2BL projectile has a shoulder length of 2.812 inches). Most projectiles have a 0.438" bore at the base for insertion of a magnet for detection by magnetic induction sensors, though in certain cases magnets are placed in the nosecone.

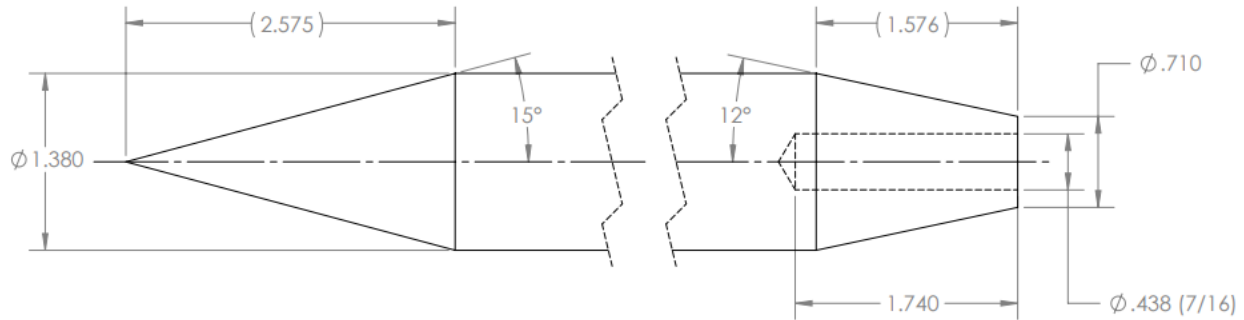


FIGURE 3.5: Drawing of a standard P380 projectile with arbitrary shoulder length. Dimensions are in inches.

For the experimental series focusing on projectile effects, one or more of the above parameters were varied. For example, the P496 projectile maintains the nosecone and tail angle, but has a shoulder diameter of 1.496" inches. Other variations of interest were longer shoulders and reduced nosecone and tail angle, which are referenced when comparing other work but which were not used in this study.

Projectile geometry is the key factor for fluid studies, but projectiles of different materials, densities, and internal structures are sometimes needed. For high pressure or high velocity operation a stronger projectile, typically made of aluminum, is sometimes deemed necessary. Polycarbonate projectiles can deform or even break under particularly intense conditions, while aluminum projectiles are far more robust. To reduce density, many aluminum projectiles are hollow, consisting of discrete pieces which may be assembled to produce the desired external geometry.

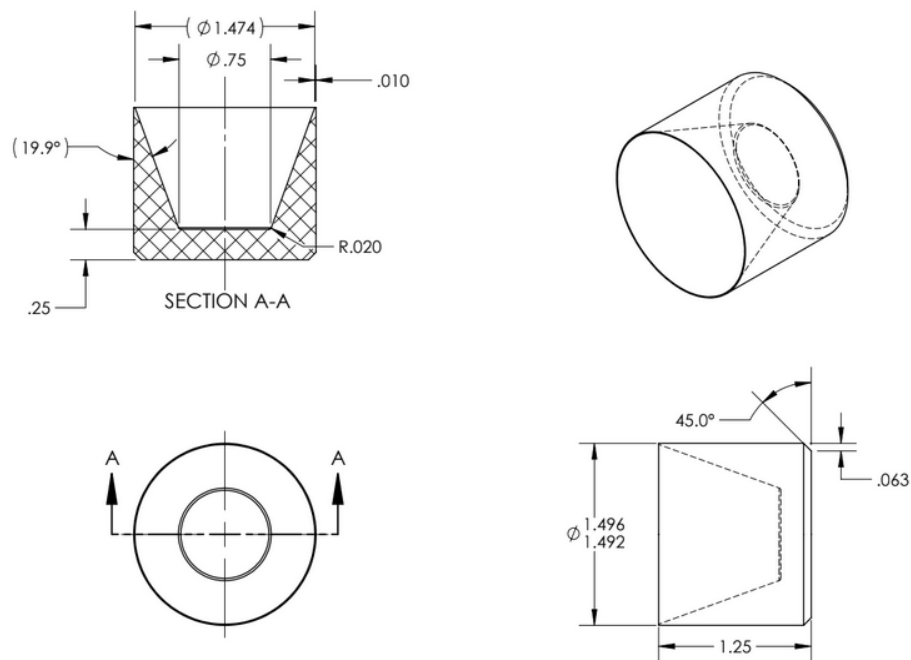


FIGURE 3.6: Obturator design used in this study. Dimensions are in inches.

### 3.2.1 Obturators

As mentioned in Section 2.1.1, subdiameter projectiles require an obturator or sabot to be made compatible with the light gas gun launch system. The obturators used in this investigation were simplified versions of the solid obturator design shown in Figure 2.9. The annular magnet groove was removed, the base thickened, and the sealing edge lengthened (Figure 3.6). These obturators were necessary for 1.380" diameter projectiles, which are subdiameter, but were not necessary for the 1.496" diameter projectiles.

## 3.3 Instrumentation

Projectile performance within the ram test section was tracked via the use of pressure transducers and magnetic induction sensors. The pressure transducers allow for the detection and tracking of conditions in the tube and are sensitive enough to record changes from projectile shock waves or



propellant combustion in real time. The magnetic induction sensors tracked the projectiles more directly by detecting the change in field strength from a magnet embedded in each projectile. Similar to the pressure sensors, these then measured signal strength as a function of time, with adjacent points compared for the calculation of projectile velocity. Instruments were typically placed in pressure/magnet pairs at any of five ports stationed equidistant along a chosen ram tube [58, 59]. Up to twenty of each probe type could be placed within the eight-meter-long ram test section, as well as five stations on the light gas gun and fifteen in the drift tube. Signals were digitized and recorded through a National Instruments PXIe-1071 data acquisition system, with two PXIe-6358 modules to monitor up to 32 data channels at a sample rate of up to 1.25 MHz.

### 3.3.1 Pressure Transducers

In-tube pressure data was detected via piezoelectric pressure transducers (PCB 119) manufactured by PCB Piezotronics. Each transducer was connected to an impedance converter, which translates the generated current to a voltage readable by the National Instruments data acquisition system. Example signals are shown in Fig. 3.7.

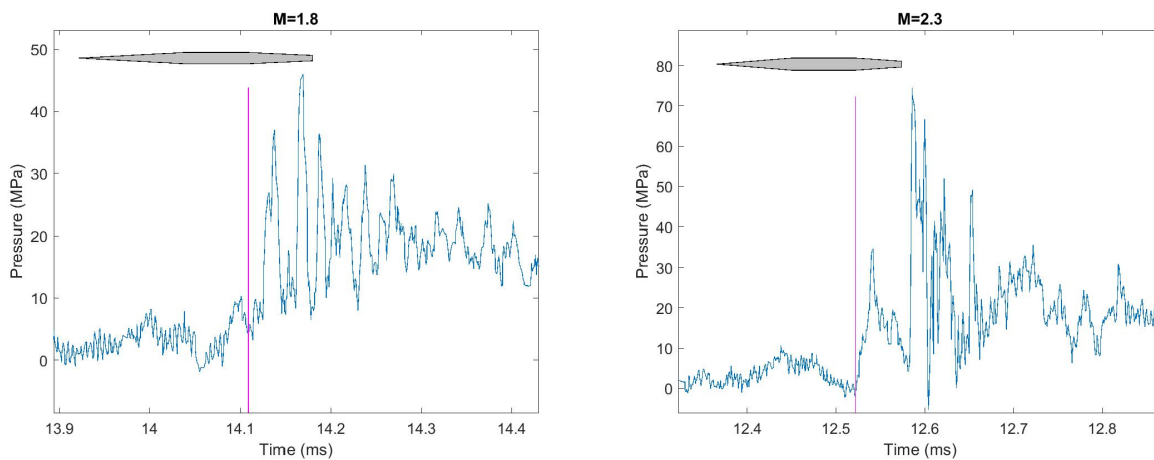


FIGURE 3.7: Signals from a single piezoelectric pressure transducer from ram accelerator experiments at  $M = 1.8$  (left) and  $M = 2.3$  (right), under otherwise identical conditions. The measured magnet time is indicated with a pink vertical line. The projectile, which had a two baffle length (2.812") shoulder, has been scaled horizontally with time according to its velocity [38]

### 3.3.2 Magnetic Induction Sensors

The magnetic induction sensors used in ram accelerator testing, first documented by Christoffer-son, function by detecting the field of a magnet embedded in a ram accelerator projectile [58]. The probes consist of a loop of wire, oriented so that the central axis of the loop sits perpendicular to the direction of projectile motion (Fig. 3.8). In this orientation the magnetic flux from the onboard magnet induces a current in the wire, which may then be measured via the data acquisition system. The signal is routed through an amplification circuit, resulting in a voltage-time waveform. Due to slight phase shifts and signal noise, a standard 10 m/s error is ascribed to any individual velocity calculations derived from the magnetic sensors in standard operation, with this error propagating to approximately 5% to total when extending it to thrust calculations averaged over longer tube regions.

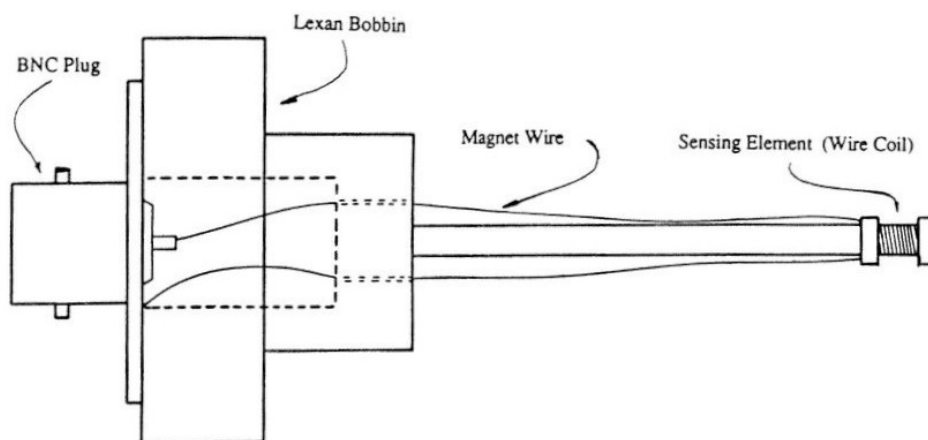


FIGURE 3.8: A schematic of a typical magnetic induction sensor for the ram accelerator [58].

Under ideal circumstances the waveform generated by a projectile passage is a symmetric wave, reminiscent of a fourth power polynomial function, with one primary maximum and two local maxima, one flanking each side of the primary maximum.<sup>1</sup> In reality the signal is more

<sup>1</sup>As will be discussed in Appendix A, none of these maxima correspond to the projectile transit, and for best results the appropriate zero-crossing must be taken. The maxima are, however, very useful when describing the shape or polarity of a signal.

commonly distorted in some way, leading to one local maximum being larger than the other. A comparison of the ideal signal and an actual signal may be seen in Figs. 3.9 and 3.10. Note that polarity is determined by the direction of coil winding and/or the north-south orientation of the embedded magnet, and has no influence on signal quality.

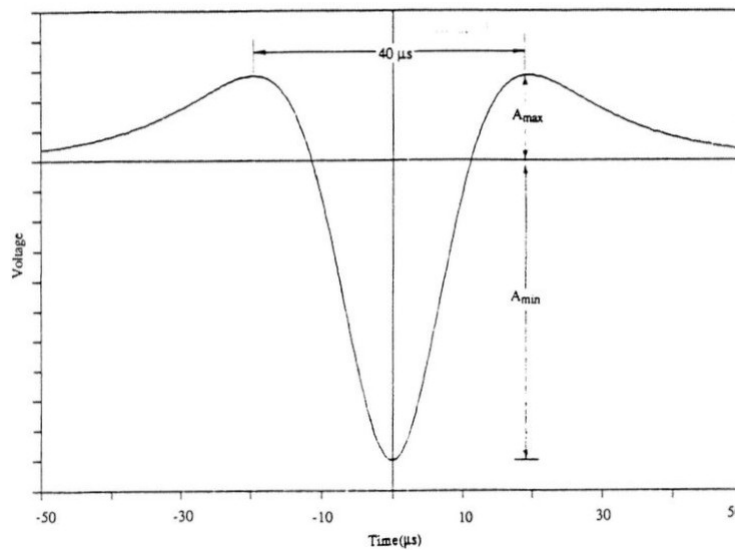


FIGURE 3.9: A computer simulation of the signal from a magnetic induction sensor during an SBRA test [58].

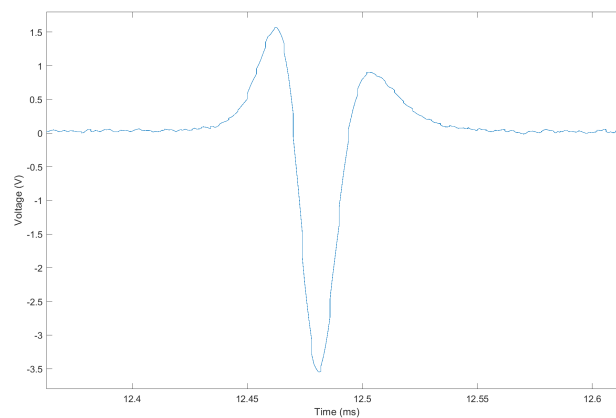


FIGURE 3.10: A typical signal from a magnetic induction sensor during a BTRA test.

Perturbations in the magnetic signal occur due to a number of causes, including (but not limited to) ionization of propellant due to combustion, projectile material, probe casing material, tube

and/or baffle material, baffle shape, and signal noise caused by electronic ringing or incomplete shielding. An in-depth analysis of the magnetic induction probes, and various causes of signal distortion, may be found in Appendix A.

### 3.4 Optical Setup

In order to capture accurate and consistent shadowgrams, light must be collimated through the sample section in question. For the BTRA, which must be contained within a closed tube, collimating the light can be difficult. While a cylindrical tube is the logical choice from a BTRA design perspective, the refractive properties of a cylinder are detrimental to imaging efforts. This is illustrated in Fig. 3.11, which shows collimated light entering an acrylic tube which, from a pressure vessel standpoint, would be sufficient for inert gas BTRA operation. Note that light in the uppermost region of the sample area is reflected internally, and thus cannot be captured at all, and that the light not reflected is scattered significantly. Such scattering leads to inconsistencies in determining shadowgram properties, as refracted angles will be disturbed, and also leads to difficulties in establishing the optical pathways discussed in Section 2.6.

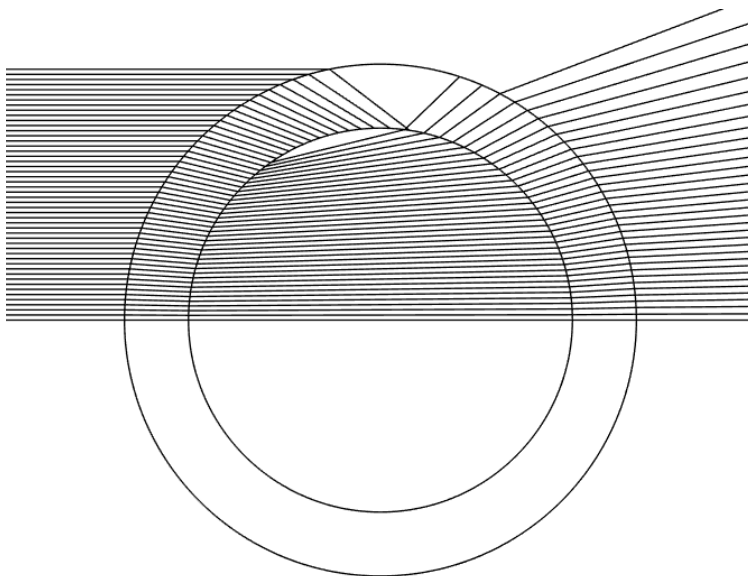


FIGURE 3.11: The scattering of collimated light through a 3" inner bore, 4" outer diameter acrylic tube.

To maintain collimation, an acylindrical tube (similar to that of Takayama) was designed [52]. The material chosen was optical acrylic, as it was deemed strong enough to withstand pressures generated in non-combustive, inert gas BTRA testing, while maintaining optical clarity. Due to differences in refractive index and central bore dimensions the final design was slightly different than Takayama's quartz tubing. The intended optical pathway, assuming collimated light, of this acrylic tube is shown in Fig. 3.12. The acylindrical tube has an inner diameter of 3", and a chamber length of 2.812", enough for two standard baffles. Full design parameters are included in Appendix B.

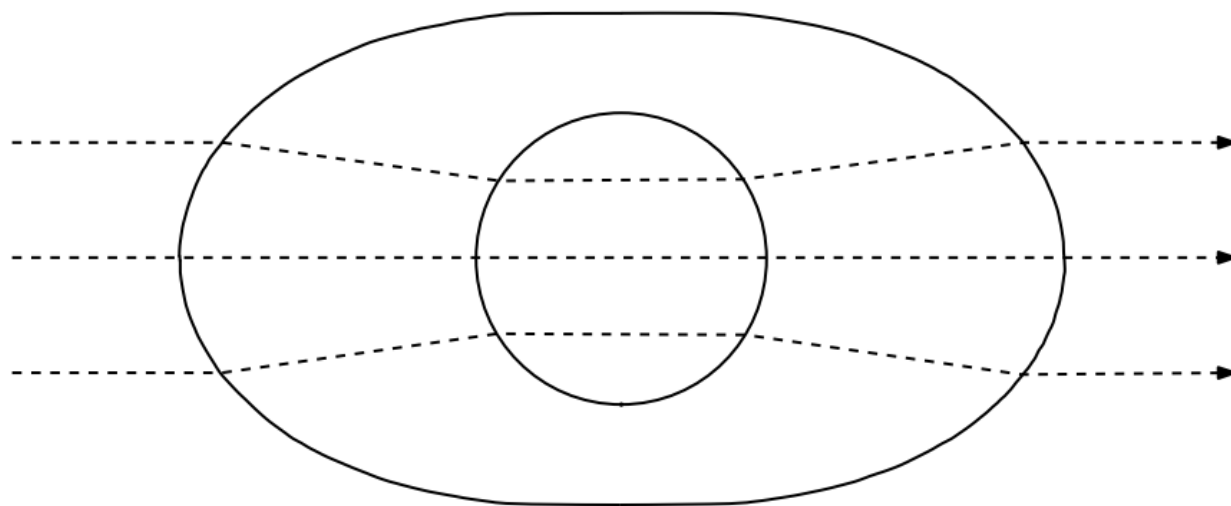


FIGURE 3.12: The ideal optical pathway in the custom-designed optical section for BTRA shadowgraphy, assuming initially collimated light.

Upon arrival the aspherical tube was qualitatively inspected and appeared to provide the expected expected distortion of optical pathways. As shown in Fig. 3.13, objects placed into the center of the tube were distorted such that the top of the inner bore was warped to align with the upper limit of the outer surface as was intended. It was soon discovered, however, that production inconsistencies had resulted in a tube which overcorrected the pathways of the light beams. Careful inspection from collimated light sources and tracing of laser beams showed that the sides of the acylindrical tube did not scatter like the cylindrical tube, but instead focused the light to a finite focal distance (Fig. 3.14).

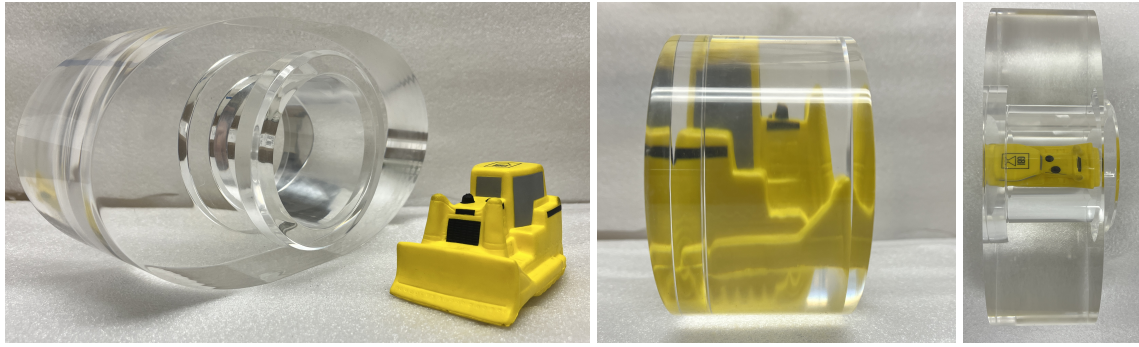


FIGURE 3.13: Qualitative image scaling in the acylindrical optical tube, with oblique view (left), side view (middle), and top view (right). Bulldozer for scale.

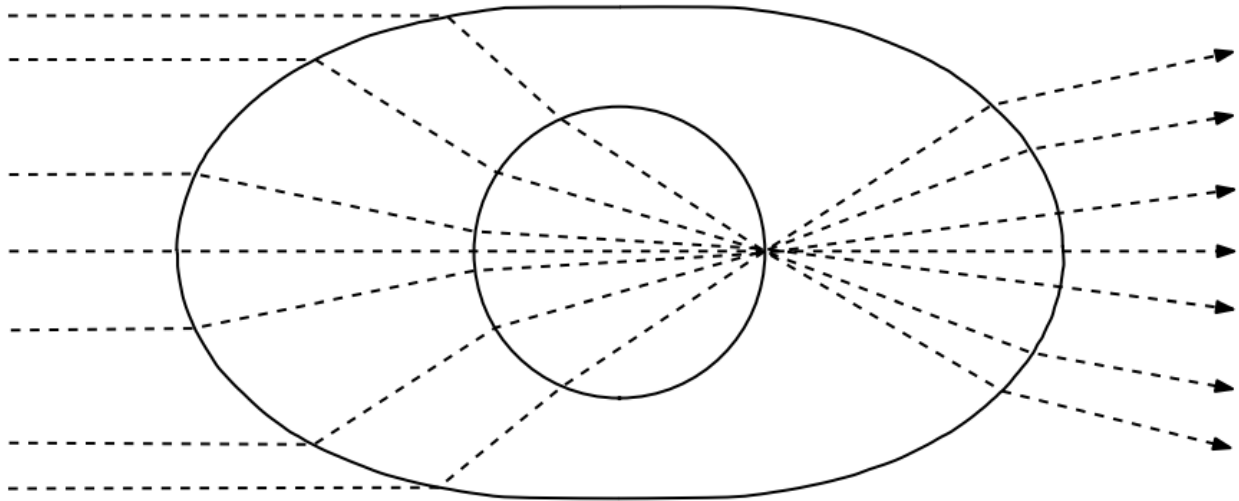


FIGURE 3.14: The actual optical pathway in the custom designed optical section for BTRA shadowgraphy, assuming collimated light.

Due to the focusing effect of the acylindrical tube, it could not simply be placed inside an existing shadowgraph setup as planned while preserving sample accuracy. With reference to Fig. 2.27, the tube was intended to be placed between points (b) and (d), but with its faulty construction, light would no longer be properly collimated upon exiting the sample region. Fortunately, further analysis found a viable optical pathway: if the light entering the acylindrical tube was **not** collimated, the focusing effect could be used to create a region of collimation within the sample area of the tube. In this configuration the acylindrical tube acts as both the sample region and the field lenses, allowing for an even simpler final experimental setup (Fig. 3.15).

Shadowgrams were captured using the above tube as well as with traditional optical elements.

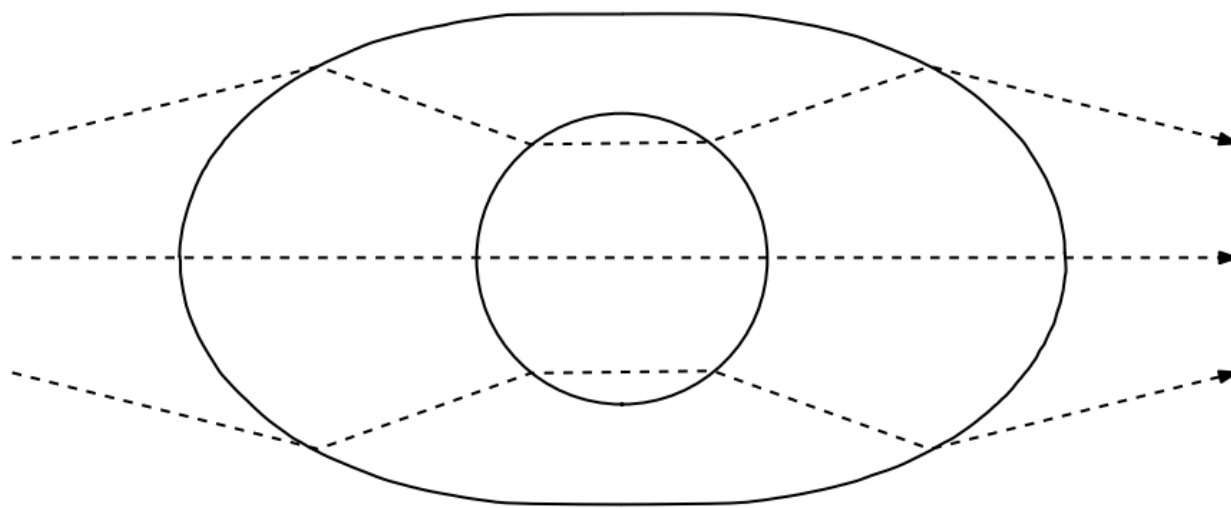


FIGURE 3.15: The optimal optical pathway in the custom-designed optical section for BTRA shadowgraphy.

The sample was illuminated via a Nila 50 LED spotlight set at a 100% duty cycle, placed so as to produce the pathways shown in Fig. 3.15. Images were captured using a Phantom T2410 high-speed camera equipped with a Samyang AF 85 mm F1.4 focusing lens placed at the camera lens' minimum focal length of approximately one meter. The camera was set to a sample rate of 94,000 frames per second with 1  $\mu$ s exposure. To maintain this framerate resolution was limited to 512 x 320 pixels and the exposure index was limited to 200,000. The data storage capacity of the camera enabled capture of between 1.5 and 2 seconds of footage, of which less fewer 50 frames ( $\sim 500$   $\mu$ s) were of the relevant interval.

### 3.4.1 Modular BTRA inserts

While the aspherical tube was designed to house standard BTRA inserts, these standard inserts would fully occlude optical pathways, rendering the experiment moot. A useful insert instead is one which replicates the geometry of the standard inserts but for which material has been removed for optical access. The simplest version of this may be seen in Fig. 3.16, in which a BTRA 500 insert was modified to contain only three rails, leaving a clear optical path across the top of the chamber.

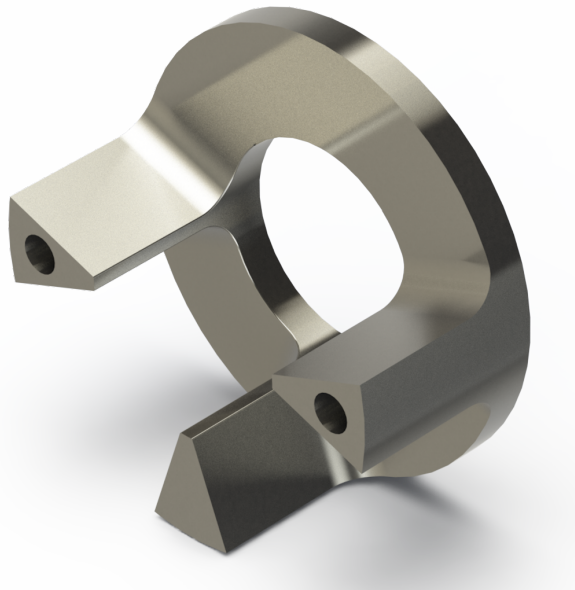


FIGURE 3.16: An idealized insert for BTRA shadowgraphy.

This design, while simple, was limited to testing of only one chamber length (or two, if identical inserts were placed end to end). As discussed previously, of interest in this study is the effect of chamber lengths on gasdynamic effects, so the production of a variety of costly individual designs was deemed out of scope. Instead a more modular design was developed, in which the rails and baffle wall were considered separate components to be assembled into unique configurations. The rails were divided into individual wedge-shaped slices, while the baffle walls were made similar to 3" diameter washers. Each geometry was then laser cut at 0.25 and 0.125" thicknesses and assembled onto alignment bolts, permitting assembly of discrete baffle geometries from a common pool of pieces. In this design, chambers of anywhere between 0.125 and 2.5 inches, and baffle walls of thicknesses between 0.125 and 1", may be investigated (with a minimum increment of 0.125"). This modular design is shown in Fig. 3.17 and full design information may be found in Appendix B.



