

The Pursuit of Hypervelocities: A Review of Two-Stage Light Gas Gun Aeroballistic Ranges

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Abstract

The ongoing pursuit of space and hypersonic flight continues to expose critical gaps in the understanding of material behavior under hypervelocity impact (HVI) and hypersonic flow conditions. Such limitations pose serious risks for aerospace vehicles, spacecraft, hardened structures, defensive systems, *etc.* Consequently, the development of materials and systems that can endure HVIs and hypersonic flight is a major obstacle in the quest for sustainable space exploration, reusable air-breathing hypersonic vehicles, and enduring protective structures. HVIs (≥ 3.0 km/s) can induce severe material deformation, erosion, fracturing, fragmentation, melting, vaporization, and sublimation. At the same time, hypersonic (\geq Mach 5) vehicles may be subjected to intense thermal and mechanical loads. Addressing these grand challenges requires a multifaceted and interdisciplinary approach, combining well-designed experiments with physics-based analytical and numerical modeling. Studying material behavior under HVIs and hypersonic conditions has been facilitated by two-stage light gas gun (2SLGG) aeroballistic ranges for almost seven decades. This current study surveys over 90 2SLGG aeroballistic ranges operational since 1990 to assess global launch and experimental capabilities. The 2SLGG's origins and research applications are explored, highlighting its significance in various fields, including shock physics, planetary science/defense, military defense, nuclear physics, hypersonic vehicle survivability and performance, and spacecraft micro-meteoroid/orbital debris protection. A summary of relevant HVI phenomena is presented to underscore the importance of 2SLGGs and to elucidate similarities and differences among various 2SLGG aeroballistic ranges and their supporting methods/tools. The 2SLGG's working principles are explained, and configurations and operations are compared. Modifications resulting in "three-stage light gas guns" are briefly mentioned for completeness. The full range of current 2SLGG performance capabilities is assessed with impact kinetic energies ranging from ~ 10 joules to nearly 100 megajoules, and the facility survey results are used to explain the variations in aeroballistic

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range tankage, experiment types, research applications, and diagnostic systems. Finally, an overview of 2SLGG performance prediction methods is provided, featuring notable empirical, analytical, and numerical approaches.

Keywords: two-stage light gas gun (2SLGG), aeroballistic range, hypervelocity impact, hypersonics, ballistics, terminal ballistics, high-speed imaging, flash X-ray imaging, photon doppler velocimetry (PDV), planar impacts, aerothermophysics, hypervelocity launchers, nuclear/pellet injection

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1. Introduction and Motivation

1 For many centuries, free flight ballistic ranges were used to study high-velocity projectile dynamics and
 2 impact physics. Such ranges nearly all employed some form of launch tube in which an energetic powder

3 was burned to generate the pressures necessary to accelerate projectiles to high velocities (*e.g.*, a cannon or
4 gun). The first gun originated around the 12th century in Europe or Asia [1]. Formal scientific study of
5 the physics of classical internal ballistics, projectile flight characteristics, and terminal impact effects did not
6 begin in earnest until around the beginning of the 19th century. Throughout history, a number of eminent
7 scholars worked on these ballistic problems, including Galileo, Newton, Robins, Lagrange, Poisson, Résal,
8 Hélié, Serrau, Moisson, Hugoniot, Gossot and Liouville, Charbonnier, Rögglä, Love and Pidduck, Cranz,
9 Fowler *et al.*, Corner, Thornhill, Hunt, and Nelson, among many others [2]. The earliest recorded existence
10 of a single-stage *laboratory* gun (cannon) was in 1742 when Benjamin Robins used a ballistic pendulum
11 to measure the muzzle velocity of a projectile [3]. His experiments proved that aerodynamic effects on
12 the projectile were nonnegligible and that the existing prevailing theories for predicting projectile ballistics
13 needed significant modifications.

14 Over the next two centuries, many studies focused on optimizing projectile shapes to minimize aerody-
15 namic drag (*cf.* [2, 3]). These were conducted with single-stage compressed gas or nitrocellulose powder
16 guns. In general, a single-stage gun consists of three main components: a pressure breech containing the
17 driver gas, a projectile, and a launch tube (barrel) as shown in Fig. 1a. These launchers can have overall
18 dimensions on the order of centimeters (*e.g.*, small firearms) to 10–50 m (*e.g.*, Schwerer Gustav [4]) and can
19 accommodate projectile diameters and masses ranging several orders of magnitude. Hypervelocity phenom-
20 ena were not widely considered until the 1930s when astronomers began to study planetary impacts. This
21 work gained little traction until the late 1940s [5] when the advent of supersonic jets, hypersonic rockets,
22 and missiles at the end of the Second World War necessitated the study of hypervelocity impacts (HVIs)
23 (*circa.* 1945) [6]. The introduction of ballistic missile technology and spacecraft shielding required laboratory
24 launch velocities of up to 6.0 km/s and >7.0 km/s, respectively. Conventional, single-stage compressed gas
25 and nitrocellulose powder guns, though, could only accommodate launch velocities up to 2.75 km/s (roughly
26 Mach 8) [6]. Significant improvements in launcher design were required in order to develop these emerging
27 technologies.

28 Rocket motors, jet engines, shock tubes, and wind tunnels all appeared to be viable tools to extend
29 the launch velocity ceiling but possessed significant limitations in fully replicating projectile/vehicle flight
30 dynamics [6]. Several launching methods were designed, developed, and implemented to accelerate objects
31 up to ~ 10 km/s (*e.g.*, Van de Graaff accelerators, plasma guns, and electromagnetic rail guns). Other
32 launching techniques, such as magnetically launched flyers, reached velocities well beyond the scope of this
33 work (15–44 km/s) [7]. In contrast, the basic structure and working principles of the single-stage powder gun
34 provided many advantages in generating the required projectile launch conditions: (*i*) the solid propellant
35 was relatively stable and non-toxic, (*ii*) the propellant ignition was more reliable compared to certain rocket

36 fuels, (*iii*) the high-pressure combustion gases were safely contained within the gun barrel, (*iv*) the muzzle
37 velocity was easily controllable and repeatable, (*v*) the projectile base pressure could be maintained for
38 a relatively long duration, and (*vi*) the high achievable projectile accelerations enabled launchers to be
39 relatively small and easily manufacturable [8].

40 During the 1940s and 1950s, Crozier and Hume [2, 6], Charters *et al.* [8], and Slawsky *et al.* [9]
41 conducted groundbreaking research that involved adding an extra stage to a single-stage gun. This innovation
42 dramatically raised the launcher’s velocity ceiling while retaining its original benefits. The resulting novel
43 apparatus soon became known as the two-stage light gas gun (2SLGG). In the nearly eight decades since its
44 inception, the 2SLGG has been reliably used to launch objects to velocities ranging roughly 2.0–10.0 km/s.
45 Even higher velocities have been reached with modifications to the 2SLGG, creating so-called “three-stage
46 light gas guns” (3SLGGs). The single-, two-, and three-stage guns are all pressure-driven launchers. Single-
47 stage launchers rapidly propel projectiles down a launch tube (barrel) using high-pressure gas, generated
48 either through controlled combustion or mechanical compression and initially contained within a pressure
49 breech [2, 10]. 2SLGGs employ the single-stage launching technique to accelerate a (usually) consumable
50 piston down a “pump tube,” rapidly compressing a light gas to extremely high pressures and temperatures.
51 This high pressure “working” gas is then released *via* a single-use, rapidly opening valve and accelerates
52 a projectile to hypervelocities (Fig. 1b). A comprehensive discussion of 2SLGG operating principles is
53 included later in this paper. The 3SLGG (or “modified 2SLGG”) uses yet another stage (see Section 3.3)
54 to achieve even higher velocities (Fig. 1c) [11]. The conceptual schematics presented in Fig. 1 highlight key
55 similarities and differences between each gun by clearly indicating all components, including the pressure
56 breech, driver gas, projectile, launch tube (barrel), pump tube, piston, working gas, diaphragm, and flyer
57 plate launcher [6, 12, 13]. The achievable impactor velocity-scale ranges for single- and multi-stage guns are
58 compared to some other relevant launching methods in Fig. 2 [7, 14]. To date, multi-stage gas guns remain
59 the predominant technique for launching macroscale projectiles to velocities exceeding roughly 5 km/s. More
60 details on these multi-stage launchers can be found in Refs. [6, 12, 13, 15].

61 Early ballistics, hypersonics, and HVI research led to over 70 years of scientific advances, starting with the
62 inception of the 2SLGG [5]. Swift [6] loosely categorized this period into five eras based on the significant
63 scientific contributions and corresponding political environment: the Early Days (1945–1957), the Space
64 Race (1958–1969), the “Dark Ages” (1970–1977) the Cold War (1978–1991), and the Commercial Space Age
65 (1996–present) [6]. Figure 3 displays a graph summarizing the findings of a previous study that examined the
66 temporal distribution of high-velocity and hypervelocity related publications over a period of 70+ years [5].
67 The figure has been adapted to emphasize significant 2SLGG-related historical milestones, as they correlate
68 well with scientific advancements made during this period [6, 11, 13, 16–32]. In the Early Days, research

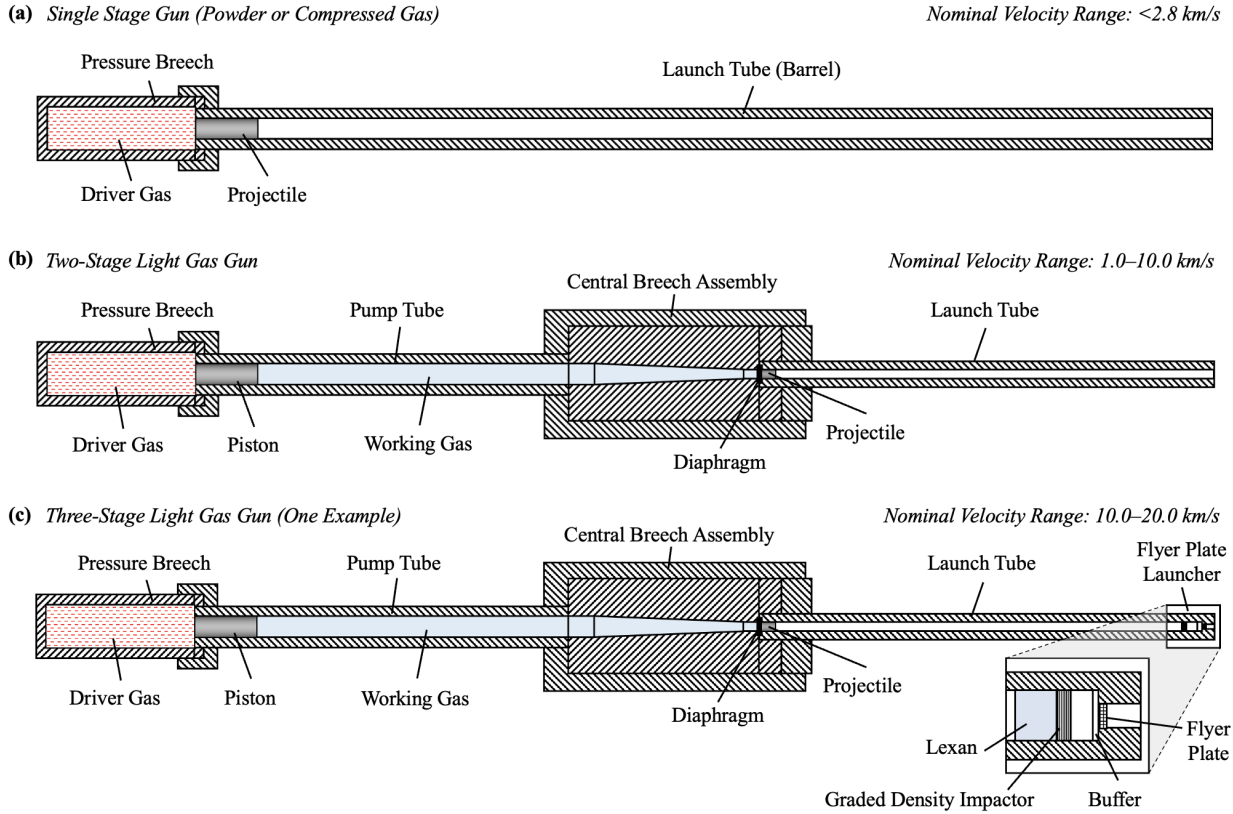


Figure 1: Conceptual schematics of a (a) single-, (b) two- [6], and (c) three-stage gun (“modified two-stage gun”) with key elements/components highlighted to indicate differences [12, 13].

69 was primarily focused on developing and optimizing the 2SLGG, with an emphasis on maximizing muzzle
 70 velocity. The first peak in scientific productivity was largely motivated by the Space Race, during which the
 71 first NASA 2SLGG was developed [17], the Aeroballistic Range Association (ARA) was founded [18], and the
 72 largest 2SLGG to date was constructed [19]. This surge in scientific output was succeeded by a significant
 73 dip that began and lasted throughout much of the Cold War. Only near the end of the Cold War was there
 74 another strong peak in scientific productivity due to the declassification of relevant data [5]. This nearly 25
 75 year period of maximum scientific discovery aligned with the founding of the Hypervelocity Impact Society
 76 (HVIS) [22] and the establishment of two commercial 2SLGG manufacturers, Thiot Engineerie and Physics
 77 Applications, Inc. (PAI) [23, 24]. The noticeable decline in the number of publications after approximately
 78 the year 2000 likely resulted from a shift in defense funding towards the War on Terror, a change that was
 79 largely driven by the September 11, 2001, attacks on the World Trade Center. Following the Cold War
 80 and post-Cold War periods, 2SLGG research has been primarily motivated by commercial space efforts,
 81 hypersonic technological developments, and the pursuit of ever-higher velocities. The need to develop next
 82 generation protective structural concepts and materials essential to ensure safe space travel and enable

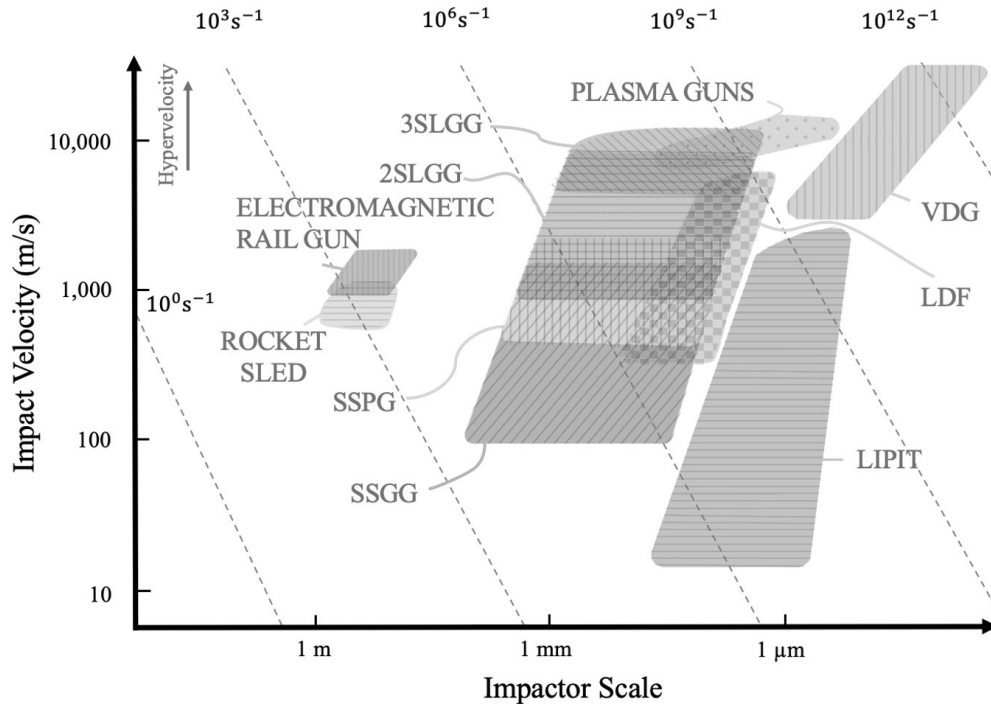


Figure 2: Impact velocity as a function of impact size for common impact testing techniques, with lines indicating constant characteristic strain rates. Techniques include single-stage gas gun (SSGG), single-stage powder gun (SSPG), two-stage light gas gun (2SLGG), three-stage light gas gun (3SLGG), Van de Graaff accelerators (VDF), laser-driven flyers (LDF), laser-induced particle impact tests (LIPIT), rocket sleds, rail guns, and plasma guns. The hatched shaded regions of the same color as the all-caps labels represent the specific velocity-scale domains in which the corresponding techniques are used. Adapted from Ref. [14].

83 hypersonic vehicle operations is anticipated to lead to an increase in scientific productivity over the next
 84 decade and beyond [33–42].

85 Ultimately, the launcher is but one part of an “aeroballistic range.” Range tankage, instrumentation, data
 86 acquisition systems, and various supporting equipment make an aeroballistic range a powerful tool to study
 87 a variety of scientific phenomena. Depending on the research application, typical launch packages can range
 88 from simple geometries, such as spheres, cylinders, and cubes, to complex scale models of spacecraft with sizes
 89 ranging from 100 microns in diameter and weighing a few micrograms [43] to 175 mm in diameter weighing
 90 several kilograms [44]. Velocities of 7 km/s are routinely achieved, and specially designed launch packages
 91 have been reportedly accelerated to roughly 11 km/s [31]. Unique projectiles have carried on-board diagnostic
 92 instrumentation, multiple bodies have been packaged to launch simultaneously, and even liquids and powders
 93 have been successfully launched [6]. These special use cases would not be possible without a unique feature
 94 of the 2SLGG: the ability to optimize the loading parameters to vary the projectile acceleration profile
 95 while still producing the same muzzle velocity. Instrumentation, diagnostic equipment, and data acquisition
 96 systems are constantly evolving due to technological advancements and are typically specific to the types

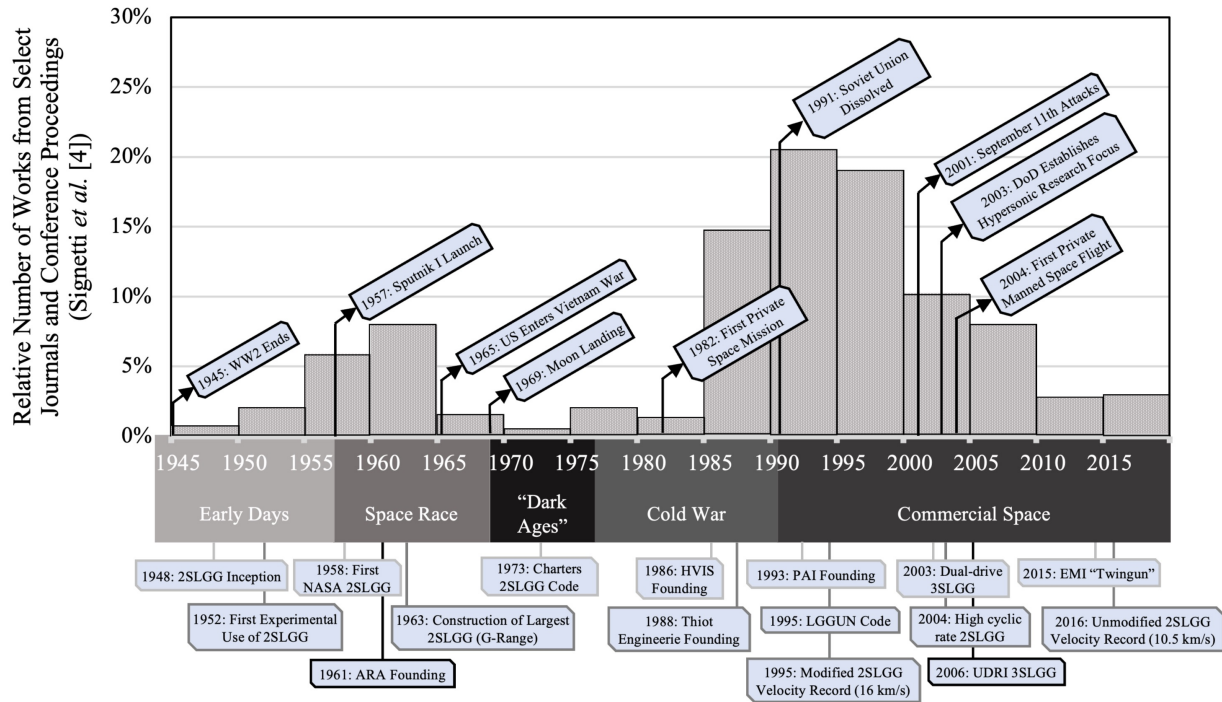


Figure 3: A temporal distribution of scientific publications on the experimental characterization, theoretical modeling, and numerical simulation of high-velocity and hypervelocity impacts, with an emphasis on key historical milestones. The figure was adapted from previous work by Signetti *et al.* [5] and Swift [6]. Key events were sourced from Refs. [6, 11, 13, 16–32].

97 of experiments that a given facility was designed to conduct. Some currently employed diagnostic methods
 98 include ultra-high-speed videography, schlieren and shadowgraphic imaging, photon Doppler velocimetry
 99 (PDV), flash X-ray radiography (FXR), velocity interferometer system for any reflector (VISAR), and laser
 100 velocimetry (see Section 6) [45–49]. The sensitivity and function of the instruments along with the data they
 101 provide determine the quality and usefulness of the actual scientific findings produced by a given facility.

102 Establishing a 2SLGG aeroballistic range is particularly challenging from time and cost perspectives due
 103 to the intrinsic complications associated with the operational aspects of the 2SLGG itself, safety concerns (use
 104 of explosives, high-pressure gas, impact ejecta, *etc.*), and experimental turnaround time. These difficulties
 105 are exacerbated by the need for megahertz-rate triggering, timing, and diagnostic systems to capture impact
 106 events *in-situ*. 2SLGG performance largely depends on interactions between pump tube piston mass, driver
 107 gas pressure and composition, initial light working gas pressure, projectile release pressure, and projectile
 108 mass. Additionally, structural features of the launcher such as chamber volume, pump tube and launch tube
 109 length and diameter, and convergence angle of central breech play a role. Peak light gas pressures can be
 110 intense enough to shatter projectiles or even deform/rupture gun components [6]. These considerations do
 111 not include the time and cost invested in designing experiments (targets, projectiles, test matrices, *etc.*)
 112 and additional experimental capabilities or performing pre- and post-impact characterization. Of course,

113 these difficulties grow nonlinearly with the scale of the range and complexity of the experiment. Hence, a
114 significant portion of 2SLGG-related research efforts have been dedicated to designing, developing, installing,
115 calibrating, using, and improving equipment and capabilities (see, *e.g.*, [50–56]).