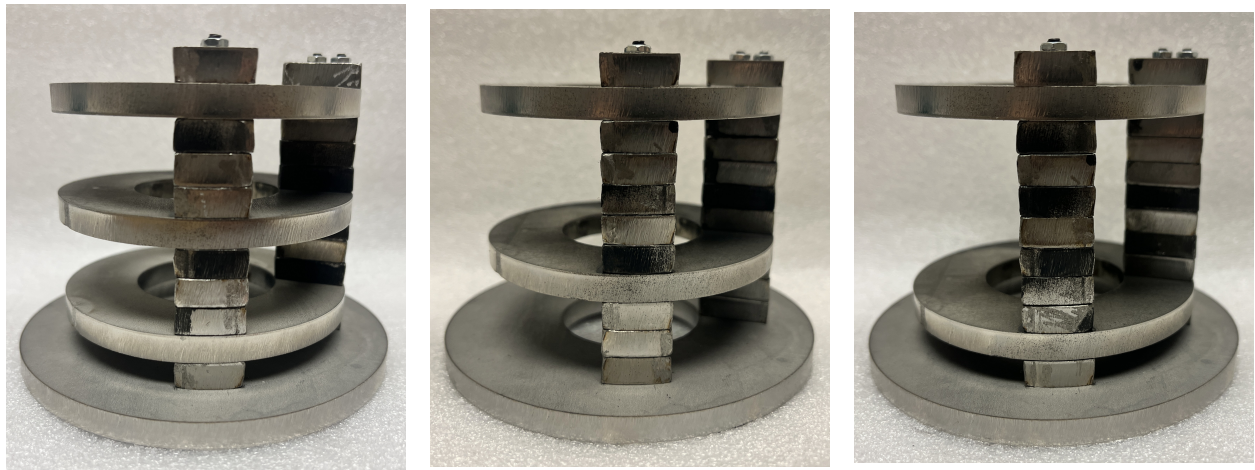


FIGURE 3.17: Modular baffle inserts for BTRA shadowgraph imaging, in 1" (left), 1.5" (middle), and 2" (right) configurations.

## Chapter 4

# Experimental Results

### 4.1 Minimum Mach Number Limits on BTRA Operation

After the conclusion of Ginos' study, further testing was conducted to verify the results of the anomalous run. It was found that, not only could a coasting supersonic projectile drop below the theoretical minimum Mach number and then start, but that a projectile could enter the test system fully below the theoretical minimum Mach and still perform successfully. In these tests, projectiles entered a four-meter-long ram accelerator test section, containing approximately 1.6 meters of 501 baffle inserts as a start stage. Using the method described in Figure 2.12 and Equation 2.13, an effective area was calculated which corresponded to a minimum flow velocity of Mach 1.76. Under the quasi-one-dimensional assumption, any projectile moving below Mach 1.76 should choke the flow in the shoulder section and drive a normal shock ahead of the projectile in a process that has been called a "sonic diffuser unstart" [60].

To explore this limit, experiments were conducted in which standard 1.38" body diameter projectiles were fired into methane-air mixtures at fill pressures of 300 psig, the established standard for UW ram accelerator experiments [17, 37, 38]. The results of these tests are shown in Figure 4.1 and summarized in Table 4.1. It was found that for these configurations operation is possible down to a velocity of  $M = 1.38$ , which is 21.7% lower than theory would predict. It was also found that to operate at low velocities the propellant had to be slightly more diluted than in optimal performance (from stoichiometric 1 part  $\text{CH}_4$  to diluted 1.3 parts  $\text{CH}_4$ ), suggesting that low

velocity operation require balancing a particular heat release and projectile velocity. Below this heat release projectiles, were unable to ignite the propellant, whereas above it projectiles were too slow to avoid unstaring.

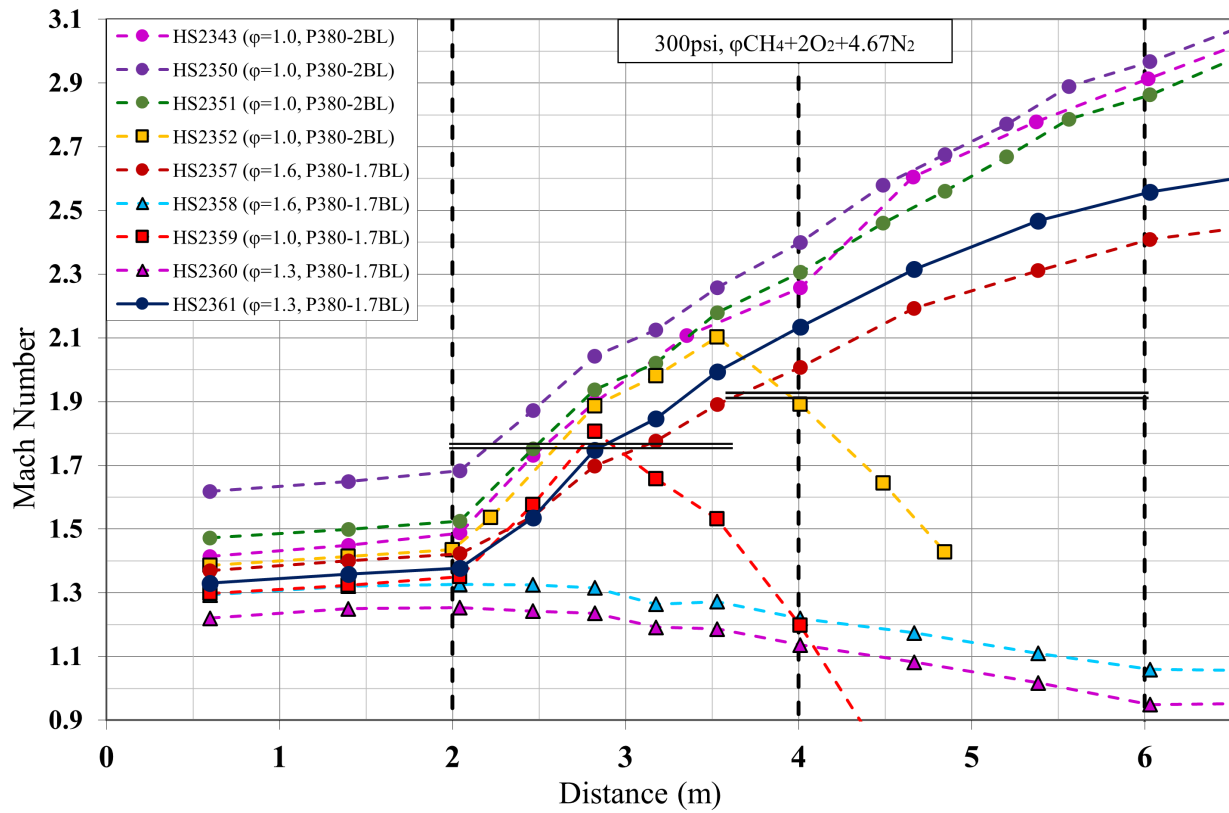


FIGURE 4.1: Velocity-position plots of ram accelerator tests where projectiles entered below the theoretical minimum operating velocity. Horizontal double lines indicate the minimum operating Mach number under quasi-one-dimensional flow conditions. Shots that accelerated projectiles throughout the four-meter-long test section are denoted by circles, with the minimum entrance velocity shot indicated by a solid line. Shots which failed to start are marked with triangles, and shots which ignited before unstaring are labeled with squares.

| Entrance Mach | Chemistry                                     | Pressure, psig | Result          |
|---------------|-----------------------------------------------|----------------|-----------------|
| 1.49          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 300            | Start           |
| 1.68          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 300            | Start           |
| 1.53          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |
| 1.44          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Delayed unstart |
| 1.42          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |
| 1.33          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Nonstart        |
| 1.35          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Delayed unstart |
| 1.25          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Nonstart        |
| 1.38          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |

TABLE 4.1: Summary of ram accelerator tests in which projectiles entered below the theoretical minimum operating Mach number ( $M = 1.76$ ). 1.380" diameter projectiles entered an oxygen enriched methane-air propellant ( $\phi\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ ) with fill pressure of 300 psig.

## 4.2 Fluid Effects within Baffled Tubes

Before work could begin on understanding the gasdynamic environment around a projectile, it was deemed important to understand how a shock propagates within a baffled tube. Work by Bernhard contradicted previously accepted conclusions, suggesting that a normal shock may travel at near-smooth-bore velocities even in a baffled tube [35]. Computational fluid dynamics (CFD) in Ansys Fluent suggested a complicated shock structure (Fig. 4.2) formed as the fluid expands into baffle chambers and contracts through the central bore, but a strong wavefront was still obvious.

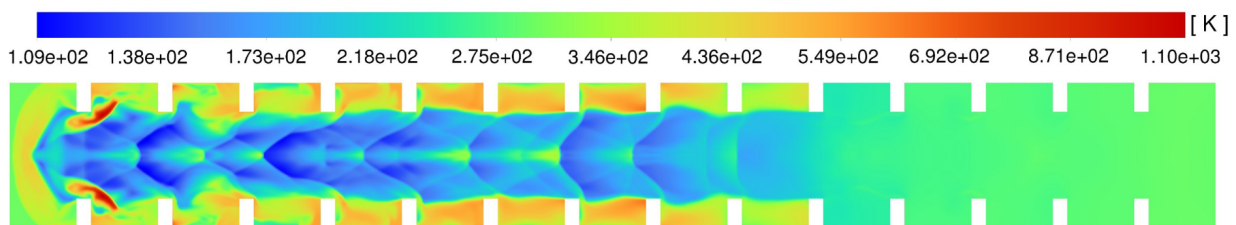


FIGURE 4.2: Semi-log profile temperature contour for a shock with initial pressure ratio 215.4 in BTRA 600 baffle inserts [35].

Bernhard's experimental work, in which the test section was configured as a shock tube with a smooth bore driver and baffled tube driven section, verified the shock front velocities predicted by CFD. Experimental data indicated that while a shock would initially be attenuated by the baffle

surfaces, it would quickly steady out at a velocity of about 75% of the smooth bore equivalent predicted by shock tube theory, and then stay at that velocity for a considerable distance [35]. At the time of Bernhard's study the necessary imaging techniques had not yet been developed to confirm predicted wave structures.

Upon production of the acylindrical tube, normal shock tests were revisited. These tests served primarily to characterize the optical properties of the acylindrical tube, leading to the optical pathway challenges discussed in Section 3.4, and the high-speed camera. In these tests a gun-launched piston drove a shock wave through a smooth bore tube, with this wave expanding into the modular baffles in the imaging section. The shadowgraphy system confirmed the occurrence of an angled normal shock front (Fig. 4.3).

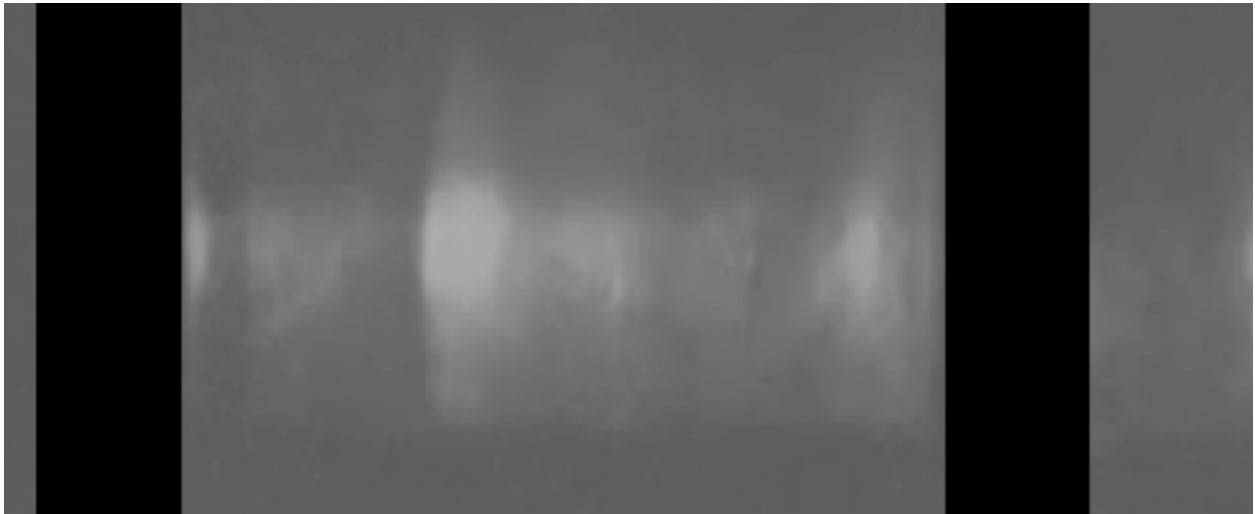


FIGURE 4.3: Digitally enhanced shadowgram of a piston-driven shock expanding into BTRA inserts and developing a non-flat shock front (as predicted in Fig. 4.2). BTRA baffle walls have been blacked out. Note that image is non-uniformly warped along the vertical axis due to lens inconsistencies.

The shock front qualitatively matched the structure predicted by Bernhard. Though these experiments were not precise enough to serve the basis for quantitative physical analysis, confirmation of a complex wave structure served as an early sign that the flowfield within the BTRA cannot be fully characterized by quasi-one-dimensional parameters.

Further experiments were conducted to determine whether this effect holds for detonation (Chapman-Jouget) waves. Historically, studies of tube walls with minor blockages (<10% tube area) suggested that tubes with obstructions slowed the propagation velocity of detonation waves [61]. More recent testing by Li et al has called this assumption into question, finding that as pressure increases the detonation wave velocity approaches the CJ velocity, even across a significant a range of blockage ratios (Fig. 4.4) [62].

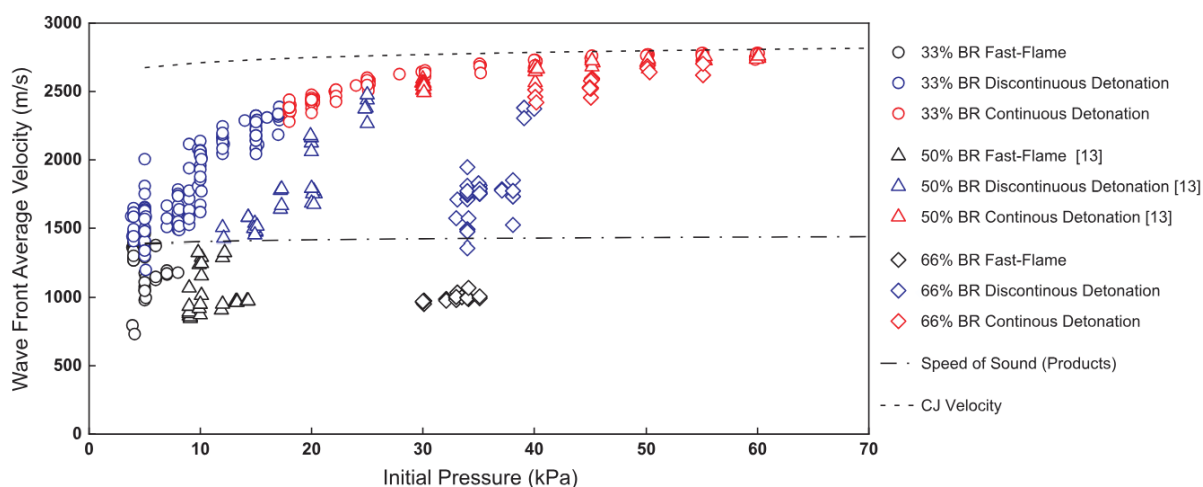


FIGURE 4.4: Average combustion wave velocity of stoichiometric  $\text{H}_2\text{--O}_2$  based on shock time-of-arrival measurements made over a four-obstacle span in the optical section for different BR obstacles. The 50% BR data is from Kellenberger and Ciccarelli. The propagation mode is highlighted by the symbol color [62].

Testing was conducted in baffle tubes to verify these claims. The eight-meter-long test section was populated with 1.64 meters of BTRA 501 inserts in the detonation region and BTRA 601 inserts in the remaining length.<sup>1</sup> An additional two-baffle-length adapter was placed at the beginning to accommodate a spark plug and fill line, and was populated with two BTRA 600 inserts. Tests were conducted on a pure methane-oxygen stoichiometric mixture ( $1\text{CH}_4+2\text{O}_2$ ) at 1.94 atm of pressure. From calculations using NASA's Chemical Equilibrium with Applications (CEA) code, the nominal Chapman-Jouget detonation velocity for this mixture in a smooth bore environment was predicted to be 2419 m/s, as shown in Fig. 4.5. Detonation velocity was found to be  $2343 \pm$

<sup>1</sup>Though one BTRA 501 insert was placed at each instrument port for better clearance.

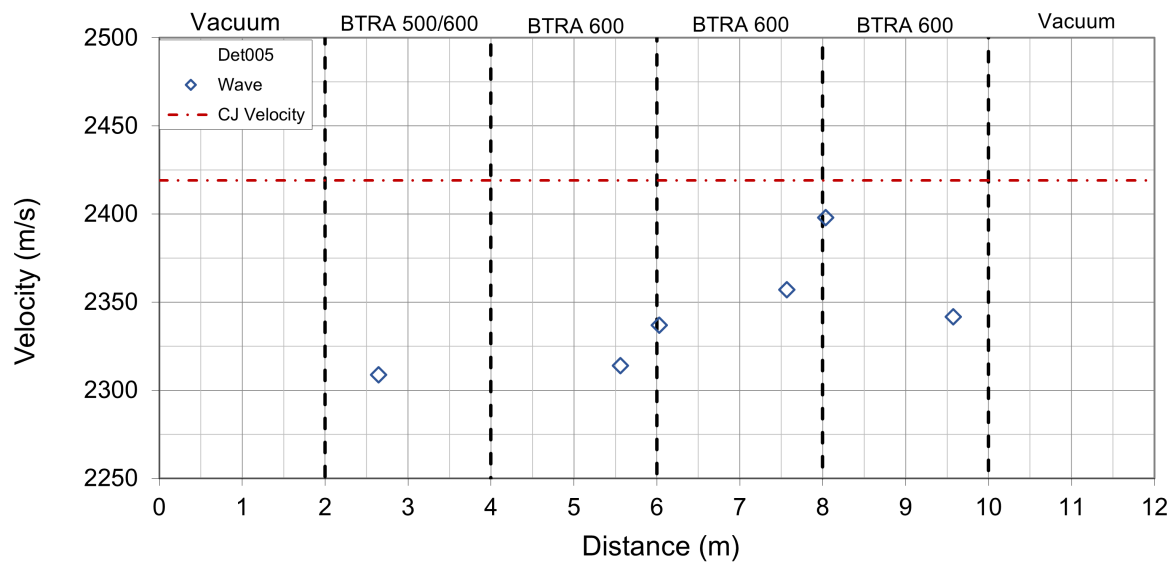


FIGURE 4.5: Velocity-position measurements of a detonation front traveling through a baffled tube with chemistry of  $1\text{CH}_4 + 2\text{O}_2$  at 27.5 psia. Detonation was initiated at the two meter mark and moved to the right.

56 m/s, or  $96.8 \pm 2.3\%$  of nominal CJ velocity. When analysis was restricted to the final six meters of test section, containing predominately BTRA 600 inserts, this range narrows to  $97.1 \pm 2.0\%$  m/s. This result was further verified through standard ram accelerator experiments, as the detonation waves generated by shots which unstarted were observed to travel within 5% of the nominal velocity for a given mixture. Both shock visualization and detonation velocities indicate that the baffle tube provides a complex environment where gasdynamic effects may not be consistent with common assumptions.

### 4.3 Shadowgraph Imaging of the Ram Accelerator

In order to determine the effects of this complex gasdynamic environment on BTRA operation, projectiles of varying sizes were fired through a series of modular baffles placed within the optical chamber described in Sec. 3.4. In these experiments the baffle chamber radius and projectile nose and tail angles were held constant, while projectile diameter, in-tube Mach number, baffle spacing, and baffle thickness were varied. All experiments were conducted with  $\text{CO}_2$  in pressures between

| Baffle Spacing (in) | Wall Thickness (in) | Proj. Diameter (in) | Pressure (atm) | Mach Number |
|---------------------|---------------------|---------------------|----------------|-------------|
| 1.0                 | 0.25                | 1.496               | 7.94           | 2.01        |
| 1.0                 | 0.25                | 1.496               | 8.48           | 3.27        |
| 1.5                 | 0.25                | 1.496               | 8.82           | 1.98        |
| 1.5                 | 0.25                | 1.496               | 8.48           | 3.42        |
| 1.5                 | 0.25                | 1.380               | 8.89           | 3.42        |
| 1.5                 | 0.25                | 1.380               | 8.48           | 2.23        |
| 2.0                 | 0.25                | 1.496               | 8.35           | 2.37        |
| 2.0                 | 0.25                | 1.496               | 8.89           | 3.31        |
| 2.0                 | 0.25                | 1.380               | 8.69           | 3.39        |
| 1.5                 | 0.5                 | 1.380               | 8.48           | 3.49        |

TABLE 4.2: Summary of varied parameters in optical baffle testing. Baffle chambers had a constant radius of 1.5", projectiles had a nosecone angle of  $15^\circ$  and a tailcone angle of  $12^\circ$ , and fill gas was  $\text{CO}_2$ .

6.8 and 8 atm. Table 4.2 summarizes the experimental parameters.

Shadowgraph images were taken with the high-speed camera focused on the top half of the optical tube, so as to capture images of the exposed baffle chamber. Distortion was mitigated through use of digital processing against a reference image, as outlined in Appendix C.2. Due to aforementioned tube inconsistencies, observations of the edge of the baffle chamber (roughly the outermost 0.375") were too low resolution for the production of useful shock images, but shadowgraphs clearly captured structure along the center bore and the inner half of the baffle chambers. A representative processed frame, showing a 1.380" diameter projectile traveling at Mach 3.39 in a 2" baffle spacing, is shown in Fig. 4.6.

Interpretation of these images suggests that the common understanding of shock behavior, particularly when interacting with baffle walls, is incorrect. Predictions based on theory suggested that the conical shock from the projectile nose would reflect off the baffle wall bore and create complex, intersecting shock patterns as illustrated in Figure 4.7 [20]. Shadowgraph observation, however, showed no signs of complicated shock patterns, with the conical nosecone shock apparently more or less unaffected by the baffle wall (Fig. 4.8). The shock pattern, it seems, is not significantly different than in the SBRA or RTRA systems.



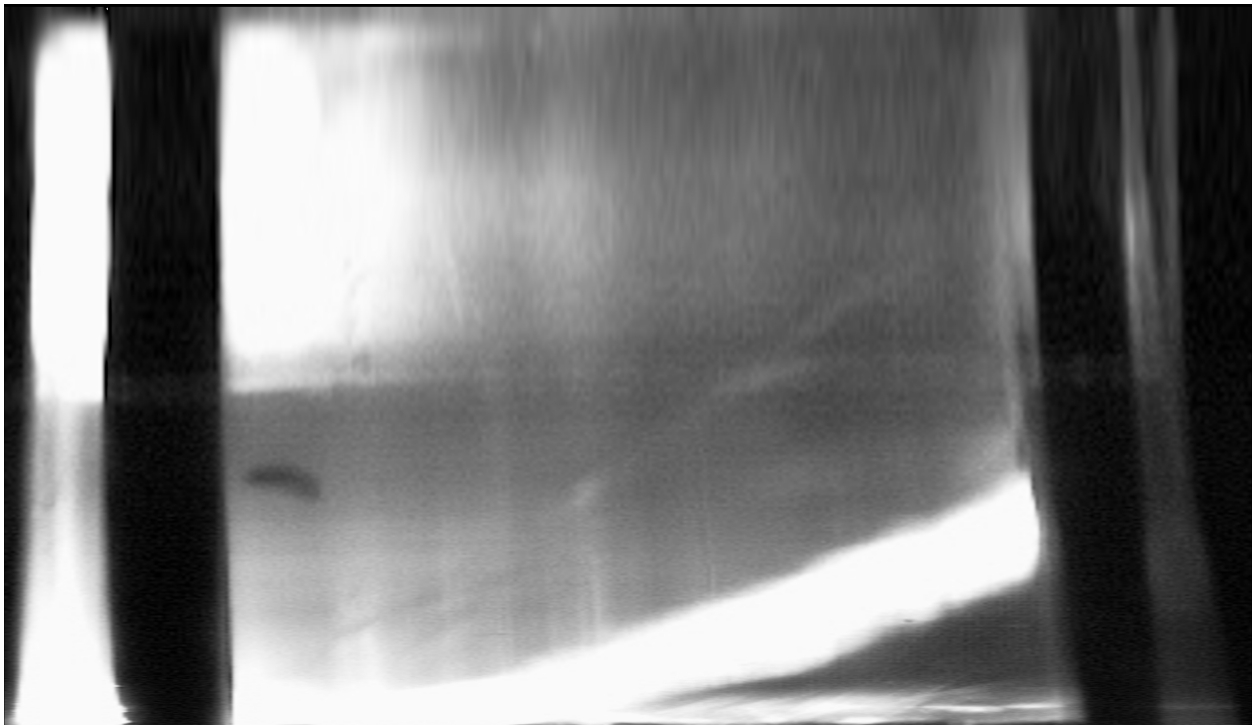


FIGURE 4.6: A processed shadowgraph frame, showing a 1.380" diameter projectile traveling at Mach 3.39 in a 2" baffle spacing. Due to the unfocused light source some illumination around the projectile nose is present, but does not represent actual gasdynamic phenomenon.

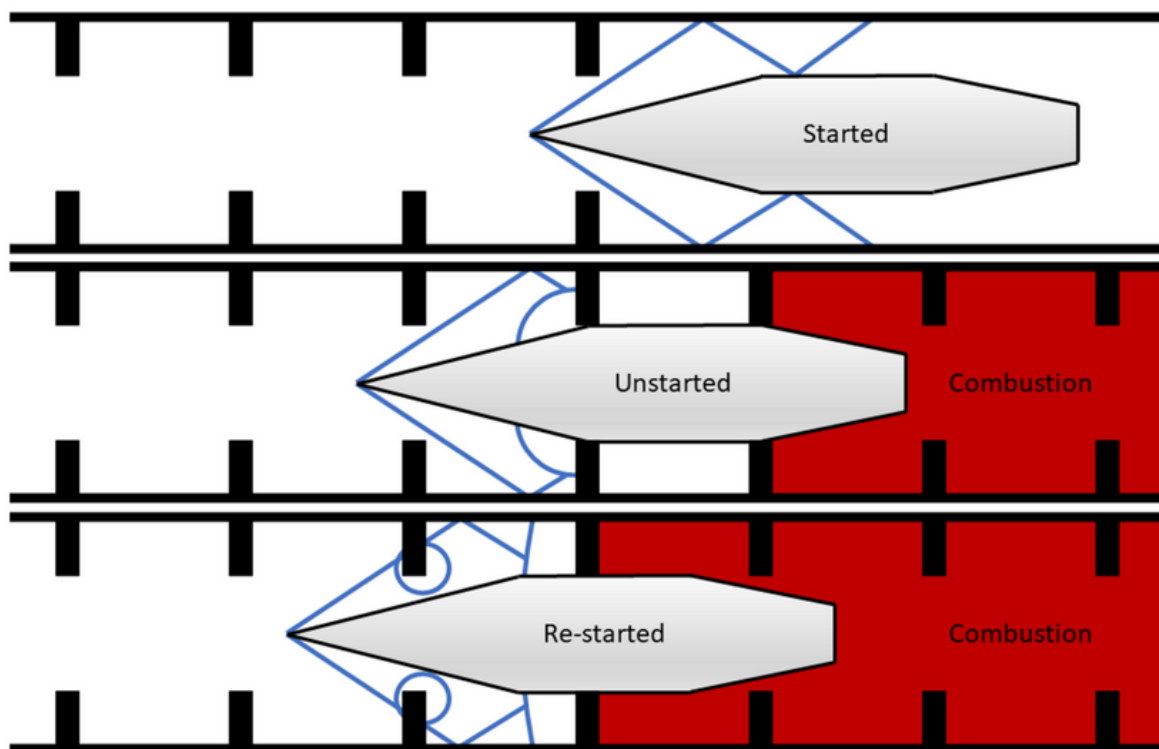


FIGURE 4.7: Conventionally accepted understanding of shock patterns within a BTRA system. Note the anticipated shock "bubbles" forming around the baffle wall [20].

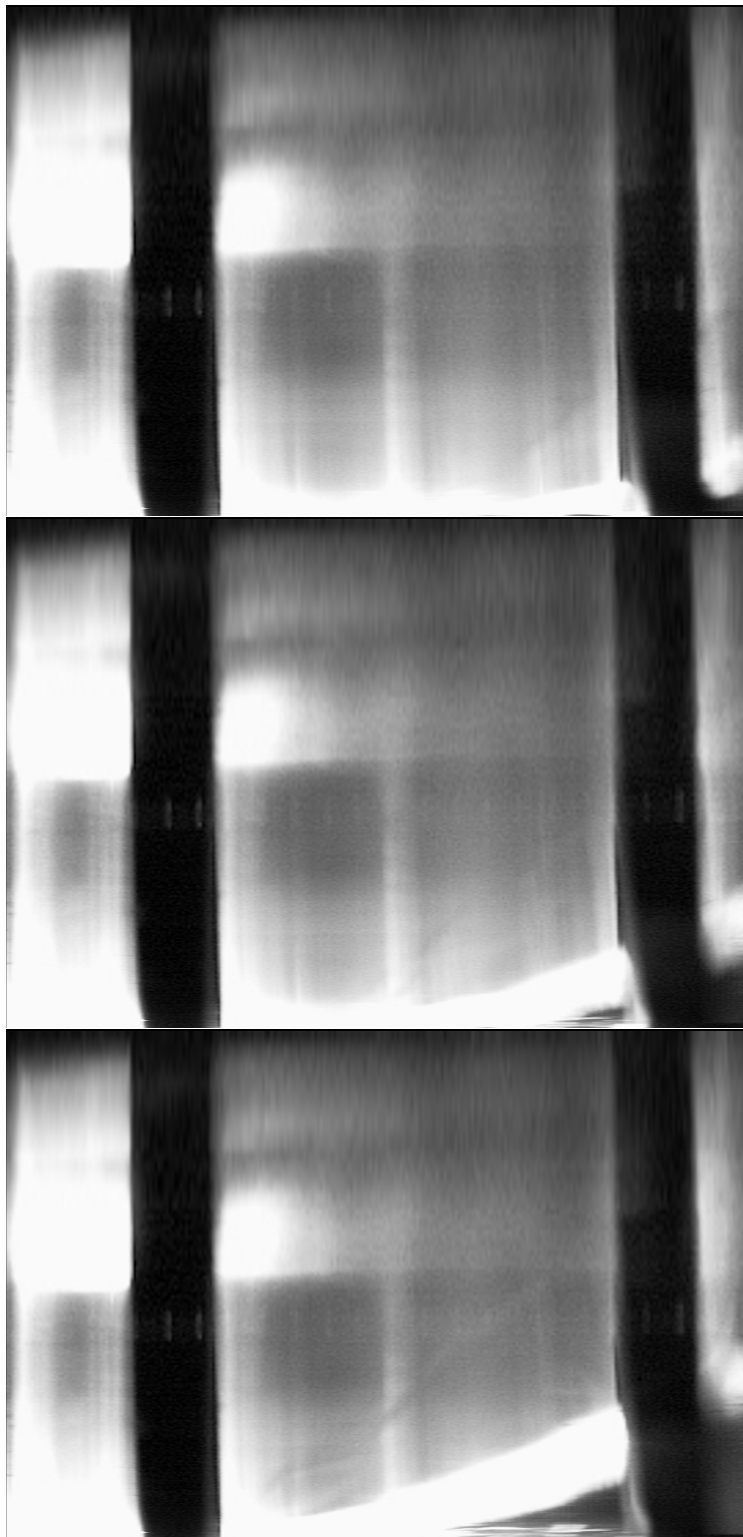


FIGURE 4.8: Procession of a 1.496" diameter projectile moving at Mach 3.42. Note the consistent angle around the right baffle wall

Although the shock emanating from the nose of the projectile appears to exhibit simple behavior, the gasdynamic environment around the shoulder is anything but simple. Projectile diameter was shown to be a significant factor in the complexity of the flow field around the projectile shoulder, as shown in Figure 4.9. This comparison illustrates what appears to be two distinct operating modes and shines a new light on many previous findings. The 1.496" diameter projectile, shown in Figure 4.9, in which the shoulder area occluded 99.2% of the central bore area, was observed to act like a piston. As the shoulder transited the baffle wall a wave, moving subsonically relative to the projectile was pushed ahead of the wall. The projectile quickly overtook this wave, leading to a confined vortex within the baffle chamber which dissipated into chaotic turbulent flow, eventually being released after full projectile transit.

These results are similar to those predicted by Daneshvaren, which predicted a high-pressure front within baffle chambers initiated by the transit of the projectile shoulder (Fig. 4.10). It also supports CFD predictions by Daneshvaren which suggest periodic increases in drag as projectiles transit baffle walls [18]. Of interest is that, somewhat contradictory to Daneshvaren's results, spacing between baffles was not seen to be a major influence on these pressure fronts. Figure 4.11 shows three configurations, with a baffle spacing (chamber length plus wall thickness) of 1.0, 1.5, or 2.0". In each case, the pressure front from the projectile shoulder stagnated and formed a vortex at roughly 0.5" from the baffle wall, regardless of distance to the next baffle downstream.

By comparison, the 1.380" diameter projectile, shown in Figure 4.12, only occluded 82.4% of the central bore area, and did not experience this effect. A small wave developed around the projectile shoulder during initial transit but the behavior quickly settled into smooth flow around the projectile. Neither the distance between baffles nor the in-tube Mach number were not observed to show significant changes in the gasdynamic environment.



FIGURE 4.9: A 1.496" diameter projectile traveling at Mach 3.42 with 1.5" spacing between baffles.

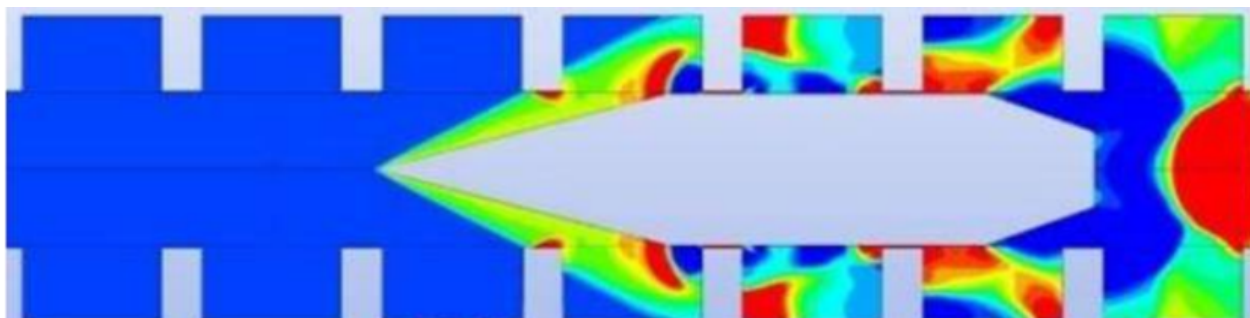


FIGURE 4.10: Computational fluid dynamic simulation of a ram projectile passing through baffle chambers. Pressure contours are shown [18]

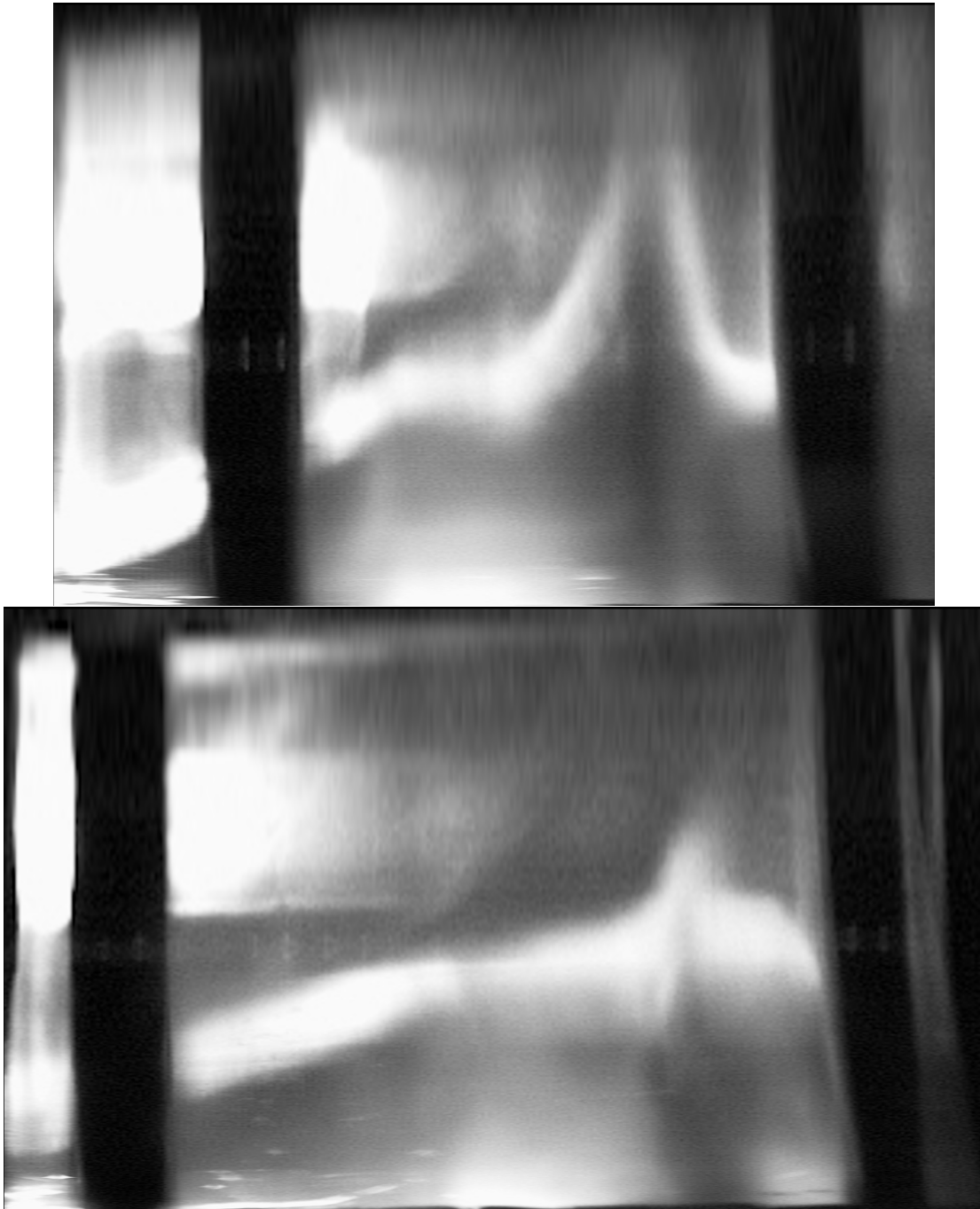


FIGURE 4.11: Comparison of pressure front generation in 1.5" (upper) and 2.0"(lower) baffle separation at Mach numbers of 3.42 and 3.31, respectively.

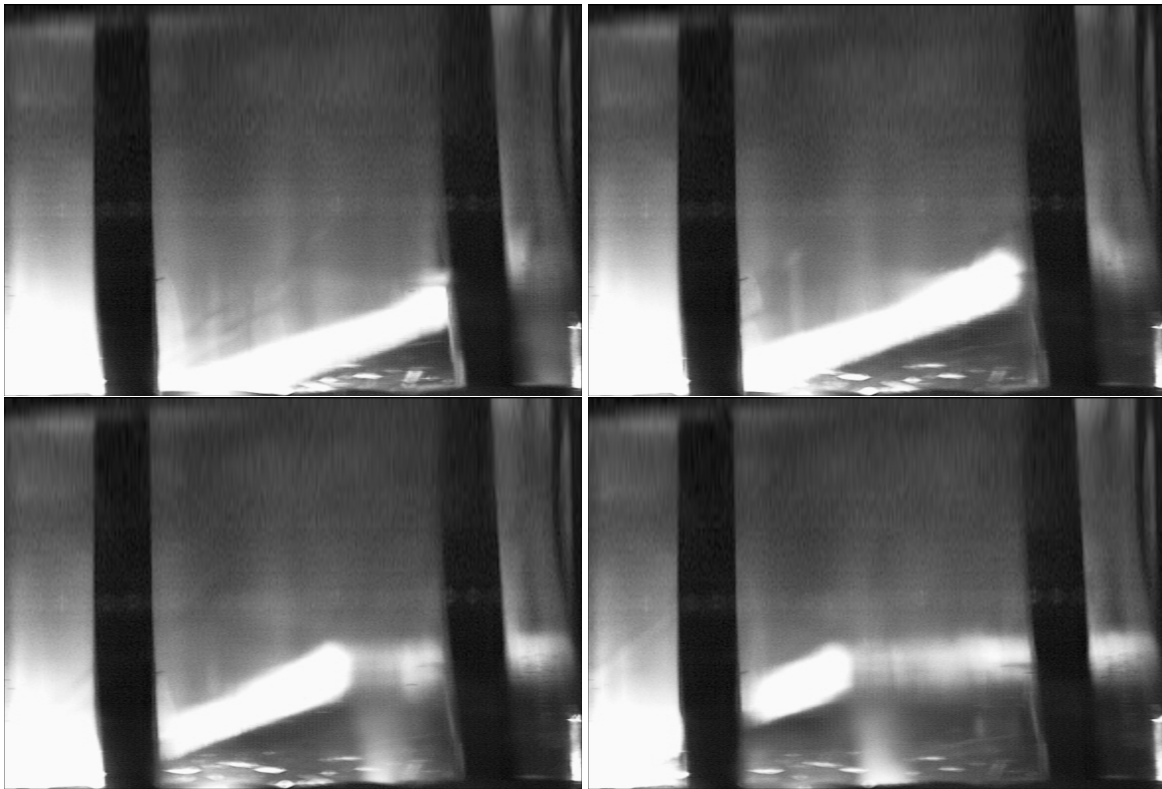


FIGURE 4.12: A 1.380" diameter projectile traveling at a Mach number of 3.42 with 1.5" spacing between baffles.

## 4.4 Effects of Bore Occlusion on BTRA Operation

Results from the shadowgraph campaign suggest that two distinct BTRA regimes are being observed: a smooth subdiameter flow, in the case of the 1.380" projectile, and a chaotic full-bore flow, in the case of the 1.496" projectile. Consideration of the fundamentals of the BTRA operation would suggest that the full-bore projectile should be more stable than the subdiameter projectile as heat release increases. When fully sealing the bore, the projectile not only better isolates the baffle chambers, but the observations also suggest that generated vortices may act as flame holders. Nonetheless, this and other laboratories have historically suggested that while full-bore projectiles are more effective at **igniting** propellant, they are less effective at **stable operation**. Further investigation was conducted to investigate this discrepancy.

Based on previous studies, a full-bore projectile appears to run only near the fringes of operation. Ginos found that in a 1.5" central bore BTRA, raw projectile thrust is optimized for diameters around 1.380", and drops off as diameter is increased or decreased, as demonstrated in Figure 4.13 [47]. Byrd found that if the projectile diameter is increased to as high as 1.485" (97.7% bore area occlusion) the thrust drops to almost zero, as shown in Figure 4.14.<sup>2</sup>

The findings of both Ginos and of Byrd suggest that, since the 1.496" projectile is beyond the thrust-equals-drag condition, it should not function at all. Experimental results disagree (Fig. 4.15). These tests resulted in non-dimensional thrust measurements on the same order of magnitude as those of 1.380" projectiles. Results from recent test series even suggest that net thrust may be comparable between the two projectiles, as shown in Figure 4.16.

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<sup>2</sup>It is worth noting that these tests were conducted in slanted baffles, as opposed to the normal baffles used in other studies, though bore diameter and spacing between walls was consistent. Testing across multiple campaigns has found that, while operating limits may differ, inclined baffles follow similar trends to normal baffles [15, 40].



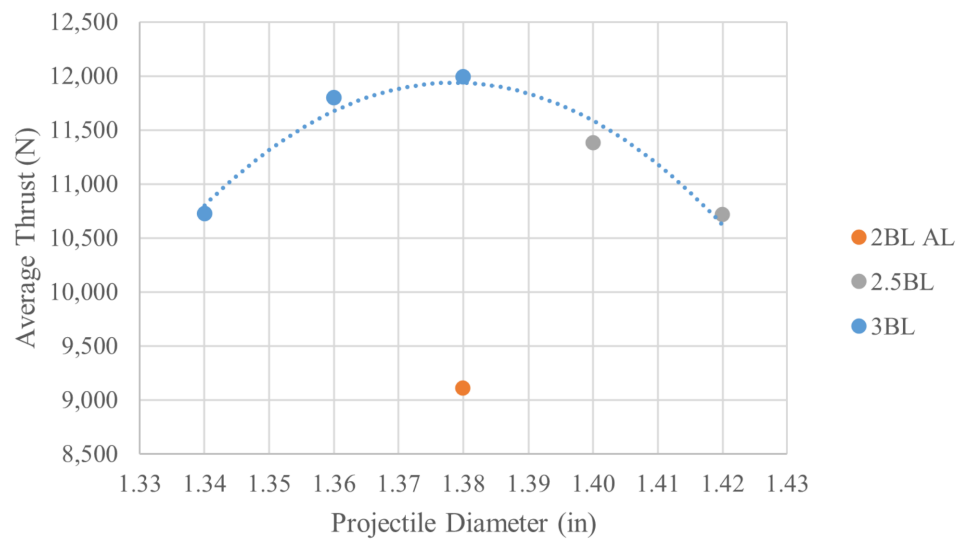


FIGURE 4.13: Thrust measured during experiments with projectiles varying in diameter from 1.34" to 1.42". Thrusts were averaged over both 3" and 2.5" normal baffle chambers [47].

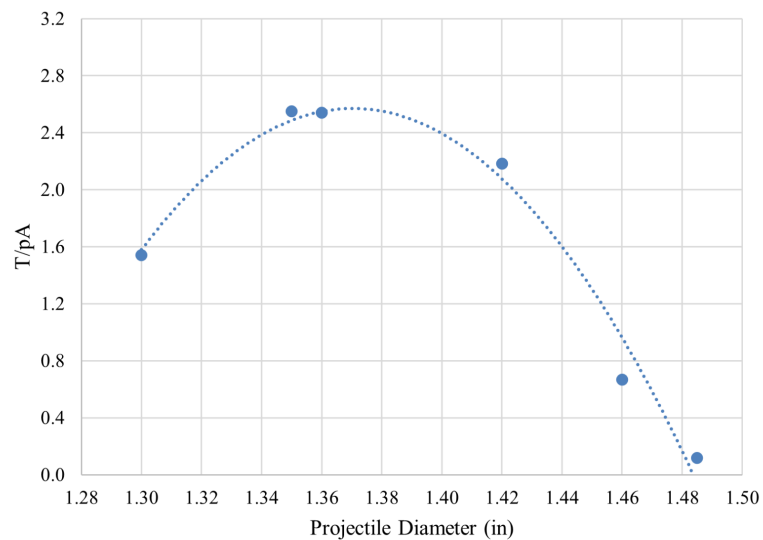


FIGURE 4.14: Non-dimensional thrust measured during experiments with projectiles varying in diameter from 1.30" to 1.485". Experiments conducted in inclined baffles [40].

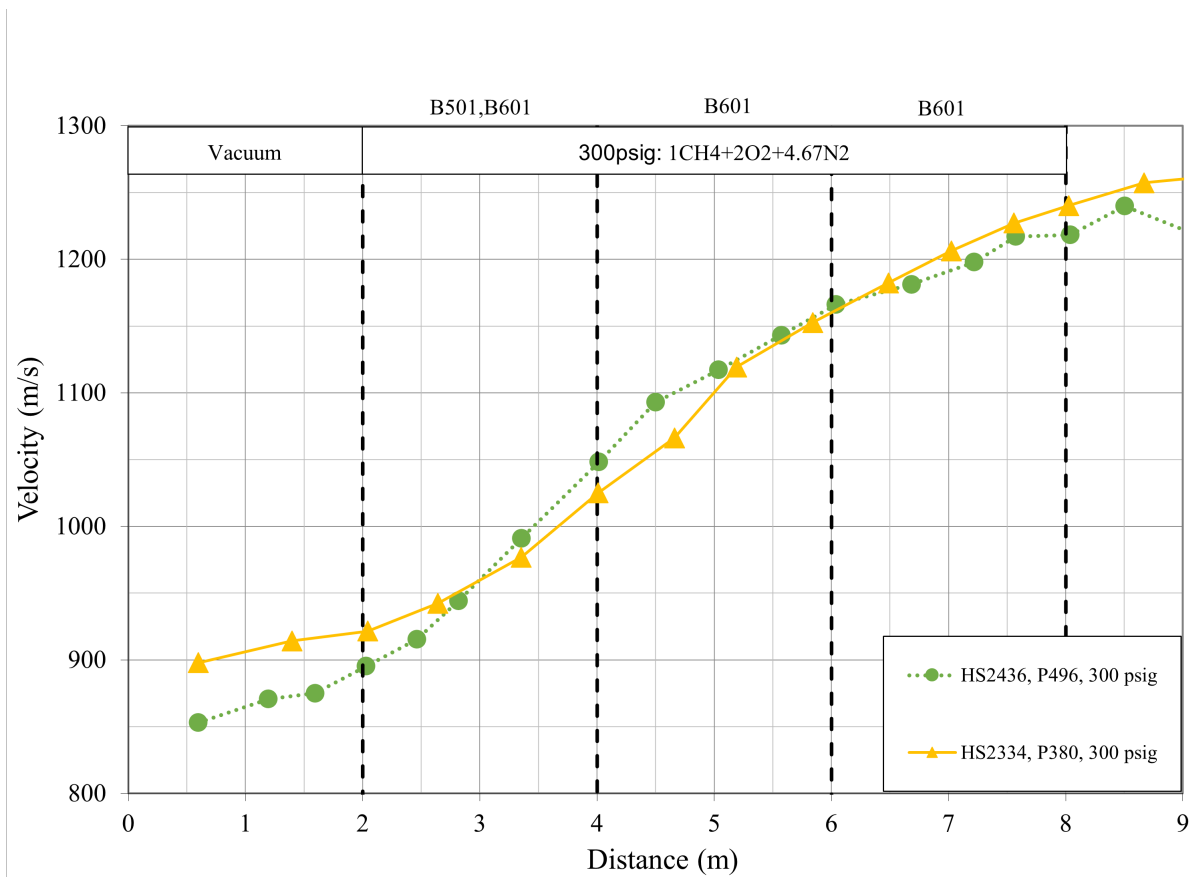


FIGURE 4.15: Velocity-position data for a representative 1.380" diameter projectile (triangles) and a representative 1.496" diameter projectile (circles). Tests conducted at 300 psig in  $\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  propellant.

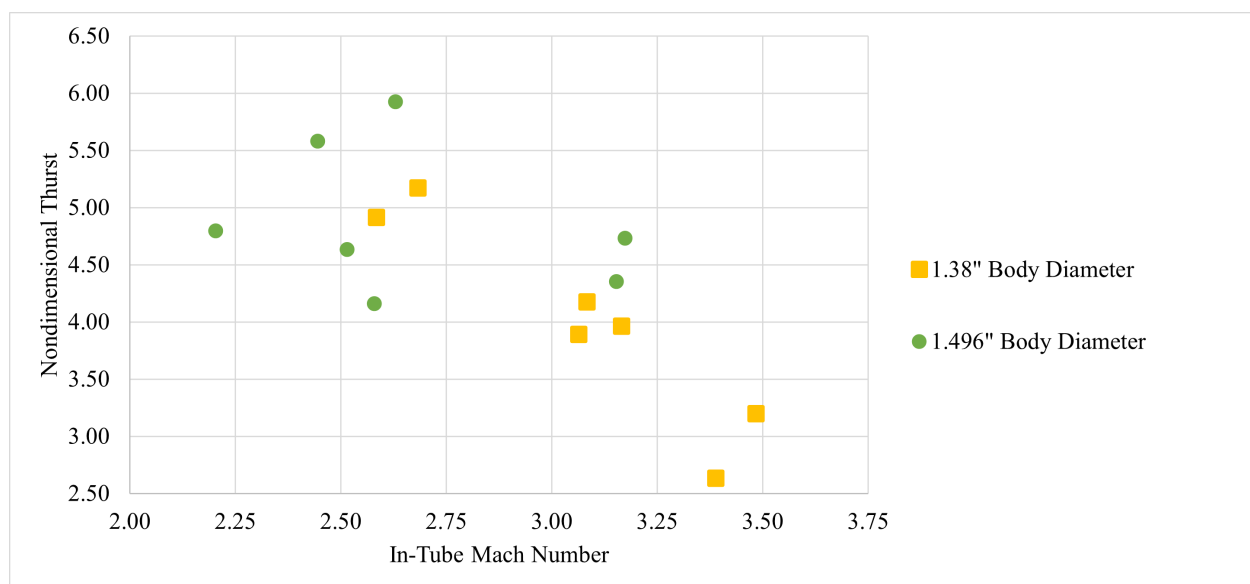


FIGURE 4.16: Non-dimensional net thrust measurements for 1.380" diameter and 1.496" projectiles in BTRA 601 baffles, with methane-air propellant mixtures.

Further, additional data may be gleaned from the shadowgraph test series. While the high-speed camera imaged only a few baffle chambers, the test section itself consisted of just over four meters of inert gas ( $\text{CO}_2$ ), in various baffle configurations. When isolating measurements to the first two-meter-long BTRA tube, the difference between 1.496" and 1.380" diameter projectiles becomes immediately obvious. P380 projectiles, denoted by triangles in Figure 4.17, experienced an average of 292 N of drag. Based on work by Alam, the CFD predicted drag coefficient for a 1.380" projectile within baffles would be roughly 1.42 at  $M = 3.25$  [63]. Observed values, however, are nearly 10 smaller less than that of CFD. These results are shown in Table 4.3.

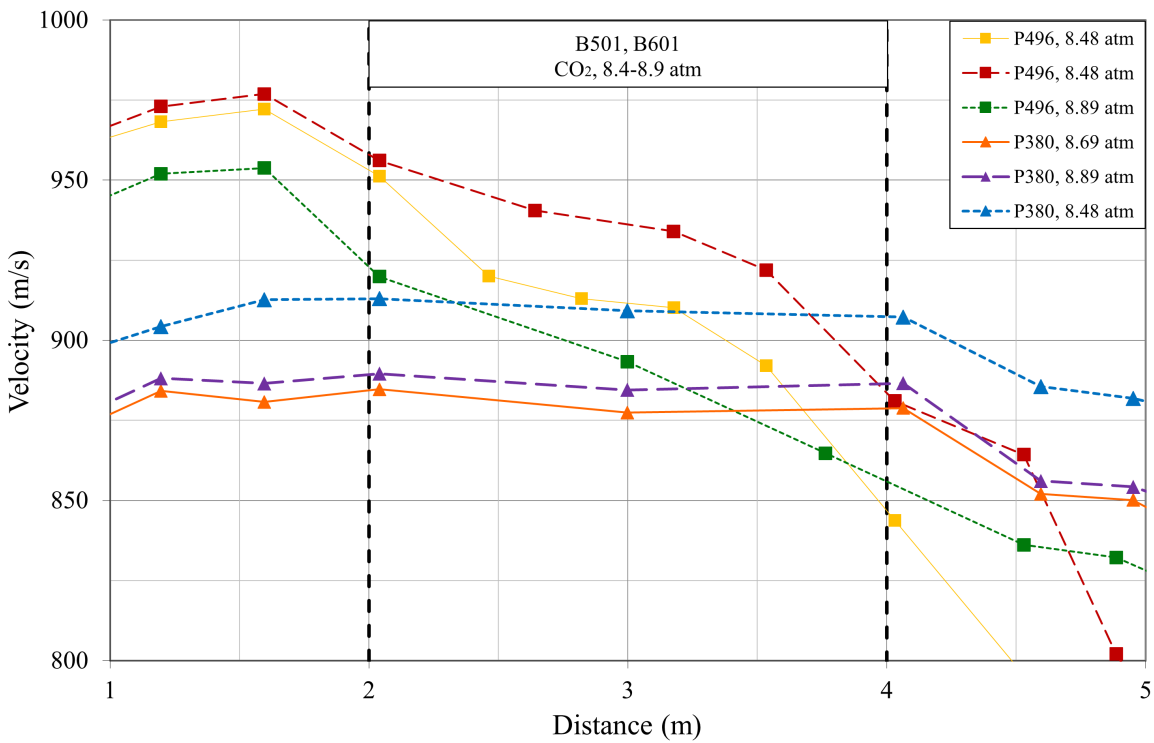
The 1.496" projectiles (denoted as squares in Figure 4.17), on the other hand, experienced significant drag. Variation was more significant in this series than with the 1.380" projectiles due to occasional breakage of the projectile tail during launch, but drag was measured as 3930 to 6460 N across the Mach 3.31 to Mach 3.48 range. A reference simulation was not available for comparison for this configuration, but estimated coefficients of drag for each experiment are listed in Table 4.4. Within the comparable velocity range the raw drag values were found to be 13.3 times higher on average when compared to P380 projectiles and estimated coefficients of drag were 10.7 times higher. This drag increase is most likely a result of interaction with baffle walls, as the 18% cross-sectional area increase is not large enough by itself to cause the drag discrepancy between projectile designs. Considering this increase in drag, the observation from Figure 4.16 that net thrust is comparable between 1.380" and 1.496" projectiles suggests that the piston mode of operation may generate higher propulsive efficiency than the ramjet mode, but that this increased performance is reduced by greater drag.

| Velocity <sub>in</sub> (m/s) | Velocity <sub>out</sub> (m/s) | Pressure (atm) | Real Drag (N) | Calculated $C_d$ |
|------------------------------|-------------------------------|----------------|---------------|------------------|
| 885                          | 879                           | 8.69           | -348          | 0.15             |
| 890                          | 887                           | 8.89           | -177          | 0.07             |
| 913                          | 907                           | 8.48           | -352          | 0.14             |

TABLE 4.3: Summary of drag experienced by P380 projectiles.

| Velocity <sub>in</sub> (m/s) | Velocity <sub>out</sub> (m/s) | Pressure (atm) | Real Drag (N) | Calculated $C_d$ |
|------------------------------|-------------------------------|----------------|---------------|------------------|
| 951                          | 844                           | 8.48           | -6460         | 2.70             |
| 956                          | 881                           | 8.48           | -4620         | 1.84             |
| 920                          | 865                           | 8.89           | -3930         | 1.60             |

TABLE 4.4: Summary of drag experienced by P496 projectiles.