116 Due to the vast array of potential research applications of 2SLGGs, there is a considerable diversity of
117 aeroballistic range capabilities and configurations. Furthermore, the research demands and experimental ca-
118 pabilities are in a state of rapid evolution, with new developments and advancements emerging continuously.
119 Several previous studies have attempted to catalog aeroballistic ranges, diagnostics, and research associated
120 with 2SLGGs worldwide (see, *e.g.*, [6, 57, 58]). These studies, however, were either limited to a few select
121 aeroballistic ranges or were conducted over 50 years ago. Consequently, the present work aims to serve as an
122 extensive review of 2SLGG aeroballistic ranges operational as of 1990 to expand the scope of known facilities
123 and capabilities. A more complete understanding of the available launching and diagnostic capabilities facil-
124 itates and motivates scientific discovery. In addition, relevant research activities are briefly summarized to
125 better understand the diversity in aeroballistic ranges. Sources for this survey include journal publications,
126 conference proceedings, technical reports, textbooks, websites, and dissertations/theses, with a percentage
127 breakdown of the sources provided in Figure 4. Relevant information from over 90 2SLGG aeroballistic ranges
128 was compiled to provide a comprehensive overview and reference of modern aeroballistic ranges as of 2023.
129 HVI phenomena are first briefly discussed. Physical limitations with single-stage guns are used to motivate
130 the working principles of 2SLGGs. The method by which 2SLGGs accelerate projectiles to hypervelocities
131 is then presented in detail with references to the current technology. The types of experiments performed
132 at aeroballistic ranges are summarized. An overview of conventional and modern diagnostic methods is
133 presented. Finally, key empirical, analytical, and numerical 2SLGG performance prediction methods are
134 surveyed.

135 **2. A Brief Overview of Hypervelocity Impact Phenomena and Research**

136 The types of experiments that a given 2SLGG aeroballistic range is designed to conduct heavily influ-
137 ence its configuration and supporting diagnostic equipment. Typically, experiments can be classified into
138 one of four categories: penetration/perforation mechanics, hypersonics/aerothermophysics, planar impacts,
139 or nuclear/pellet injection. The differences within and among each type of experiment, and therefore the
140 setup of the facilities used to conduct them, are mostly determined by the complex scenarios that occur
141 during and after HVI events. Hence, fully understanding current aeroballistic range capabilities and exper-
142 iment types requires some knowledge of HVI phenomena. Any previous or current impact study can be
143 organized into one or more of the four key velocity regimes: low/high-velocity, terminal ballistic, transi-

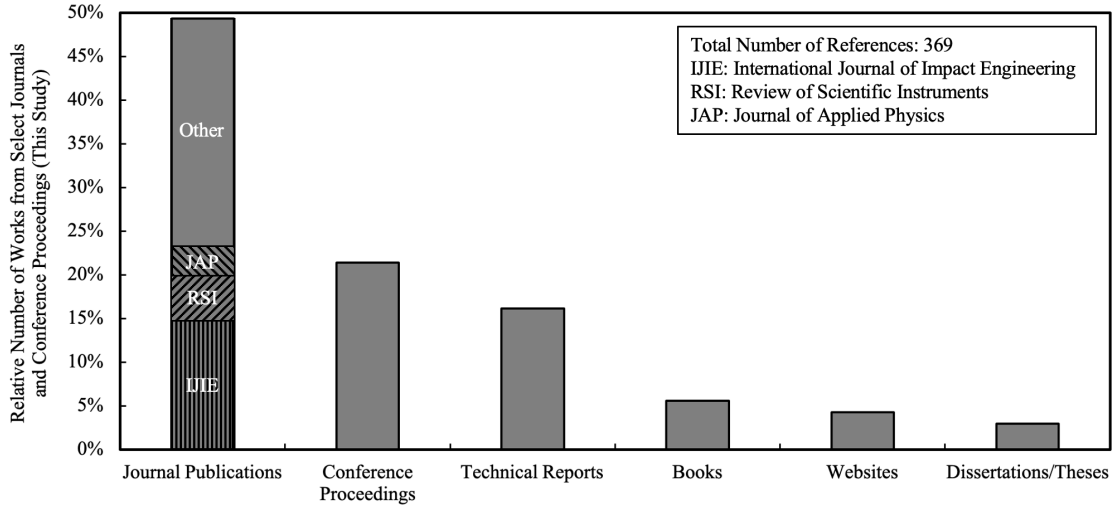


Figure 4: A percentage breakdown of the sources used in the review, encompassing a range of scholarly materials such as textbooks, technical reports, academic journals, conference proceedings, and lectures. The most common academic journals, including *International Journal of Impact Engineering* (IJIE), *Journal of Applied Physics* (JAP), and *Review of Scientific Instruments* (RSI), are shown for reference.

144 tion, and hypervelocity [5, 59]. The physics, mechanics, thermodynamics, and chemistry occurring in each
 145 regime can differ widely in some cases while in others phenomena overlap significantly, making analytical
 146 and numerical modeling challenging. In addition, most historic and current HVI studies have applications
 147 in one or more of six key application areas, including ultra-high strain rate material behavior, planetary
 148 science/defense, nuclear physics, spacecraft micro-meteoroid/orbital debris (MMOD) protection, hypersonic
 149 vehicle survivability and counter hypersonics, and protective structures for military defense (Fig. 5a). Efforts
 150 to understand impact/penetration events typically employ one or more of three approaches: experiments,
 151 analytical models, and numerical simulations (Fig. 5b) [7]. Previous studies have frequently defined hyperve-
 152 locity as impact velocities exceeding 2.5–3.0 km/s. However, this rigid definition is an oversimplification that
 153 can lead to confusion and misunderstanding. To comprehend the importance and challenges of launching
 154 projectiles to hypervelocities with reliability, it is essential to gain a precise understanding of the transition
 155 from high-velocity to hypervelocity, as well as the associated phenomenology.

156 Most everyday moving objects (baseballs, automobiles, rifle bullets, *etc.*) travel at velocities in the
 157 low/high or terminal ballistic regimes. Hypervelocity objects are only encountered in more extreme environ-
 158 ments like those where intercontinental ballistic missiles (ICBMs), rockets, explosives, hypersonic vehicles,
 159 reentry vehicles, or meteors are considered. The mechanical and thermal loading and physical response
 160 of materials in a ballistic event can be largely determined by the impact velocity. At increasingly higher
 161 velocities, the material response can include elastic-plastic deformation, rate-dependency, a variety of failure
 162 mechanisms, phase transitions, incompressible and compressible flows, shock wave propagation, thermo-

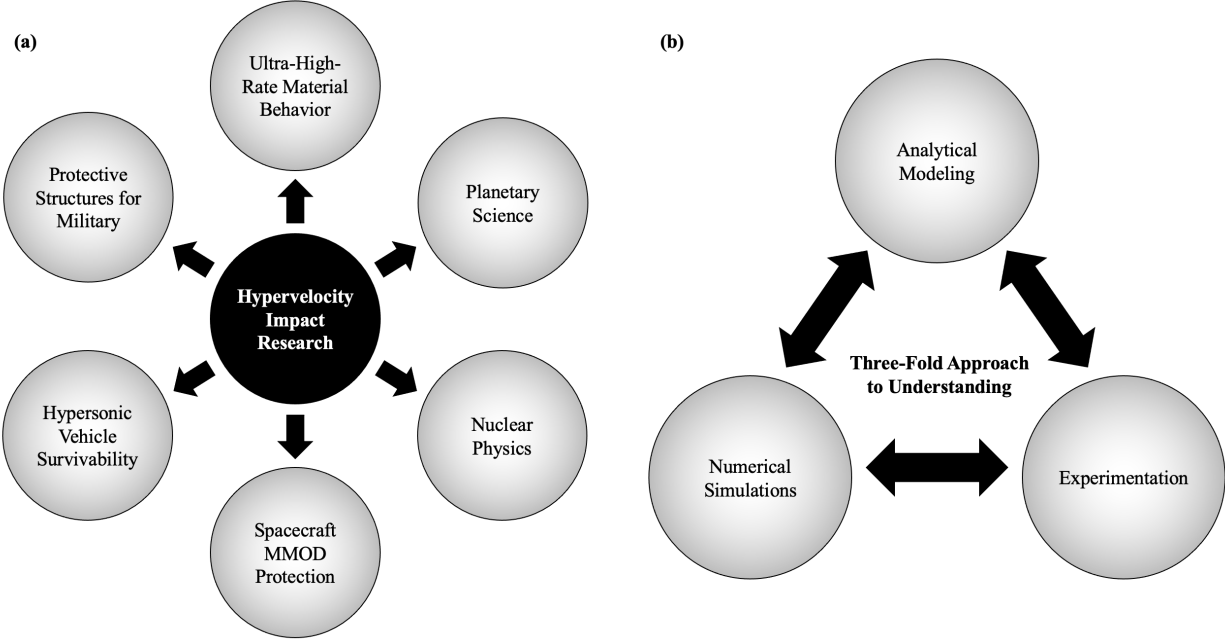


Figure 5: An overview of HVI research, including (a) the six key HVI research application areas and (b) the three-fold approach to understanding impact/penetration events presented by [7].

163 dynamic processes, *etc.* Impact velocity alone, therefore, is insufficient in describing velocity transitions
 164 without consideration of projectile/target material properties [5]. Generalizations of velocity regimes should
 165 be made with caution, especially when guiding theoretical, numerical, and/or experimental development
 166 and/or interpretation. Although the impact velocity regime is projectile/target material dependent, designating
 167 general broad impact regimes can be convenient from a conceptual perspective. In a similar way,
 168 the subsonic ($< \text{Mach } 0.7$), transonic ($\text{Mach } 0.7\text{--}1.2$), supersonic ($\text{Mach } 1.2\text{--}5$), and hypersonic
 169 ($> \text{Mach } 5$) regimes have been defined relative to a medium's speed of sound with physical phenomena
 170 marking transitions between regimes.

171 Low/high and terminal ballistic velocity impacts are characterized by, phenomenologically speaking,
 172 rigid body penetration at the low end of the velocity regime to eroding projectiles at the high end. Strain
 173 rates experienced by the projectile and target materials can range from $10^2\text{--}10^5 \text{ s}^{-1}$ [5, 60, 61]. A key
 174 characteristic of impacts in the low/high and terminal ballistic velocity regimes is the strength-dominated
 175 material response (even with thermal softening and melting present). Hence, material flow and strain-rate
 176 dependent strength effects are prevalent even at the upper bound of the terminal ballistic regime, and
 177 dynamic material behavior is generally captured using constitutive models (*e.g.*, Johnson-Cook [62], Cowper
 178 and Symonds [63], Zerilla-Armstrong [64], Arrhenius-type [65], Preston-Tonks-Wallace [66], and Steinberg
 179 [67]) and fracture/failure models (*e.g.*, Johnson-Cook [68], Xie-Wierzbicki [69], and Grady and Olsen [70]).
 180 Depending on the loading rate, constitutive parameters are typically determined using one or more dynamic

181 experimental techniques, including quasi-static or dynamic tension tests (10^{-4} – 10^1 s $^{-1}$), Split Hopkinson
 182 Pressure Bar experiments (10^2 – 10^4 s $^{-1}$) [71], Modified Taylor Tests (10^4 – 10^6 s $^{-1}$) [61, 72], and/or Inverse
 183 Planar-Plate-Impact Tests (10^6 – 10^9 s $^{-1}$) [61]. To accurately capture the material constitutive response,
 184 plastic heating must also be modeled, for example, by incorporating the Taylor-Quinney (TQ) coefficient
 185 [73]. The actual material loading conditions during impact, though, can differ significantly from established
 186 dynamic material characterization approaches that load materials in pure tension, compression, or shear.

187 The hypervelocity regime (strain rates $\geq 10^6$ – 10^8 s $^{-1}$) is characterized by hydrodynamic material behavior
 188 (*i.e.*, deviatoric stresses are negligible), implying that material strength does not play a significant role in the
 189 impact behavior. For this reason, material behavior is often characterized by density and pressure-volume
 190 relationships, *i.e.*, equation-of-state (EOS) models (*e.g.*, Mie-Grüneisen [74], Tillotson [75], and SESAME
 191 [76]). The dominating phenomena are shock wave generation and propagation, which dramatically increase
 192 internal energy and lead to material melting, vaporization, sublimation, superheated vapor generation, or
 193 even plasma production [5]. Such near-instantaneous changes in density, temperature, and pressure (up to
 194 1.0 TPa [6]) must be addressed from the perspective of thermodynamic principles (*e.g.*, Rankine-Hugoniot
 195 conditions). Impact scenarios with low target-thickness-to-projectile-diameter ratios ($t/D \leq 1$) are charac-
 196 terized by propagating shocks that accelerate the target material surrounding the impact region. Rarefaction
 197 waves frequently shatter both the projectile and target, generating ejecta/debris clouds [5, 77]. Global defor-
 198 mation is negligible in semi-infinite targets due to their inertia, and failure is governed by compression-driven
 199 cratering, melting or vaporization (due to local increases in internal energy), and possible spallation [5, 78–
 200 80]. Because the transition between the terminal ballistic and hypervelocity regime is not a discontinuity, a
 201 transition regime exists where the material response exhibits a combination of phenomena belonging to both
 202 regimes, making impacts in this regime difficult to model. The transition to hypervelocity, however, can
 203 be roughly described using a simple sonic ($v_o/\sqrt{K/\rho_0}$) [5, 81] or strength-based ($\rho_p v_0^2/\sigma_{y,p}$ and $\rho_p v_0^2/\sigma_{y,t}$)
 204 [82] criterion, where ρ_0 is the target mass density, ρ_p is the projectile mass density, v_0 is the impact ve-
 205 locity, and $\sigma_{y,p}$ and $\sigma_{y,t}$ are the projectile and target yield stresses, respectively. Even still, these criteria
 206 are an oversimplification as they do not include thermal effects or thermodynamic considerations. A more
 207 recent criterion defines the transition regime based on incipient and full melting of projectile/target materials
 208 [83]. Understanding the regime to which a given impact belongs is critical, as it determines which physical
 209 phenomena are present, what simulation/modeling tools can be applied, and which experiments should be
 210 performed. Despite a given impact regime’s medium dependency, the HVI community generally defines the
 211 transition to occur at impact velocities between 2.5–3.0 km/s [84–90], corresponding to the muzzle velocity
 212 ceiling of single-stage, powder guns (~ 2.8 km/s) [16]. For consistency, “hypervelocity” will herein correspond
 213 to projectile velocities ≥ 3.0 km/s, and “ultra-high strain rates” will refer to those $\geq 10^6$ s $^{-1}$.

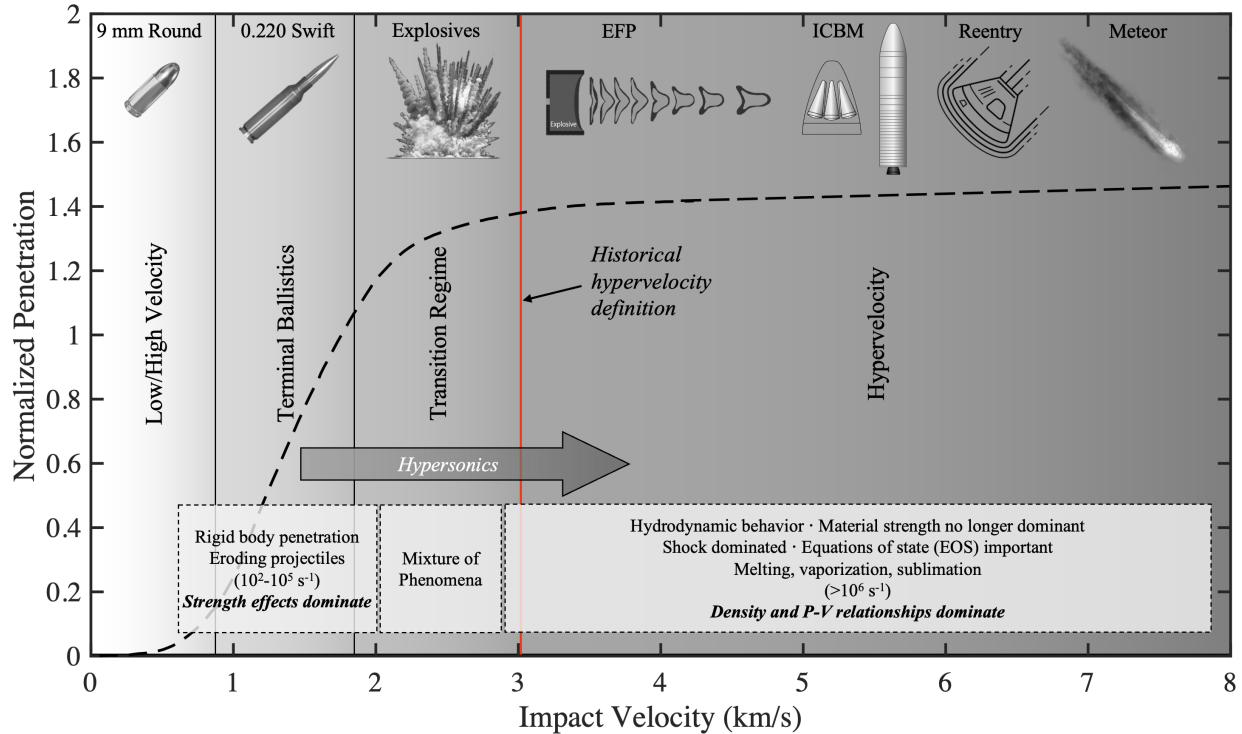


Figure 6: An illustrative plot of normalized projectile penetration as a function of impact velocity to emphasize the different physical phenomena occurring and provide examples of moving objects in each impact velocity regime [5, 83]. Here, EFP and ICBM denote explosively formed penetrator and intercontinental ballistic missile, respectively.

214 The transition regimes for both impact velocities and aerodynamic sonic speeds can be visualized for
 215 comparison *via* a variety of plots. For example, Fig. 6 shows a penetration efficiency curve (projectile-
 216 length-normalized depth of penetration as a function of impact velocity): the different impact regimes are
 217 clearly demarcated by changes in material impact response [83]. Specifically, the terminal ballistics regime is
 218 characterized by the linear portion of the curve while the hypervelocity regime exhibits a somewhat plateaued
 219 response. This trend is qualitative and only meant to emphasize the need to identify regimes. Also included
 220 in Fig. 6 are key phenomena exhibited by impacted materials in each regime, where hypersonic impacts
 221 land on the spectrum, and some relevant examples within each regime. This figure reinforces the challenges
 222 associated with studies in impact and penetration mechanics. Appropriately addressing HVI problems may
 223 require cross-disciplinary expertise in mechanics, computational and physical chemistry, thermodynamics,
 224 materials science, applied and computational physics, and planetary science. The complexity and diversity of
 225 modern HVI and hypersonics research play a central role in understanding the importance of and variations
 226 in 2SLGG aeroballistic ranges.

227 3. The Two-Stage Light Gas Gun (2SLGG)

228 While there are variations in the configurations of *aeroballistic ranges*, the operational concepts and
229 fundamental physical components of all currently utilized 2SLGGs are similar. The present section aims to
230 explain the working principles of 2SLGGs by initially providing a concise overview of the physical limitations
231 of conventional single-stage guns. Subsequently, a detailed outline of the components that characterize a
232 conventional 2SLGG is provided. The arguments regarding the predominant configurations of 2SLGGs are
233 substantiated by data gathered from existing literature.

234 3.1. The 2SLGG Working Principles

235 In general, single-stage guns convert the potential energy stored in compressed gas into projectile kinetic
236 energy. This potential energy is typically produced by utilizing high-pressure gas generated through a
237 controlled combustion process or, alternatively, mechanical compression. Once the gas is released, it rapidly
238 expands within the gun barrel, accelerating the projectile. The efficiency of this energy conversion process
239 depends on various factors, including the gas composition and the design of the gun barrel. In essence,
240 the local expansion and acceleration of driver gas particles increase the gas velocity at the expense of a
241 decrease in pressure [91]. Depending on the gas composition and the projectile velocity, the expansion and
242 acceleration of the gas can occur much more quickly than the projectile moves down the barrel, such that any
243 difference in net force on the projectile does not strongly influence projectile acceleration and is, therefore,
244 negligible. As the projectile velocity increases, however, these gas particles cannot “react” quickly enough
245 to the changes in volume, and the projectile begins to outpace the expanding gas regions. The inefficiencies
246 associated with this phenomenon will necessarily limit the maximum projectile velocity. Launchers that are
247 unable to efficiently transmit pressure increases from the high-pressure reservoir to the projectile’s base are
248 referred to as “communication-limited” [6]. The progression of successive, incremental movements describes
249 an acoustic rarefaction pressure wave, and the maximum velocity they can “react” is the definition of the
250 speed of sound in the gas [91].

251 The rise of supersonics as a field of study and the corresponding derivation of compressible flow mathe-
252 matical models motivated efforts to theorize and, later, prove that the constraining factor for conventional
253 single-stage powder guns was the molecular weight of the gaseous products of combustion [91]. This ground-
254 breaking finding was motivated by the fact that the gas used to accelerate the projectile must also accelerate.
255 Thus, as the molecular weight of the gas increases, the energy available to accelerate the projectile decreases.
256 This phenomenon is subtle but incredibly important to understanding the 2SLGG working principles and
257 can be simply demonstrated by analyzing the maximum theoretical velocity of a generalized gun. The max-
258 imum attainable muzzle velocity for both single- and multi-stage guns has been theorized at great length

259 [25, 51, 92–95]. Corner [10] presented various analyses developed by several researchers. A simple but
 260 powerful derivation attributed to Langweiler [96] gives the maximum achievable velocity (U_P) as

$$U_P \approx \sqrt{\frac{2RT}{\gamma - 1}}, \quad (1)$$

261 where R is the universal gas constant, M is the gas molecular weight, T is the gas temperature, and $\gamma = c_p/c_v$
 262 is the ratio of specific heats. Despite the associated simplifying assumptions, Eq. (1) closely correlates with
 263 observed peak velocities for single-stage gas guns, single-stage powder guns, and 2SLGGs much better than
 264 some of the more rigorous treatments [10]. It is apparent from Eq. (1) that careful selection of the gas is
 265 critical to achieving the highest possible muzzle velocity. Considering $\gamma \approx 1.00$ – 1.80 for most gases and that
 266 nearly all ideal gases have $\gamma = 1.40$ or $\gamma = 1.67$, the importance of low molecular weight is clearly paramount.
 267 However, simply using low molecular weight gas is not enough—high temperatures and pressures are required
 268 to achieve hypervelocities. These ideas are emphasized in Fig. 7a, where the maximum achievable projectile
 269 velocity, U_P , is plotted as a function of gas molecular weight at various temperatures ($\gamma = 1.4$ assumed for
 270 all gases for comparison purposes). The red vertical lines in the plot indicate key gases used in conventional
 271 launchers: hydrogen, helium, powder gases (H_2O , CO_2 , and N_2), and air. This figure clearly shows that low
 272 molecular weight and high temperatures are required to achieve hypervelocities (*i.e.*, maximum velocity is
 273 proportional to the speed of sound and temperature and inversely proportional to gas molecular weight).

274 Merely achieving high gas pressures and temperatures in the reservoir of a gun is not sufficient to reach
 275 the theoretical maximum muzzle velocity. To approach this limit, it is necessary to maintain these gas
 276 pressures at the base of the projectile for a certain time period or distance. Hence, the muzzle velocity
 277 is proportional to the barrel length, provided positive pressure is maintained at the projectile’s base and
 278 frictional effects are negligible [97]. One way to maintain muzzle velocity while decreasing peak reservoir
 279 pressure (and peak projectile acceleration) is to extend the launch tube length. In essence, the projectile
 280 base pressure is converted into kinetic energy. Specifically, the velocity and translational kinetic energy
 281 of a projectile within a barrel are proportional to the integrals of the pressure-time and pressure-distance
 282 histories, respectively:

$$v = \frac{A}{m} \int p dt, \quad KE = \frac{1}{2}mv^2 = \frac{A}{m} \int p dx, \quad (2)$$

283 where A is the projectile base area, m is the projectile mass, p is the base pressure, t is time since launch,
 284 and x is downrange position since launch (Fig. 7b) [97]. Clearly, projectile velocity and kinetic energy
 285 are dependent on the magnitude and duration of the base pressure. In 2SLGGs, high working/driver gas
 286 temperatures and pressures need to be reached and maintained while the projectile is in the launch tube.

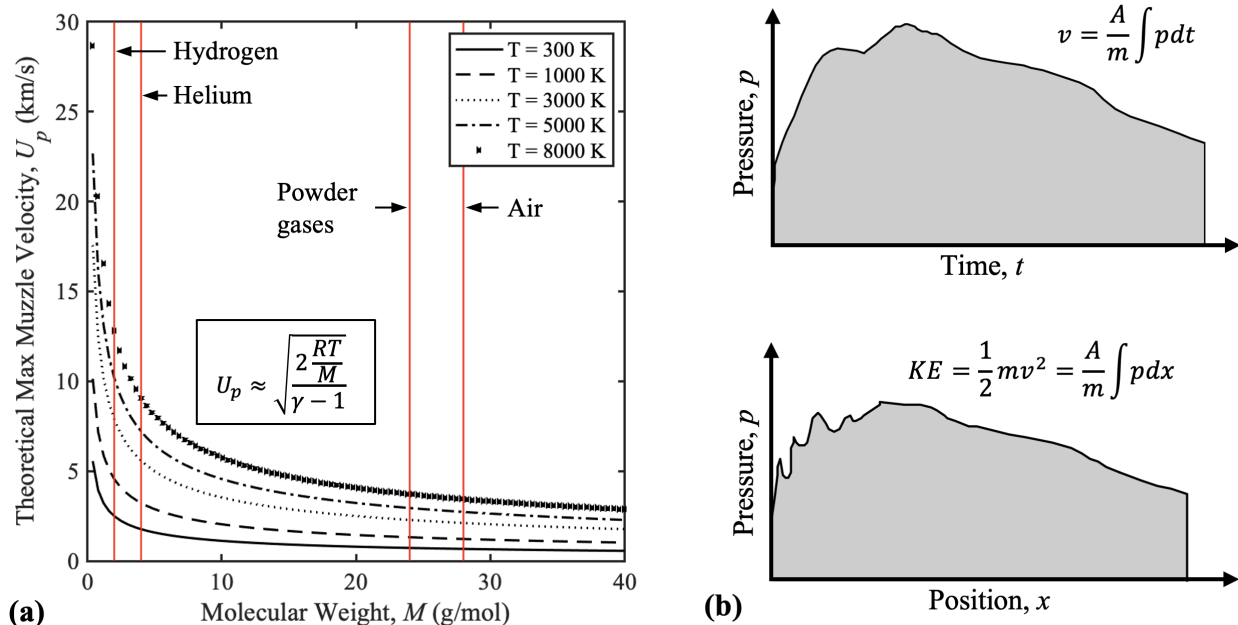


Figure 7: The working principles of pressure-driven launchers (guns), with (a) a graph of theoretical maximum muzzle velocity (U_P) as a function of gas molecular weight for relevant gases at a series of temperatures ($\gamma = 1.4$ for qualitative comparison) and (b) plots of pressure (p) versus time (t) and pressure versus downrange position (x) adapted from Ref. [95]. The maximum muzzle velocity is proportional to temperature and pressure and inversely proportional to molecular weight. Here, v is projectile velocity, A is projectile base area, m is projectile mass, and KE is projectile kinetic energy.

287 These requirements could not be satisfied by a single-stage gun due to limitations on gas conditions in the
 288 reservoir (compressed-gas guns) or gas speed of sound (powder guns).

289 In essence, a 2SLGG utilizes the energy generated by a single-stage launch system to compress a light
 290 working gas (WG), which, then, propels a projectile. Initially, helium was used as the 2SLGG WG to
 291 increase the velocity ceiling from 2.8 km/s to roughly 4.5 km/s [6]. Serious problems were soon encountered
 292 as performance increased: interior gun surfaces exposed to peak gas pressures would melt and/or boil.
 293 Evidence existed of metal droplets impacting range components, and experts speculated that vaporized steel
 294 (iron gas) mixed with the helium, significantly increasing the WG molecular weight. These problems were
 295 linked to helium's relatively high ratio of specific heats (γ) and heat convection properties [6]. The relatively
 296 small He atoms and their chemical inertness make them highly effective for convective heat transfer, which
 297 exacerbates 2SLGG barrel heating during launch. As a result, a shift towards hydrogen as the WG started
 298 in the early 1960s.

299 Despite decades of research and optimization, the essential components of 2SLGGs have remained largely
 300 unchanged since 1948 and consist of seven structural and consumable elements, including a pressure breech,
 301 pump tube, central breech, launch tube, piston, petal valve, and projectile package (*cf.* Fig. 1). These
 302 components perform the same basic functions during all operational cycles, with the pressure breech, pump

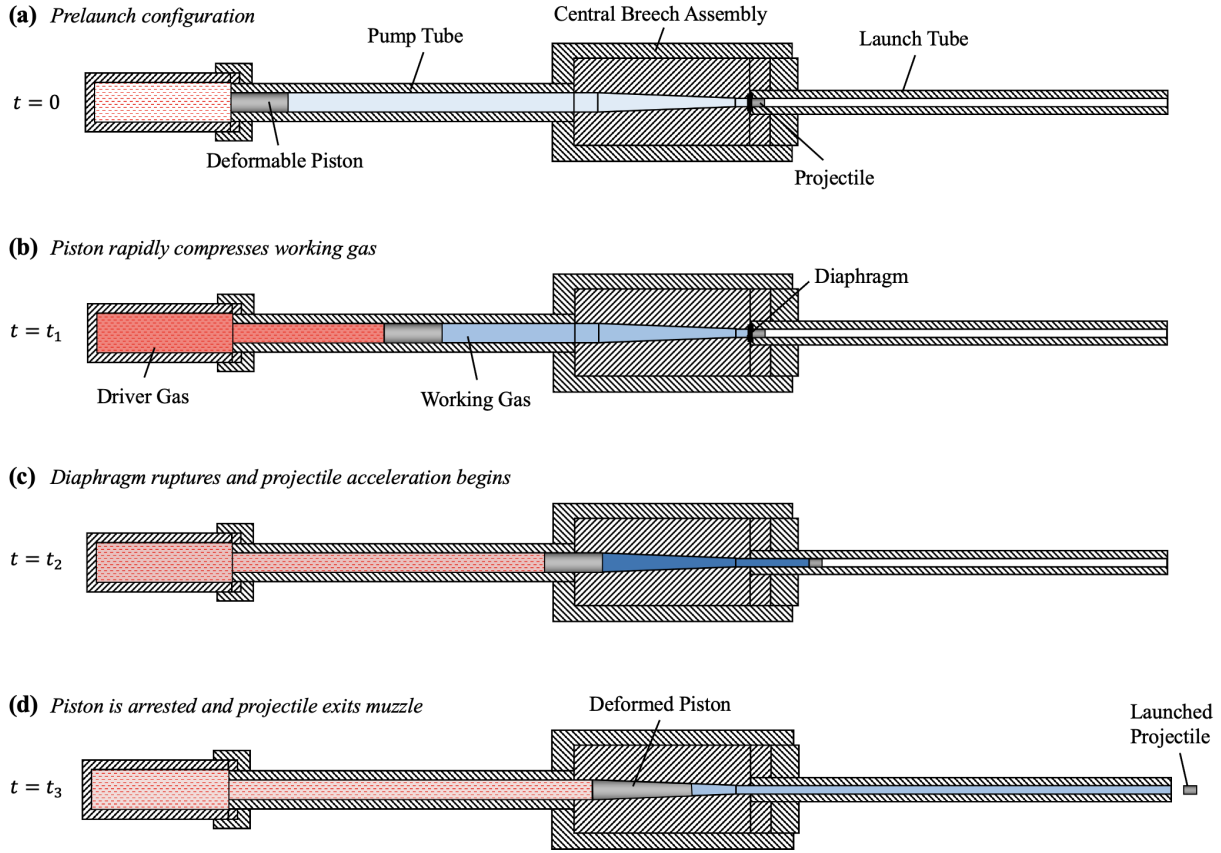


Figure 8: A schematic overview of 2SLGG working principle: (a) just before launch, (b) during WG compression, (c) when diaphragm ruptures and projectile acceleration begins, and (d) just after the projectile leaves the muzzle.

303 tube, central breech, and launch tube being coaxially arranged and rigidly coupled with gas-tight seals
 304 between each component. For illustration, Fig. 8 displays a representative 2SLGG during four key instances
 305 during a launch sequence. At the start of the internal-ballistic cycle, the piston is located at the uprange
 306 end of the pump tube, while the projectile is located at the uprange end of the launch tube, just downrange
 307 of the petal valve diaphragm (Fig. 8a). A specific amount of low-molecular-weight WG, typically hydrogen
 308 or helium, is loaded into the pump tube. When the high-pressure gas generated within the pressure breech
 309 is released, it accelerates the piston downrange within the pump tube, rapidly increasing the WG pressure
 310 and temperature (Fig. 8b). Upon reaching a critical pressure, the petal valve diaphragm ruptures, exposing
 311 the projectile's base to the WG, which then accelerates the projectile down the launch tube (Fig. 8c).
 312 Ultimately, the projectile exits the muzzle of the 2SLGG at some high-velocity or hypervelocity (Fig. 8d)
 313 and enters the range tankage (more later). These critical cycle steps are universal among most unmodified
 314 2SLGGs documented in the literature and provide a reliable and consistent means of achieving hypervelocity
 315 projectiles [15, 26, 32, 43, 98–143].

316 One powerful feature of the 2SLGG is that the piston velocity can be tailored to control the WG pressure

317 curve and, consequently, projectile acceleration. In fact, there are several potential loading parameters, such
318 as pressure breech conditions, piston mass, and initial WG pressure, that can be varied to achieve the same
319 muzzle velocity. Figure 9, which displays a representative WG pressure envelope for a 2SLGG [95, 97], helps
320 illustrate the regions where these loading conditions can be changed. The petal valve diaphragm ruptures at
321 a known pressure as the piston traverses the pump tube, with higher piston velocities corresponding to higher
322 peak WG pressure in the central breech. However, increasing the peak WG pressure has diminishing returns,
323 as acceleration-induced stresses can surpass the dynamic yield stress or toughness of the projectile material,
324 leading to projectile failure during launch. The loading parameters are, thus, typically chosen to prevent
325 over-accelerating the projectile. Additionally, the WG *temperature* must also be controlled to achieve desired
326 velocities. The currently available methods for dynamically generating both the high temperatures and
327 pressures in a 2SLGG WG are (i) shock compression and (ii) isentropic compression [6]. Shock compression
328 of the gas appears the more advantageous of the two because it can yield very high pressures and temperatures
329 on the downrange side of the shock wave. These extreme pressures, while desirable, present significant
330 challenges to designing practical containment structures (*i.e.*, the barrel). Furthermore, these shocks will
331 travel back and forth throughout the gas column, reflecting off the projectile base. These sharp pressure
332 and temperature rises are only applied in very short bursts and cause substantial positive and negative
333 accelerations to the projectile. Isentropic compression is therefore the more favorable choice and is often
334 used in modern 2SLGGs [2].

335 Although 2SLGGs share common operational conditions and key components, there are significant vari-
336 ations in how these conditions are achieved, the geometry of key components, and the resulting performance
337 capabilities. Despite these known differences, there has been little recent systematic documentation of
338 2SLGGs worldwide, making it challenging to compare the performance of different 2SLGG designs and iden-
339 tify areas for improvement. To address this gap, an extensive dataset summarizing the features of more than
340 90 2SLGGs worldwide, all of which are operational at least as of 1990, was compiled. The dataset, which is
341 presented in Table 1, includes information on each 2SLGG’s parent facility, country of origin, maximum re-
342 ported projectile velocity, launch tube bore diameter, and “drive type” (more in Section 3.2.1). The 2SLGGs
343 in Table 1 have been numbered by facility for consistency and ease of comparison, even though some may
344 have specific names designated by the parent organization. Additionally, Table 6 in Appendix A provides
345 more detailed information on the associated aeroballistic ranges, including some diagnostics, experimental
346 capabilities, and configurations. These tables provide a valuable resource for researchers, engineers, oper-
347 ators, students, project managers, and other stakeholders interested in assessing the diversity of 2SLGGs
348 and identifying trends, challenges, and opportunities for innovation. The following section highlights the
349 configurational and operational differences observed among the surveyed 2SLGGs.

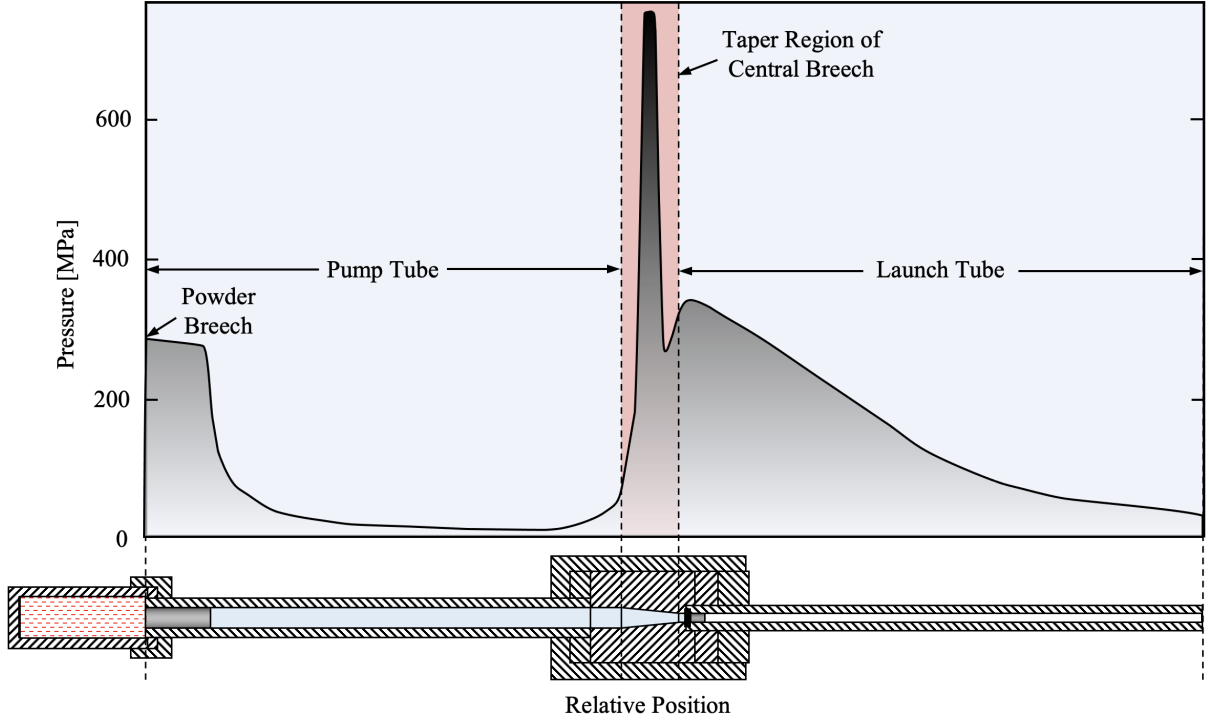


Figure 9: A representative internal pressure envelope for a 2SLGG, with pressure data sourced from Ref. [95, 97]. The plot provides insights into the 2SLGG working principles.

Table 1: An overview of the operational 2SLGG aeroballistic ranges as of 1990, detailing key information such as country of origin, maximum reported launch velocity, launch tube diameter(s), and first stage drive type. 2SLGGs can be driven by powder (P), compressed gas (C), or gaseous detonation (GD). Additional information regarding these 2SLGGs is provided in Appendix A. “*” denotes estimated values from indirect evidence in published works.

No.	Facility	Country	Max. Velocity (km/s)	Launch Tube Dia (mm)	Drive Type
1	Mississippi State University - I [32]	US	6.00	1.00	P
2	Drexel University [43, 136]	US	4.00	1.58	C
3	Caltech [100]	US	10.00	1.80	P
4	Commissariat a l’Energie Atomique - I [144, 145]	France	5.00	2.00*	P
5	National Defense Academy [101]	Japan	5.90	2.10	P
6	Commissariat a l’Energie Atomique - II [146]	France	3.40	3.00, 4.00	C
7	NASA MSFC - I [126]	US	7.50	4.00	P
8	University of Kent [137]	UK	7.70	4.30	P
9	Rice University [138, 139]	US	7.10	4.30	P
10	NASA WSTF - I [105]	US	8.50	4.32	P
11	Oak Ridge National Lab [147, 148]	US	5.00	1.90, 2.60, 3.20, 4.40	C
12	The Open University [149]	UK	7.00	4.70	P
13	NASA JSC [107]	US	8.00	5.00	P

Table 1: An overview of the operational 2SLGG aeroballistic ranges as of 1990, detailing key information such as country of origin, maximum reported launch velocity, launch tube diameter(s), and first stage drive type. 2SLGGs can be driven by powder (P), compressed gas (C), or gaseous detonation (GD). Additional information regarding these 2SLGGs is provided in Appendix A. “*” denotes estimated values from indirect evidence in published works.

No.	Facility	Country	Max. Velocity (km/s)	Launch Tube Dia (mm)	Drive Type
14	PERC, Chita [150, 151]	Japan	7.00	5.00*	P*
15	NASA MSFC - II [126]	US	7.50	5.59	P
16	Mississippi State University - II [99]	US	7.00	5.60	P
17	University of Nevada, Las Vegas [108]	US	6.80	5.60	P
18	Fraunhofer EMI - I [102]	Germany	7.00	4.00, 6.00	P
19	University of Padua [26]	Italy	5.50	4.72, 6.00	C
20	Japan Aerospace Exploration Agency [109]	Japan	7.00	7.00	P
21	Johns Hopkins University [134]	US	7.00	7.60	C
22	Cranfield University [152]	UK	...	7.60	...
23	Hypervelocity Aerodynamics Institute - I [133]	China	7.00	7.60	P
24	Denver Research Institute [153, 154]	US	7.00	7.62	...
25	Brookhaven National Lab [155]	US	1.5	7.62	C
26	KAIST [156, 157]	South Korea	3.2	7.62*	C
27	National Research Tomsk University - I [132]	Russia	5.00	8.00	C
28	Corvid [158]	US	7.00	8.00	...
29	Fraunhofer EMI - II [103]	Germany	9.00	8.50	P
30	University of New Brunswick - I [159, 160]	Canada	8.00	10.0	C
31	Imperial College London [152]	UK	4.00	10.0	C
32	Kyushu Institute of Technology [161, 162]	Japan	8.00	10.0*	P
33	TiTech [111]	Japan	8.90	11.8	P
34	Thiot Ingenierie [140, 141]	France	9.85	12.0	C
35	Texas A&M University [112, 113, 163]	US	7.00	12.7	P
36	NASA WSTF - II [105]	US	7.00	12.7	P
37	First Light Fusion - I [114]	UK	7.50	12.7	P
38	Argonne National Lab [164]	US	6.00	12.7	...
39	NASA AVGR [110, 165]	US	7.00	7.62, 12.7	P
40	Naval Surface Warfare Center - I [166]	US	6.00	7.0, 7.6, 12.7	P
41	Royal Military College of Science [115]	UK	7.00	15.0	P
42	Tohoku University - I [142]	Japan	1.00	15.0	C
43	Hypervelocity Aerodynamics Institute - II [15]	China	8.60	16.0	P
44	China Academy of Space Technology - I [167]	China	7.00	18.0	...
45	Arnold Engineering Development Complex - I [116]	US	8.00	19.0	P
46	Tohoku University - II [118]	Japan	7.50	20.0	P
47	UDRI - I [119]	US	7.50	20.0	P

Table 1: An overview of the operational 2SLGG aeroballistic ranges as of 1990, detailing key information such as country of origin, maximum reported launch velocity, launch tube diameter(s), and first stage drive type. 2SLGGs can be driven by powder (P), compressed gas (C), or gaseous detonation (GD). Additional information regarding these 2SLGGs is provided in Appendix A. “*” denotes estimated values from indirect evidence in published works.

No.	Facility	Country	Max. Velocity (km/s)	Launch Tube Dia (mm)	Drive Type
48	University of British Columbia [168]	Canada	4.00	20.0	P
49	University of New South Wales [169, 170]	Australia	4.50	22.0	C
50	Commissariat a l’Energie Atomique - III [171, 172]	France	7.90	22.0	P
51	National Research Tomsk University - II [143]	Russia	8.00	23.0	P
52	University of California, Davis [120]	US	8.00	25.0	P
53	China Academy of Space Technology - II [173, 174]	China	7.50	25.0	C
54	Hypervelocity Aerodynamics Institute - III [15]	China	...	25.0	P
55	Seoul National University [175]	South Korea	7.50	25.0	...
56	University of New Brunswick - II [159, 160]	Canada	...	25.0	P
57	National Institute for Material Science [176, 177]	Japan	7.00	18.0, 25.0	P
58	NASA WSTF - III [106]	US	7.00	25.4	P
59	Engineering Research Development Center [121]	US	7.50	25.4	P
60	Wuhan University [178]	China	5	25.4	C
61	Lawrence Livermore National Laboratory - I [179]	US	8.00	28.0	P
62	Sandia National Labs [123, 124]	US	8.00	28.0	P
63	Chinese Academy of Sciences [55]	China	...	30.0	GD
64	Los Alamos National Lab - II [180, 181]	US	8.00	28.00	...
65	UDRI - II [119, 182]	US	6.50	30.0	P
66	Northwest Institute of Nuclear Technology - I [183]	China	3.00	30.0	C
67	Swedish Defence Research Agency [184]	Sweden	...	30.0	P
68	Eglin Air Force Base [185, 186]	US	...	30.0	P
69	Southwest Jiaotong University [187]	China	8.00	30.0	...
70	University of Alabama in Huntsville - I [126]	US	8.00	19.0, 30.0	P
71	Institute of Saint-Louis [188]	France	7.00	10.0, 20.0, 30.0	...
72	Lawrence Livermore National Laboratory - II [128]	US	7.00	12.0, 20.0, 35.0	P
73	University of Alabama in Huntsville - II [126]	US	6.50	30.0, 36.0	P
74	Southwest Research Institute [127]	US	7.00	38.0	P
75	First Light Fusion - II [189]	UK	6.50	38.0	P
76	New Mexico Tech - EMRTC [130]	US	6.70	38.0	P
77	NASA Ames HFFAF [190]	US	9.00	12.7, 25.4, 38.1	P
78	Naval Surface Warfare Center - II [166]	US	7.00	19.0, 43.0	P
79	TBRL [191]	India	...	29.0, 40.0	P
80	Los Alamos National Lab - I [129]	US	3.60	50.0	P,C
81	Hypervelocity Aerodynamics Institute - IV [15, 131]	China	6.75	37.0, 50.0	P

Table 1: An overview of the operational 2SLGG aeroballistic ranges as of 1990, detailing key information such as country of origin, maximum reported launch velocity, launch tube diameter(s), and first stage drive type. 2SLGGs can be driven by powder (P), compressed gas (C), or gaseous detonation (GD). Additional information regarding these 2SLGGs is provided in Appendix A. “*” denotes estimated values from indirect evidence in published works.