FIGURE 4.17: Projectile deceleration in two meters of BTRA tubes, pressurized with roughly 100 psig of CO<sub>2</sub>. Triangles represent P380 projectiles, and squares represent 496 projectiles.

## 4.5 Baffle Chamber Diameter Effects

Tests were conducted to determine the effect of baffle chamber diameter variations on in-tube thrust and performance. Over 100 experiments were conducted using various combinations of BTRA 501, 601, and 750 inserts (3", 2.5", and 2" nominal chamber diameters), using 1.380" projectiles and propellant mixtures of  $\phi\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  in order to examine thrust as a function of chamber volume.

Extensive testing was conducted using BTRA 501 and 601 baffles. Within a propellant mixture of  $\text{CH}_4+2\text{O}_2+4.67\text{N}_2$ , which was found to be the hottest stable chemistry for smaller chamber diameter baffles, the non-dimensional thrust increased by roughly 40% between the two designs, as demonstrated by Figure 4.18 [37]. This relation was shown to hold consistently across multiple experimental campaigns and propellant mixtures [33, 37, 38, 43].

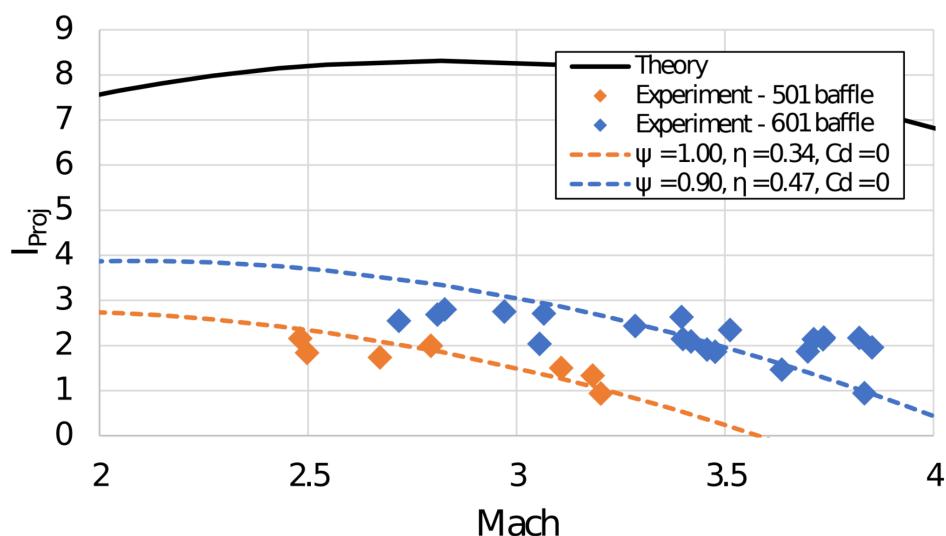


FIGURE 4.18: Experimental and theoretical performance of a methane/air BTRA projectile in 3" and 2.5" baffles, as well as ideal TCRA theoretical performance. Tests used projectiles with a shoulder diameter of 1.380 inches and length of 3 baffle lengths, nose and tail angles of  $15^\circ$  and  $12^\circ$ , respectively, and  $\text{CH}_4+2\text{O}_2+4.67\text{N}_2$  propellant [33].

Measurement of thrust in the BTRA 751 inserts proved significantly more challenging. Across an experimental campaign with 1.380" projectiles and an in-tube fill pressure of  $300 \pm 10$  psig,

projectiles were shown to experience violent unstarts. These unstarts were too violent for polycarbonate projectiles, which showed frequent failure even when operated at lower heat release. Because of these frequent failures, the polycarbonate projectiles from the batch used in these tests was suspected to have flaws arising from material quality and/or fabrication induced micro-cracks. Nonetheless, limited testing saw some success. A test using an aluminum projectile at  $Q = 8.7$  ran for roughly 1.75 meters before unstarting, with post-shot imaging showing that the stronger projectile survived intact. This shot achieved a non-dimensional thrust of 5.20 within the relevant section. A single polycarbonate projectile did survive the environment, appearing to run for the full two-meter-long test section in the same mixture, generating a non-dimensional net-thrust of 3.90.<sup>3</sup> While these tests were not statistically sufficient for confirming performance, they suggest a net thrust increase of 20-50% over BTRA 601 inserts at similar  $Q$  in the 300 psig range.

## 4.6 In-Operation Testing of BTRA Chamber Lengths

Testing was conducted to investigate the performance of 1.380" BTRA projectiles within baffles of varying lengths. To do this, BTRA 501 and 601 inserts were inserted in alternating orientations, effectively creating a two-meter-long test section of either BTRA 502 or 602 inserts with chambers with twice the length and twice the baffle thickness of the standard configuration (Figure 4.19). These tests were critical for understanding whether the approach introduced in Equation 2.17 is accurate, as the volume void ratio  $\beta$  within a BTRA 502 insert is identical to a BTRA 501 insert.

These experiments, though limited in scope, suggested that net thrust increased as baffle spacing was increased. In the case of the BTRA 602 inserts, net thrust (averaged over the two-meter tube section) was increased between 10% and 20% on average versus BTRA 601 inserts. Data scatter in the BTRA 502 inserts was significant, with double-length inserts outperforming the standard configuration between 7% and 30%. The double-chamber-length experiments, along with a representative sample of standard results, are shown in Figure 4.20.

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<sup>3</sup>It is possible that, while pressure and magnet data showed good running, the polycarbonate projectile was deforming in this test. The aluminum projectile is likely a more accurate experiment.

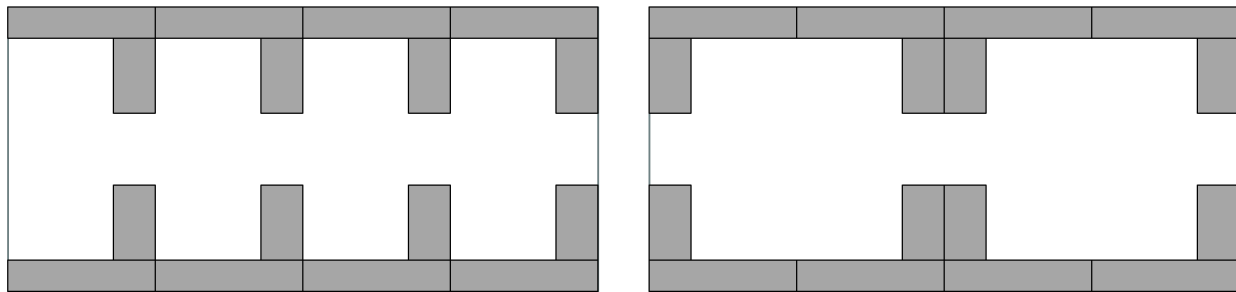


FIGURE 4.19: Not-to-scale comparison of four BTRA 601 inserts arranged normally (left) and rearranged to create two BTRA 602 inserts (right).

Despite these promising results, stability in the longer BTRA chambers has been called into question. Testing at higher pressures suggests that the operational limits of the longer chambers are reduced. Within the BTRA 602 inserts projectiles were observed to unstart at operating pressures of 450 psig within a  $\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$  mixture with a standard 1.380" shoulder diameter, 2.812" shoulder length, projectile. Prior experimental campaigns had established this to be a safe mixture for such projectiles and chemistry up to operating pressures of 600 psig (Fig. 4.21). Projectiles with longer shoulder lengths, which would presumably better isolate the baffle chambers, may serve to mitigate this effect.



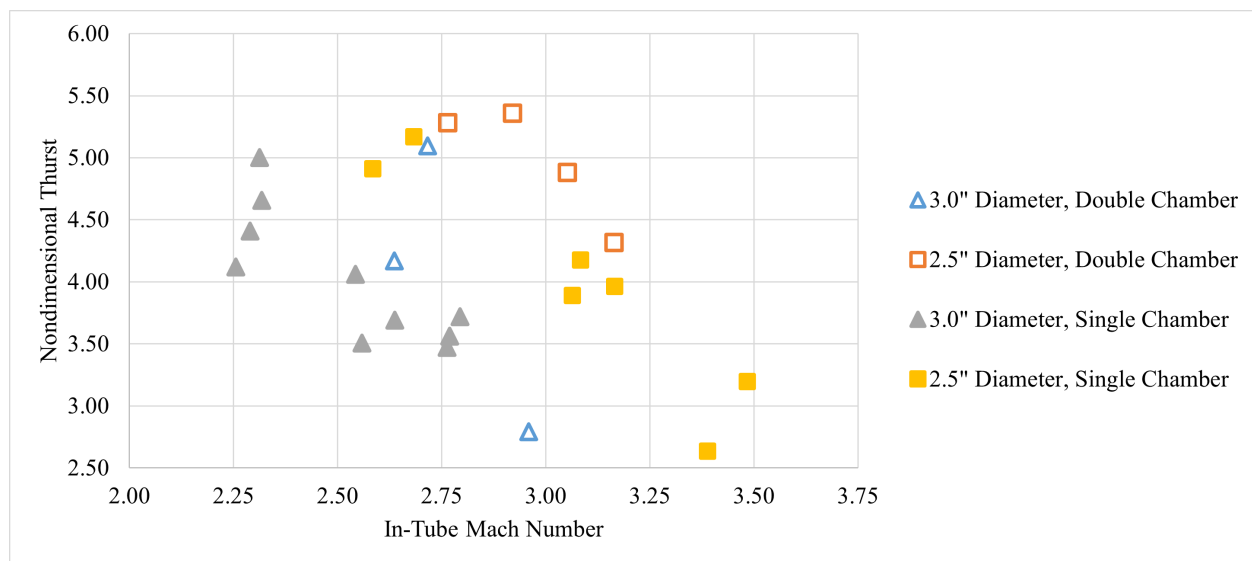


FIGURE 4.20: Pressure-normalized net-thrust measurements for testing in 3" baffle chambers (triangles), and 2.5" chambers (squares/diamonds). Open symbols represent double chamber length, and closed represent single length. Experiments conducted in methane-air propellant mixtures.

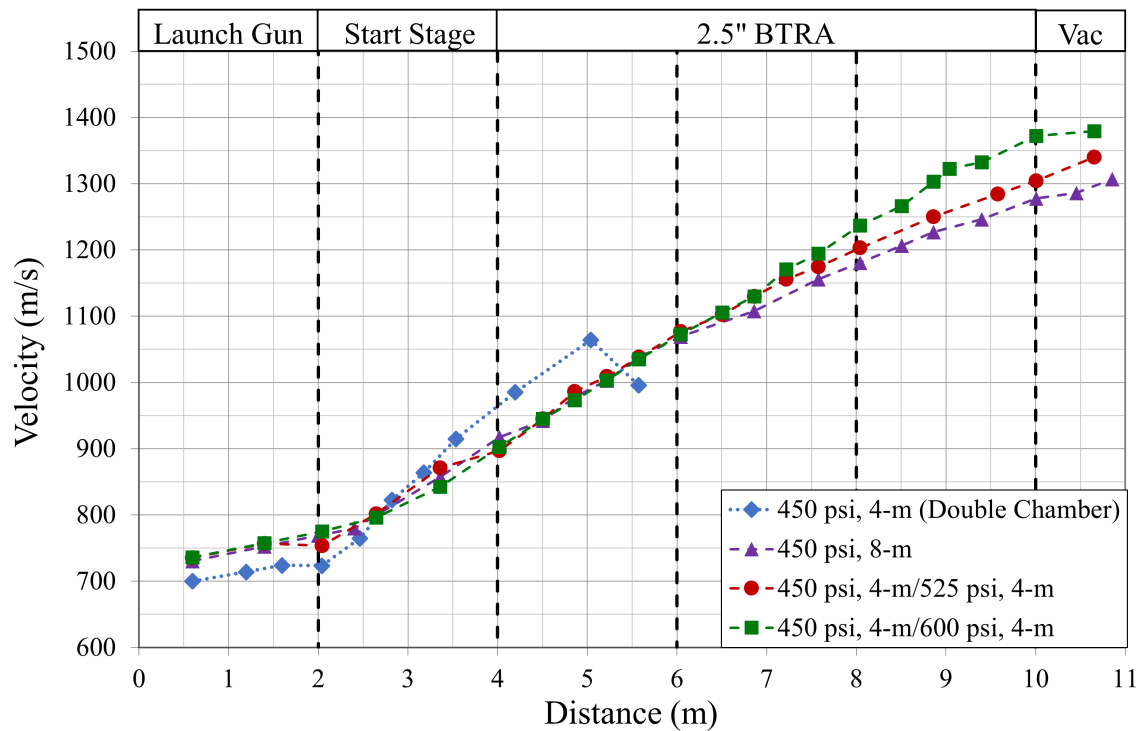


FIGURE 4.21: Velocity-position data for four experiments with 1.380" projectiles in  $\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$  propellant mixtures. Shot one (blue diamonds) which unstared, was conducted in a high performing 2-m-long start stage, before entering a 2-m-long double-chamber-length baffle test section. Shots two through four, which were stable, were conducted in a lower performing start stage before entering a 6-m-long single-chamber-length test section. Note that the projectile used in shot one was less dense than the others, resulting in higher acceleration, but did not differ significantly in geometry.

## Chapter 5

# Conclusions and Future Work

### 5.1 Discussion of Significant Results

The observation of BTRA projectiles igniting and running while below the theoretical area-Mach number limit suggested that a more complex flow environment was developing within baffle chambers. Novel experiments were conducted to investigate, confirm, or reject hypotheses previously put forward by theoretical and numerical efforts in the baffled-tube ram accelerator system. Analysis of the BTRA has historically been limited to a one-dimensional fluid simplification, as it has been found to be sufficient in smooth bore systems. However, new phenomena were observed that question the extensibility of this simplification in other configurations.

BTRA operation was proven to be successful even when entering a baffle tube at only 78% of the theoretical minimum velocity, based on the area-Mach relation for one-dimensional flow. This finding, while promising for the development of the ram accelerator as a technology, suggests that proper understanding of the BTRA system requires more in-depth, multidimensional work.

Initial investigation was limited to pure gasdynamic effects, without the influence of a projectile. The curved structure of shock waves passing through baffles that was originally predicted by CFD was confirmed through shadowgraph imaging, which verified that a complex gasdynamic environment forms within baffle chambers. Detonation waves were initiated and found to travel with a velocity within 5% of the equivalent smooth-bore propellant CJ detonation velocity, confirming recent trends about high-pressure detonations in tubes with blockage features.

More specific to ram operations were results from shadowgraph imaging of projectiles transiting baffle inserts in a clear acylindrical tube. Operation of a shadowgraph apparatus, with tube walls acting as focusing lenses, was demonstrated. Imaging from these efforts revealed two distinct modes of ram accelerator operation. A projectile which nearly fully occludes the tube bore was observed to operate in a piston-like mode, generating turbulent pressure fronts and vortices within the baffle chamber. This pattern was observed to be consistent regardless of baffle wall separation. Smaller diameter projectiles, which permit flow between the baffle bore and the projectile, generated relatively calm flow within the baffle chambers. In either case, the shock environment around baffle walls was observed to be far simpler than expected, with complex shock reflections absent from recorded imaging. These results are consistent with previously unexplained phenomena in BTRA systems, in which full-bore projectiles were more effective at igniting a propellant. It was also found that drag on full-bore projectiles was an order of magnitude higher than on sub-caliber ones, even though overall thrust did not show as significant a discrepancy. This suggests that there are distinct operating ranges for which a full bore projectile may be preferable to a sub-diameter projectile (or vice versa), and a fully optimized BTRA system may make use of varying bore diameters across the system so that a single projectile design may be considered full-bore or sub-diameter at different times.

Tube geometry was varied in combustive tests as well. Baffles with narrower chamber diameters were confirmed to generate higher thrust on ram projectiles, confirming prior studies. A new, narrower baffle insert was tested with the BTRA 751 insert, leading to the result that the useful range of propellant heat release is limited by baffle diameter, and that higher-thrust baffles are not capable of operating in high heat release mixtures.

Chamber length was varied by arranging BTRA 501 and 601 inserts to create an insert configuration with double-length chambers and walls. The BTRA 502 and 602 inserts were found to have higher net thrust generation than their single-chamber equivalents, an effect that cannot be predicted based on the volume void ratio  $\beta$ . While this net thrust increase could be the result of improved propellant mixing and burning, it is more likely that the increased distance between

baffle walls instead reduces drag on the projectile. This is in line with simulations by Daneshvaren and results from the shadowgraph imaging efforts.

It was also observed that, while drag was decreased in the longer baffle chambers, maximum heat release was also affected. Projectiles suffered from unstarts at 450 psig in standard mixtures in BTRA 602 inserts, a chemistry which had previously demonstrated stable operation in excess of 600 psig in BTRA 601 inserts. This has troubling implications for the proposed rail sweeper design. As proposed by Legee and discussed in Section 2.3.1, the rail sweepers have been observed to prevent unstarts in low heat release systems by effectively "resetting" the flow around the projectile [20]. The sweeper system is desirable in large-scale operation, for both cost and maintenance, as it allows a predominantly RTRA design to make use of higher energy propellants. But the instabilities observed in the double-chamber test series suggest that this limit is much lower than anticipated, and more consideration will have to be made concerning optimization between BTRA and RTRA-sweeper systems.

## 5.2 Future Work

This study showed significant, novel development in the understanding of BTRA systems across a variety of geometric variations. Further work is needed to fully characterize the system, however. Recommended future topics of investigation include:

- Longer projectile shoulders: Prior test campaigns had found that net thrust increases with projectile shoulder length, even though mass eventually overtakes this performance gain. Such tests were conducted with single-chamber baffle inserts. The results of the work presented here suggest that longer chambers may be preferable in operation, but no attempt was made to proportionally increase projectile length as well. An in-depth study may serve to compare whether there is an optimal ratio of baffle chamber length and projectile shoulder length and whether this ratio holds over a variety of chamber geometries.

- Establishment of consistent running in BTRA 751 inserts: Trends from testing of BTRA 501 and 601 inserts showed that by narrowing baffle chamber radius increased thrust was generated on the projectile for a given heat release. The few shots which ran successfully in BTRA 751 inserts aligned with this trend but a full investigation is needed to determine whether the drop in heat release required to stabilize performance outweighs the increase in thrust.
- Investigation of rail sweepers: Once BTRA 751 performance is understood, lengthening of the chamber into a rail sweeper mode is preferable, assuming that thrust continues to increase with chamber length. Determination of the relationship between heat release, projectile velocity, and sweeper spacing is of critical importance to a fully-implemented ram accelerator for large-scale operations.

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## Appendix A

# Analysis of Magnetic Induction Sensor Perturbations

This appendix describes the workings of the magnetic induction sensors used in the UW ram accelerator facility. It begins with a simplified review of the physics and design, as first presented by Christofferson [58]. It then presents new developments focused on the specific environment of the BTRA system.

### A.1 Magnetic Induction Sensor Theory

The basis of the magnetic induction sensors is simple: a loop of any conductive material, when placed in a changing magnetic field, will generate an electric current along its path in accordance with Faraday's Law of Induction [64].

$$\begin{aligned}\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \oint_L \vec{E} \cdot d\vec{l} &= -\frac{d}{dt} \int_S \vec{B} \cdot d\vec{a}\end{aligned}\tag{A.1}$$

Calculating the current induced in a loop of wire is a standard exercise in introductory physics classes, but the key steps are repeated here. In summary, the loop of wire is a circular boundary,

reducing the line integral to simply the circumference of the wire. Likewise the surface integral on the right side reduces to the flux through the loop, leading to

$$\begin{aligned} emf &= \oint_l \vec{E} \cdot d\vec{l} \\ \Phi &= \int \int_S \vec{B} \cdot d\vec{a} = B_n \left( \frac{\pi d^2}{4} \right) \end{aligned} \quad (\text{A.2})$$

where  $emf$  is the induced electromotive force,  $B_n$  is the magnetic field strength normal to the loop, and  $d$  is the loop diameter. For a probe with number of turns  $N$ , the induced signal can be found as:

$$emf = -N \frac{dB_n}{dt} \left( \frac{\pi d^2}{4} \right) \quad (\text{A.3})$$

Determination of the magnetic field at the point of the loop is considerably more complicated. For a permanent magnet, whether solid or annular, the magnetic field at radius  $\vec{r}$  is a function of the strength of its poles ( $p$ ) and the vector between them ( $\vec{l}$ ). This is visualized in Figure A.1.

$$\begin{aligned} \vec{m} &= p\vec{l} \\ \vec{B}(r) &= \frac{\mu_0}{4\pi} \frac{3\hat{r}(\hat{r} \cdot \vec{m}) - \vec{m}}{|\vec{r}|^3} \end{aligned} \quad (\text{A.4})$$

Christofferson continues the analysis to include shielding effects, projectile motion, and the tube wall [58]. The following study instead uses an open source solver which natively includes these effects to calculate  $B_n$ , as described in the next section.

## A.2 Observation of Magnetic Signals in BTRA Configurations

It was observed that magnetic signals within BTRA systems do not conform to the signals seen in SBRA systems or theory. Most noticeable is the difference in signal shape. SBRA signals tended to occur in what is called a "dipole" signal, with one positive and negative peak (Figure A.2). BTRA signals, on the other hand, have been observed in "quadrupole" patterns (Figure A.3), with

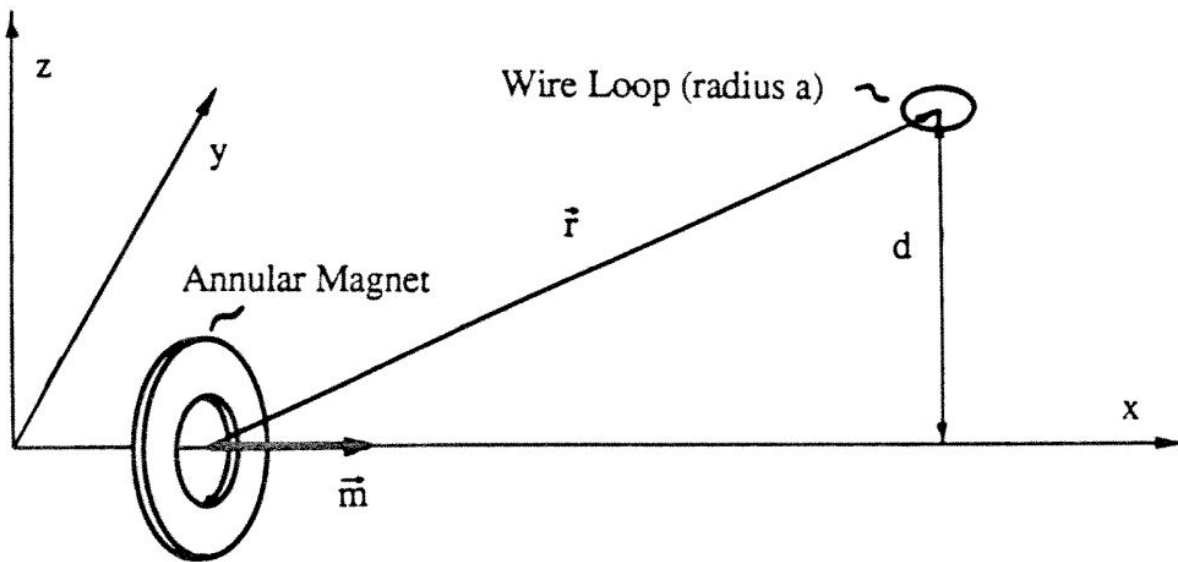


FIGURE A.1: Geometry of an annular magnet, moving along the x-axis, and the distance vector to a loop of wire [58].

one large positive peak and two small negative ones (or one negative and two positive, depending on magnet polarity). Additionally, the BTRA signals are not always symmetric, and one small peak may have different amplitude than the other.

Historically, interpretation of the quadrupole signals has been difficult. In a perfectly symmetric signal the uppermost peak is the logical point to measure, but given the asymmetry, and the fact that a noisy or weak quadrupole begins to resemble a dipole, some have suggested that using a zero crossing would be more accurate. This distinction is of critical importance to properly interpreting BTRA performance data.

A secondary experimental observation provided key insight into this problem: magnetic probe signals varied significantly depending on probe depth. In SBRA testing the base of the probes consistently sat flush with the tube wall (aka "surface probes"). In BTRA experiments, the baffle chambers provided the opportunity for deeper probe placement, and probe necks were altered to obtrude 0.25" radially into the tube (hereafter referred to as "in-tube" probes). When hardware was limited, older SBRA probes were sometimes used in BTRA experiments, and it was observed that their signals, while weaker, often recorded dipole signals. This revealed that placement affected



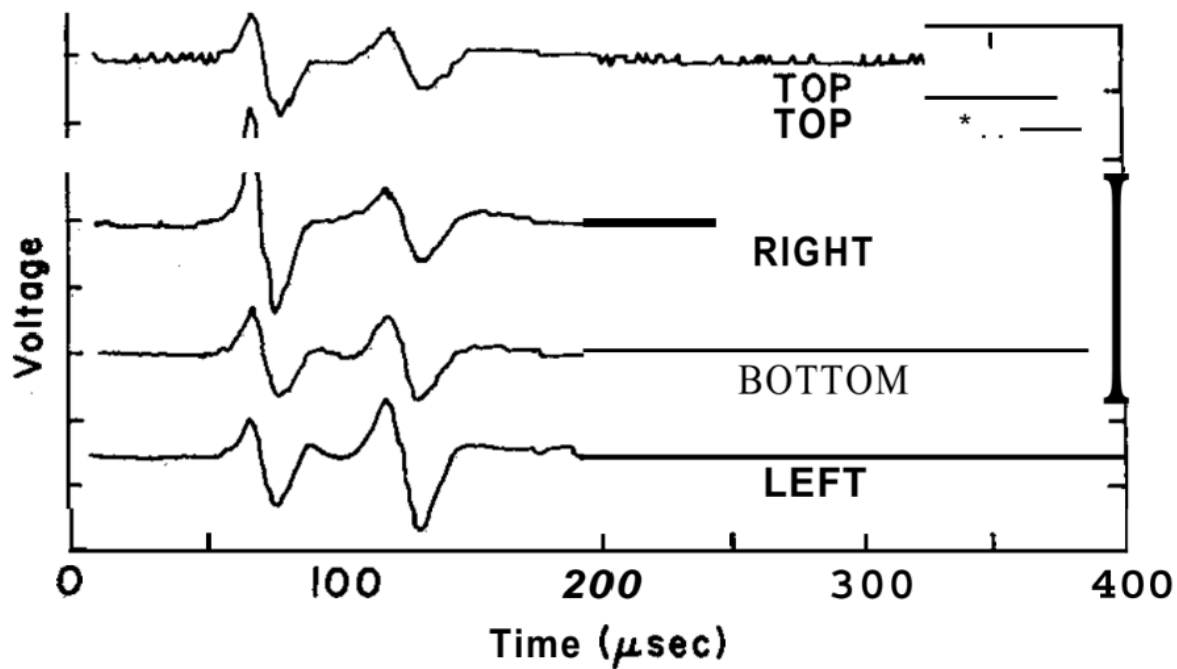


FIGURE A.2: Magnetic signal traces from four magnetic detectors located at the same axial position but 90 deg apart azimuthally. Projectile moving at roughly 1400 m/s [65]. In this test projectiles were equipped with front and rear magnets, resulting in multiple signals per instrument station.

not just the strength of a signal, but its shape.

As a result of this new observation a method of simulating and predicting magnetic signals was developed which could replicate the complex geometries of the BTRA. The open-source electromagnetics, heat flow, and current flow software Finite Element Method Magnetics (FEMM 4.2) was selected due to its use by colleagues and proven capability. Using the OctaveFEMM scripting set, programs were developed in Matlab which would populate a length of BTRA test geometry in a 2D plane, which may be passed into FEMM and simulated as a series of axisymmetric magnetostatics problems (see Appendix C.3) [66]. The magnetic flux through a sensor region would be calculated at one position, the projectile would be advanced, and the process repeated. In this way the magnetic field through the relevant points was found<sup>1</sup>. By calculating the magnetic field

<sup>1</sup>To be precise, this method did not find the flux through the probe area. It instead found the flux through a thin cylinder around the axisymmetric simulation region with height equaling the diameter of the probe loops. This does not impact the shape of the signal but does amplify the signal by a constant factor. As this study focuses on the relative properties of signals this constant amplification factor was not considered necessary to correct.

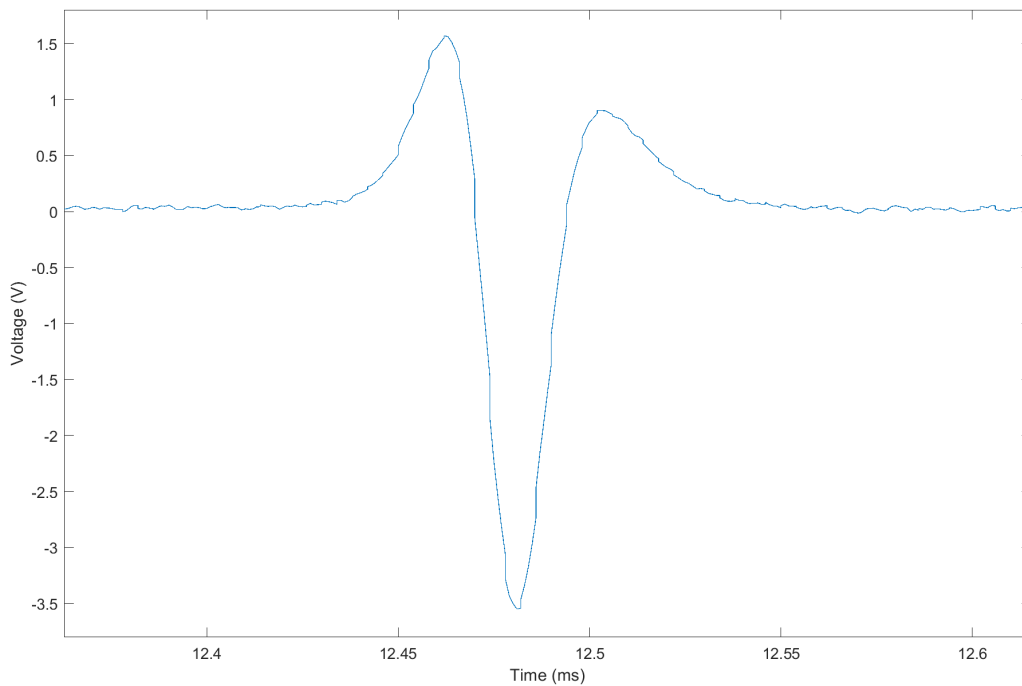


FIGURE A.3: Typical magnetic signal from a BTRA calibration shot (tube kept at vacuum), with a velocity of  $1010 \pm 10$  m/s.

through the environment magnetic flux vs time was determined. As discussed in Section A.1, the signal produced by the probe is a function of the change in flux, or  $\frac{dB}{dt}$ , so the flux vs time array was numerically differentiated to reproduce an actual signal.

The 601 baffle geometry was used as the control geometry, as it has been used most extensively in real-world testing and could be easily referenced to confirm accuracy. Projectile geometry was set to the laboratory standard P380 projectile (though in most cases it was set as a low permeability material, so this geometry typically had negligible impact), and the control velocity was 1000 m/s. The magnetic field was generated by a 0.25" thick, 0.375" diameter neodymium magnet, as is used in BTRA testing. In all cases, regardless of baffle geometry, the probe is placed at the center of the instrument hole in the default insert, not evenly between walls. This means that the probe center to nearest wall face distance is always 0.453 inches, true to real-world testing.

Region properties were assigned using the closest approximation in the FEMM materials library. Unless otherwise stated, all non-conductive materials (polycarbonate projectiles, in-tube gasses, etc) were assigned as air, per recommendations from FEMM documentation [67]. The tube wall and baffles, being ferromagnetic steel, were set as 416 stainless steel.<sup>2</sup> The probe housing was set as a non-ferrous 304 stainless steel, and its internals were also set to air. A sample of a simulation in progress is shown in Figure A.4.

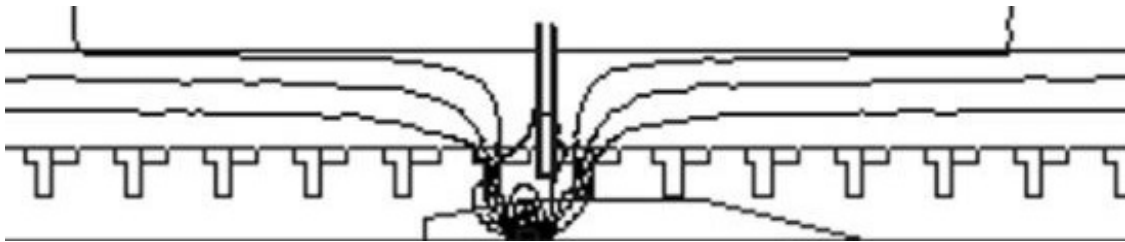


FIGURE A.4: Simulated magnetic field lines just before a projectile passes the magnetic probe. Note that the field lines are attracted to the baffle walls, and flow into the shell tube through them.

Returning to the study, the simulation technique was employed to compare surface probes and in-tube probes. These simulations confirm that in a dipole signal the projectile transit occurs at the central zero point (Figure A.5), and therefore suggest that quadrupole signal transit occurs at the second zero crossing. Moreover, they suggest that the quadrupole/dipole distinction may be more nebulous than previously thought.

Further, simulations were conducted to determine the effects of probe-baffle distance on signal shape. 501 baffle inserts were shifted further down, effectively moving the probe through the chamber. As expected, the wall nearer to the magnetic probe has the greatest effect on the signal shape. Researchers were surprised to discover that the walls do not directly impact the two local maxima of the signal, as initially predicted. Instead the nearer wall appears to distort the ideal dipole, resulting in a slight phase shift and amplifying either the dipole minimum or maximum.

<sup>2</sup>In reality the baffle inserts and BTRA shell tubes are made from 17-4 PH stainless steel. This material does not exist within the FEMM library, and 416 stainless steel has approximately 4x the permeability, so effects portrayed in this work are exaggerated from true signals.

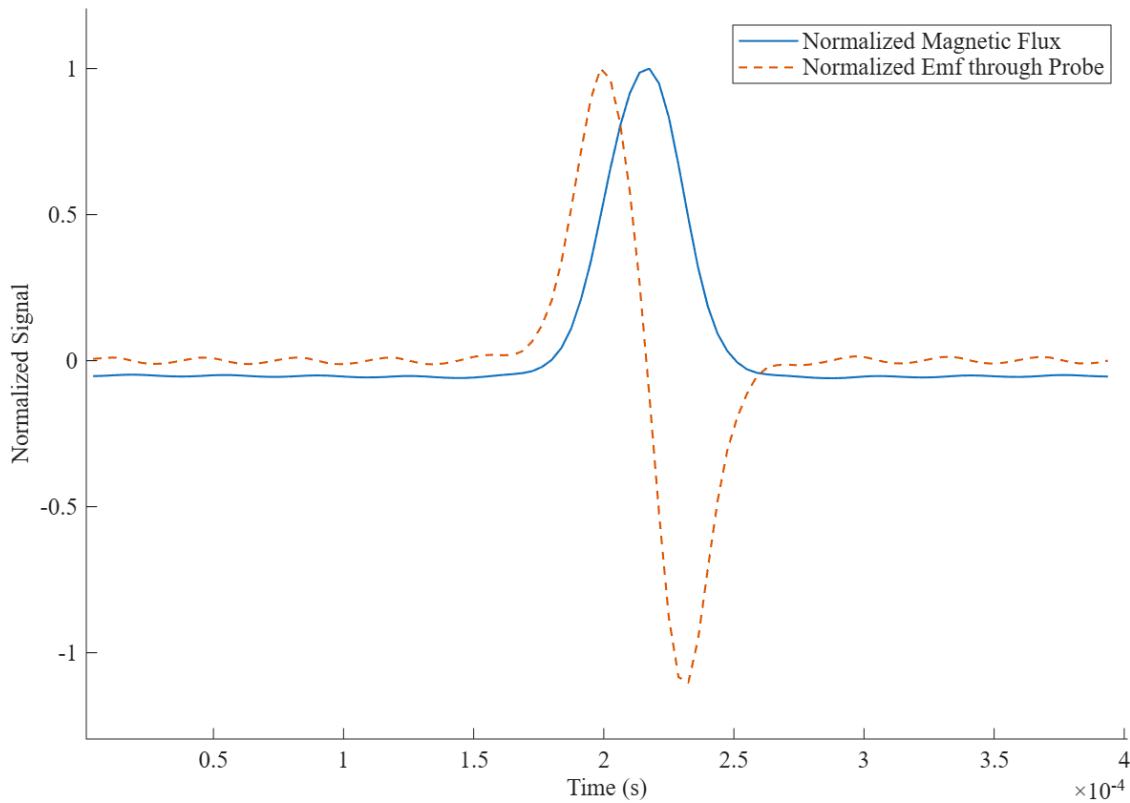


FIGURE A.5: Simulated magnetic flux and signal data for a surface probe. Signal amplitude normalized for simplicity. Note that, as expected, the peak magnetic flux (corresponding to the transit of the projectile) occurs at the dipole zero crossing. Projectile traveling at 1000 m/s in 601 baffle inserts.

The other dipole peak is then pulled to a lower amplitude, and another peak begins to form opposite it.

Due to geometric complexity, this sensor position test was not continued beyond the 501 baffle inserts, but it is expected that each BTRA insert geometry would produce a similar effect.

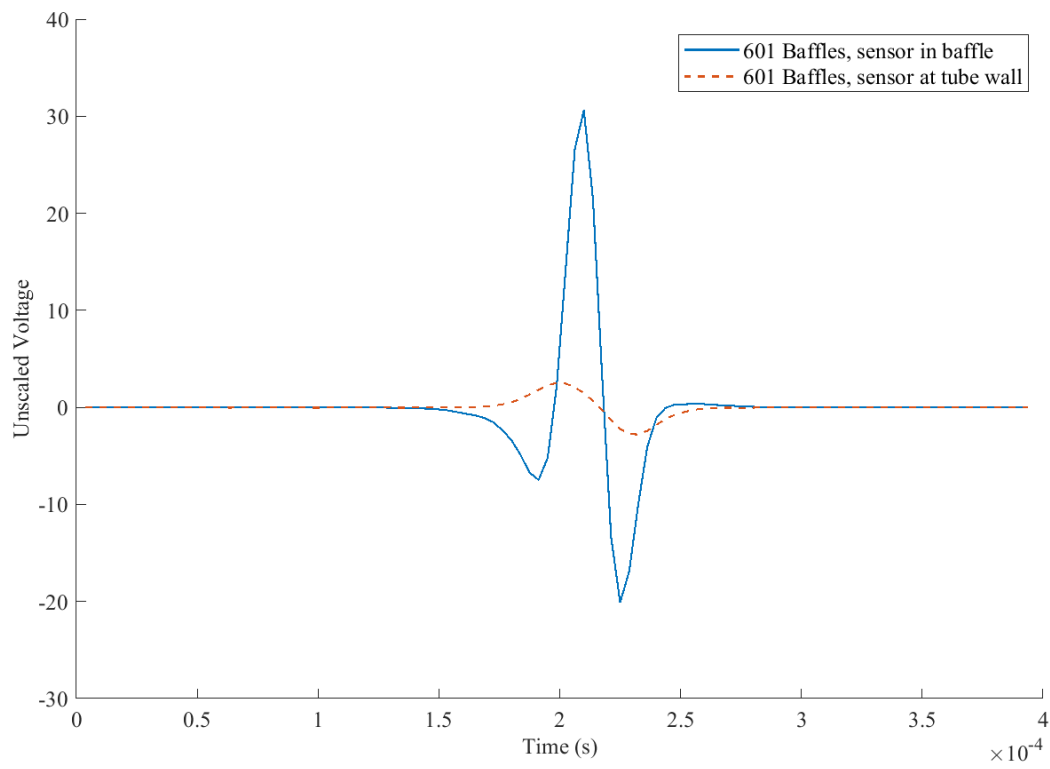


FIGURE A.6: Simulated magnetic probe data for surface and in-tube probes. Projectiles traveling at 1000 m/s in 601 baffle inserts.

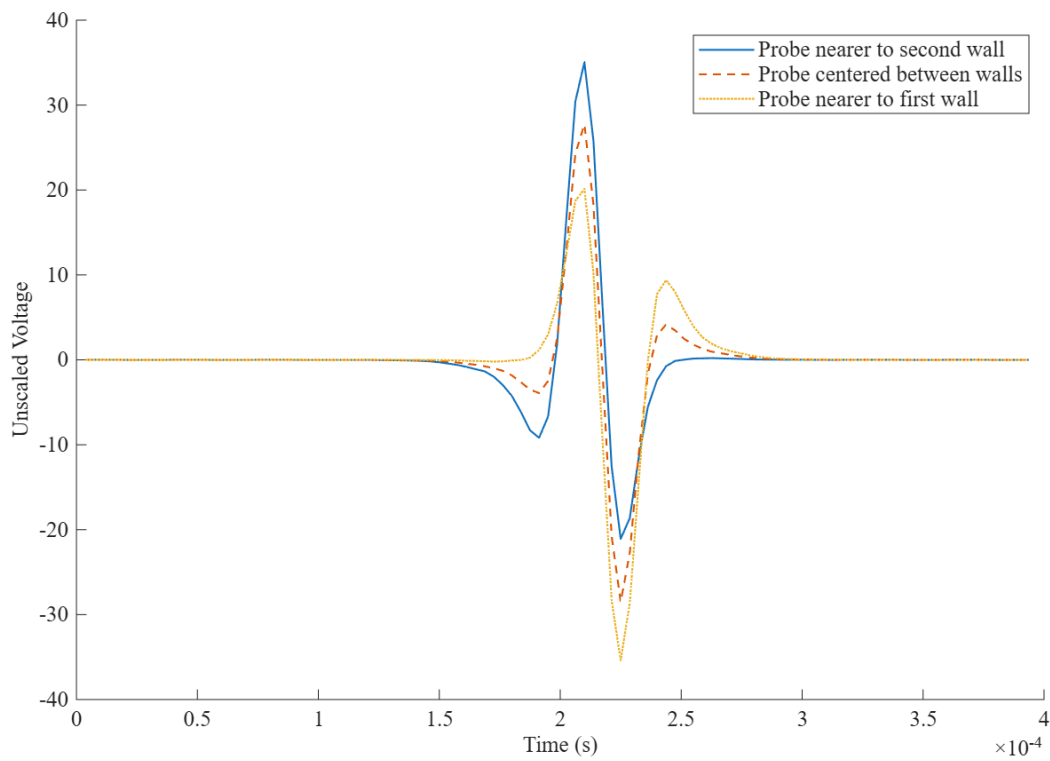


FIGURE A.7: Simulated magnetic probe data probes which were near the downstream baffle wall, centered, and near the upstream wall. Projectiles traveling at 1000 m/s in 501 baffle inserts.

### A.2.1 Impacts of Baffle Geometry on Magnetic Signals

With the simulation script established, additional work was done to determine the effects of baffle geometry on magnetic signals. For baffles made of a material with low permeability the geometry should have no effect. The baffles in this study, however, were a high permeability steel, and necessitated investigation. In these simulations all tests used the in-tube magnet probe geometry, as it was more accurate to standard testing conditions.

Of immediate interest is the effect of chamber diameter on signal strength. Simulations were conducted for BTRA tubes consisting of 501, 601, and 751 baffles, the three diameter configurations used in this work. Rails were ignored to reduce the geometry from 3D to an axisymmetric 2D design. These simulations, shown in Figure A.8, shows that signal strength is reduced as the baffle chamber depth is reduced. Since baffle chamber is reduced by creating a thicker shell on the outer edge of the baffle, this effectively reduces the separation between the probe tip and the tube wall. This is seen clearly by tracking the signal trace of the 751 baffle, which begins to look much like a smooth bore dipole.

The effect of changing spacing between baffles, and of changing baffle wall thickness, was also investigated. For these simulations chamber diameter was held constant, with the baffle walls being altered. Aside from Fig. A.7, the magnetic probe sensor was not moved from its control position, meaning that the probe center to nearest wall face distance remained 0.453 inches, and the next wall was moved further away. This is in line with the configuration used in real-world testing.

Figure A.9 shows simulated signal results for the series using 50X baffles. Two main findings can be drawn from this. First: as baffles are moved further apart, the signal widens and grows. This moves the uppermost peak to the left, supporting the finding that the zero-crossing-point is the transit location. The second is that wall thickness has an affect on signal shape, even when further from the probe. Comparing the double spacing/standard thickness with the double spacing/double thickness wall, one may observe that the increased thickness serves to pull the signal into a sharper

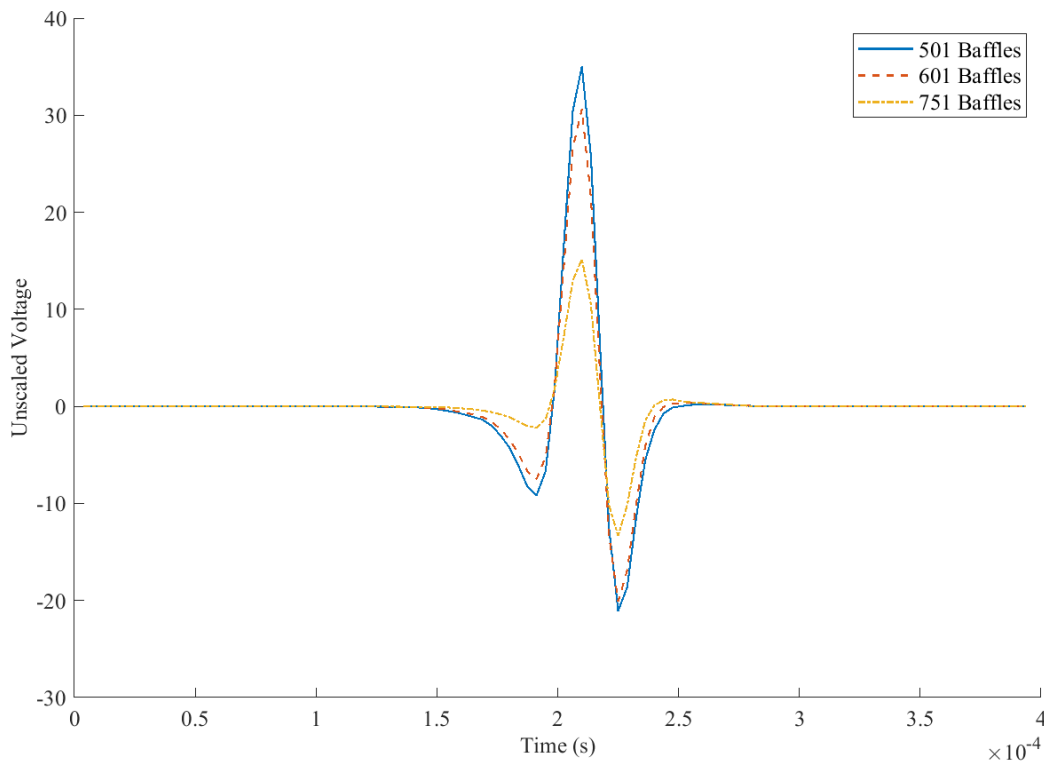


FIGURE A.8: Simulated magnetic probe data for three baffle chamber diameters. Projectiles traveling at 1000 m/s.

curve than the thin wall at a similar location. Additionally, it is seen that the baffle wall has an affect on the signal even from relatively high distances (in the double spacing tests the further wall was 2.109 inches from the probe, instead of the standard 0.703).

Simulations of the standard and double 601/602 designs show similar trends, with the curious note that maximum signal strength is unvaried. It is believed that this is an affect of the remaining baffle shell interfering with the field.

The 751 inserts show the extreme end of this effect. In this configuration even the long-necked probes are effectively flush with the baffle wall, making them similar to a 2" SBRA system. The 751 inserts may then be compared with the rail tubes used in Leege's study, which were of the same diameter (Figure A.11) [20]. This allows for comparison between a system with and without baffles, though results are limited by the lack of probe protrusion. In these simulations the thicker



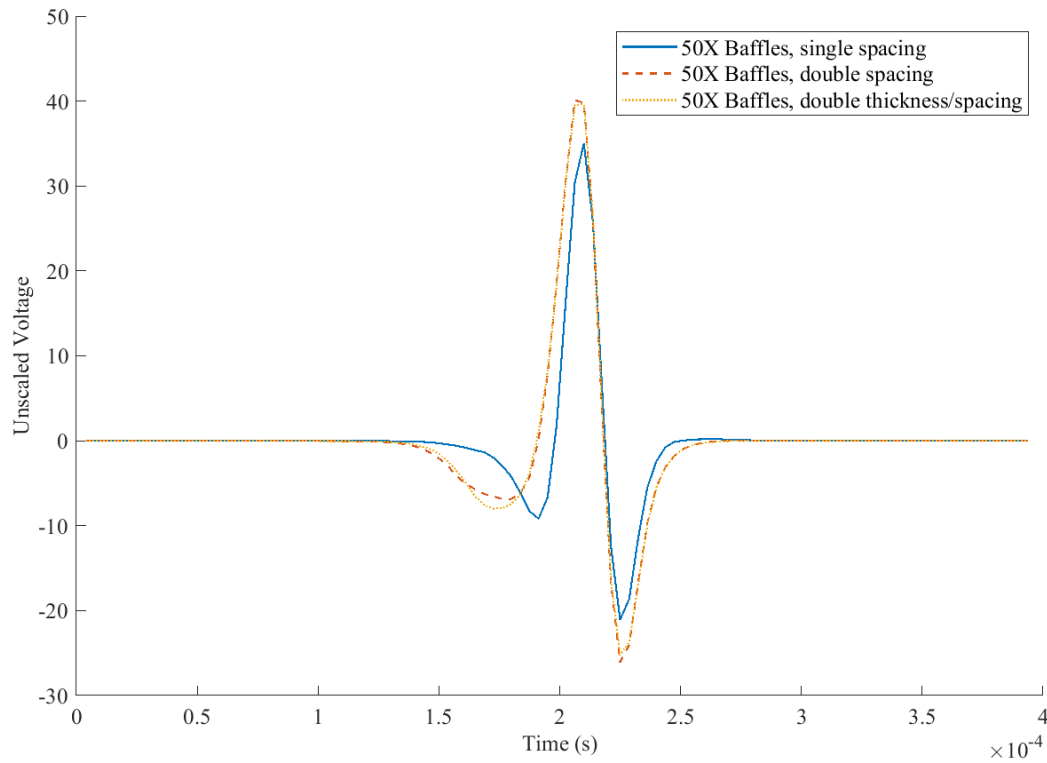


FIGURE A.9: Simulated magnetic probe data for three 50X baffle chamber lengths. The solid blue line represents the 501 inserts used in this study, the dotted yellow line represents 502 baffles, and the dashed orange line represents an untested iteration with double chambers and standard walls. Projectiles traveling at 1000 m/s.

baffle shell appears to dominate signal shape, with the walls having only minimal effect.

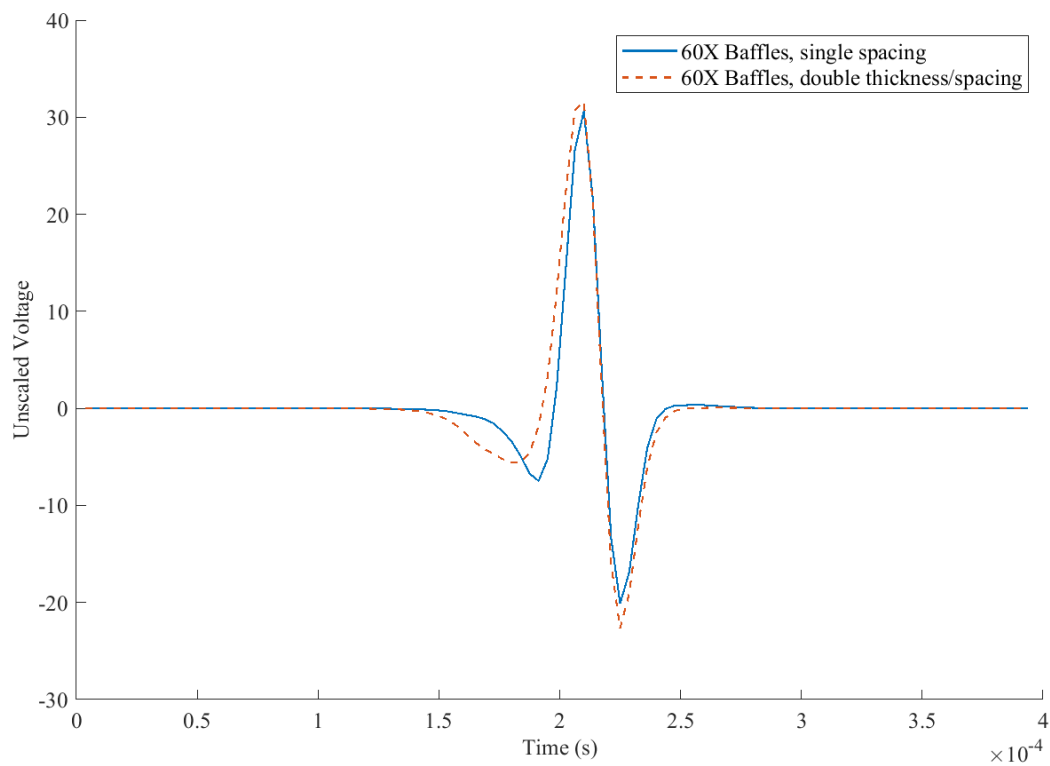


FIGURE A.10: Simulated magnetic probe data for two 60X baffle chamber lengths. The solid blue line represents the 601 inserts used in this study, and the dashed orange line represents the 602 inserts. Projectiles traveling at 1000 m/s.

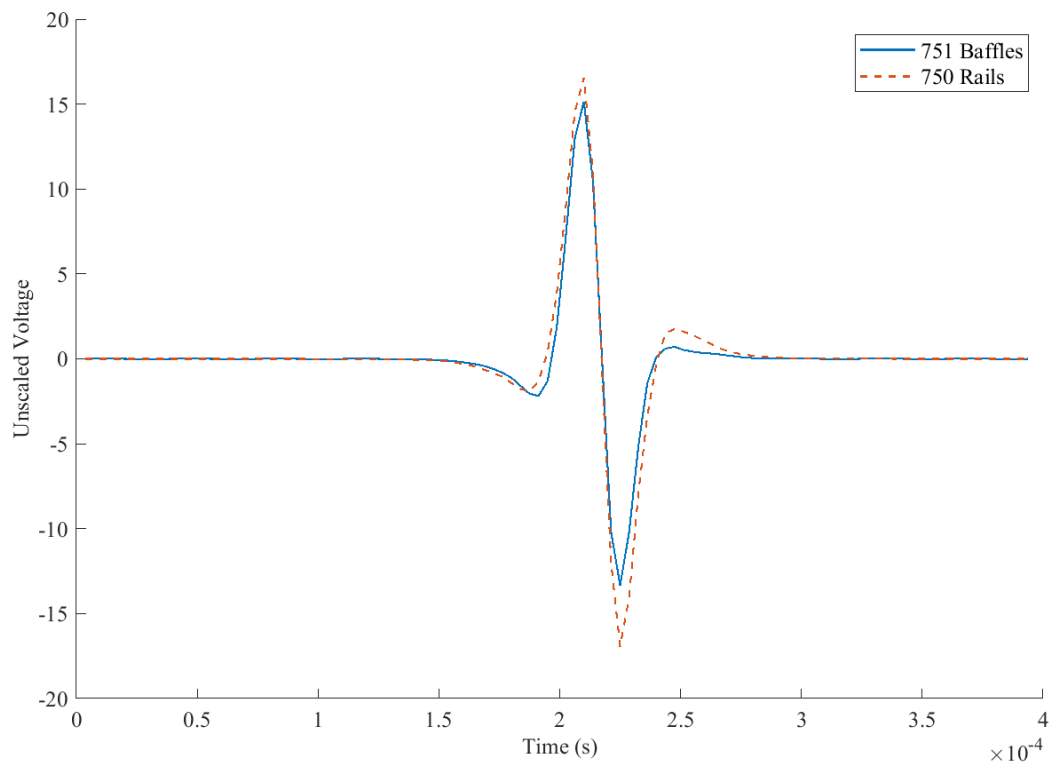


FIGURE A.11: Simulated magnetic probe data for a series of 751 BTRA inserts, and an RTRA configuration with the same diameter. Projectiles traveling at 1000 m/s.

### A.2.2 Impact of Material Effects on Magnetic Signals

Material science is of great relevance to ram accelerator research. While some materials are sufficient for low-energy or low-velocity testing, Section 4.5 showed how projectiles can fail under certain conditions. To support this effort simulations were also conducted which varied the material of components in the system, namely the projectile and the prove itself. For this series three projectile materials were tested: air<sup>3</sup>, aluminum 6061-T6, and 416 stainless steel. Polycarbonate and aluminum<sup>4</sup> projectiles were both used in the experimental efforts of this study, and steel has been proposed as a high-strength solution for more intense ram accelerator environments. With this selection the differences between a plastic, a low permeability metal, and a high permeability metal may be compared. As standard, simulations were conducted in BTRA 601 inserts at 1000 m/s for easy comparison.