No.	Facility	Country	Max. Velocity (km/s)	Launch Tube Dia (mm)	Drive Type
82	Arnold Engineering Development Complex - II [116, 117]	US	6.75	64.0	P
83	Lawrence Livermore National Laboratory - III [128]	US	8.00	20.0, 28.0, 64.0	P
84	Fraunhofer EMI - III [104]	Germany	7.80	25.0, 50.0, 70.0	P
85	TAMU Ballistics Aero-optics and Materials [192, 193]	US	...	102	P
86	University of Alabama in Huntsville - III [126]	US	6.00	56.0, 152	P
87	Arnold Engineering Development Complex - III [116, 117]	US	6.90	83.8, 102, 203	P
88	Agency for Defence Development [194]	South Korea	...	...	C
89	Harbin Institute of Technology [195]	China	3.00	...	...
90	Northwest Institute of Nuclear Technology - II [196]	China	7.20	...	...
91	Beihang University [197]	China	6.50	...	...
92	Shenyang Ligong University [198]	China	7.00	...	...

3.2. A Configurational and Operational Comparison of 2SLGGs

All 2SLGGs operate by compressing a light WG (He, H₂, *etc.*) using a drive mechanism similar to that used in a single-stage launcher to directly accelerate a projectile. However, the compressed WG achieves higher pressures and temperatures than those attainable by single-stage launchers, thereby facilitating more efficient energy transfer to the projectile. Five key components are generally shared across all 2SLGGs: (1) a pressure breech, (2) a pump tube, (3) a central breech, (4) a petal valve (burst) diaphragm, and (5) a launch tube (barrel). 2SLGG pressure breech drive type, pump tube diameter and length, central breech transition geometry, launch tube diameter and length, and pump-tube-to-launch-tube diameter ratio can all be readily varied to meet specific performance and launch demands. The customizability of these design features has resulted in vast differences among 2SLGGs in operation today as partially outlined in Table 1.

3.2.1. Pressure Breeches and Drive Types

The uprange-most component of a given 2SLGG is the pressure breech (*cf.* Figs. 1 and 8). The configuration and working principle of the pressure breech determines a given 2SLGG’s “drive type.” 2SLGGs can be powder-driven [98, 102, 110, 116, 121, 127, 199], gas-driven [26, 118, 129, 134, 136], or gaseous-detonation-driven [55]. Powder-driven 2SLGGs are simple and widely used, while gas-driven systems offer more precise control and potentially cleaner operation. Much less prevalent is the gaseous detonation method, which uses a controlled detonation of a gaseous mixture. Despite these variations in drive type, the purpose

367 of the pressure breech is consistent: to accelerate the compression piston downrange.

368 Powder-driven guns use the expanding gases from a chemical propellant (*e.g.*, nitrocellulose or gunpowder)
369 housed in a sealed powder chamber to begin the operational cycle (*i.e.*, “powder-driven”). The pressure
370 breech is sealed on the uprange end by a breech block and on the downrange end by a (most often) deformable
371 compression piston, typically machined from a polymeric material. Commonly, the main powder charge is
372 ignited by a smaller, faster burning charge in conjunction with a booster (Fig. 10). The entire 2SLGG cycle
373 is initiated by a remote control firing system. The rapidly expanding gases can reach breech pressures on
374 the order of hundreds of megapascals, accelerating the piston downrange and rapidly compressing the WG.
375 This method is employed in guns of all sizes, ranging from some of the smallest [32] to mid-range [105] to
376 the largest [44] operational 2SLGGs.

377 Alternatively, “cold” compressed gas-driven 2SLGGs employ large reservoirs of high-pressure gas (*e.g.*,
378 air, nitrogen, helium) and fast-acting valves to induce compression piston motion (Fig. 10b). Typically,
379 the advantages associated with this method are greater repeatability in 2SLGG muzzle velocity and less
380 involvement of hazardous materials. On the other hand, gas-driven guns generally possess a lower velocity
381 ceiling for a given projectile size/mass. Moreover, they are typically not viable for relatively larger projectiles
382 because the volume of the compressed gas reservoirs required for launch within the hypervelocity regime
383 becomes cost and/or space prohibitive. Nonetheless, many facilities with small [26, 136] and medium sized
384 [118, 134] 2SLGGs still prefer this method to accelerate the piston.

385 Lastly, gaseous detonation may be used to accelerate the piston, where an ignition device is used to
386 initiate the process. Once the gas pressure reaches some critical pressure, a diaphragm ruptures and piston
387 acceleration begins (Fig. 10c). This approach, however, is much less prevalent than the powder and cold-gas
388 methods. Roughly 76% of surveyed 2SLGGs operational worldwide are powder-driven, while only 23% and
389 1% are cold gas-driven and gaseous-detonation-driven, respectively (Fig. 10d). The majority of currently
390 operational guns designed and built prior to 1990 are powder-driven, largely due to the intrinsic performance
391 advantages. Regardless of the drive type, the pressure breech is ultimately used to generate high-pressure
392 gas to accelerate the (usually) consumable piston down the pump tube and rapidly compress the WG.

393 3.2.2. Pump Tubes

394 The sole purpose of the pressure breech is to launch the deformable compression piston down the pump
395 tube at velocities near 1 km/s. Common to all 2SLGGs, pump tubes are thick-walled, hollow, metal cylinders
396 ($L/D \approx 50\text{--}100$) through which the piston travels and compresses the WG. The pump tube is thus both
397 simultaneously a barrel *and* a dynamically evolving reservoir (piston cylinder). In fact, the pressure breech
398 combined with the pump tube is analogous to a single-stage powder or gas gun (*cf.* Fig. 1) with the key

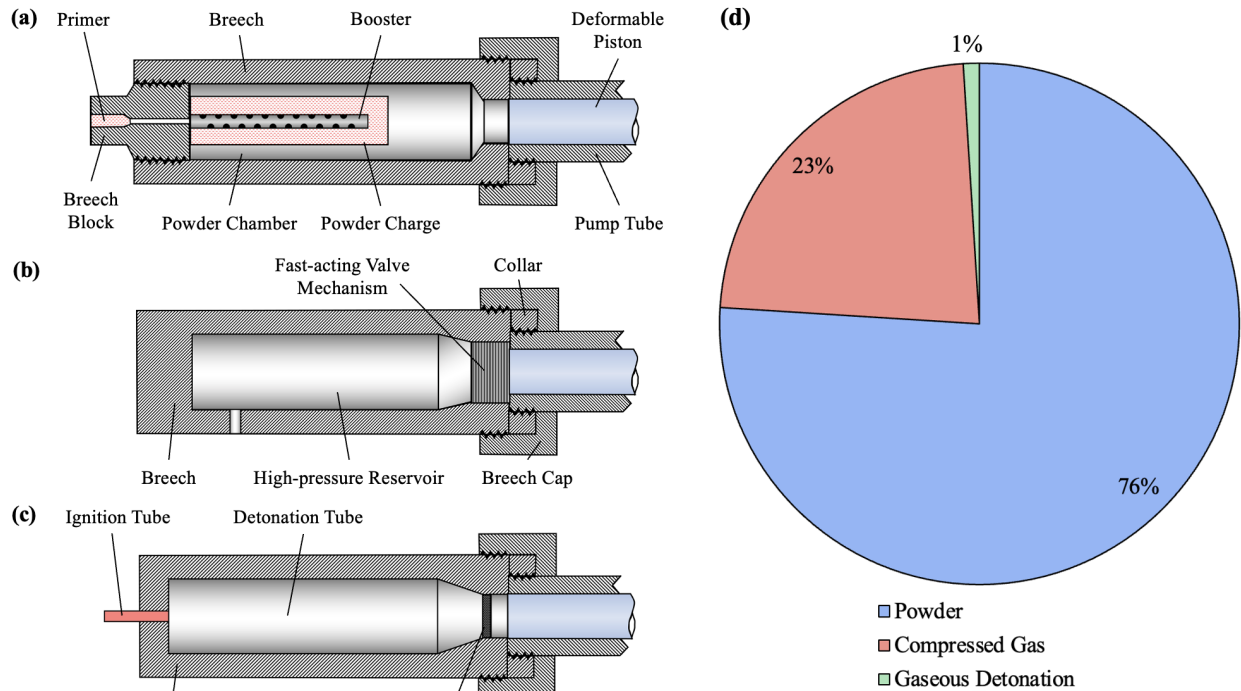


Figure 10: The three common driver systems for 2SLGGs, with simple schematics of the (a) powder-driven, (b) compressed-gas-driven, and (c) gaseous-detonation-driven components and (d) a breakdown of the percentage of 2SLGGs that employ each system.

399 difference, of course, being that the “projectile” in this case is the piston. Pump tubes are usually several
 400 times larger in diameter than the 2SLGG launch tube to ensure projectile base pressures are maintained
 401 during acceleration.

402 3.2.3. Central Breech Assemblies

403 The pump tube facilitates WG compression into the central breech assembly (also termed “high-pressure
 404 section,” “high pressure coupling,” or “accelerated reservoir” [6, 97, 124, 200]), which couples the downrange
 405 end of the pump tube to the uprange end of the launch tube. The breech core serves as a transition between
 406 the pump tube and launch tube inner diameters and is typically a hollow cylinder of conical cross-section
 407 with included neck-down transition angle, β . A rupture diaphragm (*i.e.*, burst disc, petal valve) with
 408 accompanying cassette assembly is fixed between the downrange end of the central breech and uprange end
 409 of the launch tube. During a given cycle, the WG pressure and temperature reach maximum values within
 410 the central breech (*e.g.*, up to 1 GPa and >1000 K, respectively). For this reason, most central breech
 411 assemblies include coupling devices and high-pressure seals that are specially designed to prevent central
 412 breech decoupling and gas leakage during WG compression [6].

413 The dual collar-breech-cap mechanism serves as one simple way to compress the central breech core

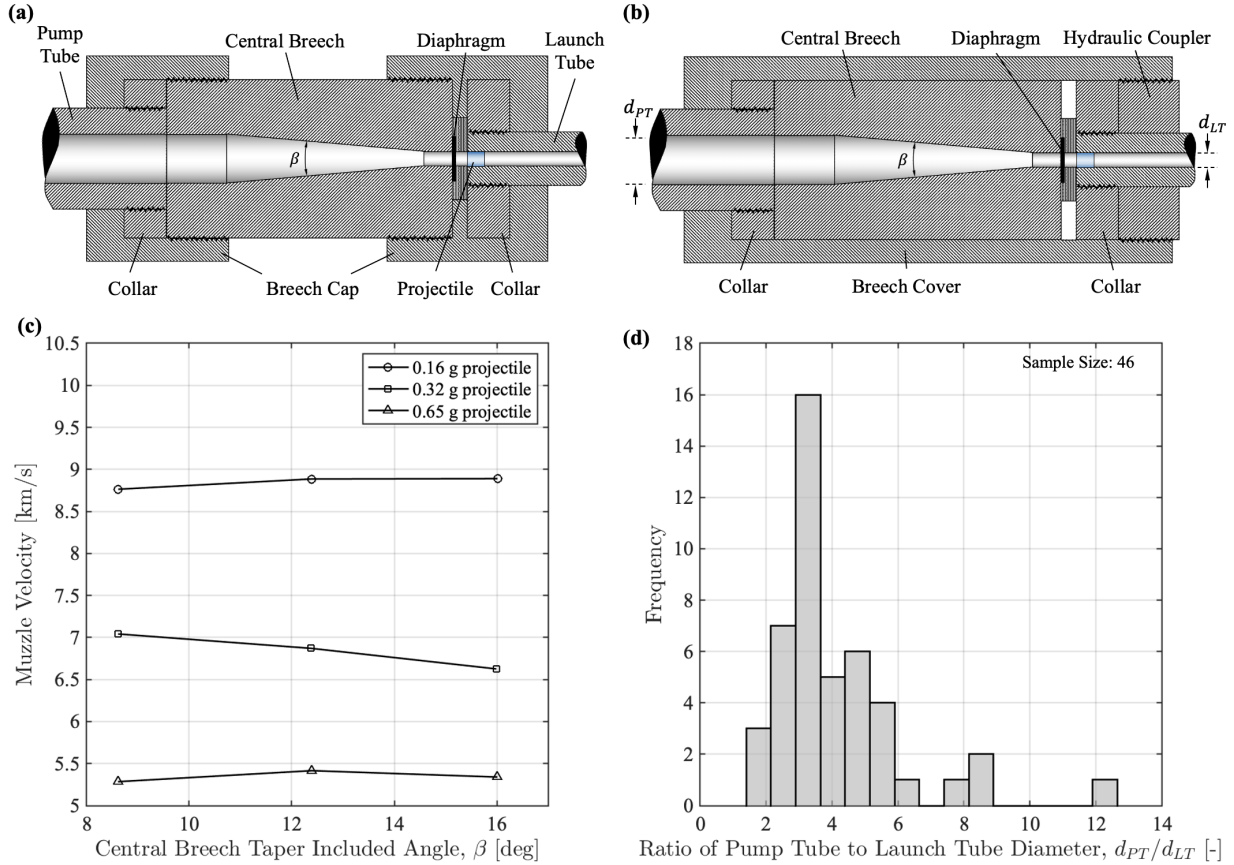


Figure 11: An overview of the central breech assembly used in 2SLGGs, featuring (a,b) schematics of two common central breech assembly configurations, (c) a demonstrative plot of experimental muzzle velocity *versus* central breech taper angle (β), and (d) a histogram of the pump-tube-to-launch-tube-diameter ratios (d_{PT}/d_{LT}). The histogram reveals that the most prevalent ratio is approximately three. Data in (c) is obtained from NASA Ames 7.1 mm/39 mm 2SLGG, and the figure was adapted from Ref. [2].

414 between the pump and launch tubes (Fig. 11a). Breech caps and annular metallic collars are fixed to
 415 the downrange end of the pump tube and uprange end of the launch tube. The breech caps are then
 416 tightened onto the threaded central breech core, compressing the seals located at the pump tube and launch
 417 tube interfaces. Since the inception of 2SLGGs, the designs of seals have undergone significant evolution.
 418 References [2, 6] present overviews of these designs.

419 Another way to couple the central breech between the pump and launch tubes is *via* a “breech cover”
 420 design. Instead of compressing each central breech interface individually, the entire central breech assembly
 421 is compressed by equal and opposite axial forces applied to the collars by the breech cover and a hydraulic
 422 coupler (Fig. 11b). The hydraulic coupler can readily apply coupling forces that exceed 500 kN. Since
 423 coupling forces must grow with geometric scale, the breech cover design is typically employed in medium-
 424 to large-scale 2SLGGs. While these two central breech assembly configurations outline common coupling
 425 mechanisms, other designs do exist.

426 The prevailing central breech geometry used in current isentropic 2SLGGs owes its origins to Curtis
 427 [2, 201]. Key features of this geometry include a slender central breech taper section with a transition angle
 428 ranging $\beta = 6^\circ\text{--}16^\circ$ and a relatively heavy piston typically constructed from a deformable yet incompressible
 429 plastic such as polyethylene. During the pump tube WG compression phase, the piston enters the tapered
 430 region of the central breech and experiences deceleration due to retarding forces from the conical wall and
 431 increasing WG pressure. This process generally halts the piston’s motion, minimizing the need for additional
 432 gas buffers and enabling an optimized WG compression ratio in a non-destructive manner. The slender taper
 433 ensures a smooth flow transition with minimal central breech erosion/wear; however, it can generate and
 434 intensify shock waves as the piston enters the taper [202, 203]. As the piston extrudes into the taper, its
 435 downrange face velocity increases inversely proportional to the corresponding area change, potentially causing
 436 compression waves to rapidly merge into shock waves if the acceleration is significant. These shock waves
 437 may increase projectile velocity but can also cause undesirable base pressure fluctuations. Nevertheless,
 438 using a slender taper may lead to enhanced projectile velocities relative to those attainable using a constant
 439 diameter section. The accelerated gas particles may also gain additional kinetic energy, reducing the pressure
 440 drop between the reservoir and the projectile. This effect is more prominent in high-speed piston guns but
 441 may be less significant in guns with large chambrage and slow pistons [2].

442 The effect of transition/taper angle (β) on muzzle velocity has been previously investigated. For example,
 443 0.16 g, 0.32 g, and 0.65 g projectiles were launched by the NASA Ames 7.1 mm/39 mm 2SLGG using
 444 equivalent loading conditions and only varying β [2]. The experimental data from this study are plotted in
 445 Fig. 11c, which clearly shows that muzzle velocity is not significantly influenced over the range $\beta = 8^\circ\text{--}16^\circ$.
 446 Other studies have shown a decrease in performance for higher transition angles [51, 204]. The optimal taper
 447 angle is still an active area of research and development, with currently available central breech and piston
 448 materials being key limiting factors. Recent studies, however, indicate that the optimal transition angle is
 449 generally between $\beta = 7^\circ\text{--}14^\circ$ [91, 204].

450 Another factor that affects the central breech’s geometry is the ratio of the pump tube inner diameter
 451 to the launch tube bore diameter (d_{PT}/d_{LT}). This ratio not only enables the comparison of 2SLGGs across
 452 various length scales but also significantly impacts their performance and efficiency. Consequently, this ratio
 453 has been the focus of numerous 2SLGG optimization studies (*cf.* [50, 51, 53, 54, 183, 205–208]). This has
 454 led to a relative decrease in both pump tube diameters and lengths and an increase in WG starting pressure
 455 since 2SLGG operations began in the 1950s. Operational 2SLGGs have a wide range of d_{PT}/d_{LT} ratios due
 456 to laboratory space restrictions, modest performance requirements, *etc.* Figure 11d shows a histogram of all
 457 d_{PT}/d_{LT} values available for the 2SLGGs from Table 1. Clearly, $d_{PT}/d_{LT} \approx 3$ is most common, which aligns
 458 with designated optimal values from the literature [2, 50, 51]. As an aside, most larger values of d_{PT}/d_{LT}

459 correspond to 2SLGGs with *multiple* launch tubes of various diameters for a single pump tube. In general,
 460 both β and d_{PT}/d_{LT} are chosen for a given gun based on design/performance requirements.

461 3.2.4. Rupture Diaphragms (Petal Valves)

462 For all 2SLGGs, the WG is compressed in the pump tube and the central breech until its pressure reaches
 463 some critical value necessary to burst the rupture diaphragm (*cf.* Figs. 11a and 11b). In most cases, the
 464 rupture diaphragm (aka petal valve) is a metallic circular disc of thickness e with two perpendicular radial
 465 grooves of depth ε (Fig. 12a). The pressure at which the diaphragm ruptures can be partially controlled
 466 by varying the depth of the grooves for a given disc thickness. This rupture pressure (or release pressure)
 467 has a second-order effect on 2SLGG performance, with higher rupture pressures resulting in modest muzzle
 468 velocity gains [2]. Most often, the rupture pressure (p) is determined experimentally as a function of petal
 469 valve geometry, leading to simple empirical expressions, such as

$$p = \frac{A}{B} e^{3/2} (\varepsilon/e)^{-1/2}, \quad (3)$$

470 where empirical parameter A depends on diaphragm dimensions, groove depth, and material properties
 471 (elastic limit, fracture toughness, *etc.*), $B = 1 + 3.75(\varepsilon/e)^3$, and $0.05 < \varepsilon/e < 0.4$ [95, 209]. For illustration,
 472 Eq. (3) is plotted as a function of ε/e for various values of A in Fig. 12b, with common burst pressures
 473 highlighted. Simple expressions like Eq. (3) facilitate critical burst pressure optimization and, ultimately,
 474 muzzle velocity enhancement. For a given 2SLGG, the burst diaphragm material and geometry, however,
 475 are often held constant across experiments to nominally remove projectile release pressure as a variable.

476 3.2.5. Launch Tubes

477 Once the WG reaches the critical release pressure, the rupture diaphragm opens (Fig. 12b inset), and the
 478 hot, high-pressure WG rapidly travels into the uprange end of the launch tube, initiating projectile acceler-
 479 ation. Similar to pump tubes, launch tubes are thick-walled, hollow cylinders with length-to-diameter ratios
 480 ranging $L_{LT}/D_{LT} \sim 100\text{--}400$. The launch tube functions similar to a traditional gun barrel, as it contains
 481 high-pressure gas that accelerates the projectile. The term “launch tube” is used primarily to differentiate
 482 it from the pump tube, rather than to indicate any significant functional differences. Launch tubes can
 483 be categorized as either rifled or smooth-bore. Rifled launch tubes provide projectile spin stabilization and
 484 enable sabot separation (see Section 3.2.6) in a vacuum through gyroscopic forces; however, they also intro-
 485 duce uncertainty in projectile rotational kinetic energies. In contrast, smooth bore launch tubes contribute
 486 negligible rotational kinetic energy but require aerodynamic drag for sabot separation. Rifling for larger bore
 487 diameters can be challenging, particularly if the launch tube is segmented. Therefore, smooth bore launch

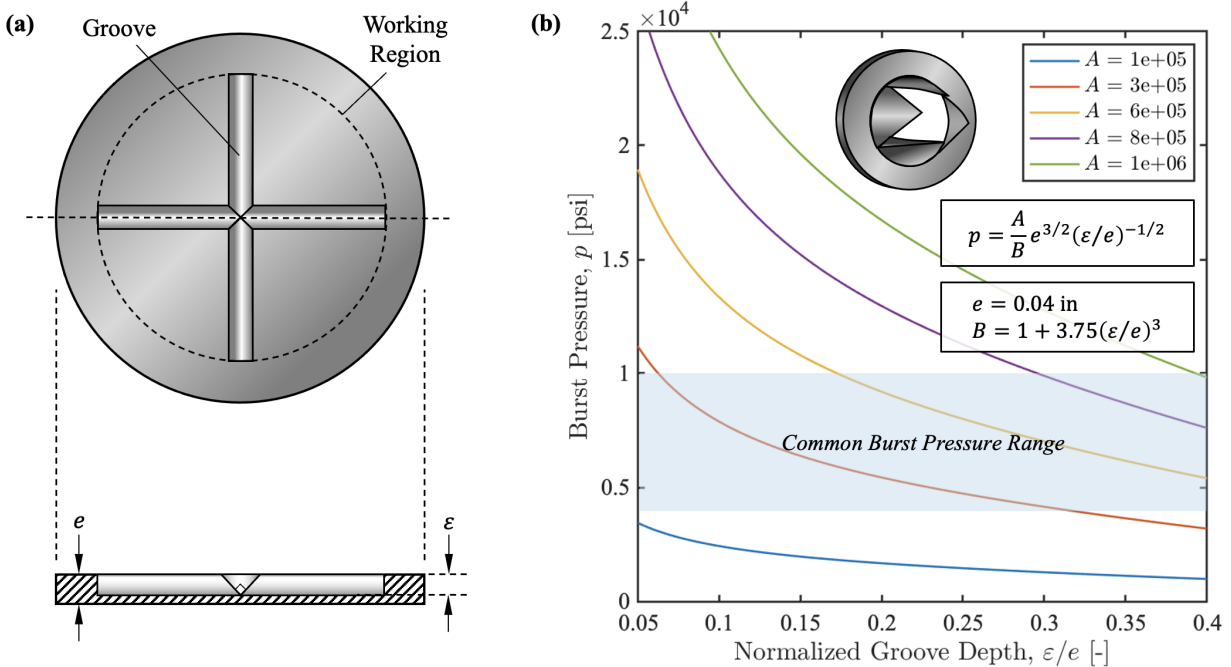


Figure 12: An overview of the rupture diaphragm (petal valve) configuration commonly used in 2SLGGs, featuring (a) a schematic of the petal valve with total thickness e and groove thickness ε , and (b) an empirical plot of the petal valve burst pressure as a function of groove depth for various values of constant A . This relationship is valid for groove thicknesses in the range of $0.05 < \varepsilon/e < 0.4$. The constant A depends on diaphragm dimensions, groove depth, and material properties such as the elastic limit and stress intensity factor for crack propagation, as described in Refs. [95, 209].