Two simulations were conducted using the solid steel projectile to gauge geometric influences. In one the magnet was placed at axial position where between the projectile tail and shoulder meet, and in the other it was placed near the tip of the nosecone. These positions were chosen as they are both used in real-world ram accelerator tests. The results are shown in Figure A.12. These signals show that high permeability projectiles can directly interfere with the signal strength and shape, and testing with them should take this into account. Specifically, signal strength is nearly doubled when the magnet is placed in the nose versus the tail/shoulder due to the thickness of the material surrounding it.

From an instrumentation perspective neither position is optimal. Figure A.13 shows just how serious the impact of a high permeability material can be. Comparing Figures A.12 and A.13 one can see that the steel reduces signal strength by factors of between 50 and 100.

Finally, analysis was conducted on the effect of magnetic probe housing material on signal

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<sup>3</sup>FEMM documentation recommends using air for any nonconductive material, in this case substituting polycarbonate

<sup>4</sup>In an effort to save mass, experimental efforts using aluminum typically use a three piece hollow projectile design (with air trapped inside), which had the same outer geometry as the solid polycarbonate projectiles. For the simulated work a solid aluminum body was used, as the permeability of aluminum and air are very similar.

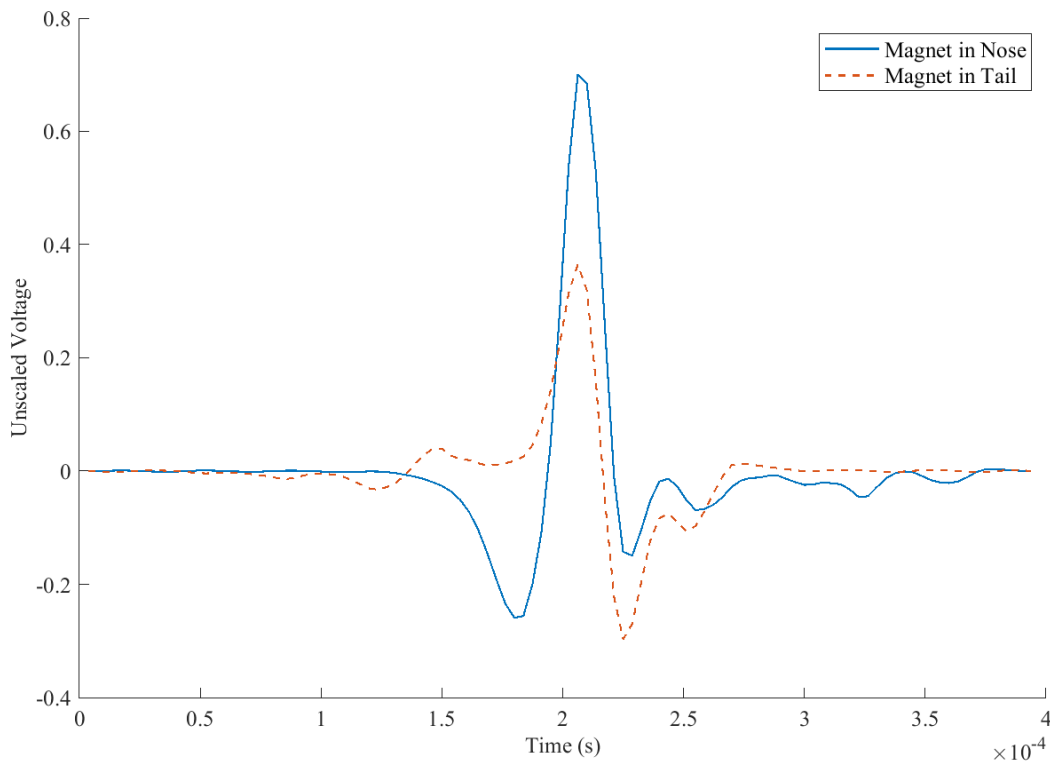


FIGURE A.12: Simulated magnetic probe data for two projectiles made of 416 stainless steel. Projectiles traveling at 1000 m/s through BTRA 651 inserts.

strength. Throughout the frequent heat cycling of repeated ram accelerator testing, it is not uncommon for probes to slowly gain permeability, resulting in an anecdotal loss of signal strength. This is confirmed by Figure A.14, showing the difference between 304 and 416 stainless steel housings.

Considering the results of all simulations, and comparing to real-world experimental data, it is thought that all signals, regardless of baffle geometry, are some form of distorted dipole signal. As baffle geometry is changed magnetic field lines propagate differently, resulting in one peak of the dipole being amplified and the other reduced, with additional peaks beginning to emerge flanking the dominant peak. A slight phase shift was observed in extreme cases. Regardless of the number or arrangement of peaks, projectile transit is thought to be most accurately interpreted by taking the time at the dipole zero crossing.

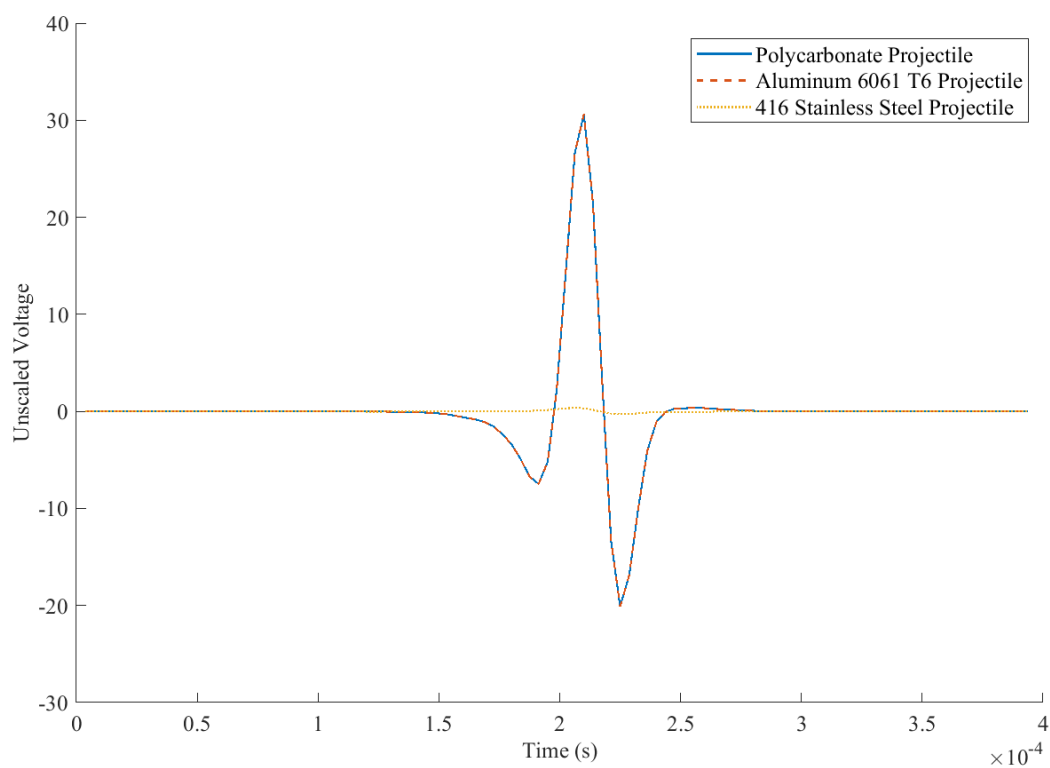


FIGURE A.13: Simulated magnetic probe data for projectiles of varying material permeability. Projectiles traveling at 1000 m/s through BTRA 651 inserts.

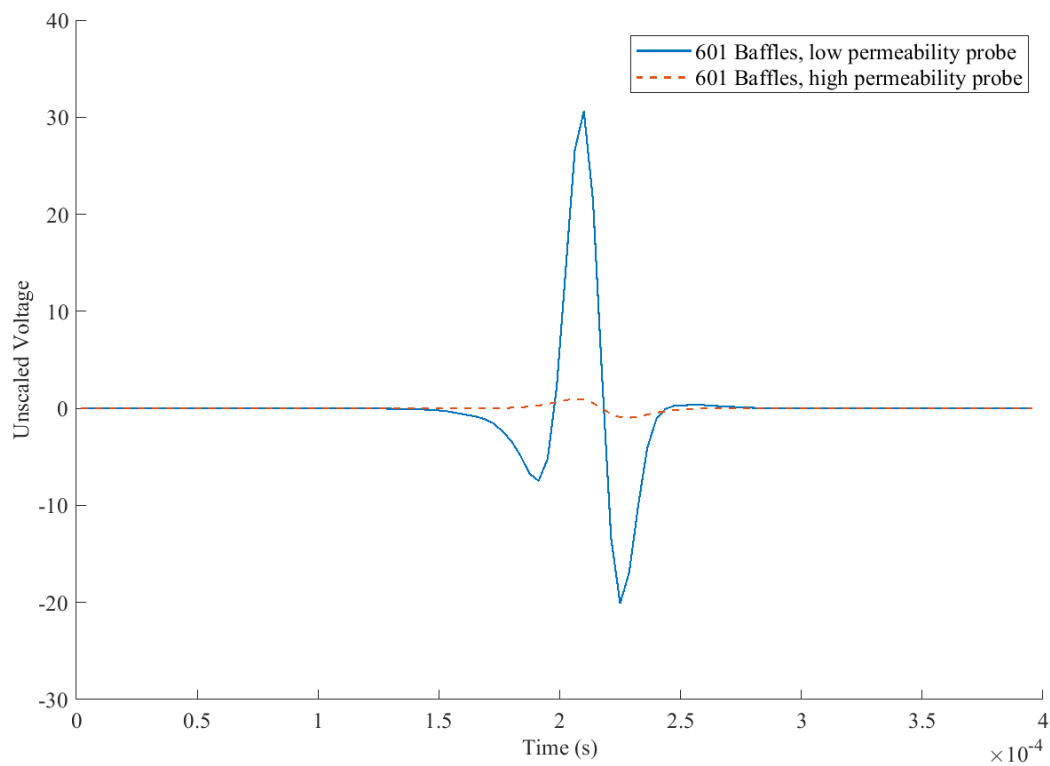


FIGURE A.14: Simulated magnetic probe data for magnetic probes with housings made of 304 (solid blue) and 416 (dashed orange) stainless steel. Projectiles traveling at 1000 m/s through BTRA 651 inserts.

FIGURE B.1: Engineering schematic of the aspherical optics tube used in this study. Dimensions are in inches.



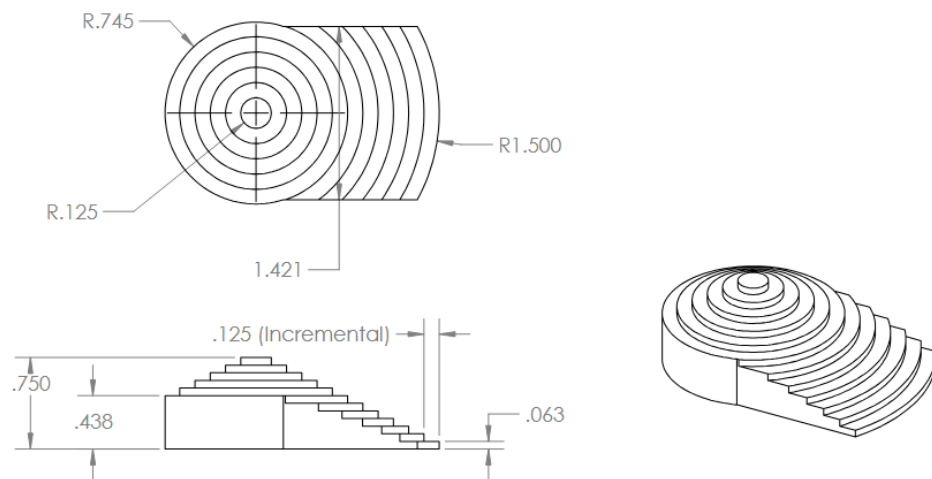


FIGURE B.2: Engineering schematic of the optical calibration tool used in this study. Dimensions are in inches.

## B.2 Modular Baffles

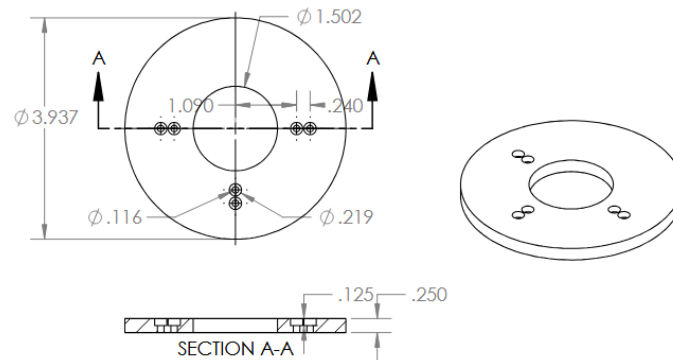


FIGURE B.3: Engineering schematic of the baseplate used in construction of modular baffles. Dimensions are in inches.

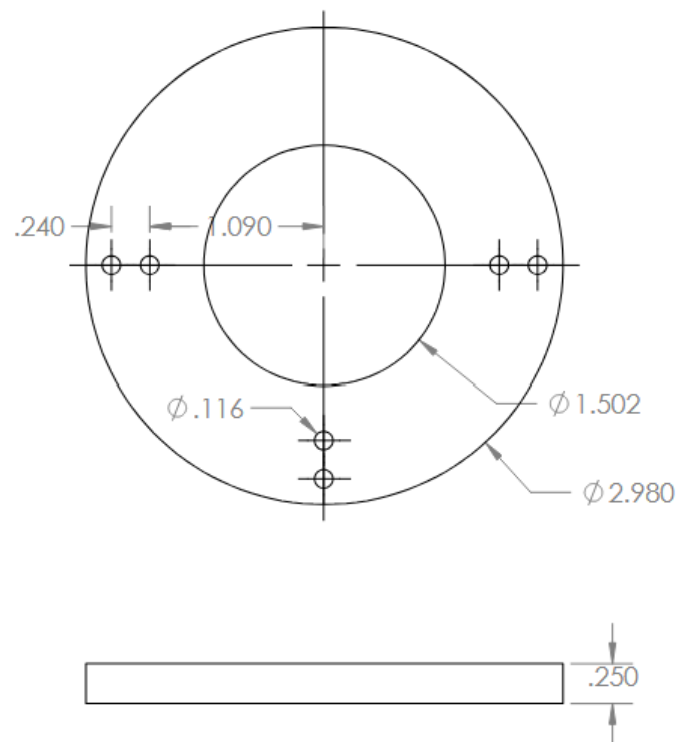


FIGURE B.4: Engineering schematic of the baffle wall used in construction of modular baffles. Different thicknesses are compatible. Dimensions are in inches.

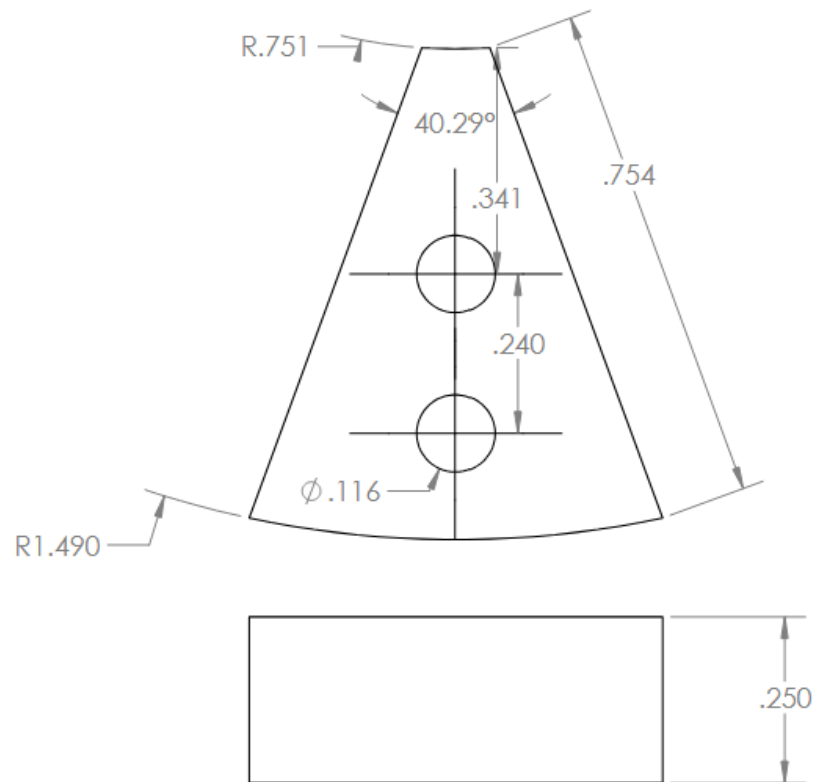


FIGURE B.5: Engineering schematic of the rail wedge used in construction of modular baffles. Different thicknesses are compatible. Dimensions are in inches.

### B.3 Projectile Designs

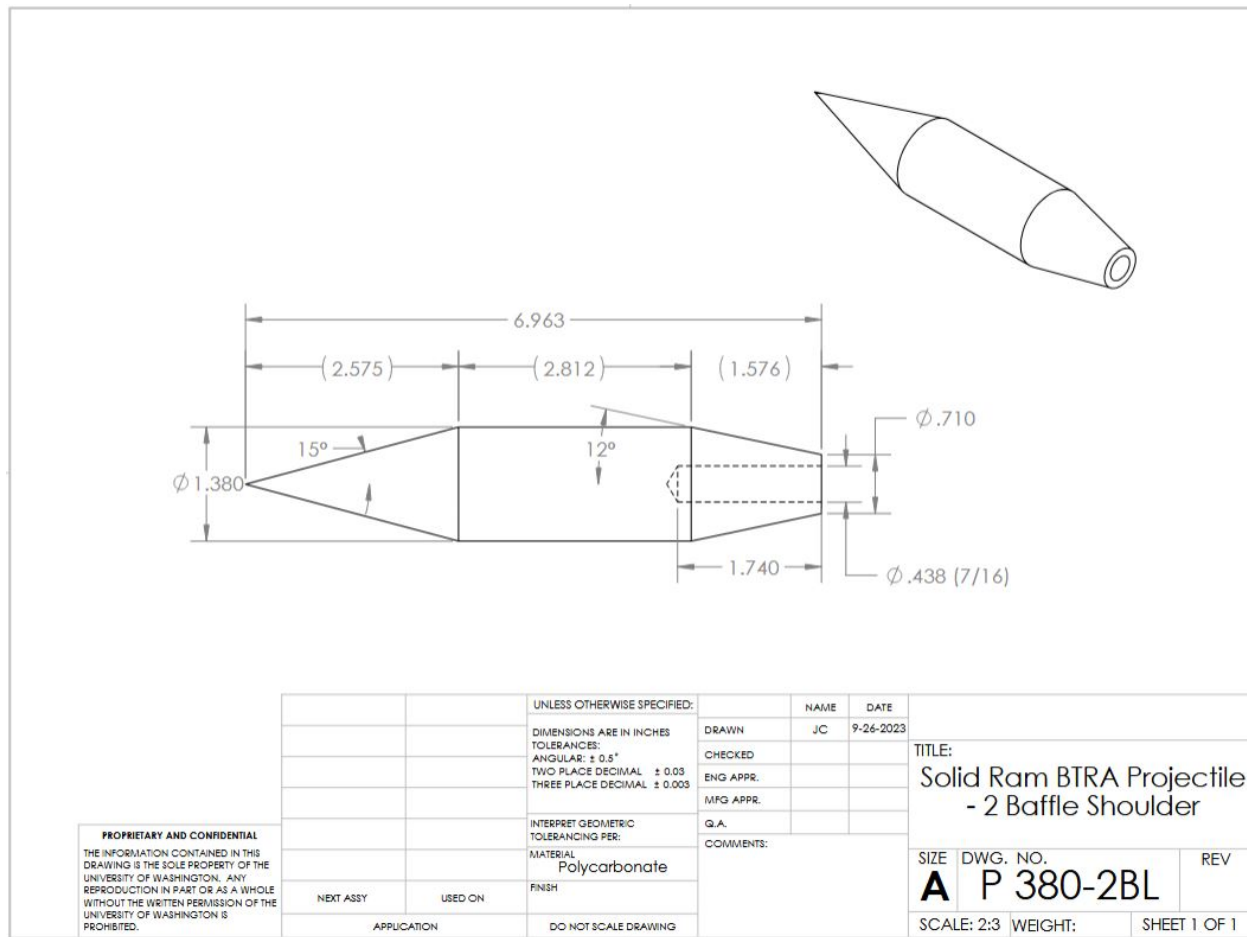


FIGURE B.6: Engineering schematic of a P380 projectile with a shoulder of two standard baffle lengths. Dimensions are in inches.

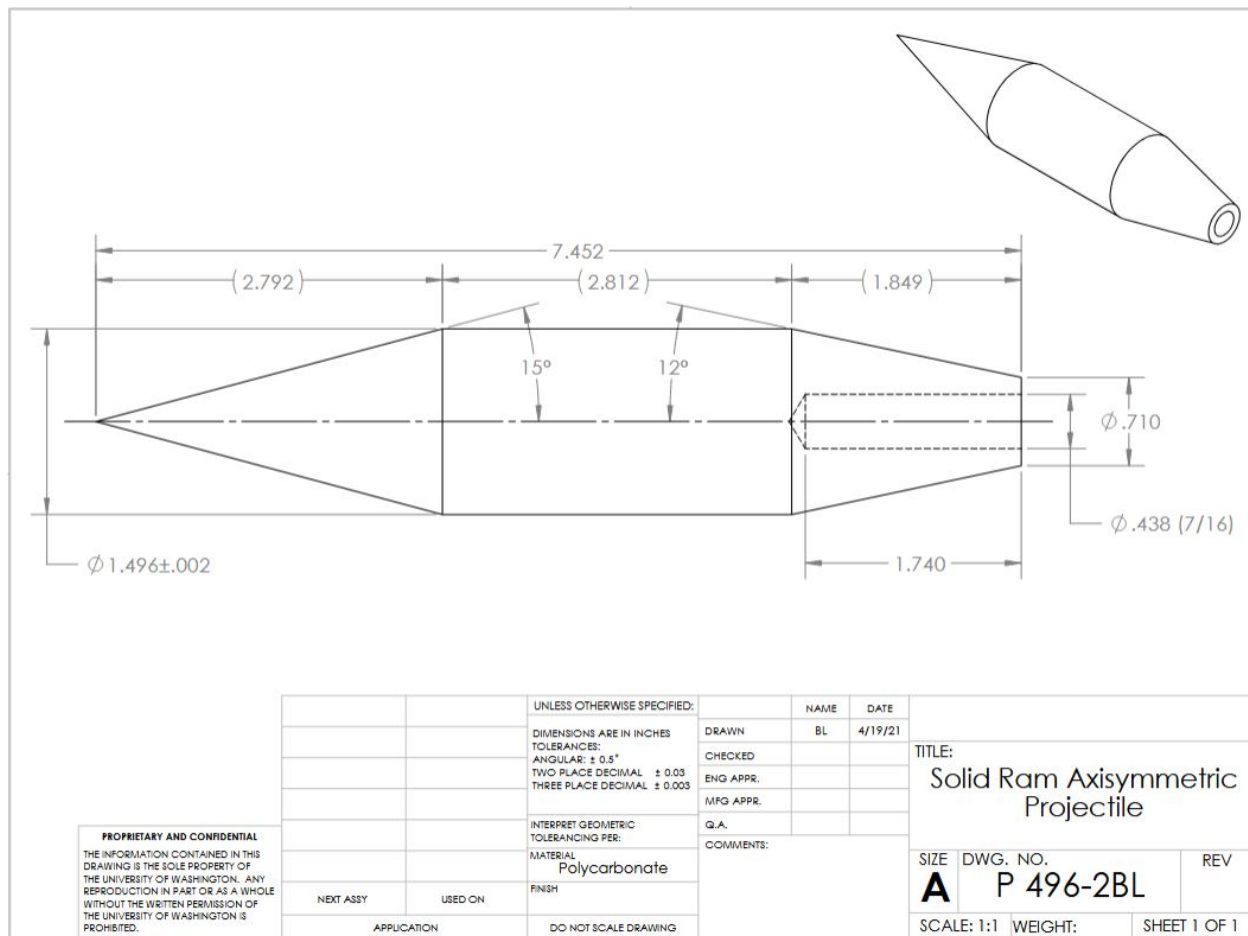


FIGURE B.7: Engineering schematic of a P496 projectile with a shoulder of two standard baffle lengths. Dimensions are in inches.

## B.4 Baffle Designs

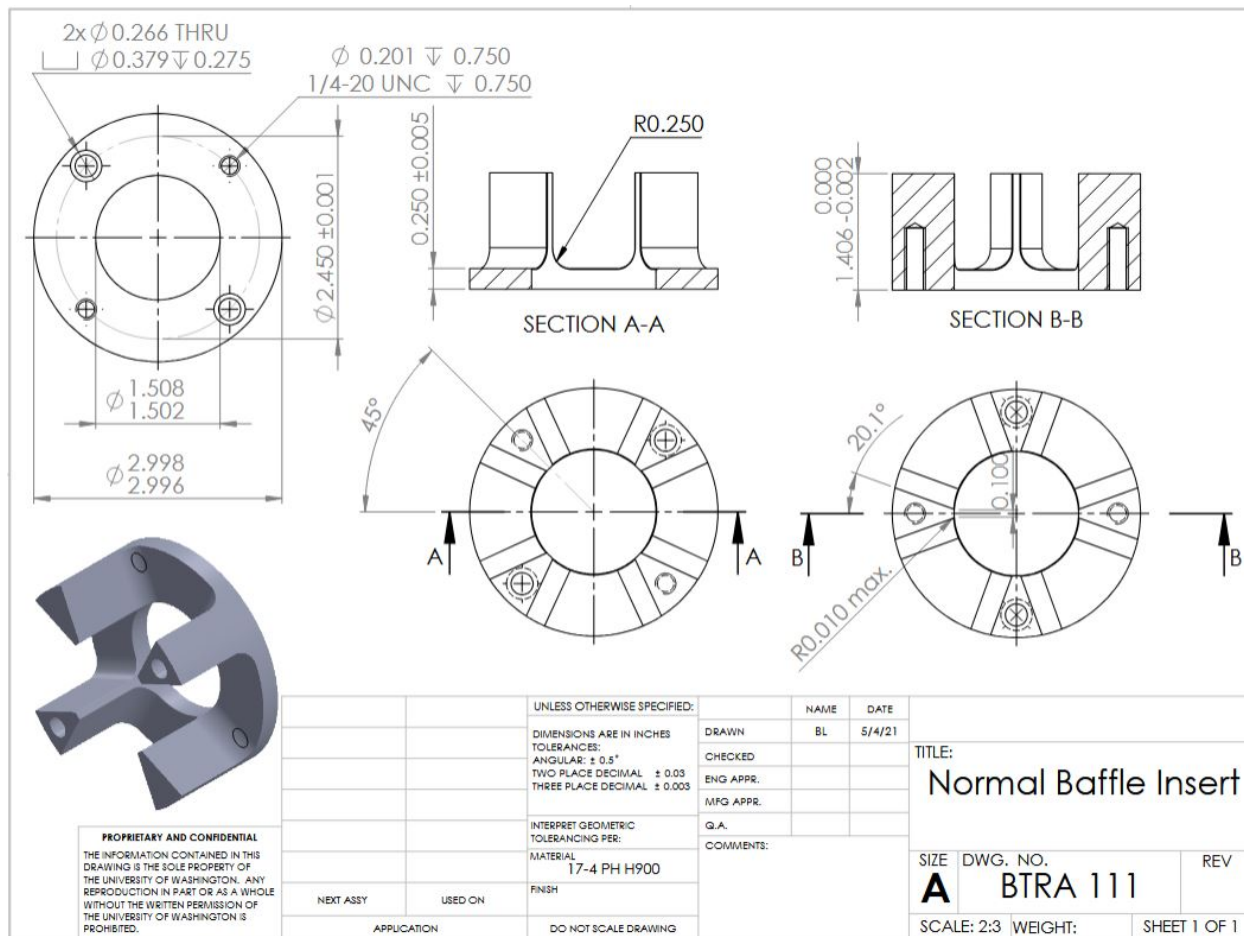


FIGURE B.8: Engineering schematic of a 501 baffle insert. Note that designation has been updated since design, leading to an incorrect part number listed on the drawing. Dimensions are in inches.

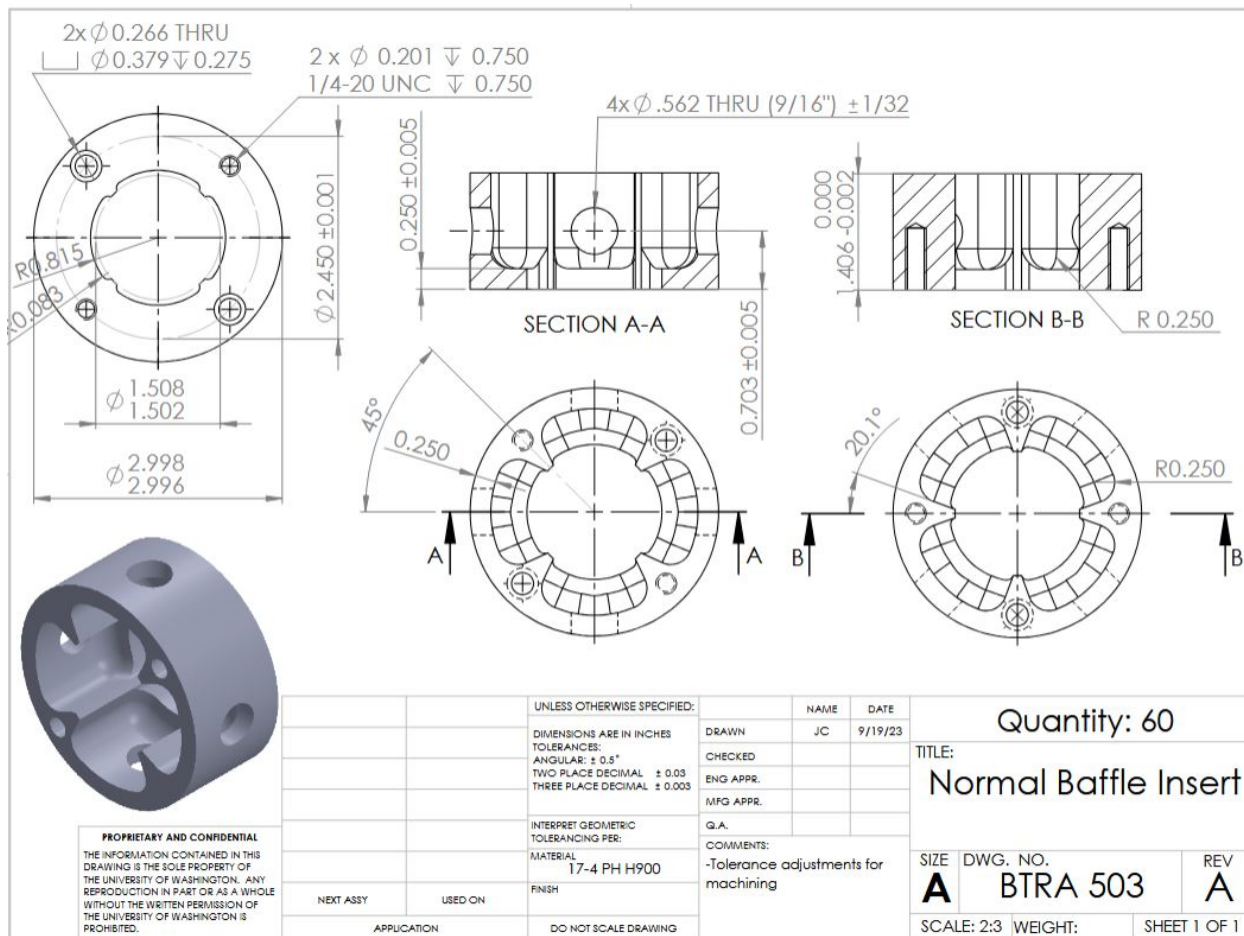


FIGURE B.9: Engineering schematic of a 601 baffle insert. Note that designation has been updated since design, leading to an incorrect part number listed on the drawing. Dimensions are in inches.

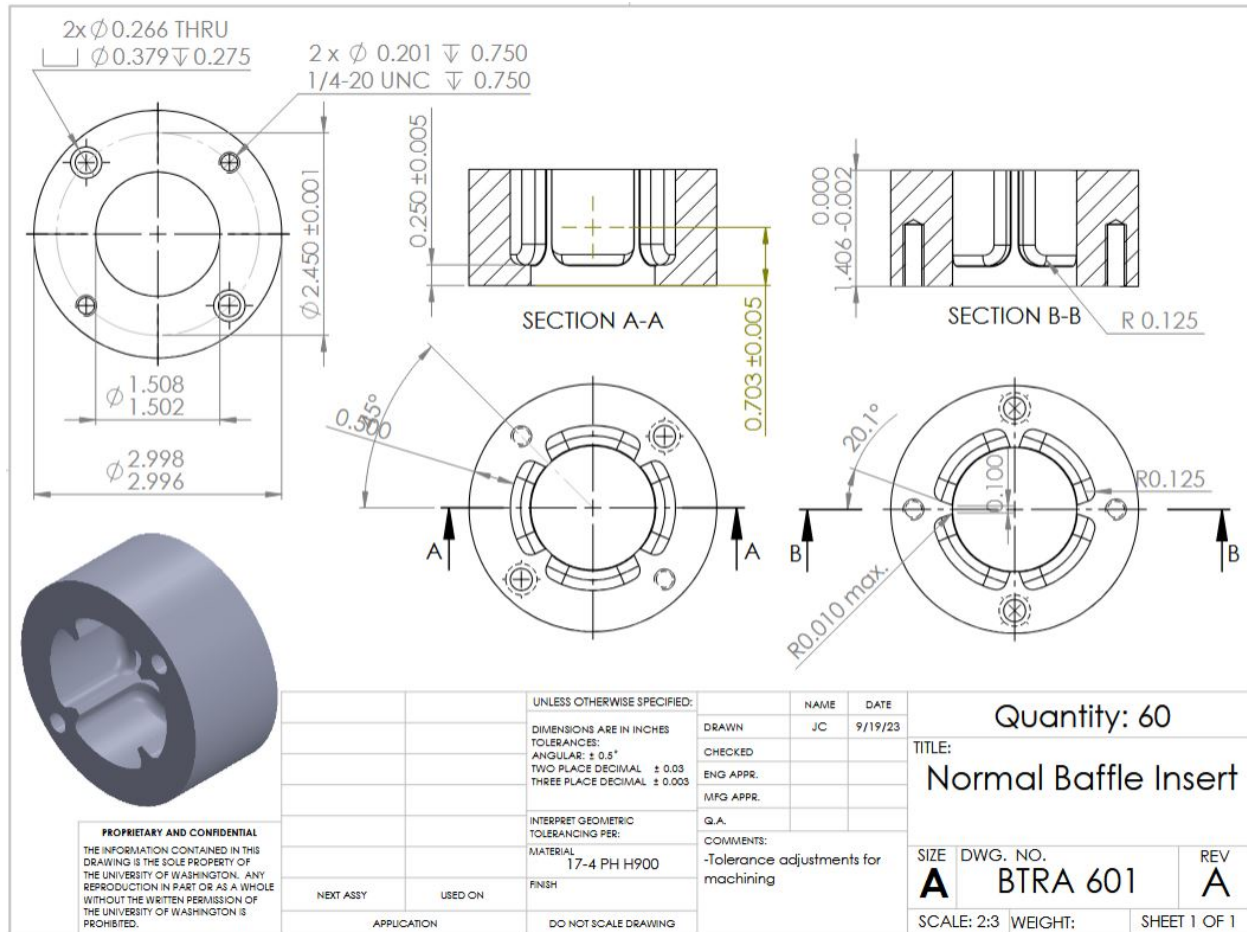


FIGURE B.10: Engineering schematic of a 751 baffle insert. Note that designation has been updated since design, leading to an incorrect part number listed on the drawing. Dimensions are in inches.



## Appendix C

# Reference Scripts

This appendix contains relevant scripts developed as a part of this dissertation study.

### C.1 Light Gas Gun Prediction Algorithm

Below is the algorithm used to predict performance of the UW ram accelerator light gas gun over a series of pressure values, based on the technique developed by Donkelaar [68]. Written in Matlab.

```
1 %% Performance prediction for UW Ram Accelerator Light Gas Gun
2 % script written by J. Correy
3 % method developed by F. Donkelaar
4
5 clc
6 close all
7 clear
8
9 %% Projectile properties
10 % Set the physical properties of the projectile (and obturator/sabot)
11
12 D = 1.5; %diameter, inches - use sealing diameter, whether obturator or ...
    projectile
13 m = .160; %mass, kg - total mass
```

```
14
15 %% Gun configuration
16 % set the operating pressures and gas velocities for the shot
17
18 Prange = flip([3500:100:4500]); % range and intervals of pressures to ...
    sample
19
20 err = 100; % potential error in chamber pressure, psi. Only used if ...
    error bars are enabled
21
22 %Helium
23 a0 = 973; % speed of sound, m/s
24 y = 1.41; % heat capacity ratio, dimensionless
25
26 %Nitrogen
27 % a0 = 354;
28 % y = 1.4;
29
30 %Argon
31 % a0 = 324;
32 % y = 1.67;
33
34 %% Process velocities
35 figure
36 hold on
37
38 vFin = zeros(2,length(Prange)); % create array to store exit velocities ...
    per breech pressure
39 vFin(1,:) = Prange(:);
40 for i = [1:length(Prange)]
41     [vel,x,t,P] = LGGPredic(Prange(i),a0,m,D,y);
42 plot(x,vel,'DisplayName', string(Prange(i)));
```

```
43 xlabel('Barrel length (m)');
44 ylabel('Velocity (m/s)');
45 vFin(2,i) = vel(end);
46
47 legend
48 end
49
50 %% Error bar plots
51 % [velplus,x,t,P] = LGGPredic(Prange(i)+err,a0,m,D,y);
52 % plot(x,velplus,'b');
53 % [velmin,x,t,P] = LGGPredic(Prange(i)-err,a0,m,D,y);
54 % plot(x,velmin,'b');
55 %end
56
57 % realign Y axis scale to allow for easier plot reading
58 set(gca,'YAxisLocation','right')
59
60 function [vel,x,t,P] = LGGPredic(P0,a0,m,D,y)
61
62 fudgefactor = 0.95; % use if system shows consistent over/under ...
    performance. Set to 1 if nominal operation
63
64 D=D*0.0254; % convert diameter to m
65 P0=P0*6894.76; % convert bank pressure to N/m2
66 dt=0.00001; % timestep, s - set to suffuciently small increment
67 tf=0.1; % cutoff timestep, s - used only if overflow error in for loop
68 t=(0:dt:tf);
69 x=zeros(size(t));
70 P=x; % pressure array, N/m^2
71 vel=x; % velocity array, m/s
72 acc=x; % acceleration array, m/s^2
73 for i=1:length(x)-1
```

```

74     P(i)=P0*(1-vel(i)/(2*a0/(y-1)))^(2*y/(y-1));
75     acc(i+1)=P(i)*pi*0.25*D^2/m;
76     vel(i+1)=vel(i)+dt*acc(i);
77     x(i+1)=x(i)+vel(i)*dt;
78     if x(i) > 8 % adjust to match launch tube length, m
79         break
80     end
81 end
82 vel(:)=vel(:).*fudgefactor;
83 % trim excess array entries
84 vel([i:end])=[];
85 P([i:end])=[];
86 x([i:end])=[];
87 t([i:end])=[];

```

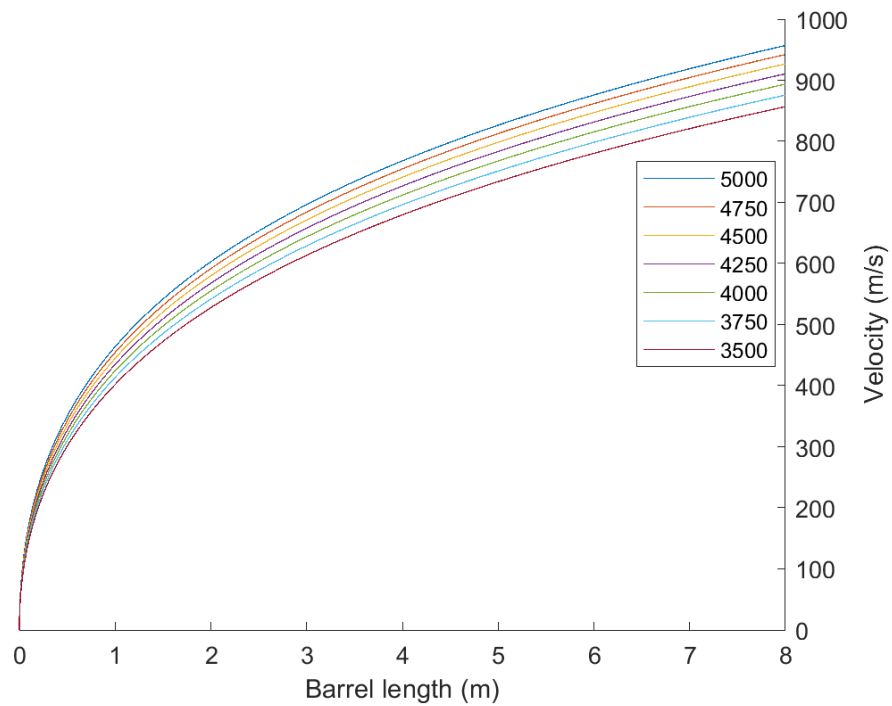


FIGURE C.1: Expected velocities for a 200 gram projectile. Breech pressures in psi.

## C.2 Image Distortion Processing

Below is a script and function to correct distortion generated from an imperfect aspherical optics tube. Values in the `ImgCorrection.m` function must be set using reference measurements, as shown in Fig. C.2. Written in Matlab.

```
1 %% Bulk image correction for aspheric shadowgraph imaging
2 % script written by J Correy
3
4 shotName = 'OBI004'; % update to match shot being processed
5
6 %set animation parameters
7 gifName = append(shotName, '.gif');
8 frameLength = .0002;
9
10 %read frames
11 frames = dir(fullfile(shotName, 'Original'));
12 numFrames = numel(frames);
13 %process individual frames. Will loop until it runs out of frames
14 for i = 1:numFrames
15     %process frames by calling correction script
16     filepath = fullfile(frames(i).folder, frames(i).name);
17     I = imread(strcat(shotName, '\Original\Frame ...
18         (' , string(numFrames-i), ').png'));
19     J = ImgCorrection(I);
20     imwrite(J, strcat(shotName, '\Scaled\Frame (' , string(i), ').png'))
21     %create animation
22     if i == 1
23         imwrite(J, gifName, 'gif', 'LoopCount', Inf, 'DelayTime', frameLength)
24     else
25         imwrite(J, gifName, 'gif', 'WriteMode', 'append', 'DelayTime', frameLength);
```

```
25     end
26 end
```

```
1  %% Image transformation script
2  % script used to de-distort images captured through imperfect lenses
3  % populate based on tare image
4  % written by J Correy
5
6  function [J] = ImgCorrection(I)
7
8  % measure source image dimensions
9  xWidth = length(I(1,:)); %pixels
10 yHeight = length(I(:,1));
11
12 % set x scaling. Enter distance in pixels and inches between known points
13 dpiX = 180/1;
14
15 % Measure band heights: measure in pixels the distance from the top to ...
    the measurement points, with the final being the total image height
16
17 yBands = [0, 4, 7, 13, 25, 44, 75, 115, 180, 237]; %measured in pixels
18
19 % enter the proper heights for the image. These are the real-world ...
    distances
20 yCorrected = [1.375, 1.25, 1.125, 1, .875, .75, .625, .5, .375, .25];
21 % adjust to be measured from top
22 yCorrected = -1*(yCorrected-yCorrected(1));
23
24 % set DPI. Recommend first stripe of known size.
25 dpiY = (yBands(end-1)-yBands(end-2))/(yCorrected(end-1)-yCorrected(end-2));
26
```

```
27 % calculated final pixel positions
28 yCorrectedPixels = yCorrected*dpiY;
29
30 dpiCorrected = dpiY/dpiX;
31
32 % populate initial matrix
33 pointsInitial = ...
    [zeros(length(yBands),2);xWidth*(1+zeros(length(yBands),2))];
34 pointsInitial(:,2) = yHeight/yBands(end)*[yBands';yBands'];
35
36 % populate ideal matrix
37 pointsFinal = ...
    [zeros(length(yBands),2);xWidth*dpiCorrected*(1+zeros(length(yBands),2))];
38 pointsFinal(:,2) = ...
    yHeight/yBands(end)*[yCorrectedPixels';yCorrectedPixels'];
39
40 % create transformation matrix
41 tform = ...
    images.geotrans.PiecewiseLinearTransformation2D(pointsInitial,pointsFinal);
42
43 % transform image
44 J = imwarp(I,tform,"cubic");
```

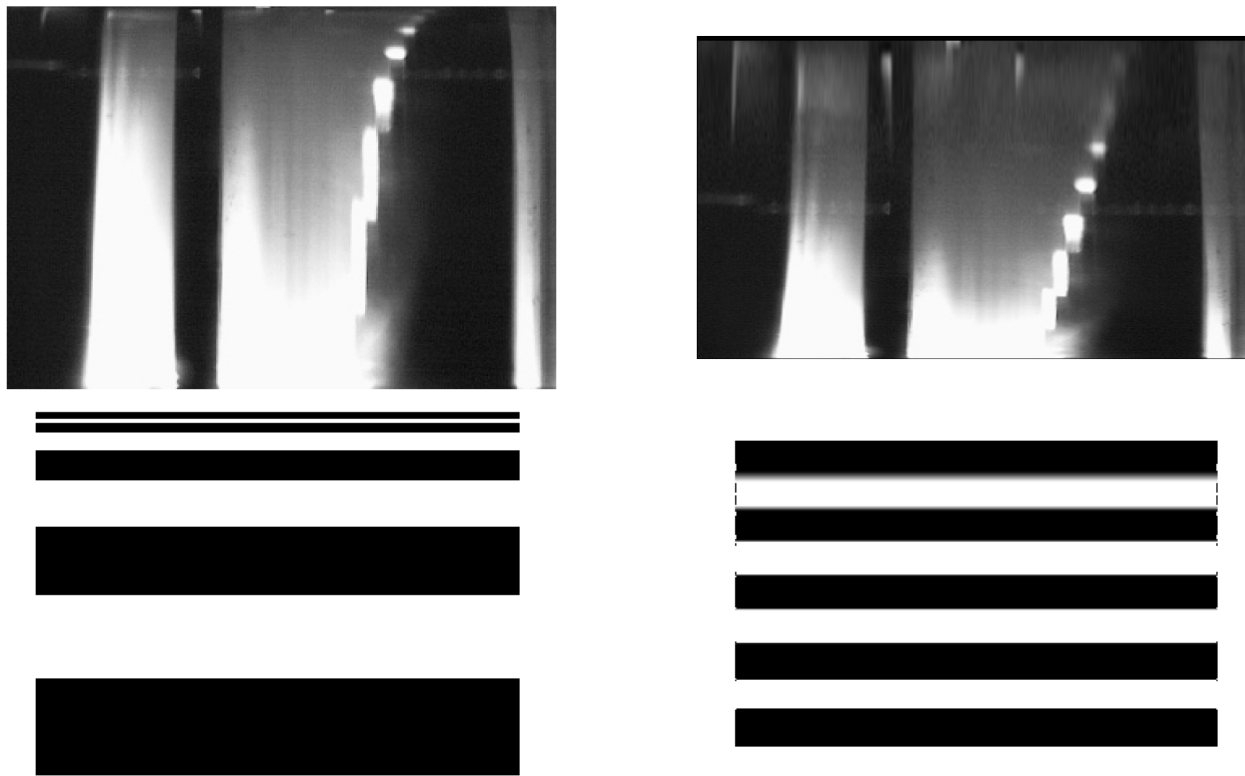


FIGURE C.2: Top: Reference image, shadowgraph optical apparatus with calibration tool inserted. Raw image on left, scaled on right. Bottom: Reference stripes, measured from calibration tool, demonstrating image scaling.

## C.3 Scripts for Magnetic Field Simulation

Below is a collection of scripts to simulate the magnetic probe signal detected from BTRA experiments, as discussed in Appendix A. Written in Matlab, requires Image Processing Toolbox and FEMM 4.2 to be installed with correct pathways.

### C.3.1 Simulation Controller Script

```
1 close all
2 clear
3 clc
```



```
4
5 %% Simulation Settings
6 simName = 'matlabWIP.fem';
7 simImageName = 'ProjMatAirTail601Slow';
8 simSteps = 200; %projectile step size refinement. Must be >numBaffles. ...
    More than -200 can screw up the image exports
9 runRender = 1; %Requires Image Processing Toolbox. set to 0 to skip ...
    field rendering
10 plotRatio = 1.618; %x/y ratio for plot exports
11
12 %% Establish Problem Parameters
13 %sets problem information
14
15 inchesToMeters = 0.0254;
16
17 %Projectile and magnet
18 projVel = 500; %Projectile Velocity, m/s
19 projDia = 1.38; %set projectile Outer Diameter (inches). MUST BE LESS ...
    THAN BAFFLE BORE (1.5)!!!
20 projShoulder = 2; %set projectile shoulder length (baffles)
21 projNoseAngle = 15; %set projectile nose angle (degrees)
22 projTailAngle = 12; %set projectile tail angle (degrees)
23 projBaseDia = 0.710; %set diameter at truncated base (inches)
24 projMat = 'Air'; %set projectile material (only actually matters if ...
    magnetic) 'Aluminum, 6061-T6', '416 Stainless Steel', etc. Type ...
    'Air' for any insulator (like polycarbonate)
25 projMagPos = 'Tail'; %set whether the magnet is embedded in the 'Nose' ...
    or 'Tail' of the projectile
26
27 %Probe
28 probeType = 'Long'; %set to long or short
29
```

```
30 %Baffle
31 baffleType = '601'; %specify baffle type
32 numBaffles = 21; %total number of baffles simulated. Must be odd
33 baffleLength = 1.406; %axial length of baffle, inches
34 probeBaffleOverride = 0; %set to 1 for different baffle geometry at the ...
    probe station
35 probeBaffleType = 'PortBaffle501'; %overrides baffle geometry at probe ...
    station
36
37 %Magnet - I'm still debugging some issues with the magnets, so don't ...
    set above 1
38 numMags = 1; %Number of magnets
39
40 %% Establish FEMM Environment
41 openfemm
42 newdocument(0)
43 mi_probdef(0, 'inches', 'axi', 1E-8, 0, 30, 0)
44 mi_zoom(-2, -2, 2, 8)
45
46 %Materials library
47 mi_getmaterial('Air')
48
49 %% Create baffle geometry
50 if strcmp(baffleType, '601')
51     Baffles601
52 end
53 if strcmp(baffleType, '501')
54     Baffles501
55 end
56 if strcmp(baffleType, '602')
57     Baffles602
58 end
```

```
59 if strcmp(baffleType, '502')
60     Baffles502
61 end
62 if strcmp(baffleType, '751')
63     Baffles751
64 end
65 if strcmp(baffleType, '751Rails')
66     Rails751_Seed % populates the necessary geometry to generate the port
67 end
68 if strcmp(baffleType, 'Smooth')
69     Smoothbore_Seed % populates the necessary geometry to generate the port
70 end
71
72 if probeBaffleOverride == 1
73     if strcmp(probeBaffleType, '501')
74         PortBaffle501
75     end
76 end
77
78 %% Create probe geometry
79 if strcmp(probeType, 'Long')
80     ProbeLong
81 end
82 if strcmp(probeType, 'Short')
83     ProbeShort
84 end
85 if strcmp(probeType, 'Smooth')
86     ProbeSmooth
87 end
88
89 %% Correct geometry if rails
90 if strcmp(baffleType, '751Rails')
```

```
91     Rails751 % populates rails, analagous to 2" smooth bore
92 end
93 if strcmp(baffleType, 'Smooth')
94     Smoothbore % populates rails, analagous to 2" smooth bore
95 end
96
97 %% Create tube wall
98 TubeWall
99
100 %% Create boundary
101 Boundary
102
103 %% Add magnet
104 Magnet
105
106 %% Add Projectile
107 Projectile
108
109 %% Move projectile and mag into region
110
111 mi_clearselected();
112 mi_selectgroup(2);
113 mi_movetranslate(0,totalProjLength)
114 projBase = projOutline(1,2);
115
116 DrawProjectile
117 mi_clearselected();
118 mi_selectgroup(5);
119 %mi_saveas(simName)
120
121 %% Simulate
122 mi_saveas(simName)
```

```
123 closefemm
124
125 iter=1;
126 currPos = 0;
127 Bn = [0;0;0];
128
129 openfemm
130 opendocument(simName)
131 Run_Simulation %run initial simulation to set up variables
132 moveDistance = totalProjLength; %set initial condition far from boundaries
133
134 currPos = moveDistance;
135
136 transitDistance = ((numBaffles)*baffleLength-2*totalProjLength);
137 probePos = ((numBaffles-1)/2*baffleLength);
138
139 moveDistance = numBaffles*baffleLength/simSteps;
140 centerpoint = 1;
141 closePass = probePos/2;
142 while currPos - totalProjLength < transitDistance
143     iter=iter+1;
144     MoveMagnet
145     MoveProjectile
146     Run_Simulation
147     currPos = currPos+moveDistance;
148     Bn(3,iter) = currPos;
149     currPass = abs(currPos - probePos);
150     if (currPass<closePass)
151         closePass = currPass;
152         centerpoint = iter;
153     end
154 end
```

```
155
156 %%convert x positions to times
157 correctedData = [flip(Bn(1,:));flip(Bn(3,:))];
158 correctedData(2,:) = inchesToMeters*(currPos-correctedData(2,:))/projVel;
159
160 %% Plot Results
161 fluxPlot = figure;
162 plot(correctedData(2,2:iter-1),correctedData(1,2:iter-1))
163 xlabel('Time (seconds)')
164 ylabel('Bn (Teslas)')
165 title('Simulated Magnetic Field (normal)')
166 subtitle(append(baffleType, ' Baffles'))
167 set(gcf, 'units', 'pixels', 'position', [10,100,imageHeight*plotRatio,imageHeight])
168 saveas(fluxPlot, append(simImageName, ' Flux.png'))
169
170 %% Simulate Probe Results
171 VirtualProbe
172
173 %% Create Render and Move Images to New Folder
174 if runRender == 1
175     FileOrganizer
176 end
177
178 %% Save EMF data
179 fileName = strcat(simImageName, '.csv');
180 emfTime = [correctedData(2,2:iter-1);EMF(1:end-1)];
181 writematrix(emfTime,fileName)
```

### C.3.2 Simulation Calls

**Baffles601.m** is one of many scripts that may be designed in order to populate the baffle inserts in the magnetic simulations. It is presented here as an example for designing specific insert configurations.

```

1  %create 601 baffles
2
3  %% Baffle Specifications
4  baffleOD = 3; %Outer diameter of baffle, inches
5  baffleBore = 1.5; %Bore size of baffle, inches
6  baffleLength = 1.406; %Baffle length (axial), inches
7  baffleHole = 0.562; %Hole/Slot diameter, inches
8  baffleSection = 0.25; %Thickness of planar baffle piece, inches
9  baffleWall = 0.25; %Thickness of outer baffle wall, inches
10 baffleMat = '416 Stainless Steel'; %Baffle material, or nearest ...
    (magnetically) in FEMM library
11 mi_getmaterial(baffleMat)
12
13 %% Generate First Baffle
14 %generates "center" baffle, set so that the probe is at y=0
15 mi_drawpolygon([baffleOD/2-baffleWall,-(baffleHole/2);
16                baffleOD/2-baffleWall,-(baffleLength/2-baffleSection);
17                baffleBore/2,-(baffleLength/2-baffleSection);
18                baffleBore/2,-(baffleLength/2);
19                baffleOD/2,-(baffleLength/2);
20                baffleOD/2,-(baffleHole/2)]);
21 mi_drawpolygon([baffleOD/2-baffleWall,(baffleHole/2);
22                baffleOD/2-baffleWall,(baffleLength/2);
23                baffleOD/2,(baffleLength/2);
24                baffleOD/2,(baffleHole/2)]);