488 tubes become more prevalent as the diameter increases (*e.g.*, $D_{LT} \geq 12.7$ mm).

489 Since the diameter of the launch tube determines the diameter of the projectile or model that can be
 490 launched, a given 2SLGG is typically described by its “bore size” alongside its range of attainable muzzle
 491 velocities. Furthermore, the launch tube diameter serves as the most reliable indicator of overall 2SLGG size,
 492 as all components typically scale in proportion to the bore size. Figure 13a presents a histogram of launch
 493 tube bore sizes for the 2SLGGs examined in this study (Table 1). Although bore sizes can exceed 200 mm
 494 (*e.g.*, Arnold Engineering Development Complex (AEDC) Range-G), the majority of 2SLGGs feature launch
 495 tubes with diameters under 40 mm (*cf.* Table 1). This observation aligns with expectations, as the cost
 496 and complexity of aeroballistic ranges escalate nonlinearly with gun size. Consequently, national research
 497 priorities and long-term available funding play substantial roles in the distribution of launch tube diameters
 498 (L_{LT}/D_{LT}).

499 Another key parameter for 2SLGGs is the length-to-diameter ratio of the launch tube. For a given 2SLGG
 500 and set of operational parameters, increasing L_{LT}/D_{LT} has been demonstrated to increase muzzle velocity
 501 up to a certain threshold [2]. Beyond this critical point, frictional (and other) losses hinder further velocity
 502 gains and can, in fact, considerably reduce the projectile velocity. For example, Fig. 13b shows muzzle
 503 velocity *versus* launch tube length-to-diameter ratio (“bore-normalized launch tube length”) data for two

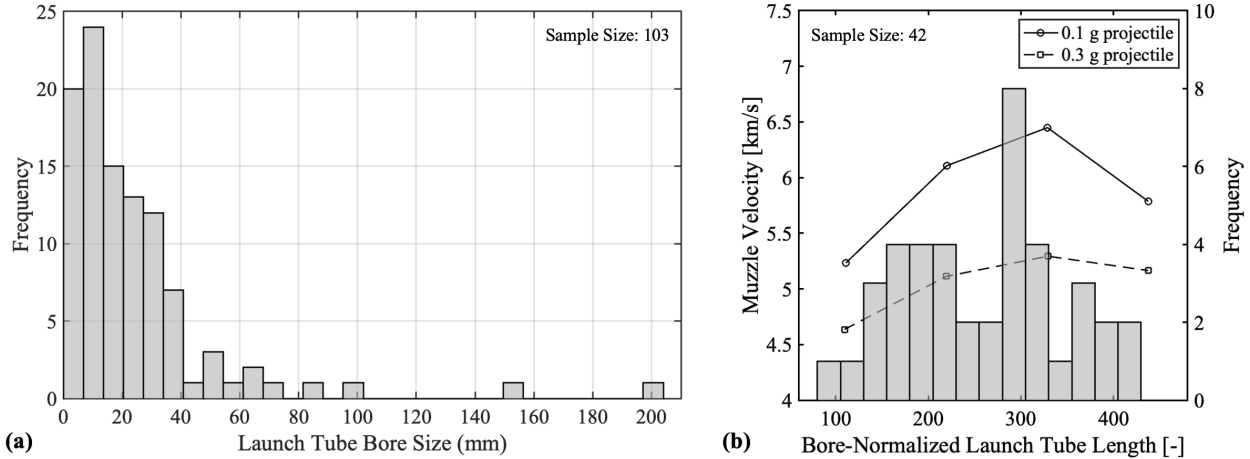


Figure 13: 2SLGG launch tube geometry: (a) an illustrative plot of experimental muzzle velocity *versus* bore-normalized launch tube length superimposed on a histogram of bore-normalized launch tube length and (b) a histogram of the bore sizes of launch tubes used in 2SLGGs worldwide. The histogram demonstrates that the majority of 2SLGG launch capability is reserved for projectiles with a diameter of approximately 40 mm or smaller. The sample size in the histogram is larger than the total number of 2SLGGs, as some facilities possess multiple launch tubes for the same 2SLGG.

504 different mass projectiles taken from the NASA Ames 7.1 mm/39 mm 2SLGG [2]. A peak in muzzle velocity
 505 for both projectile masses corresponds with an optimal ratio of $L_{LT}/D_{LT} \approx 325$. Superimposed on these
 506 trends is a histogram of all available launch tube length-to-diameter ratios for the 2SLGGs from Table 1.
 507 This distribution shows that research, performance, and laboratory space requirements have led to notable
 508 differences not only in launch tube diameters but also launch tube length-to-diameter ratios. The initial
 509 projectile velocity increase with increasing launch tube length in Fig. 13b is consistent with elementary
 510 predictions obtained using Eq. (2), which suggests that sustaining a positive projectile base pressure for
 511 extended durations or distances enhances muzzle velocity (*cf.* Figs. 7a and 7b). The trend holds until
 512 the negative frictional forces between the projectile and the bore surpass the positive force exerted on
 513 the projectile’s base by the WG or there is a loss of positive base pressure (*i.e.*, finite reservoir effects).
 514 Expanding the velocity ceiling is not the sole purpose for adjusting the launch tube length-to-diameter ratio;
 515 lengthening the launch tube at a fixed diameter also moderates the acceleration profile needed to propel a
 516 specific projectile to a desired velocity. This feature may be advantageous when launching fragile or intricate
 517 projectiles or models to hypervelocities.

518 3.2.6. Projectiles and Sabots

519 Throughout this discussion, the term “projectile” has been used broadly to denote the object being
 520 launched. Specifically, projectiles can encompass single, full-caliber geometries with diverse length-to-
 521 diameter ratios or, more frequently, projectile “packages” comprised of a sub-caliber projectile and its
 522 corresponding sabot [2, 210]. Sabot geometries can vary substantially, but their primary functions include

523 obturating the launch tube (inhibiting WG blowby) and sustaining the projectile during acceleration. Of
524 course, it is undesirable for the sabot to interfere with the experiment. To avert this issue, segmented sabots
525 are strategically designed to facilitate radial separation of each sabot component during the projectile’s free
526 flight *via* gyroscopic or aerodynamic forces. Eventually, the projectile traverses a thick, metallic annular
527 disc that captures the sabot fragments (see Section 5.1). Ideally, only the projectile enters the diagnostic
528 field of view and/or comes into contact with the target. Complex sabot designs and separation mechanics
529 can differ significantly than described here and are driven by the specifics of a given experiment (see Section
530 5.2) [2, 210–214]. As such, an in-depth discussion on sabots is beyond the scope of this present work.

531 3.3. Notable Modifications to the 2SLGG

532 The pursuit of increasingly higher muzzle velocities has resulted in significant modifications to the 2SLGG,
533 giving rise to what is known as “three-stage light gas guns” (3SLGGs). As these devices fall somewhat outside
534 the focus of this review, they are only *briefly* discussed here to provide some illustrative examples, broader
535 insights, and perspectives. 3SLGGs can be distinguished from 2SLGGs largely due to the inclusion of *i*) dual,
536 in-line pump tubes, *ii*) parallel pump tubes, *iii*) spall pillow (or flyer plate) muzzle attachments, and *iv*)
537 preheating of the WG. Although some significant performance improvements are possible, these modifications
538 are not necessarily consistently applied or widely adopted. Often, these modifications are research subjects
539 themselves (see, *e.g.*, [11, 12, 30, 132, 215–218]).

540 Several approaches to modifying the basic 2SLGG configuration involve incorporating an additional light
541 gas compression stage. For example, the effectiveness of the 2SLGG inspired the creation of one 3SLGG
542 concept, which incorporates an extra *in-line* compression stage to enhance performance (*i.e.*, 2SLGG +
543 LGG). Although this appears a reasonable and natural extension to the 2SLGG, the few instances in which
544 this technique has been attempted have resulted in only modest increases in muzzle velocity (up to roughly
545 9 km/s) while adding significant design challenges [11, 132, 215]. The energy required to accelerate *two*
546 compression pistons, along with the inevitable frictional losses, offsets any significant increases in projectile
547 muzzle velocity. Consequently, the modest improvements in velocity, combined with higher consumable,
548 construction, and labor costs, have led to its limited adoption. The increased complexity of optimizing
549 performance parameters (powder mass, pump tube pressures, piston masses, *etc.*) for this 3SLGG also
550 makes it less predictable and more operationally complex.

551 The inclusion of an extra in-line pump tube is distinct from a dual, *parallel* pump tube arrangement.
552 One of the most innovative developments to the light gas compression stage is Fraunhofer EMI’s “Twingun,”
553 featuring two pressure breech and pump tube assemblies arranged in parallel [30]. The pump tubes share a
554 common central breech. Both pressure breeches are powder driven, and the charges can be detonated with

555 precisely delayed timing. This results in pistons intentionally traveling asynchronously downrange in the
556 pump tubes. The time difference between the piston arrival times can be controlled to “smoothen” the WG
557 pressure curve and, thus, the projectile acceleration profile. Smoother acceleration profiles generally broaden
558 the type and mass range of projectiles that can be launched by a given 2SLGG, since many projectiles can
559 fail in the launch tube if subjected to sufficient peak accelerations.

560 Other 2SLGG modifications that do not incorporate an additional compression stage have also been
561 referred to as 3SLGGs. One notable example that has resulted in significant muzzle velocity gains leverages
562 a 2SLGG-launched projectile to initiate an additional launch strategy. The process generally involves using
563 a projectile assembly with varying density to strike a stationary (often metallic) flyer plate [12, 13, 217, 218].
564 As a result of the impact, transient, structured, high-pressure waves (*e.g.*, 100 GPa) are produced, enabling
565 the relatively gentle acceleration of the plate to extreme speeds without material failure. The design of the
566 variable-density impactor is essential for ensuring the flyer plate’s smooth acceleration without excessive
567 heating that could cause melting or vaporization of the flyer plate. Moreover, the pressure wave must be
568 adjusted to prevent the flyer plate from experiencing spall fractures. These requirements are crucial for
569 effectively launching flyer plates to velocities beyond the capabilities of unmodified 2SLGGs. For instance,
570 employing these techniques has allowed the launching of titanium (Ti-6Al-4V) and aluminum (6061-T6)
571 alloy plates with thicknesses between 0.5 mm and 1.0 mm (and masses from 0.1 g to 1 g) to speeds exceeding
572 15 km/s [13].

573 An alternative 3SLGG incorporates an extra preheating and filling stage in the pump tube, which enables
574 broader control over the initial energy of the WG (*cf.* [216]). This increase in the initial gas temperature not
575 only allows for potentially higher muzzle velocities but also helps suppress peak pressures in the reservoir,
576 even while increasing the amount of powder charge for higher projectile velocities. In this way, the preheating
577 process can contribute to achieving high velocities while also enabling relatively low projectile accelerations.
578 The latter aspect is particularly useful for testing intricate and delicate projectiles and models. Although
579 this method offers potential advantages, there is a scarcity of available data, and practical obstacles include
580 effectively heating the WG and managing its temperature in an experimentally repeatable manner. Even
581 with the relatively low adoption of these techniques, the featured 3SLGGs demonstrate how innovative
582 modifications to the 2SLGG can enhance muzzle velocity and projectile launch survivability. An overview
583 of these techniques can be found in Table 2.

584 **4. A Brief Comparison of 2SLGG Performance Capabilities**

585 Variations in 2SLGG configurations and operations have given rise to a broad spectrum of performance
 586 capabilities. For instance, 2SLGGs that can propel projectiles/models at velocities between 2 and 4 km/s
 587 are typically suitable for most hypersonic applications, whereas projectile velocities must exceed 6 km/s for
 588 most MMOD problems. The achievable velocity range alone, however, is an inadequate 2SLGG selection
 589 criterion, as a majority of MMOD problems can be addressed by employing relatively small, easily launched
 590 metallic spheres of various diameters while hypersonic problems generally require launching larger and more
 591 sophisticated projectiles/models. Of course, the range tankage also plays an integral role in the aeroballistic
 592 range selection process (see Section 5.1). For these reasons, the performance ceiling of a 2SLGG is often
 593 measured by the highest kinetic energy it can transfer to a projectile during launch. Factors such as the
 594 gun’s size, shape, drive type, and working gas, as well as the projectile’s ability to withstand the launch
 595 accelerations, heavily influence this performance threshold. In other words, the highest performing 2SLGGs
 596 have the greatest achievable kinetic energies.

597 Comparing a given 2SLGG’s maximum muzzle velocity and launch tube diameter (Table 1) provides some
 598 indication of its performance capabilities. An increase in launch tube diameter (and thus gun size) generally
 599 corresponds to an increase in the projectile mass that can be launched to a given peak muzzle velocity (*i.e.*,
 600 peak projectile kinetic energy scales with gun size). However, determining the maximum kinetic energy for
 601 all documented 2SLGGs presented a challenge, as most studies did not explicitly provide this information and
 602 many 2SLGGs do not operate at full performance capacity. When possible, appropriate projectile mass and
 603 velocity data from published experimental results were utilized to calculate representative kinetic energy
 604 values. These estimates, along with explicitly reported kinetic energy limits, are provided in Fig. 14 in
 605 descending order for a representative sample of operational 2SLGGs. Achievable peak projectile energies
 606 range from a few joules to nearly 100 megajoules (roughly equivalent to 25 kg of TNT). The lowest plotted
 607 projectile kinetic energy of ~ 20 J corresponds to Mississippi State University’s (MSU) ~ 4 m long, 1 mm bore
 608 2SLGG range (the smallest bore reported, Fig. 15a, [32]), while the highest energy of ~ 96 MJ was achieved

Table 2: A list of representative “three-stage light gas gun” (3SLGG) capabilities. Each capability is characterized by the third stage differentiating it from a standard 2SLGG, including dual in-line and parallel pump tubes, spall pillow or flyer plate muzzle modifications, and working gas preheating.

No.	Facility Name	Country	Third Stage
1	National Research Tomsk University [132]	Russia	Dual pump tube, in-line
2	University of Dayton Research Institute (UDRI) [11]	US	Dual pump tube, in-line
3	Fraunhofer EMI – “Twingun” [30]	Germany	Dual pump tube, parallel
4	Tokyo Institute of Technology [216]	Japan	Dual drive (powder and compressor), preheating
5	Lawrence Livermore National Laboratory [215]	US	Dual pump tube, in-line
6	Sandia National Laboratory [12]	US	Spall pillow/flyer plate
7	China Academy of Space Technology [218]	China	Spall pillow/flyer plate

609 by AEDC’s ~ 280 m long, 203 mm bore 2SLGG range (the largest bore reported, Fig. 15b, [116, 117])¹. The
610 other operational 2SLGGs span the range of achievable kinetic energies. Hence, many space, hypersonic,
611 and military research problems can be readily addressed at a nearly continuous scale of projectile size/mass
612 and impact energy.

613 The peak projectile kinetic energy does not offer a comprehensive understanding of a 2SLGG’s perfor-
614 mance capabilities, as it may only apply to a limited number of projectile materials and/or geometries. In
615 particular, this peak value may not translate to a wide range of projectile masses, as heavier/denser projec-
616 tiles becoming increasingly difficult to launch for a given 2SLGG. For this reason, the range of velocities that
617 can be achieved for designated launch package masses may provide a better comparison metric in the evalu-
618 ation of 2SLGG performance. Experimentally generating a comprehensive collection of 2SLGG performance
619 data, however, can be cost-prohibitive and time-consuming. Even when such data is available, many facilities
620 do not openly disclose complete and readily accessible datasets. Instead, the range of achievable velocities
621 and projectile sizes are commonly reported, whereas projectile masses are not. Despite these limitations,
622 some representative performance data was obtained from the open literature for a subset of operational
623 2SLGGs worldwide. This projectile launch velocity *versus* mass data is summarized in Fig. 16, with each
624 marker type corresponding to a different facility. The graph also features lines of constant kinetic energy
625 to give an idea of relative scale and to highlight the extensive range of combined launch capabilities. The
626 listed 2SLGGs cover a kinetic energy range spanning seven orders of magnitude. Moreover, for a specific
627 gun, the maximum muzzle velocity decreases as the projectile mass increases, while the kinetic energy ceil-
628 ing remains unchanged. Hence, launch mass and velocity data provides a more complete picture of 2SLGG
629 launch capabilities compared to kinetic energy ceilings, peak muzzle velocities, or achievable muzzle velocity
630 ranges.

631 The breadth of achievable kinetic energies depicted in Figs. 14 and 16 highlights the remarkable potential
632 of modern 2SLGGs to address a diverse array of problems in ballistics, HVIs, hypersonics, shock physics, *etc.*
633 In addition, these tools facilitate the investigation of *scaling effects* on impact physics and aerothermophysics,
634 which is essential for understanding phenomenology and refining modeling techniques (*cf.* [223–225]). As
635 physical phenomena may significantly differ with scale, the ability to vary scale across multiple orders of
636 magnitude in length and energy is of paramount importance. By leveraging these resources, robust scaling
637 laws can be developed while also readily addressing scale-induced changes in energy absorption, deforma-
638 tion/failure behaviors, thermodynamics, and aerodynamics that are governed by factors such as model size,

¹Drexel’s 2SLGG aeroballistic range is actually shorter and has a lower reported maximum kinetic energy (Fig. 14) than MSU’s due to its lower performance requirements. The MSU-I 2SLGG has the smallest bore diameter.

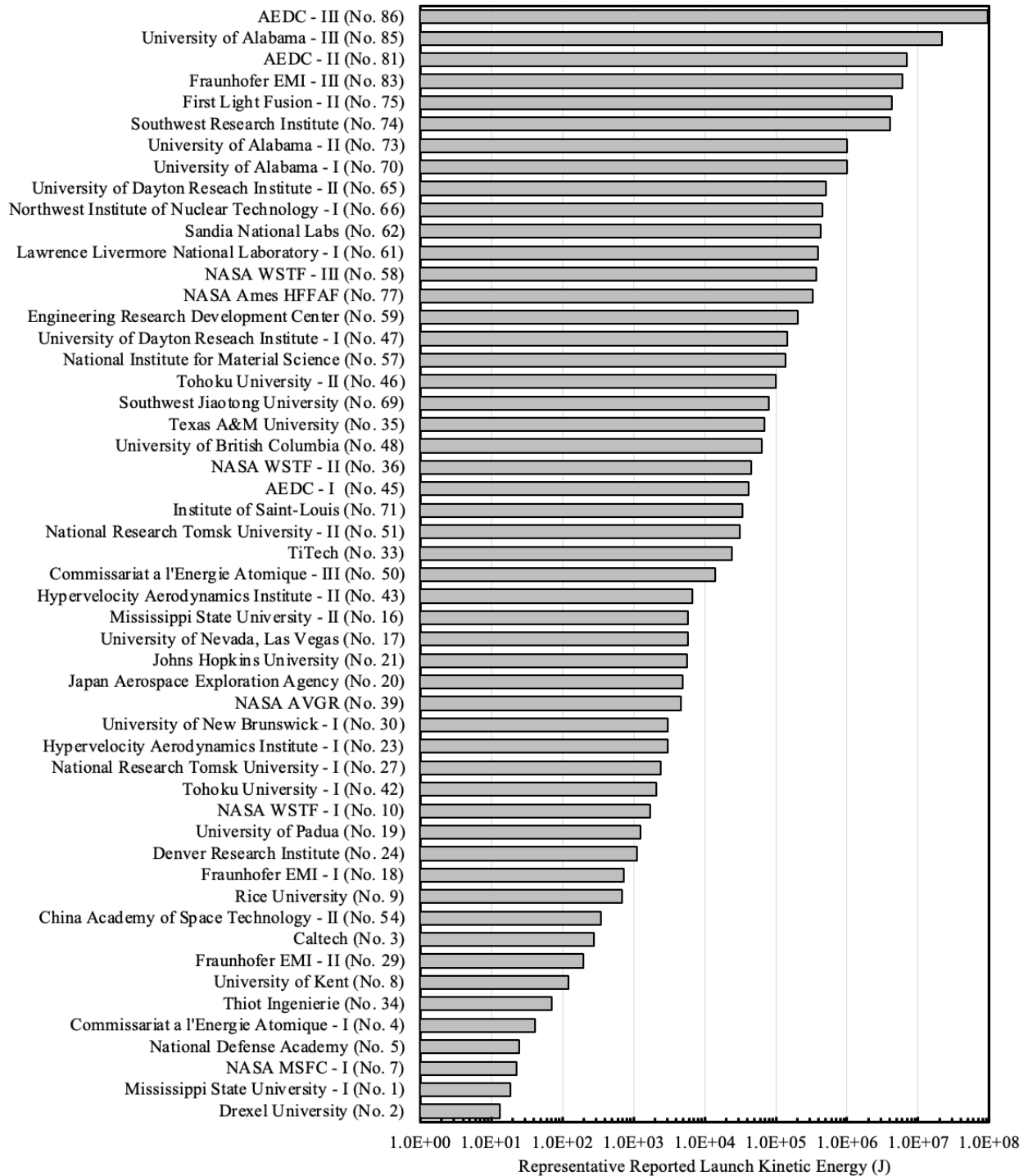


Figure 14: Representative projectile kinetic energy capabilities for 52 out of the 92 2SLGGs included in this study, suggesting that current launch capabilities span roughly seven orders of magnitude. The kinetic energy values reported may not be representative of the *rated* capabilities of the 2SLGGs, as not all reported 2SLGG operate at maximum performance.

639 impact energy, event duration, material heterogeneity, and adiabatic heating. Emerging microscopic ballis-
640 tic testing methods, such as Laser-Induced Particle Impact Testing (LIPIT) [14, 226], have the potential to

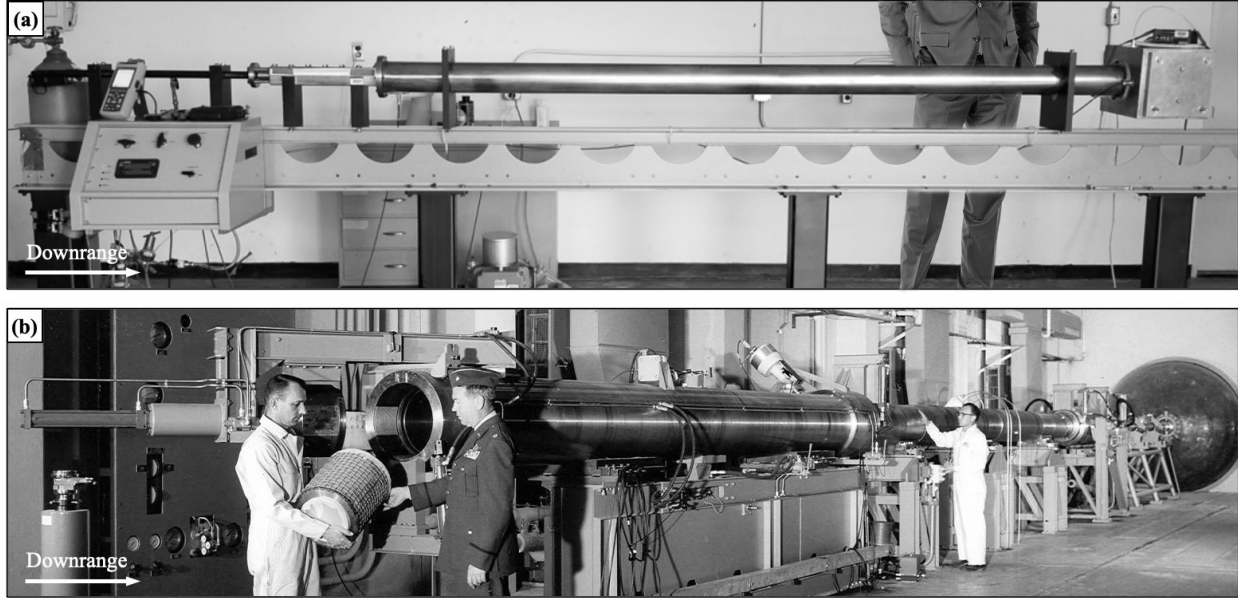


Figure 15: Photos of the smallest and largest operational 2SLGGs: (a) Mississippi State University's ~ 4 m long, 1 mm bore 2SLGG range and (b) AEDC's ~ 280 m long, 203 mm 2SLGG range. Photos were sourced from Refs. [32] and [219], respectively.