```

```
25
26 %% Select Nodes to Copy
27 mi_selectnode(baffleOD/2-baffleWall,-(baffleHole/2));
28 mi_selectnode(baffleOD/2-baffleWall,-(baffleLength/2-baffleSection));
29 mi_selectnode(baffleBore/2,-(baffleLength/2-baffleSection));
30 mi_selectnode(baffleBore/2,-(baffleLength/2));
31 mi_selectnode(baffleOD/2,-(baffleLength/2));
32 mi_selectnode(baffleOD/2,-(baffleHole/2));
33 mi_selectnode(baffleOD/2-baffleWall,(baffleHole/2));
34 mi_selectnode(baffleOD/2-baffleWall,(baffleLength/2));
35 mi_selectnode(baffleOD/2,(baffleLength/2));
36 mi_selectnode(baffleOD/2,(baffleHole/2));
37 mi_setgroup(1);
38
39 mi_selectsegment(baffleOD/2-baffleWall,-(baffleHole/2-.01));
40 mi_setgroup(1);
41 mi_selectsegment(baffleOD/2-baffleWall-.01,-(baffleLength/2-baffleSection));
42 mi_setgroup(1);
43 mi_selectsegment(baffleBore/2,-(baffleLength/2-baffleSection)-.01);
44 mi_setgroup(1);
45 mi_selectsegment(baffleBore/2+.01,-(baffleLength/2));
46 mi_setgroup(1);
47 mi_selectsegment(baffleOD/2,-(baffleLength/2)+.01);
48 mi_setgroup(1);
49 mi_selectsegment(baffleOD/2-.01,-(baffleHole/2));
50 mi_setgroup(1);
51
52 mi_selectsegment(baffleOD/2-baffleWall+.01,(baffleHole/2));
53 mi_setgroup(1);
54 mi_selectsegment(baffleOD/2-baffleWall,(baffleLength/2)-.1);
55 mi_setgroup(1);
56 mi_selectsegment(baffleOD/2-.01,(baffleLength/2));
```



```

57 mi_setgroup(1);
58 mi_selectsegment(baffleOD/2, (baffleHole/2) - .01);
59 mi_setgroup(1);
60
61 %% Assign Baffle Materials
62 mi_addblocklabel((baffleOD/2 - baffleWall + baffleOD/2)/2, ...
    (baffleHole/2 + baffleLength/2)/2);
63 mi_selectlabel((baffleOD/2 - baffleWall + baffleOD/2)/2, ...
    (baffleHole/2 + baffleLength/2)/2);
64 mi_setblockprop(baffleMat, 1, 0, 0, 0, 1, 0)
65
66 mi_addblocklabel((baffleOD/2 - baffleWall + baffleOD/2)/2, ...
    - (baffleHole/2 + baffleLength/2)/2);
67 mi_selectlabel((baffleOD/2 - baffleWall + baffleOD/2)/2, ...
    - (baffleHole/2 + baffleLength/2)/2);
68 mi_setblockprop(baffleMat, 1, 0, 0, 0, 1, 0)
69
70 %% Translate Baffles
71 %generates further baffles
72 mi_selectgroup(1)
73 mi_copytranslate(0, baffleLength, numBaffles-1)

```

**ProbeLong.m** establishes the geometry and condition for a probe which extends 0.5" into the baffle chamber.

```

1 % create long magprobes
2
3 %% Probe Specifications
4 %only part that extends into tube
5 baffleOD = 3; %Outer diameter of baffle, inches
6 probeLength = 0.75; %probe length into tube, inches

```

```

7 probeBase = 0.060; %probe face thickness, inches
8 probeOD = 0.245; %probe neck OD, inches
9 probeID = 0.125; %probe neck ID, inches
10 probeShoulderOD = 0.320; %probe/tube seal diameter, inches
11 probeShoulderLength = 2.385-probeLength; %length between probe neck and ...
    threads, inches
12 wallShoulder = 0.25; %length of wall shoulder that catches probe, inches
13
14 probeMat = '304 Stainless Steel'; %set probe material, or nearest material
15 mi_getmaterial(probeMat)
16
17 %mi_clearselected();
18
19 %% Draw Probe
20 %draws in-tube section of probe centered at y=0
21 mi_drawpolygon([baffleOD/2+wallShoulder,-probeShoulderOD/2;
22                 baffleOD/2+wallShoulder,-probeOD/2;
23                 baffleOD/2+wallShoulder-probeLength,-probeOD/2;
24                 baffleOD/2+wallShoulder-probeLength,probeOD/2;
25                 baffleOD/2+wallShoulder,probeOD/2;
26                 baffleOD/2+wallShoulder,probeShoulderOD/2;
27                 baffleOD/2+wallShoulder+probeShoulderLength,probeShoulderOD/2;
28                 baffleOD/2+wallShoulder+probeShoulderLength,probeID/2;
29                 baffleOD/2+wallShoulder-probeLength+probeBase,probeID/2;
30                 baffleOD/2+wallShoulder-probeLength+probeBase,-probeID/2;
31                 baffleOD/2+wallShoulder+probeShoulderLength,-probeID/2;
32                 baffleOD/2+wallShoulder+probeShoulderLength,-probeShoulderOD/2]);
33
34 %% Select Sensor Nodes
35 mi_selectnode(baffleOD/2-probeLength+probeBase+wallShoulder,probeID/2);
36 mi_selectnode(baffleOD/2-probeLength+probeBase+wallShoulder,-probeID/2);
37 mi_setgroup(3)

```

```

38
39 %% Set Probe Material
40 mi_clearselected()
41 mi_addblocklabel((baffleOD+probeShoulderLength)/2+wallShoulder,-probeOD/2);
42 mi_selectlabel((baffleOD+probeShoulderLength)/2+wallShoulder,-probeOD/2);
43 mi_setblockprop(probeMat,1,0,0,0,0,0)
44
45 %% Select Nodes
46 mi_selectnode(baffleOD/2+wallShoulder,-probeShoulderOD/2);
47 mi_selectnode(baffleOD/2+wallShoulder,-probeOD/2);
48 mi_selectnode(baffleOD/2-probeLength+wallShoulder,-probeOD/2);
49 mi_selectnode(baffleOD/2-probeLength,probeOD/2);
50 mi_selectnode(baffleOD/2+wallShoulder,probeOD/2);
51 mi_selectnode(baffleOD/2+wallShoulder,probeShoulderOD/2);
52 mi_selectnode(baffleOD/2+probeShoulderLength+wallShoulder,probeShoulderOD/2);
53 mi_selectnode(baffleOD/2+probeShoulderLength+wallShoulder,probeID/2);
54 mi_selectnode(baffleOD/2-probeLength+probeBase+wallShoulder,probeID/2);
55 mi_selectnode(baffleOD/2-probeLength+probeBase+wallShoulder,-probeID/2);
56 mi_selectnode(baffleOD/2+probeShoulderLength+wallShoulder,-probeID/2);
57 mi_selectnode(baffleOD/2+probeShoulderLength+wallShoulder,-probeShoulderOD/2);
58
59 %% Move Probe to Center
60
61 mi_movetranslate(0,(numBaffles-1)/2*baffleLength)
62 mi_clearselected()

```

**TubeWall.m** creates the shell tube boundary, with a hole for the probe.

```

1 %create tube wall
2
3 %% Wall Specifications

```

```

4 wallOD = 6; %Wall outer diameter, inches
5 wallID = baffleOD; %Wall inner diameter, inches
6 holeSize = probeShoulderOD; %Diameter of instrument holes
7 wallMat = '416 Stainless Steel'; %Wall material, or nearest ...
    (magnetically) in FEMM library
8 mi_getmaterial(wallMat)
9
10 %% Draw Wall
11 mi_drawpolygon([wallID/2,-baffleLength/2;
12                wallOD/2,-baffleLength/2;
13                wallOD/2, ...
                    numBaffles/2*baffleLength-holeSize/2-baffleLength/2;
14                wallID/2+wallShoulder, ...
                    numBaffles/2*baffleLength-holeSize/2-baffleLength/2;
15                wallID/2+wallShoulder, ...
                    numBaffles/2*baffleLength-holeSize/2-baffleLength/2+ ...
                    (probeShoulderOD-probeOD)/2;
16                wallID/2, ...
                    numBaffles/2*baffleLength-holeSize/2-baffleLength/2+ ...
                    (probeShoulderOD-probeOD)/2;
17                ]);
18
19 mi_drawpolygon([wallOD/2, ...
                numBaffles/2*baffleLength+holeSize/2-baffleLength/2;
20                wallID/2+wallShoulder, ...
                    numBaffles/2*baffleLength+holeSize/2-baffleLength/2;
21                wallID/2+wallShoulder, ...
                    numBaffles/2*baffleLength+holeSize/2-baffleLength/2- ...
                    (probeShoulderOD-probeOD)/2;
22                wallID/2, ...
                    numBaffles/2*baffleLength+holeSize/2-baffleLength/2- ...
                    (probeShoulderOD-probeOD)/2;

```

```

23         wallID/2, numBaffles*baffleLength-baffleLength/2;
24         wallOD/2, numBaffles*baffleLength-baffleLength/2])
25
26 %% Add Wall Material
27 mi_addblocklabel((wallID/2+wallOD/2)/2, ...
    (numBaffles/2*baffleLength-holeSize/2-baffleLength/2)/2);
28 mi_selectlabel((wallID/2+wallOD/2)/2, ...
    (numBaffles/2*baffleLength-holeSize/2-baffleLength/2)/2);
29 mi_setblockprop(wallMat,1,0,0,0,0,0)
30
31 mi_addblocklabel((wallID/2+wallOD/2)/2, ...
    (numBaffles*baffleLength+holeSize/2- ...
    baffleLength+numBaffles/2*baffleLength+holeSize/2-baffleLength)/2);
32 mi_selectlabel((wallID/2+wallOD/2)/2, ...
    (numBaffles*baffleLength+holeSize/2- ...
    baffleLength+numBaffles/2*baffleLength+holeSize/2-baffleLength)/2);
33 mi_setblockprop(wallMat,1,0,0,0,0,0)

```

**Boundary.m** creates an outer boundary of air to fully enclose the simulation region and establish boundary conditions.

```

1  %set boundary parameters
2  boundOffsetZ = 0; %vertical boundary offset
3  boundOffsetR = 1; %radial boundary offset
4
5  %% Draw boundary
6
7  mi_drawpolygon([0,-baffleLength/2-boundOffsetZ;
8                wallOD/2+boundOffsetR,-baffleLength/2-boundOffsetZ;
9                wallOD/2+boundOffsetR,(numBaffles-.5)*baffleLength+boundOffsetZ;
10               0,(numBaffles-.5)*baffleLength+boundOffsetZ])

```

```

11
12 %% Add outside material
13
14 mi_addblocklabel(wallOD/2+boundOffsetR/2,0);
15 mi_selectlabel(wallOD/2+boundOffsetR/2,0);
16 mi_setblockprop('Air',1,0,0,0,0,0)
17
18 if boundOffsetZ == 0
19     mi_addblocklabel(.1,0);
20     mi_selectlabel(.1,0);
21     mi_setblockprop('Air',1,0,0,0,0,0)
22 end
23
24 %% Create Boundary Properties
25
26 c0 = 0;
27 c1 = 0;
28 mi_addboundprop('ABC',0,0,0,0,0,0,c0,c1,'Mixed')
29
30 %% Assign Boundary Properties
31
32 mi_clearselected()
33 mi_selectsegment(wallOD/2+boundOffsetR/2, -baffleLength/2-boundOffsetZ);
34 mi_selectsegment(wallOD/2+boundOffsetR, 0);
35 mi_selectsegment(wallOD/2+boundOffsetR/2, ...
    (numBaffles-.5)*baffleLength+boundOffsetZ);
36
37 mi_setsegmentprop('ABC',0,1,0,0)

```

**Magnet.m** places the magnet at its initial position. The magnet is always started from the same position to ensure consistency between configurations.

```
1  %create tube wall
2
3  %% Magnet Specifications
4  magOD = 3/8; %Magnet outer diameter, inches
5  magHeight = .25*numMags; %height of combined magnets, inches
6  magMat = 'N52'; %Magnet material
7  mi_getmaterial(magMat)
8
9  %% Draw Magnet
10
11  mi_drawpolygon([0,-magHeight/2;
12                0,magHeight/2;
13                magOD/2,magHeight/2;
14                magOD/2,-magHeight/2]);
15
16  %% Set Magnet Material
17
18  mi_addblocklabel(magOD/2/2,0);
19  mi_selectlabel(magOD/2/2,0);
20  mi_setblockprop(magMat,1,0,0,90,2,0)
21
22  %% Set Magnet Group (for later iterations)
23
24  mi_clearselected();
25  mi_selectnode(0,-magHeight/2);
26  mi_selectnode(0,magHeight/2);
27  mi_selectnode(magOD/2,magHeight/2);
28  mi_selectnode(magOD/2,-magHeight/2);
29  mi_selectsegment(magOD/4,magHeight/2);
30  mi_selectsegment(magOD/4,-magHeight/2);
31  mi_selectsegment(magOD/2,0);
```

```
32 mi_setgroup(2);
```

**Projectile.m** creates the projectile geometry, and places it according to the 'projMagPos' condition in Simulation\_Handler\_BTRA.m. Currently accepted positions are 'Nose' and 'Tail', though others may be added by the user. Projectile diameter, shoulder length, base diameter, and nose or tailcone angles may be set in Simulation\_Handler\_BTRA.m, but the general projectile shape is currently limited to the standard geometry.

```
1 %% Create Projectile Design
2
3 noseLength = projDia/2/tand(projNoseAngle);
4 baseLength = (projDia-projBaseDia)/2/tand(projTailAngle);
5
6 totalProjLength = baseLength+projShoulder*baffleLength+noseLength;
7
8 projOutline = [0,0;
9               projBaseDia/2,0;
10              projDia/2,baseLength;
11              projDia/2,baseLength+projShoulder*baffleLength;
12              0, totalProjLength;
13              0,0];
14
15 projSegments = zeros(4,2);
16 projSegments(1,:) = projOutline(1,:)+[projBaseDia/4,0];
17 projSegments(2,:) = ...
    projOutline(2,:)+[(projDia-projBaseDia)/4,baseLength/2];
18 projSegments(3,:) = projOutline(3,:)+[0,projShoulder*baffleLength/2];
19 projSegments(4,:) = projOutline(4,:)+[-projDia/4,noseLength/2];
20
21 projOutline(:,2) = totalProjLength-projOutline(:,2);
22 projSegments(:,2) = totalProjLength-projSegments(:,2);
```



```

23
24 if projMagPos == 'Nose'
25     magShift = ...
26         -0.5*magHeight+baseLength+projShoulder*baffleLength+1.8-magHeight;
27     projOutline(:,2) = projOutline(:,2)+magShift;
28     projSegments(:,2) = projSegments(:,2)+magShift;
29 elseif projMagPos == 'Tail'
30     magShift = -0.5*magHeight+1.74;
31     projOutline(:,2) = projOutline(:,2)+magShift;
32     projSegments(:,2) = projSegments(:,2)+magShift;
33 end

```

**Run\_Simulation.m** translates the user input into the FEMM software and analyses the current magnetic field geometry. It is called once to initialize the situation, and multiple times later as part of the processing loop.

```

1 %% Refresh Simulation
2 %openfemm
3 %opendocument(simName)
4 mi_analyze
5 mi_loadsolution
6
7 %% Calculate Line Integral
8 mo_selectpoint(baffleOD/2-probeLength+probeBase+wallShoulder, ...
9     probeID/2+baffleLength*(numBaffles-1)/2)
10 mo_selectpoint(baffleOD/2-probeLength+probeBase+wallShoulder, ...
11     -probeID/2+baffleLength*(numBaffles-1)/2)
12
13 BnTemp=mo_lineintegral(1);
14 Bn(1,iter) = BnTemp(1);
15 Bn(2,iter) = BnTemp(2);

```

```

14
15 %% Save Image of Field
16 if runRender == 1
17     mo_hidepoints
18     mo_hidegrid
19     mo_savebitmap(append(simImageName, ' Position ', num2str(iter), '.bmp'))
20     cropRatio = ...
        (wallOD/2+boundOffsetR) / ((numBaffles-.5)*baffleLength+boundOffsetZ) - ...
        (-baffleLength/2-boundOffsetZ));
21     I = imread(append(simImageName, ' Position ', num2str(iter), '.bmp'));
22     imageHeight = length(I(:,1,1));
23     imageWidth = round(imageHeight*cropRatio);
24     I2 = imcrop(I,[0 0 imageWidth imageHeight]);
25     imwrite(I2,append(simImageName, ' Position ', num2str(iter), '.bmp'));
26 end

```

**MoveMagnet.m** and **MoveProjectile.m** select and translate the magnet and projectile, respectively, based on the simulation parameters. Their code is identical, save for line 3 which is set to group 2 for the magnet and group 5 for the projectile. **MoveMagnet.m** is presented below.

```

1 % moves magnet
2 mi_clearselected();
3 mi_selectgroup(2);
4 mi_movetranslate(0,moveDistance);
5 mi_saveas(simName)
6 %closefemm

```

**VirtualProbe.m** transforms the magnetic field data collected by the **Run\_Simulation.m** loop into the signal that would be produced by a magnetic probe under those conditions (minus the amplitude scaling factor, see Section A.2).

```

1  %% Virtual Mag Probe Simulator
2  %interprets B-field from the main simulator as a probe would
3
4  %% Probe characteristics
5  resistance = 22; %Resistance of probe itself (measured), Ohms.
6  numLoops = 30; %number of loops in the probe
7  loopDiameterID = 0.08; %bobbin OD for wire portion
8  loopDiameterOD = 0.089; %bobbin OD for tangent portion
9  loopDiameterAvg = (loopDiameterID+loopDiameterOD)/2; %use in calcs
10 inchesToMeters = 0.0254;
11 loopDiameterAvg = loopDiameterAvg*inchesToMeters;
12
13 %external factors
14 multiplexMultiplier = 1;
15 BNCresistance = 0;
16
17 %% Data Interpreter
18 dBdt = ...
    gradient(correctedData(1,2:iter))./gradient(correctedData(2,2:iter));
19 dBPlot = figure;
20 plot(correctedData(2,2:iter-1),dBdt(1:end-1))
21 title('Simulated Field Change through Probe')
22 xlabel('Time (seconds)')
23 ylabel('dB/dt (Teslas/second)')
24 subtitle(append(baffleType, ' Baffles'))
25 set(gcf, 'units', 'pixels', 'position', [10,100,imageHeight*plotRatio,imageHeight])
26 saveas(dBPlot, append(simImageName, ' dBdt.png'))
27
28 %% Raw EMF Calculation
29 EMF = numLoops*dBdt*(pi*loopDiameterAvg^2/4)*multiplexMultiplier; ...
    %note: need to add axisymmetric area correction, currently too high

```

```

30 EMFPlot = figure;
31 plot(correctedData(2,2:iter-1),EMF(1:end-1))
32 hold on
33 title('Simulated Emf through Probe')
34 xlabel('Time (seconds)')
35 ylabel('Emf (Volts)')
36 subtitle(append(baffleType, ' Baffles'))
37 set(gcf, 'units', 'pixels', 'position', [10,100,imageHeight*plotRatio,imageHeight])
38 saveas(EMFPlot, append(simImageName, ' EMF.png'))

```

**FileOrganizer.m** is used only if creating an animation of the magnetic field evolution, and compiles each frame of the simulation into a .gif file for easy viewing.

```

1 %% Move produced plots to new folder
2 mkdir(simImageName)
3
4 gifName = append(simImageName, '.gif');
5 frameLength = 10^4/(projVel*simSteps);
6
7 currPlotPoint = figure;
8 title('Simulated Emf through Probe')
9 xlabel('Time (seconds)')
10 ylabel('Emf (Voltage Units)')
11 set(gcf, 'units', 'pixels', 'position', [10,100,imageHeight*plotRatio,imageHeight])
12 %currPlotPoint.Position(3:4) = [imageHeight*plotRatio,imageHeight];
13 %axisLim = max(abs(EMF));
14 %set(gca, 'YLim', [-axisLim axisLim])
15 set(gca, 'YTick', []);
16 set(gca, 'XLim', [0 correctedData(2,end-1)])
17 hold on
18 plot(correctedData(2,1:2), [0, EMF(1)], 'k-')

```

```

19
20 [frame, currPlot] = getframe(gcf);
21 k=1;
22 currentMax = 0;
23 totalMax = max(abs(EMF));
24 for k = 1:iter-1
25     frameName = rgb2gray(imread(append(simImageName, ' Position ', ...
26         num2str(iter-k+1), '.bmp')));
27     set(gca, 'YLim', [-1.25*totalMax 1.25*totalMax])
28     if k == 1
29         plot(correctedData(2,1:2), [0, EMF(1)], 'k-')
30     end
31     if (k > 1) && (k < iter-1)
32         plot(correctedData(2,2:k+1), EMF(1:k), 'k-')
33     end
34     set(gca, 'XLim', [0 correctedData(2,iter-1)])
35     [frame, currPlot] = getframe(gcf);
36     frameField = imresize(frameName, [length(frame(:,1)), ...
37         round(length(frame(:,1))*cropRatio)]);
38     combinedFrame = [im2gray(frameField), im2gray(frame)];
39     if k == 1
40         %% For 1st image, start the 'LoopCount'.
41         imwrite(combinedFrame, gifName, 'gif', 'LoopCount', Inf, 'DelayTime', frameLength);
42     else
43         imwrite(combinedFrame, gifName, 'gif', 'WriteMode', 'append', ...
44             'DelayTime', frameLength);
45     end
46 close(currPlotPoint)
47

```

```
48 i = 1;
49 while i < iter+1
50     delete(append(simImageName, ' Position ', num2str(i), '.bmp'))
51     i = i+1;
52 end
53
54 movefile(gifName, simImageName)
55 movefile(append(simImageName, ' Flux.png'), simImageName)
56 movefile(append(simImageName, ' dBdt.png'), simImageName)
57 movefile(append(simImageName, ' EMF.png'), simImageName)
```

## **Appendix D**

### **Key Data**

| Entrance Mach | Chemistry                                     | Pressure, psig | Result          |
|---------------|-----------------------------------------------|----------------|-----------------|
| 1.49          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 300            | Start           |
| 1.68          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 300            | Start           |
| 1.53          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |
| 1.44          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Delayed unstart |
| 1.42          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |
| 1.33          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Nonstart        |
| 1.35          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Delayed unstart |
| 1.25          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Nonstart        |
| 1.38          | $1\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ | 301            | Start           |

TABLE D.1: Summary of ram accelerator tests in which projectiles entered below the theoretical minimum operating Mach number ( $M = 1.76$ ). 1.380" diameter projectiles entered an oxygen enriched methane-air propellant ( $\phi\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ ) with fill pressure of 300 psig.

| Baffle Spacing (in) | Wall Thickness (in) | Proj. Diameter (in) | Pressure (atm) | Mach Number |
|---------------------|---------------------|---------------------|----------------|-------------|
| 1.0                 | 0.25                | 1.496               | 7.94           | 2.01        |
| 1.0                 | 0.25                | 1.496               | 8.48           | 3.27        |
| 1.5                 | 0.25                | 1.496               | 8.82           | 1.98        |
| 1.5                 | 0.25                | 1.496               | 8.48           | 3.42        |
| 1.5                 | 0.25                | 1.380               | 8.89           | 3.42        |
| 1.5                 | 0.25                | 1.380               | 8.48           | 2.23        |
| 2.0                 | 0.25                | 1.496               | 8.35           | 2.37        |
| 2.0                 | 0.25                | 1.496               | 8.89           | 3.31        |
| 2.0                 | 0.25                | 1.380               | 8.69           | 3.39        |
| 1.5                 | 0.5                 | 1.380               | 8.48           | 3.49        |

TABLE D.2: Summary of varied parameters in optical baffle testing. Baffle chambers had a constant radius of 1.5", projectiles had a nosecone angle of  $15^\circ$  and a tailcone angle of  $12^\circ$ , and fill gas was  $\text{CO}_2$ .

| Velocity <sub>in</sub> (m/s) | Velocity <sub>out</sub> (m/s) | Pressure (atm) | Real Drag (N) | Calculated $C_d$ |
|------------------------------|-------------------------------|----------------|---------------|------------------|
| 885                          | 879                           | 8.69           | -348          | 0.15             |
| 890                          | 887                           | 8.89           | -177          | 0.07             |
| 913                          | 907                           | 8.48           | -352          | 0.14             |

TABLE D.3: Summary of drag experienced by P380 projectiles when entering a  $\text{CO}_2$  BTRA section. Tube was populated with seven BTRA 501 inserts at the beginning, followed by 49 BTRA 601 inserts.



| Velocity <sub>in</sub> (m/s) | Velocity <sub>out</sub> (m/s) | Pressure (atm) | Real Drag (N) | Calculated $C_d$ |
|------------------------------|-------------------------------|----------------|---------------|------------------|
| 951                          | 844                           | 8.48           | -6460         | 2.70             |
| 956                          | 881                           | 8.48           | -4620         | 1.84             |
| 920                          | 865                           | 8.89           | -3930         | 1.60             |

TABLE D.4: Summary of drag experienced by P496 projectiles when entering a CO<sub>2</sub> BTRA section. Tube was populated with seven BTRA 501 inserts at the beginning, followed by 49 BTRA 601 inserts.

| Average Mach | Inserts                 | Pressure (psig) | Net Thrust (N) | $I_{SBRA}$ |
|--------------|-------------------------|-----------------|----------------|------------|
| 2.96         | BTRA 502                | 303             | 6993           | 2.79       |
| 2.64         | BTRA 502                | 305             | 10507          | 4.17       |
| 3.01         | BTRA 502                | 449             | 18619          | 5.10       |
| 2.94         | BTRA 501                | 303             | 8781           | 3.51       |
| 2.76         | BTRA 501                | 303             | 8693           | 3.47       |
| 2.77         | BTRA 501                | 303             | 8920           | 3.56       |
| 2.64         | BTRA 501                | 303             | 9274           | 3.69       |
| 2.54         | BTRA 501                | 303             | 10130          | 4.06       |
| 2.26         | BTRA 501                | 303             | 10278          | 4.12       |
| 2.29         | BTRA 501                | 303             | 11006          | 4.41       |
| 2.79         | BTRA 501                | 303             | 9221           | 3.72       |
| 2.32         | BTRA 501                | 303             | 11619          | 4.66       |
| 2.31         | BTRA 501                | 303             | 12444          | 5.00       |
| 3.16         | BTRA 602                | 303             | 10814          | 4.32       |
| 3.05         | BTRA 602                | 303             | 12222          | 4.88       |
| 2.76         | BTRA 602                | 302             | 13187          | 5.28       |
| 2.92         | BTRA 602                | 452             | 19715          | 5.36       |
| 2.94         | BTRA 601 (501 at ports) | 303             | 11713          | 4.68       |
| 3.15         | BTRA 601 (501 at ports) | 303             | 10801          | 4.31       |
| 3.17         | BTRA 601 (501 at ports) | 303             | 11361          | 4.54       |
| 3.07         | BTRA 601 (501 at ports) | 304             | 11288          | 4.49       |
| 3.00         | BTRA 601 (501 at ports) | 302             | 11295          | 4.53       |
| 2.83         | BTRA 601 (501 at ports) | 302             | 14284          | 5.72       |
| 2.85         | BTRA 601 (501 at ports) | 302             | 13322          | 5.34       |
| 3.16         | BTRA 601 (501 at ports) | 300             | 9243           | 4.41       |
| 2.85         | BTRA 601 (501 at ports) | 304             | 11001          | 4.41       |
| 2.85         | BTRA 601 (501 at ports) | 302             | 10614          | 4.27       |

TABLE D.5: Summary of key data in Fig. 4.20. SBRA thrust used for easier comparison between baffle diameters. Testing was conducted with 1.380" diameter projectiles entered an oxygen enriched methane-air propellant ( $\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ ) with nominal fill pressure of 300 psig.

| Average Mach | Inserts                  | Pressure (psig) | Net Thrust (N) | $I_{SBRA}$ |
|--------------|--------------------------|-----------------|----------------|------------|
| 2.45         | 45xBTRA 601s, 6xBTRA 601 | 199             | 9396           | 5.58       |
| 2.63         | 45xBTRA 601s, 6xBTRA 601 | 299             | 14639          | 5.92       |
| 2.20         | 45xBTRA 601s, 6xBTRA 601 | 300             | 11890          | 4.80       |
| 2.52         | 45xBTRA 601s, 6xBTRA 601 | 300             | 11487          | 4.63       |
| 2.58         | 45xBTRA 601s, 6xBTRA 601 | 300             | 10308          | 4.16       |
| 3.15         | 5xBTRA 601s, 51xBTRA 601 | 296             | 10651          | 4.35       |
| 3.17         | 5xBTRA 601s, 51xBTRA 601 | 306             | 11949          | 4.73       |
| 2.94         | BTRA 601 (501 at ports)  | 303             | 11713          | 4.68       |
| 3.15         | BTRA 601 (501 at ports)  | 303             | 10801          | 4.31       |
| 3.17         | BTRA 601 (501 at ports)  | 303             | 11361          | 4.54       |
| 3.07         | BTRA 601 (501 at ports)  | 304             | 11288          | 4.49       |
| 3.00         | BTRA 601 (501 at ports)  | 302             | 11295          | 4.53       |
| 2.83         | BTRA 601 (501 at ports)  | 302             | 14284          | 5.72       |
| 2.85         | BTRA 601 (501 at ports)  | 302             | 13322          | 5.34       |
| 3.16         | BTRA 601 (501 at ports)  | 300             | 9243           | 4.41       |
| 2.85         | BTRA 601 (501 at ports)  | 304             | 11001          | 4.41       |
| 2.85         | BTRA 601 (501 at ports)  | 302             | 10614          | 4.27       |

TABLE D.6: Summary of key data in Fig. 4.16. TCRA thrust used for easier comparison between different  $\beta$  values. Testing was conducted with 1.380" diameter projectiles entered an oxygen enriched methane-air propellant ( $\text{CH}_4 + 2\text{O}_2 + 4.67\text{N}_2$ ) with nominal fill pressure of 300 psig. Note: A 601s insert is a 601 insert which has had its instrument holes widened for better access, resulting in a 2.8% fluid volume gain.