641 extend these scaling boundaries, expediting material discovery and phenomenological understanding at even
 642 lower energies (nanojoules to microjoules) and higher strain rates (*e.g.*, $>10^9$ s $^{-1}$; Fig. 2).

643 5. Differences in 2SLGG Aeroballistic Ranges

644 In the preceding sections, key similarities and differences between 2SLGGs worldwide have been presented,
 645 with an emphasis on gun working principles, operations, configurations, and performance. However, each
 646 2SLGG is an integral part of a corresponding aeroballistic range. 2SLGGs, single-stage gas guns, single-stage
 647 powder guns, rail guns, and three-stage guns can all assemble into their own aeroballistic range. Hence, an
 648 aeroballistic range typically consists of a launcher and a characteristic tankage assembly, which can vary
 649 significantly across different facilities. The tankage configuration is heavily dependent on the experiments
 650 that the range is designed to perform (impact physics, aerothermophysics, planar impacts, and nuclear/pellet
 651 injection, *etc.*), specific research application (ultra-high-rate material behavior, planetary science/defense,
 652 nuclear physics, spacecraft MMOD protection, hypersonic vehicle performance and survivability, military
 653 protective structures, *etc.*), and facility affiliation (government, academic, private, *etc.*). In this section,
 654 the key differences in aeroballistic ranges are highlighted, with a focus on tankage assemblies and their
 655 corresponding research applications.

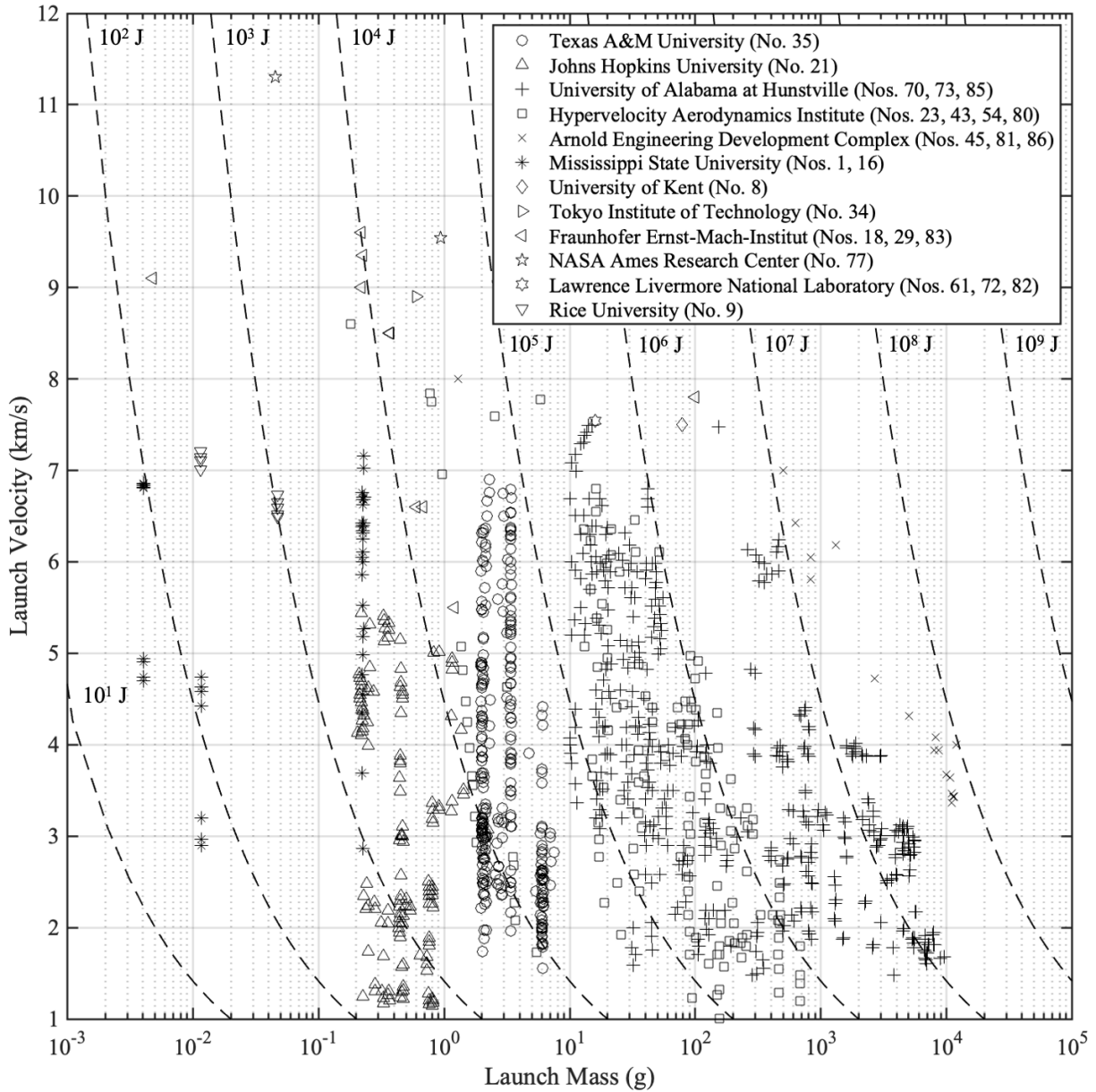


Figure 16: Projectile launch velocities ($N \sim 1100$) from a sampling of 2SLGG facilities, with data sourced from Refs. [15, 58, 104, 126, 163, 220–222]. The results provide valuable insights into 2SLGG performance and potential applications in hypervelocity research, facilitating comparisons between representative research facilities and their equipment.

5.1. 2SLGG Aeroballistic Range Tankage Assemblies

Aeroballistic range tankage design and construction are at least as diverse and intricate as 2SLGG geometries, sizes, and capabilities. Tankage configurations can differ significantly in form, function, and sophistication, depending on the research requirements. Throughout a given aeroballistic range's lifetime, however, substantial tankage modifications are not uncommon. Despite the wide disparity in aeroballistic range complexity and research thrusts, the majority of tankage assemblies can be categorized into three

662 representative configurations: (1) a separated blast tank and target tank, (2) a near-muzzle tank, and/or
663 (3) a combined blast tank and “free flight” range tank. Each configuration has two overarching objectives:
664 to create a well-controlled and well-characterized environment for the desired experiment and to support
665 *in-situ* diagnostic instrumentation.

666 The first and most predominant tankage configuration consists of two separated tanks [103–105, 109, 119,
667 123, 126, 127, 134, 141, 154]. The uprange most “blast” tank is positioned in-line with to the downrange target
668 (or terminal) tank. The blast tank serves dual functions: providing a free flight range for the projectile and
669 capturing the hot, high-pressure WG *via* rapid expansion and baffling. The blast tank is typically equipped
670 with access hatches and plumbing ports, which allow for efficient cleaning and gas evacuation. The 2SLGG
671 launch tube muzzle is inserted into the uprange end of the blast tank, where a circumferential seal is created
672 between the barrel’s outer diameter and the blast tank. This seal, in conjunction with airtight seals on all
673 hatches, ports, and windows, enables the tankage assembly to be placed under near-vacuum conditions. Such
674 conditions are vital for reducing projectile aerodynamic drag and heating, lowering oxygen concentration,
675 and controlling the internal atmosphere to generate desired test conditions.

676 Upon exiting the muzzle, the projectile package (often consisting of the projectile and a sabot) commences
677 free flight in the blast tank. Depending on whether the 2SLGG barrel is rifled or smoothbore, the sabot
678 separates from the projectile either through gyroscopic forces induced by barrel rifling or aerodynamic forces
679 induced by the sub-atmospheric pressure of an inert gas (*e.g.*, N₂) in the blast tank. Independent of the
680 separation mechanism, the sabot pieces are typically arrested by an annular metallic plate, known as the
681 sabot stopping or stripping plate, at the downrange end of the blast tank [109, 115, 163, 227]. The projectile
682 then proceeds into the target tank, either directly or through a short (“drift”) tube, depending on the tankage
683 layout. Some form of velocimetry system typically captures the projectile velocity just before or just after
684 entering the target tank (see Section 6). For example, laser velocimetry “curtains” can be passed through
685 two sets of optical ports just uprange of the target tank [26, 101, 102, 119, 128, 133, 137, 140, 163, 168, 228–
686 230]. The terminal tank houses the target sample (or equivalently contains an observation volume) for a
687 given experiment and often contains intricate structures for supporting instrumentation and target fixturing.
688 External fixturing equipment, such as optical tables, can be employed to support diagnostic tools and
689 associated equipment [134, 163]. The projectile’s flight terminates within the target tank, typically *via* target
690 impact. To facilitate *in-situ* data capture, most target tanks feature a multitude of diagnostic windows and
691 feed-through ports, which support both internal and external diagnostic instrumentation. Different liquids,
692 gasses, and aerosolized particles can also be introduced *via* these feed-through ports to generate different
693 target tank environmental conditions [113, 163, 229, 231–233]. A simple, representative schematic of this
694 tankage configuration is provided in Fig. 17a.

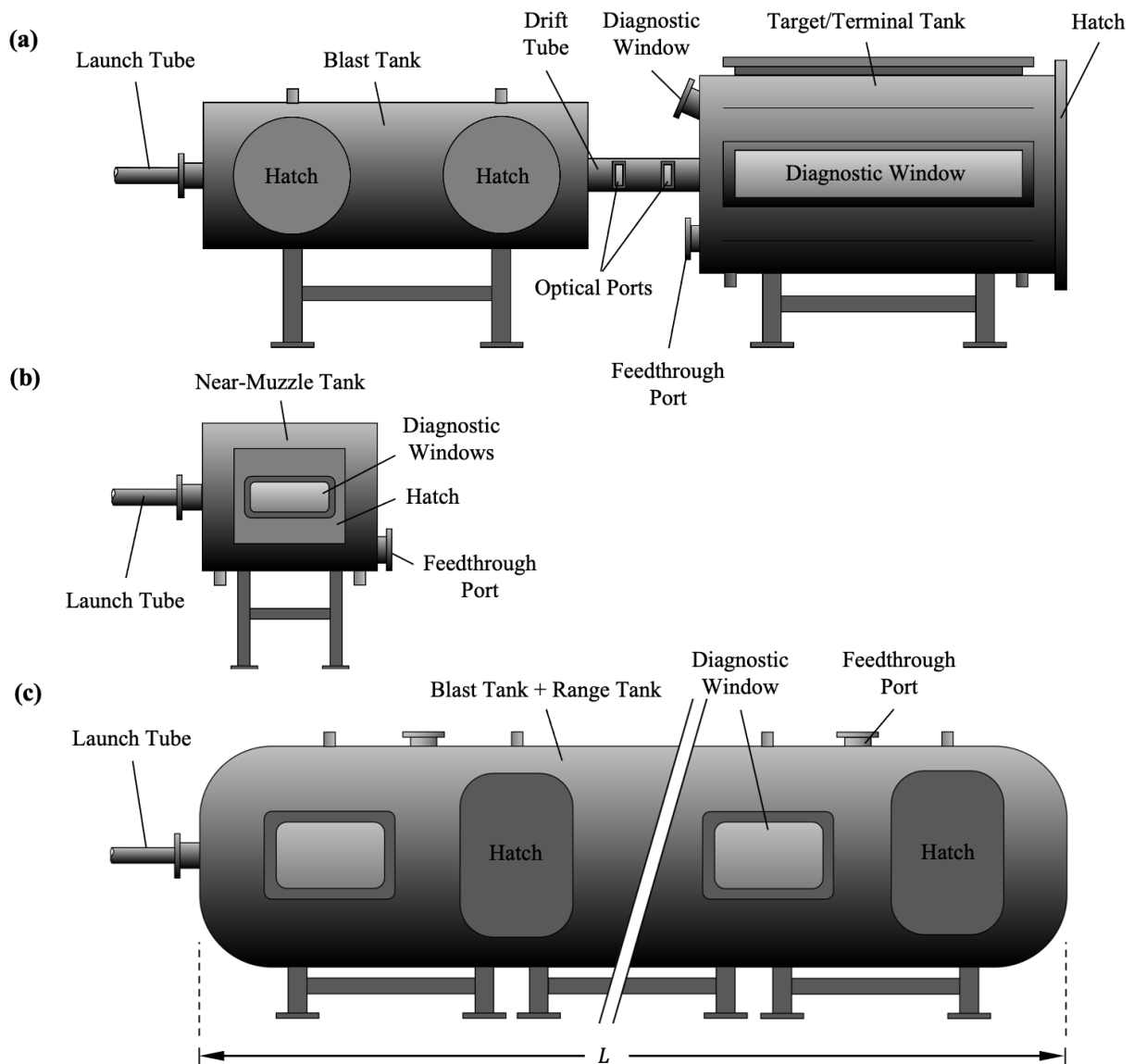


Figure 17: An illustration of common aeroballistic range tankage configurations used with 2SLGGs: (a) the separated blast tank and target tank, (b) the near-muzzle chamber, and (c) the combined blast tank and target tank. The choice of tankage configuration depends on the research area, with (a) separated blast and target tank used most commonly for terminal ballistic investigations, (b) near-muzzle tanks used for shock physics experiments, and (c) combined tanks for hypersonic experiments ($L \gg$ gun length).

695 In the separate blast and target tank design, the relatively long free flight path from muzzle to target
 696 can lead to significant projectile pitching, yawing, or even tumbling, particularly in smooth bore 2SLGGs,
 697 where the projectiles are not spin-stabilized by rifling. This behavior is detrimental to experiments that
 698 require high planarity upon impact, rendering the two-tank configuration unfavorable for such purposes.
 699 To address this issue, a single chamber, situated directly downrange of the launch tube muzzle, is typically
 700 employed [120, 128, 134]. The launch tube is inserted into this near-muzzle chamber, forming an airtight seal

701 for gas evacuation purposes. However, sabot separation is not possible in this configuration, necessitating
702 the use of *i*) full-bore, cylindrical sabots with projectiles attached to the downrange end of the sabot or *ii*)
703 full-bore cylindrical projectiles [58, 234–236]. In other words, the sabot is part of the experiment in some
704 way for near-muzzle chamber experiments. A 2SLGG combined with a near-muzzle chamber can also be
705 used to perform flyer plate experiments [118, 218, 237–240]. Near-muzzle tanks can accommodate various
706 target geometries, enabling both normal and oblique impacts with high planarity [241, 242]. Similar to
707 the separated tank configuration, near-muzzle chambers are equipped with diagnostic windows, hatches,
708 and feed-through ports. Some facilities have even integrated near-muzzle chambers into their aeroballistic
709 ranges, directly uprange of the blast tank, to support a broader range of experiments [134]. A basic diagram
710 illustrating a typical near-muzzle chamber can be found in Fig. 17b.

711 For some research applications, it may be crucial to accurately characterize and analyze the shock struc-
712 ture and flow field surrounding projectiles or models during flight. Conventional separated blast and target
713 tank assemblies present significant challenges for such observations, primarily due to their relatively short
714 lengths, which result in short flight durations caused by projectile velocities on the order of km/s. To over-
715 come this limitation, some research facilities utilize an integrated blast tank and range tank assembly that
716 is substantially longer than the associated 2SLGG [15, 110, 117, 243]. This tankage design is typically found
717 in facilities with 2SLGGs on the larger end of the kinetic energy and length scales (*cf.* Fig. 14 and Table
718 1). These assemblies feature enclosed, large-diameter tubes through which the projectile or model travels.
719 The range tanks’ internal conditions can be precisely controlled, enabling hypersonic research under various
720 test conditions, by modifying parameters such as gas pressure, humidity, and composition [15, 229, 232].
721 Strategically placed diagnostic windows, stations, and hatches along the range tank facilitate *in-situ* char-
722 acterization of test articles. Guide rails extending the length of the range tank can be employed that help
723 maintain projectile stability and level flight during ballistic hypersonic testing, while feed-through ports allow
724 for the creation of diverse environmental conditions throughout the range tank [15, 116, 117, 232]. Addition-
725 ally, the tankage assembly can incorporate a target tank, further supporting large-scale impact studies and
726 enhancing research capabilities [15, 110, 117, 243]. Figure 17c shows an illustrative example of a combined
727 blast and range tank, where the tank length (L) is generally much larger than the 2SLGG length. This
728 tankage configuration is a defining feature of AEDC’s Range-G, the largest aeroballistic range in routine
729 operation globally [116, 117]. Constructed in 1962, Range-G has been instrumental in the development of
730 defense technology, pioneering many hypersonic and hypervelocity research thrusts. The range is capable
731 of launching projectiles up to 7 km/s, utilizing barrels that can be interchanged to accommodate various
732 projectile diameters, up to 203.2 mm. The 3 m diameter and 305 m long test chamber can be conditioned
733 to pressures from 0.2 torr (26.7 pascals) to 1.7 atmospheres (172 kilopascals). This chamber can also mimic

734 specific weather conditions like rain or snow, providing vital capabilities for the development and assessment
735 of hypersonic vehicle survivability. Along the tankage, the facility is equipped with an extensive assortment
736 of diagnostic instruments, including shadowgraph cameras, high-speed video cameras, and digital X-ray
737 sensors, that allow for detailed *in-situ* analysis and observation.

738 Operational techniques and technologies pioneered by AEDC's Range-G and similar facilities are being
739 adapted and enhanced in new 2SLGG aeroballistic ranges, such as the Ballistic, Aero-Optics, and Materials
740 (BAM) Test Range at Texas A&M University (TAMU) [192, 193, 243]. Once complete, the BAM Range
741 will include a 67 m long, 10 cm bore 2SLGG; a 12 m long, 3 m diameter HVI target chamber; and a 1 km
742 long, 2.4 m diameter ballistic hypersonics tube with strategically placed state-of-the-art diagnostic stations
743 along its length. The BAM Range will be one of the largest facilities in the world and will be well-suited for
744 evaluating laser propagation, hypersonic aerothermodynamics, and material and structural HVI responses.
745 The BAM Range will complement the existing Range-G and other model-scale facilities dedicated to HVI
746 and hypersonic research.

747 5.2. 2SLGG Experiment Types and Research Applications

748 2SLGG aeroballistic ranges have been instrumental in driving groundbreaking advancements across var-
749 ious fields, including experimental impact physics, aerothermophysics, nuclear physics, shock physics, and
750 beyond. Key challenges in these domains are addressed by experiments performed at 2SLGG aeroballistic
751 ranges worldwide, with known facilities in at least a dozen countries including the United States (46.7%),
752 China (15.2%), Japan (8.7%), United Kingdom (7.6%), France (5.5%), Canada (3.3%), Germany (3.3%),
753 South Korea (3.3%), Russia (2.1%), Australia (1.1%), India (1.1%), Italy (1.1%), and Sweden (1.1%) (Fig.
754 18). This global participation highlights the fact that experiment types and research applications are not
755 restricted to a particular country of origin and are truly international endeavors supported by a diverse,
756 multidisciplinary scientific community.

757 A strong correlation exists between specific aeroballistic range tankage configurations and the experiments
758 conducted at the corresponding facilities. Experiments involving hypervelocity penetration and perforation
759 mechanics are the most common. Conventional impact experiments typically involve launching a hypere-
760 velocity projectile at a specific target, focusing on either the projectile, the target, or their combined response.
761 The majority of aeroballistic ranges that conduct these experiments feature separated blast and target tank-
762 age configurations, as detailed previously in Section 5.1 and Fig. 17. Depending on the relative velocity,
763 as well as the materials and geometries of the projectile and target, impacts can involve predominantly
764 penetration (cratering) and/or perforation for a wide range of target obliquities. These events are charac-
765 terized by a variety of phenomena, including severe deformation, erosion, fragmentation, heating, melting,

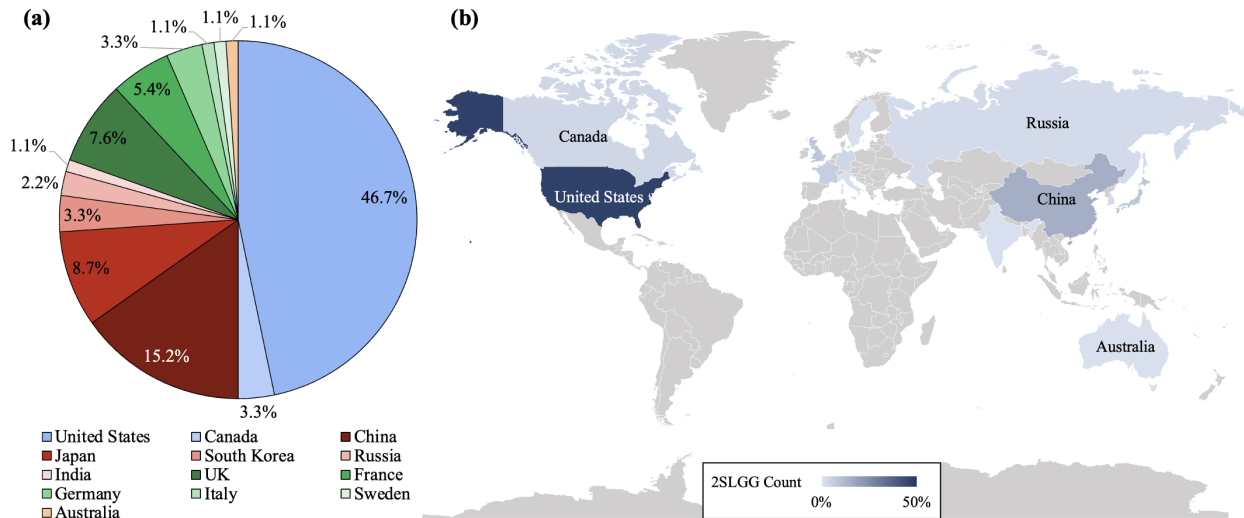


Figure 18: The geographic distribution of 2SLGGs worldwide, featuring (a) a percentage breakdown of 2SLGGs by country and (b) a global heat map highlighting the countries that possess 2SLGGs.

766 vaporization, and sublimation of the projectile or target [244–247]. Most studies have adopted a single
 767 projectile impact approach, varying the projectile material, geometry, and/or velocity against one or more
 768 normal or oblique targets of varying geometry [248]. A wide array of target materials have been studied
 769 with this approach, including metals [162, 249–252], polymers [112, 253–255], ceramics [256, 257], composites
 770 [200, 258, 259], granular and geo-materials [104, 120, 149, 225, 260–265], reactive materials [266–269], and
 771 radioactive materials. Generally, monolithic or composite target geometries have been plates, cylinders, or
 772 blocks of defined thickness [248, 270–273]. Target structures, including Whipple shield concepts, are also
 773 commonly tested [274, 275]. Projectile materials and sizes also vary, with high density projectiles being
 774 more challenging to launch. Projectile materials include metals, polymers, ceramics, composites, and reac-
 775 tive materials [163, 248, 267, 272, 273, 276, 277], while projectile geometries span spheres, ogives, long rods,
 776 cylinders, and cones [248, 267, 271, 278–280]. Simultaneously launched distributed particle impacts have
 777 also been conducted to study impact interactions and aggregate damage formation mechanics [211, 227, 281–
 778 288]. Most research involving hypervelocity penetration/perforation also incorporates analytical modeling
 779 or numerical simulations to supplement experimental data [5, 83, 249, 258, 259].

780 Applications of HVI experiments encompass the development of novel protective materials and struc-
 781 tures for military and space purposes, planetary science, defense, hypersonic vehicle survivability, counter-
 782 hypersonics, *etc.* Impact testing for protective structure development typically involves launching projectiles
 783 that represent realistic threats at candidate materials or structures. In the context of spacecraft protection,
 784 targets often include Whipple shields or stuffed Whipple shields [274, 275, 289–294]. Protective structure
 785 development for military applications usually entails testing on metals, high-performance concretes, or novel

786 materials and material structures [248, 250, 295–299]. For planetary science or defense, experiments generally
787 involve impacts on granular materials to characterize crater formation and momentum enhancement, as well
788 as perform Hugoniot measurements [104, 120, 149, 225, 260–265]. Representative atmospheric particles, such
789 as dust and ice, have been launched at potential hypersonic vehicle materials and geometries to assess surface
790 damage formation and resulting disturbances to the hypersonic flow field [113, 163, 229, 231, 232, 300].

791 Immediately following an impact, compressive stress waves propagate through both the projectile and
792 target, leading to increased internal energy, pressure, and density [7, 301]. When the impact velocity is
793 sufficiently high, the amplitude of these stress waves can exceed the yield stress of the materials involved,
794 causing an elastic precursor wave to be succeeded by a slower-moving plastic wave. Additionally, if the
795 impact-induced wave speed surpasses the local speed of sound in the projectile and target, strong shocks
796 may form. These conditions can result in significant projectile/target temperature rises, plastic deformation,
797 flow and melting, and material fracture and fragmentation. In cases where the impact velocity is even
798 higher, projectile and target vaporization or sublimation may occur [244]. Although this brief overview
799 provides a highly simplified explanation of the impact process, it serves to highlight the complexity of
800 the phenomenon, as shear waves and tensile waves can also form depending on geometries and loading
801 conditions. HVIs often involve complex and coupled projectile/target interactions, making the stress and
802 thermodynamic states challenging to quantify (see Section 2). In response, planar impact experiments
803 have been developed to dramatically simplify the physics of the problem [7, 301]. Facilities that perform
804 planar impact experiments generally use a near-muzzle chamber configuration [120, 128, 129, 134, 217, 238]
805 (see Section 5.1 and Fig. 17b). These experiments typically involve a planar projectile (*i.e.*, flat disc) of
806 known material being launched at a target material of interest, with specialized diagnostic tools measuring
807 arrival times and free surface velocities as stress waves traverse the target material. By combining these
808 measurements with one-dimensional (1D) Rankine-Hugoniot relations, the material shock response can be
809 characterized, informing equations of state and facilitating applications in shock physics, ultra-high-rate
810 material behavior, and Hugoniot data generation. Los Alamos National Laboratory (LANL) has conducted
811 extensive planar impact testing to characterize the shock response of various materials, including metals,
812 polymers, ceramics, *etc.* [76]. The resulting equations of state not only provide a deeper fundamental
813 understanding of material behavior but also support modeling and simulation efforts for penetration and
814 perforation problems [5] (see Section 2).

815 In 2SLGG experimentation, the focus can shift from traditional impact testing to studying the *projectile's*
816 behavior as it traverses a prescribed atmospheric environment (including aerosolized particles) at hypersonic
817 speeds ($> \text{Mach } 5$, see Section 2). Although such research has been ongoing for decades [229], the increasing
818 global interest in the development of hypersonic weapons and vehicles has prompted the United States and

819 other nations to prioritize the advancement and implementation of hypersonic technologies [28]. Moreover,
820 reentry vehicles also experience hypersonic flight conditions, further underscoring the importance of these
821 experiments [302].

822 A critical aspect of hypersonic/aerothermophysics experimentation involves characterizing the flow field
823 surrounding the hypersonic model as well as the thermal and mechanical loads to which the vehicle is
824 subjected [303]. Depending on the Mach number, flow phenomena can include strong shocks and expansion
825 fans, turbulence, and extreme gas pressures and temperatures, with gases potentially ionizing in the vicinity
826 of the hypersonic vehicle [304]. Consequently, much of the research in this field is devoted to vehicle geometry
827 optimization, thermal protection system development and survivability testing, and flow field characterization
828 for computational or theoretical model development and validation [6, 302, 303, 305–311]. Complex flight
829 ranges that incorporate various diagnostic tools and techniques are necessary for such characterization, and it
830 is not uncommon for the projectile itself to be instrumented [6, 116, 117]. Although 2SLGGs are not the only
831 launching devices used (see Section 1), they offer several advantages, such as the ability to achieve hypersonic
832 speeds over a relatively small distance with subscale models and relative ease of implementation in closed,
833 indoor aeroballistic ranges (see Section 1). For hypersonic/aerothermophysics experiments, most range
834 tankage configurations consist of combined blast tanks and range tanks (see Section 5.1 and Fig. 17c) [15, 116,
835 117, 190, 192, 193]. Closed range tankage is generally more desirable, as it allows for control of the internal
836 tank gas pressure, temperature, humidity, and composition, simulating a variety of atmospheric conditions
837 and altitudes. This atmospheric control enables experiments under realistic flight conditions and parametric
838 studies for theoretical and computational fluid dynamics (CFD) model development and implementation. As
839 hypersonic technology continues to be prioritized, the importance of hypersonic/aerothermophysics testing
840 will likely continue to increase.

841 One particularly unique application of a 2SLGG is in nuclear fusion research. One of the difficulties
842 of maintaining a fusion reaction is consistently providing fuel to sustain the reaction [312–314]. Given the
843 extreme temperatures and pressures required for fusion, material entering the reactor can quickly degrade
844 from usable fusion fuel to waste mass. Some researchers have proposed using 2SLGGs to launch fuel into
845 their reactor cores to prevent the fuel from being degraded before reaching the fusion reaction site. These
846 facilities typically have relatively small bore launch tubes (~ 5 mm) and modest velocity ceilings (~ 5 km/s)
847 compared to other comparable 2SLGGs, but they have some of the highest experimental cyclic rates in
848 the field (~ 1 – 10 launches per second) [146, 148]. While these 2SLGGs are relatively few in number, they
849 represent a creative application of 2SLGG technology and illustrate its diverse utility.

850 The experiment types and research applications highlighted herein emphasize the versatility of 2SLGG
851 aeroballistic ranges in addressing a wide variety of complex research problems. Many facilities are de-

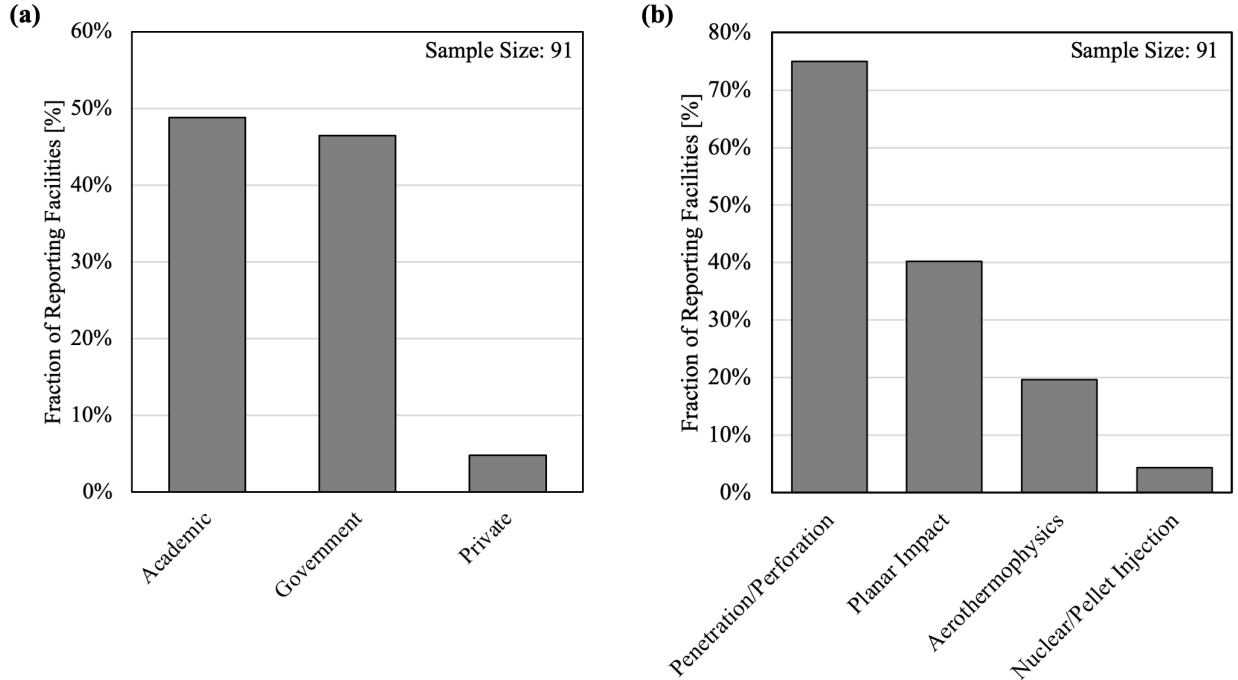


Figure 19: An overview of the research applications of 2SLGGs, detailing (a) the fraction of 2SLGGs used in academic, government, and private laboratories, and (b) the fraction of 2SLGGs employed in various types of experiments, including perforation/penetration mechanics, planar impacts, hypersonic/aerothermophysics, flyer plate impacts, and nuclear/pellet injection.

852 signed to facilitate multiple experiment types, whereas some are predominantly reserved for specific testing
 853 (*i.e.*, government-affiliated labs that characterize reactive and/or radioactive material). Histograms of aer-
 854 oballistic range affiliation and experimentation type are provided in Figs. 19a and 19b, respectively, for
 855 reference. Affiliations include academic (46%), government (49%), and private (5%), while experiment types
 856 performed at the aeroballistic ranges span penetration/perforation mechanics (75%), planar impact (40%),
 857 hypersonic/aerothermophysics (20%), flyer plate impact (14%), and nuclear/pellet injection (4%). Essential
 858 information on these experiment types, as well as representative applications, can be found in Table 3.

Table 3: A list of key types of experiments performed using a 2SLGG, along with their associated research applications and representative facilities.

Experiment Type	Research Applications
Penetration/Perforation Mechanics (PM)	military protective materials/structures, MMOD spacecraft protection, planetary science and defense, hypersonic vehicle survivability
Planar Impacts (PI)	ultra-high strain rate behavior of materials, shock physics
Hypersonic/Aerothermophysics (HA)	hypersonic vehicle survivability and performance, hypersonic flow field characterization, reentry vehicle survivability and performance
Nuclear/Pellet Injection (N)	nuclear fusion

859 6. Diagnostic Tools and Techniques

860 The progress in 2SLGG aeroballistic range research has largely depended on the concurrent development
861 of diagnostic techniques and tools. Consequently, the field of *in-situ* diagnostics for ballistic events has a
862 history spanning over 150 years [315]. Given that 2SLGG-launched projectiles can achieve speeds up to
863 10 km/s, a collection of ultra-high sampling rate diagnostics is typically required for real-time observations
864 during experiments [315]. These diagnostic instruments, some specifically designed for 2SLGG laboratories
865 and others adapted from pre-existing technologies, allow researchers to investigate HVI events and hypersonic
866 projectile flight across much of the electromagnetic spectrum (from infrared to X-ray), as well as monitor
867 various shock interactions. Diagnostic options have grown as impact velocities have increased and new
868 technologies have emerged. Apart from *in-situ* diagnostic tools, many laboratories also utilize instruments
869 for “postmortem” forensic analyses of projectiles and targets, although the majority of these tools are not
870 exclusive to aeroballistic range testing and are not discussed in this context.

871 Diagnostics in 2SLGG aeroballistic range research can generally be grouped according to the method
872 applied or the specific equipment utilized. Notable diagnostic *techniques* encompass still imaging [315],
873 schlieren imaging [113, 300, 316, 317], particle tracking [113, 318–321], shadowgraphy [26, 32, 104–106, 112,
874 116, 127, 134, 141, 159, 163, 322–325], strobe photography [326, 327], high-speed spectroscopy [328–330],
875 and digital image correlation (DIC) [159, 160, 331]. These methods play a crucial role in capturing and
876 examining projectile/target behavior during HVI and hypersonic flight. To facilitate these techniques, a
877 variety of diagnostic *instruments* are employed. Common tools include high-speed cameras [26, 32, 104–106,
878 116, 121, 127, 134, 141, 159, 163, 315, 332–336], flash X-ray systems [15, 105, 107, 115, 119, 133, 134, 140, 142,
879 152, 163, 166, 171, 175, 176, 337, 338], laser Doppler velocimeters [103], velocity interferometer system for any
880 reflector (VISAR) [49, 100, 120, 166, 339, 340], streak cameras [102, 103, 114, 118, 177, 315], high-speed film
881 [315], and photonic Doppler velocimetry (PDV) systems [47, 108, 128, 129, 134, 169, 194, 341, 342]. Moreover,
882 additional diagnostic tools support the analysis, such as X-ray velocimeters [104, 116, 117, 343], laser Doppler
883 vibrometers [265, 344], accelerometers [103, 105, 119], strain gauges [105, 106, 119, 152, 166, 176, 177, 182],
884 load cells [103, 104, 119, 182], and microwave reflectometers [15, 133]. The timeline in Fig. 20 highlights
885 several key milestones in *in-situ* diagnostic development. However, not all prevalent diagnostic platforms
886 could be integrated into the timeline, as some techniques have no clear origin in the literature (*e.g.*, using
887 laser curtains for projectile intervalometry). Together, the mentioned tools and techniques (as well as others)
888 provide a wide range of data types necessary for investigating HVI and hypersonic phenomena. Typically,
889 the selection of diagnostic techniques and tools utilized at a specific facility is closely related to the type of
890 experiment conducted (see Section 5.2). The following passages highlight some of the primary diagnostic

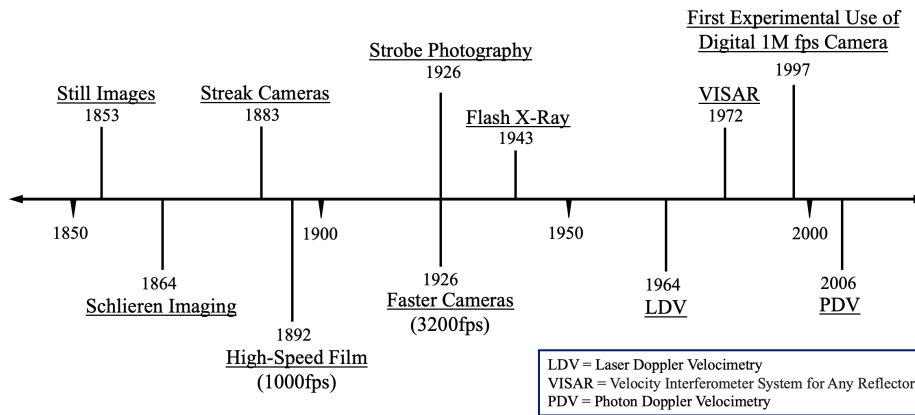


Figure 20: A timeline detailing the development of key diagnostics used in conjunction with 2SLGG aeroballistic ranges. The dates reported in this figure were sourced from Refs. [47, 49, 315, 316, 326, 332, 337, 344].

891 methods and instruments employed in 2SLGG aeroballistic range experiments.

892 In aeroballistic range experiments, the diagnostic triggering mechanism is a critical component due to the
 893 high projectile velocities (>2 km/s) and the short event durations of many diagnostic tools (microseconds).
 894 Velocimetry systems, which typically consist of two or more velocity “gates,” are most commonly employed
 895 to provide these diagnostic triggers. As a projectile sequentially passes through each gate, the time difference
 896 between the gate arrivals is combined with the known distance between gates to compute a projectile velocity.
 897 Concurrently, a preset or dynamic (velocity-dependent) delay trigger signal (*e.g.*, 5 V TTL) is sent to the
 898 diagnostic instruments. Although velocimetry systems operate in a similar fashion, various instruments can
 899 be employed to capture the projectile velocity, including lasers, induction coils, shorting pins, and continuous
 900 X-ray sources.

901 Many ranges, for instance, often use laser intervalometry or laser velocimetry systems (LVSs) [26, 101, 102,
 902 119, 128, 133, 134, 137, 140, 163, 168, 228–230]. The shift to LVSs was partially driven by the introduction of
 903 cheaper and more reliable LED lasers. An LVS involves projecting two or more laser “curtains” perpendicular
 904 to the projectile’s free flight path, with emitters on one side and photodiodes on the other. Projectile velocity
 905 is then calculated by dividing the gate distance by the time between laser curtain voltage drops, as detected
 906 by a high sampling rate oscilloscope.

907 X-ray beams and detectors can also be used instead of laser curtains and photodetectors, resulting in
 908 a velocimetry system that can better circumvent false triggers caused by airborne particulates, debris, and
 909 muzzle blasts [104, 116, 117, 343]. Induction coils can similarly serve as gates, as a voltage generated when the
 910 projectile travels through the coil can be detected by an oscilloscope [235]. Shorting pins, on the other hand,
 911 are employed in applications involving direct contact between two bodies [345]. A thin electrically charged

912 wire creates a voltage drop when contacted by a moving body and subsequently bent to make contact with
913 a local “ground.” Despite being frequently damaged or destroyed during experiments, shorting pins are still
914 widely utilized in several laboratories due to their usefulness in taking timestamp measurements in confined
915 or heavily shielded spaces where optical techniques are not feasible [114, 120, 168, 345]. These sacrificial
916 methods, in addition to “make” or “break” screens [346], can also be extended to capture the velocity of
917 other relevant objects, such as impact ejecta, debris, or the 2SLGG compression piston, demonstrating their
918 versatility in various experimental contexts.

919 High-speed imaging (HSI) has become the most prevalent diagnostic tool in 2SLGG facilities; nearly 70%
920 of reporting facilities have implemented HSI (Fig. 21). Historically, researchers utilized various ingenious
921 mechanical techniques to capture impact events or hypersonic flights at megahertz resolution with film
922 cameras [315]. However, over the past three decades, advances in digital computing, memory storage speed,
923 digital optical arrays, and lighting have led to the implementation of digital cameras for video recording
924 [26, 32, 104–106, 116, 121, 127, 134, 141, 159, 163, 199, 315, 332]. Digital images offer two main advantages:
925 (1) ease of duplication and sharing and (2) the ability to harness computerized post-processing techniques
926 to extract more data points and types than possible with film images. Many modern facilities employ
927 commercial cameras like the Hyper Vision (Shimadzu Corp.) [333], Kirana (Specialized Imaging Ltd.) [334],
928 Phantom (Vision Research) [335], and Photron FASTCAM (Photron) [336], with frame rates exceeding
929 ~ 1 GHz and exposures down to ~ 50 ns or less. The total number of frames can exceed 100, and the frame
930 rate can be adjusted depending on the experiment duration. In general, an increase in the frame rate is
931 inversely proportional to image resolution and record duration (number of frames). This relationship imposes
932 some limitations, but capabilities are improving as technology advances. Depending on the experiment type,
933 one or more high-speed cameras can be used, and they can support various diagnostic techniques such as
934 shadowgraphy, schlieren imaging, digital particle tracking, and DIC.

935 Shadowgraphy is one of the most common imaging techniques used in 2SLGG aeroballistic range research
936 [26, 32, 104–106, 112, 116, 127, 134, 141, 159, 163, 322–325]. It involves positioning a high-speed camera on
937 one side of the target tank opposite a high-intensity light source (*e.g.*, a high-intensity LED [347] or flash
938 bulbs [348]). Both the camera and light sources are arranged perpendicular to the launch tube (and projec-
939 tile flight) axis, allowing maximum light entry through the camera lens. This setup enables image capture
940 at minimal exposure times and maximum frame rates, producing high-contrast images. Schlieren imaging
941 is another established technique for examining density variations in gas flows across subsonic, supersonic,
942 and hypersonic environments [316]. As a result, it can be used to effectively visualize flow characteristics
943 like bow shocks, turbulence, and interactions between shocks and particles. The technique works by selec-
944 tively obstructing refracted light from areas with high-density gradients, which are then represented through

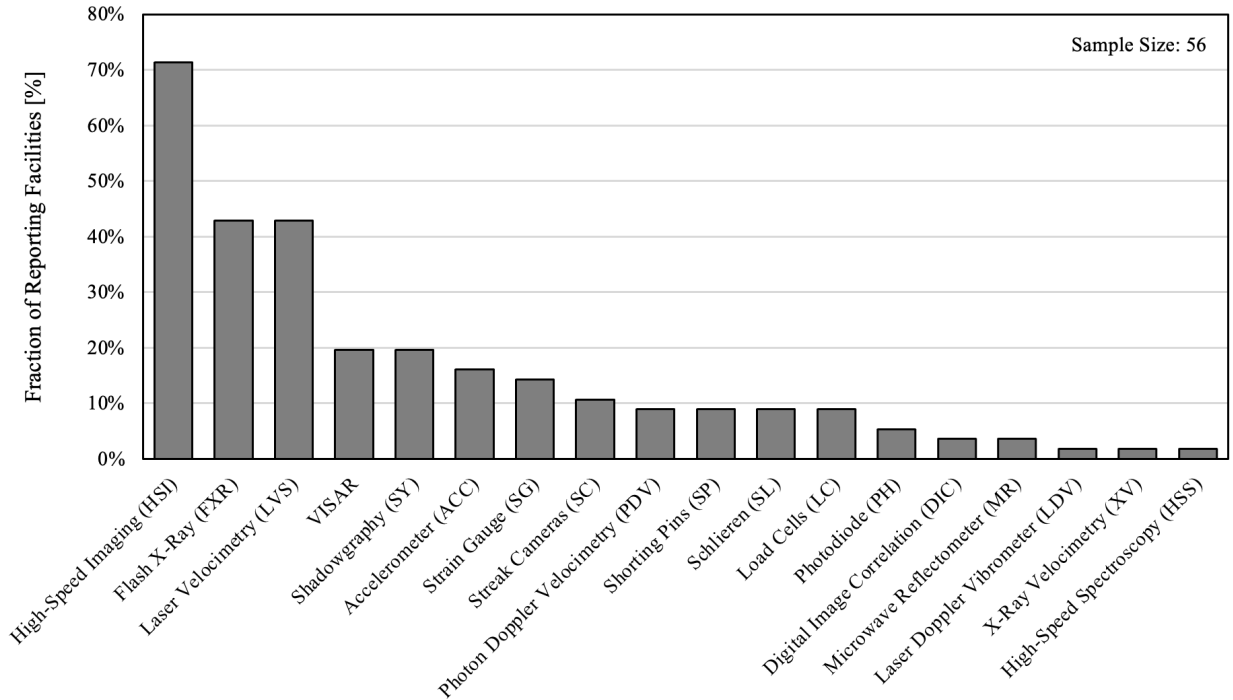


Figure 21: The percentage of key supporting diagnostics and instruments used at 56 of the 92 reporting facilities. Abbreviations correspond to those used in Appendix A, Table 6.

945 changes in light intensity [316]. Although various schlieren setups exist, a straightforward lens-based system
 946 has demonstrated its effectiveness in analyzing structures within hypersonic flows [46, 113, 300, 317].

947 Videography alone yields only qualitative data and necessitates additional post-analysis tools. To produce
 948 more quantitatively significant data, custom image processing algorithms have been developed that utilize
 949 high-speed videography images of projectiles, targets, debris fragments, and other elements to obtain time-
 950 resolved data on fragment sizes, two-dimensional (2D) positions, velocities, and rotations [113, 318, 319, 321].
 951 This information can be employed to estimate the kinetic energy and momentum of both the incoming
 952 projectile and ejecta/debris, as well as the absorption and transfer of impact energy. Another way to extract
 953 quantitative information from high-speed images is *via* DIC [159, 160, 331]. Appropriately arranged single
 954 (2D DIC) or stereoscopic [three-dimensional (3D) DIC] cameras can be employed to capture the temporal
 955 evolution of a random speckle pattern on a target surface. Post-processing algorithms can extract 2D or
 956 3D surface displacements from the images that can be used to approximate the rapidly evolving strain field
 957 [349]. In these ways, visible light cameras combined with one or more of the various diagnostic techniques
 958 can provide rich qualitative and quantitative data, the quality of which will only improve as technology
 959 advances and new techniques emerge.

960 High-speed visible light cameras offer valuable insights into ultra-high-rate events. During HVI events,
 961 however, the ejecta and debris from both the impact and exit sides of the target can obstruct the observation

962 of projectile and target erosion, plastic deformation, fracture, and/or fragmentation processes. Additionally,
963 as the penetration or perforation event progresses, the target itself can obscure the view of the projectile.
964 Flash X-ray (FXR) systems, employed in 45% of surveyed facilities (Fig. 21), address many of these challenges
965 by generating short-duration, high-intensity pulses, to capture a series of high-rate radiographs [15, 105, 107,
966 115, 119, 133, 134, 140, 142, 152, 163, 166, 171, 175, 176, 338]. Powered by super-capacitors charged up
967 to hundreds of kilovolts, FXR systems can penetrate dense ejecta/debris fields, as well as intact targets, to
968 more clearly capture projectile/target interactions during impact. FXR systems can be either single-anode
969 or multi-anode [350]. Single anode systems typically consist of one or more “tubes” or cylindrical “heads”
970 fixed at various angles on planes perpendicular to the launch tube axis (projectile flight axis). For each
971 head, a radiograph film is positioned on the opposite side of the target from the X-ray source and along
972 the head axis. Upon triggering, each head generates a multi-nanosecond pulse of high-energy X-rays at a
973 predetermined voltage, commonly in the range 10–1000 kV, with higher voltages providing greater X-ray
974 penetration capability. However, these single-anode systems have limitations because they can only capture a
975 single instant in time. Multiple heads are required to capture temporally and spatially varying radiographs,
976 but cost and space limitations make multi-head FXR systems unobtainable for many facilities. Multi-
977 anode systems partially overcome these limitations by using a single tube with multiple anodes to generate
978 temporally spaced X-ray pulses [350]. A colinear scintillator screen detects these pulses and produces a
979 rapidly decaying image captured by a high-speed camera [351]. This approach allows operators to capture
980 approximately ten radiographs in a shadowgraph fashion, with the FXR source serving as the illumination.
981 Although FXR systems have numerous potential applications, they are predominantly used in penetration
982 and perforation mechanics experiments (see Section 5.2).

983 In planar impact experiments, the primary focus lies in studying the transmission and reflection of
984 impact-induced high-amplitude stress or shock waves through a sample (see Section 5.2). High-speed cam-
985 eras are generally unsuitable for observing shock wave behavior in non-transparent media. Hence, many
986 facilities employ free-surface velocity measurement techniques to determine shock arrival times and free-
987 surface velocity histories. One widely used method in planar impact and shock physics experiments is PDV
988 [108, 128, 129, 134, 169, 194, 341, 342], which was developed at LLNL by Strand *et al.* in 2006 and has
989 largely supplanted the earlier VISAR systems [47]. PDV works by reflecting incident laser light from an
990 optical fiber off a free surface and back into the optical fiber. The movement of the target surface causes the
991 reflected light to undergo a Doppler shift, generating a detectable beat frequency that can be analyzed by an
992 oscilloscope to compute the instantaneous free surface velocity. Faster oscilloscopes enable the measurement
993 of higher free surface velocities. By employing PDV measurements, researchers can characterize a material’s
994 shocked state using Rankine-Hugoniot relations to facilitate equation of state development and implementa-

995 tion. PDV arrays offer advantages over VISAR, as they are simpler to assemble using more affordable and
996 more widely available components, allowing laboratories to construct systems with a greater number of data
997 channels than VISAR technology permits [352]. As the technology has matured, complete commercial PDV
998 systems have even become available [353, 354].

999 The advancement of diagnostic techniques and tools has become a primary focus in 2SLGG aeroballistic
1000 range research, as high-fidelity data capture for all experiment types relies heavily on the quality and speed
1001 of data acquisition. In certain instances, the application of existing methods or instruments to a new research
1002 problem can render novel, innovative data. For example, digital in-line holography (DIH) is gaining traction
1003 as a promising diagnostic technique for 2SLGG aeroballistic ranges [231, 355–357]. Utilizing high-speed
1004 cameras, DIH facilitates the acquisition of 3D position, velocity, and acceleration data of hypervelocity and
1005 hypersonic particles from 2D images. This method involves capturing the interference pattern generated
1006 by the interaction between a reference light and the light scattered by the object of interest [358, 359].
1007 Subsequently, the recorded hologram can be digitally reconstructed, enabling the measurement of the object’s
1008 size, shape, and position in 3D space for each high-speed image (time step). This innovative approach has
1009 significant implications for tracking HVI-induced ejecta and debris, as well as estimating target energy
1010 dissipation.

1011 Additionally, ultra-high-speed spectroscopy has emerged as another promising diagnostic tool, offering
1012 valuable insights into the chemical composition and physical properties of materials under extreme condi-
1013 tions. For example, this technique has been employed to investigate the bright flash emitted during an
1014 HVI, uncovering critical information about the underlying physical processes, such as material ionization
1015 and plasma generation [328–330]. By analyzing the emitted light from materials subjected to high tem-
1016 peratures or pressures, researchers can gain a deeper understanding of the material’s atomic and molecular
1017 structure nanoseconds after impact, thereby elucidating energy absorption and failure mechanisms more
1018 comprehensively. Despite significant progress, the current advanced diagnostic methods and technologies
1019 provide limited insight into the physical phenomena that take place during crucial hypervelocity, hyper-
1020 sonic, and other ultra-high-speed events. Hence, there is a substantial need to tailor existing technologies to
1021 tackle issues associated with aeroballistic range research. Table 4 presents a selection of essential diagnostic
1022 methods and tools, as well as their applications.

1023 **7. Performance Prediction Methods for Two-Stage Light Gas Guns**

1024 Predicting 2SLGG muzzle velocity for a given experiment presents a significant challenge due to the
1025 relatively large number of operational parameters (powder mass and type, working gas pressure and type,

1026 petal valve burst pressure, projectile mass, *etc.*). This issue is compounded by intrinsic frictional losses
 1027 and launch tube bore erosion, as well as variations in powder burn rate, piston release pressure, petal valve
 1028 burst pressure, and other factors. Yet, robust performance predictive tools/methods are necessary to reduce
 1029 experimental costs and turnaround times. Hence, a number of analysis techniques have been researched
 1030 since the early development of 2SLGGs [2, 20]. The level of sophistication and accuracy of a given model
 1031 varies based on its intended application(s). For example, many 2SLGG users need only algorithms for muzzle
 1032 velocity prediction. More comprehensive predictive tools used by 2SLGG designers, however, must also be
 1033 able to resolve breech pressures, pump tube piston and projectile dynamics, compressible flows, petal valve
 1034 mechanics, precise event timing, bore erosion, *etc.*, in addition to projectile muzzle velocity. As a result,
 1035 various predictive methodologies have been explored, including empirical models, closed-form solutions, and
 1036 numerical models. This section highlights some notable 2SLGG performance prediction techniques.

1037 *7.1. Empirical Approaches*

1038 One simple yet effective way to predict 2SLGG muzzle velocity is through interpolation or careful extrapolation
 1039 of previous experimental data. Typically, such performance “curve fitting” models seek to reliably
 1040 predict muzzle velocity *for a given 2SLGG*. Statistical analyses and normalization metrics can, however,
 1041 enable some comparison between 2SLGGs of different sizes and simplify interpolation operations. Even so,
 1042 large (and costly) data sets are required to span a given 2SLGG’s performance envelope and to quantify its
 1043 associated random errors for similar or even identical inputs. Many 2SLGG users will fix key operational
 1044 parameters (*e.g.*, WG and petal valve burst pressures) to reduce random error and simplify prediction pro-
 1045 cedures. Despite these limitations, simple empirical prediction approaches are usually the most accurate (for

Table 4: A representative list of diagnostics and instruments commonly utilized in 2SLGG aeroballistic range facilities. The table includes examples of diagnostic and instrument applications, as well as the names of representative facilities that employ each respective diagnostic or instrument.

No.	Experimental Diagnostic/Instrument	Representative Applications
1	High-Speed Imaging (HSI)	Projectile/target characterization (HVI); flow characterization (hypersonic)
2	Flash X-Ray (FXR)	Projectile/target characterization during HVI
3	Laser Velocimetry System (LVS)	Hypervelocity/hypersonic projectile velocimetry
4	VISAR	HVI target free surface velocity measurements
5	Shadowgraphy (SY)	High-contrast hypervelocity/hypersonic projectile/target imaging
6	Accelerometer (ACC)	Target vibration and load measurements during HVI
7	Strain Gauge (SG)	2SLGG performance diagnostics,
8	Streak Cameras (SC)	Phenomena boundary tracking and particle path recording
9	Photon Doppler Velocimetry (PDV)	HVI target free surface velocity measurements; projectile velocity history
10	Shorting Pins (SP)	2SLGG compression piston velocimetry; general velocimetry
11	Schlieren (SL)	Hypersonic flow field visualization
12	Load Cells (LC)	Projectile-target momentum transfer measurements
13	Photodiode (PH)	Muzzle flash detection (diagnostic triggering); projectile velocimetry
14	Digital Image Correlation (DIC)	<i>In-situ</i> target deformation measurements during HVI
15	Microwave Reflectometer (MR)	Piston and projectile velocity measurement while inside the barrel
16	Laser Doppler Vibrometer (LDV)	HVI target free surface velocity measurements
17	X-Ray Velocimetry (XV)	Hypervelocity/hypersonic projectile velocimetry through dense debris
18	High-Speed Spectroscopy (HSS)	HVI flash characterization

1046 a given gun) and, therefore, have historically been the most widely used methods.

1047 More recently, simple curve fitting methods have been augmented with more sophisticated neural net-
1048 works. Fraunhofer EMI [104, 343] pioneered this effort, developing a neural network to predict 2SLGG
1049 muzzle velocity and optimize operational parameters. Efforts to incorporate machine learning have also
1050 been reported elsewhere [360]. Many computational resources and advanced regression techniques have
1051 recently emerged, including artificial neural networks [361], support vector regression [362], and Gaussian
1052 process regression [363], each with their own complexities, strengths, degree of accuracy, and precision. Neu-
1053 ral networks are particularly promising for regression tasks since they function as universal approximators
1054 [364]. While not currently in widespread use, neural network and machine learning prediction approaches
1055 for 2SLGG performance will undoubtedly become more prevalent as these technologies continue to mature
1056 and large empirical data sets become increasingly available.

1057 7.2. Closed Form Solutions

1058 Despite the large number of operational parameters and uncertainties in 2SLGG usage, a number of sim-
1059 ple, closed-form solutions/equations have been derived from first principles to estimate the highest possible
1060 2SLGG muzzle velocity (U_P) [2, 10]. Recall, one noteworthy equation, credited to Langweiler [96], calculates
1061 U_P based on WG temperature (T), molecular weight (M), and ratio of specific heats (γ), *i.e.*,

$$U_P \approx \sqrt{\frac{2RT}{\gamma - 1}}, \quad (1)$$

1062 where Eq. (1) is repeated here for ease of comparison. This expression provides a reasonable estimate of the
1063 maximum achievable muzzle velocity, but it does not consider the specifics of the gun or the projectile. In
1064 contrast, Swift [6] described a relationship for U_P that takes into account key projectile features:

$$U_p \approx \sqrt{\frac{2Gd_p^3}{m_p}}, \quad (4)$$

1065 where m_p is the total launch mass, d_p is the launch tube diameter, and G is an empirical fitting parameter
1066 with units of pressure ($G = 40.0$ GPa for most guns). These models are clearly limited in that they cannot be
1067 used to optimize a set of launch parameters. Further, they are typically only applicable over a narrow portion
1068 a gun's performance (kinetic energy) envelope. Nevertheless, such closed-form expressions provide valuable
1069 insights into the fundamental physics of 2SLGGs. For instance, Eq. (1) illustrates that gun performance is
1070 proportional to WG temperature and inversely proportional to WG molecular weight, relationships that can
1071 be explained by variations in gas sound speed and the energy required for gas acceleration. Similarly, Eq.
1072 (4) reveals that maximum projectile velocity decreases with increasing projectile mass for a given launch

1073 tube diameter and that launch tube diameter can be increased to enhance the kinetic energy ceiling.

1074 7.3. Physics-Based Numerical Models

1075 Empirical and analytical prediction methods cannot resolve key processes that ultimately dictate 2SLGG
1076 muzzle velocity, such as powder combustion, piston release and translation, frictional heating, WG compres-
1077 sion, petal valve rupture, projectile acceleration, and more. 2SLGG operations must be understood and
1078 simulated to effectively design and optimize individual components. Numerical codes rooted in computa-
1079 tional fluid dynamics (CFD) principles can be used to probe the physics of 2SLGG launches. In general, the
1080 WG dynamics, for example, are captured using established CFD algorithms that approximate the solution
1081 to differential equations derived from fundamental fluid flow conservation equations (continuity, momentum,
1082 and energy) [365]. Key 2SLGG sub-domains (*e.g.*, pump and launch tube volumes) are generally discretized
1083 into cells with set moving boundaries and initial conditions. The Piston Compression Light Gas Gun Per-
1084 formance (PCLGGP) [20] and the Light Gas Gun (LGGUN) [25] codes have been particularly influential
1085 and well-adopted. Despite nearly five decades of development and refinement [20, 25, 51, 92, 204], these
1086 approaches can have difficulty predicting 2SLGG performance given the wide range of potential operational
1087 parameters and configurations.

1088 The PCLGGP code (aka “Charters Code” [20]) evolved from the first CFD-based 2SLGG prediction code
1089 developed at the Naval Ordnance Laboratory. This code employs a 1D, Lagrangian, time-implicit, transient,
1090 finite volume approach with moving boundary conditions. Compressible flows are modeled using the von
1091 Neumann-Richtmyer Artificial Viscosity method, Gaussian-upwind finite difference methods for numerical
1092 integration, and equations of state for light gas gun fluids and components. Key assumptions incorporated
1093 into PCLGGP include a 1D domain, adiabatic and frictionless flow (non-isentropic flow due to shock waves),
1094 and idealized powder gases composed of a perfect mixture of common combustion products. The code
1095 does not account for heat transfer, viscous diffusion (except for shock wave damping), turbulence, and heat
1096 conduction effects. The tube walls are considered adiabatic and frictionless, and the gun components serve
1097 as a fixed, inertial reference frame. The code approximates projectile muzzle velocity along with breech
1098 pressures, gas temperatures, piston velocity, projectile acceleration, *etc.* Because of the 2SLGG operational
1099 cycle idealizations (neglecting friction, heat loss, *etc.*), PCLGGP tends to over-predict muzzle velocity by
1100 $\sim 10\text{--}20\%$. Despite these limitations, the predictions generally agree with empirical data from numerous
1101 experiments and offer helpful guidance for 2SLGG operators and designers in a straightforward manner.

1102 Over 30 years, Bogdanoff *et al.* [25, 51, 92, 204] developed the more sophisticated LGGUN that accounts
1103 for the effect of launch tube erosion (*e.g.*, the entrainment of droplets of barrel wall material into the WG)
1104 in limiting the maximum achievable muzzle velocity for 2SLGGs [92]. In essence, LGGUN is a “quasi-1D,”

1105 Lagrangian, time implicit, transient, finite volume approach with moving boundary conditions [25] that
 1106 employs the Godunov method for highly compressible flows and the MacCormic predictor-corrector scheme
 1107 for time advancement. The code accounts for piston-pump tube wall friction, gas viscosity effects, and has
 1108 robust, empirically fitted equations of state. The “quasi” one-dimensionality accounts for radial heat transfer
 1109 through the launch tube wall due to axially accelerating gases/solids during each time-step. In addition,
 1110 LGGUN can be used model shock tunnels and other 1D, hypersonic flows. The code, however, relies on several
 1111 empirical fits and requires sensitive fitting parameters, which makes input data file formation challenging
 1112 and requires expertise when interpreting predicted results [25]. LGGUN’s complexity and theoretical rigor
 1113 make it less user-friendly than PCLGGP but can provide insight into specific aspects of 2SLGG operational
 1114 performance.

1115 Both PCLGGP and LGGUN complement empirical and analytical approaches to enable better 2SLGG
 1116 prediction, development, and optimization. These codes have further motivated other 2LSGG numerical
 1117 prediction efforts [50, 94, 360, 366–370]. Table 5 presents a partial list of other relevant empirical, analytical,
 1118 and numerical 2SLGG prediction efforts and provides key details for each.

1119 8. Conclusions

1120 Over the past seven decades, two-stage light gas gun (2SLGG) aeroballistic ranges have been instrumental
 1121 in advancing the study of material behavior under hypervelocity impacts (HVIs) and hypersonic conditions.
 1122 This review article provides a broad overview of more than 90 2SLGG aeroballistic ranges that have been
 1123 operational since 1990, describing their working principles and assessing global experimental capabilities.
 1124 2SLGG launch tube diameters range from 1 mm to 203 mm, and aeroballistic ranges span from around a
 1125 meter in length to hundreds of meters. Maximum muzzle velocities have surpassed 10 km/s for standard

Table 5: An overview of analytical, empirical, and numerical prediction techniques for 2SLGG performance, including predictor/model name, classification, and key model details. Prediction techniques without definitive names are identified by reporting authors.

No.	Predictor/Model Name	Class	Key Details
1	Lexow <i>et al.</i> (2015) [104, 343]	Empirical	Neural network
2	Shojaei <i>et al.</i> (2022) [360]	Empirical	Machine learning; Random forest regression
3	Langweiler (1938) [10]	Analytical	Maximum theoretical muzzle velocity prediction
4	Swift (2005) [6]	Analytical	Maximum muzzle velocity prediction for 2SLGGs
5	Zhuang and Lu (2016) [366]	Numerical	1D ODEs; 2 linked models
6	Patin and Courter (1986) [94]	Numerical	1D; Time-dependent; 4 linked models; Nonlinear ODEs
7	Rajesh <i>et al.</i> (2007) [367]	Numerical	No viscosity/heat transfer; 5th order Runge-Kutta
8	Majzoobi <i>et al.</i> (2018) [368]	Numerical	Expansion on work by Rajesh <i>et al.</i> [367]
9	Dong and Cao (2022) [205]	Numerical	Employed Ansys Fluent, 6DOF, and dynamic mesh
10	LGGUN (Bogdanoff, 1995) [25]	Numerical	Godunov code; Quasi-1D; includes bore erosion & friction
11	PCLGGP (Charters <i>et al.</i> , 1973) [20]	Numerical	Linear ODEs; Ignores heat transfer and friction
12	QUICKGUN (Milora <i>et al.</i> , 1990) [369]	Numerical	Uses “method of characteristics”
13	Piacesi <i>et al.</i> (1963) [370]	Numerical	Uses Richtmyer-von Neuman “q” method
14	Rynearson and Rand (1972) [50]	Numerical	Uses isentropic compression method; nonlinear ODEs

1126 2SLGGs, with even higher velocities for modified 2SLGGs, and kinetic energy thresholds range from a few
1127 joules to nearly 100 megajoules. 2SLGG aeroballistic ranges are located worldwide in countries such as
1128 the United States (46.7%), China (15.2%), Japan (8.7%), United Kingdom (7.6%), France (5.5%), Canada
1129 (3.3%), Germany (3.3%), South Korea (3.3%), Russia (2.1%), Australia (1.1%), India (1.1%), Italy (1.1%),
1130 and Sweden (1.1%), with affiliations spanning academic (46%), government (49%), and private (5%) sectors.
1131 The study delves into the origins and research applications of 2SLGGs, emphasizing their relevance across
1132 various disciplines, including shock physics, planetary science, defense, nuclear physics, hypersonic vehicle
1133 survivability and performance, and spacecraft protection. A synopsis of HVI phenomena accentuates the
1134 need for 2SLGGs and clarifies the commonalities and disparities among diverse 2SLGG aeroballistic ranges
1135 and supportive methodologies.

1136 2SLGG working principles, configurations, and operations are also examined and compared. The maxi-
1137 mum muzzle velocity is inversely proportional to working gas molecular weight and directly proportional to
1138 gas temperature, prompting many facilities to adopt hydrogen as the working gas. 2SLGGs can be powder-
1139 driven, compressed gas-driven, and gaseous detonation-driven, with powder-driven systems being the most
1140 common (80%) and highest-performing. The review presents current 2SLGG performance capabilities and
1141 uses facility survey findings to report current aeroballistic range tankage configurations, experiment types,
1142 research applications, and diagnostic instruments and techniques. Generally, range tankage can be cate-
1143 gorized by one or more of the following configurations: (a) a separated blast tank and target tank, (b) a
1144 near-muzzle chamber, or (c) a combined blast tank and free flight range tank. The most prevalent diagnostic
1145 tools employed in these facilities include high-speed imaging (70%), flash X-ray (45%), laser velocimetry
1146 (45%), and PDV and/or VISAR (30%). In addition, a brief overview of 2SLGG performance prediction
1147 methods is presented. While many facilities depend on historical experimental data to predict muzzle veloc-
1148 ity, analytical and numerical predictive tools can supplement empirical models/data. Overall, this
1149 study underscores the multifaceted and interdisciplinary strategies and capabilities available to characterize
1150 HVIs and hypersonic phenomena over a range of environmental conditions and spatial scales.

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1159 notation herein.

1160 **Appendix A**

1161 This appendix presents a summary of key aeroballistic range features reported in the literature: organization type, diagnostics, research class, and
 1162 range tankage configuration (open *vs.* closed). These features, distinct from the *2SLGG performance/operational* data presented in Table 1, describe
 1163 a given range’s capabilities rather than the corresponding 2SLGG, itself. This data was instrumental in creating figures and making broad conclusions
 1164 in this review paper. It provides a broader perspective on the research capabilities and application areas for the 2SLGG aeroballistic ranges reported
 1165 in Table 1.

Table 6: Aeroballistic range features available in the literature. Here, key reported diagnostic instruments and methods include high-speed imaging (HSI), flash X-ray (FXR), laser velocimetry (LVS), velocity inteferometer system for any reflector (VISAR), shadowgraphy (SY), accelerometers (ACC), strain gauges (SG), streak cameras (SC), photon doppler velocimetry (PDV), shorting pins (SP), schlieren (SL), load cells (LC), photodiode (PH), digital image correlation (DIC), microwave reflectometers (MR), laser doppler vibrometers (LDV), X-ray velocimetry (XV), and high-speed spectroscopy (HSS) (see Fig. 21 and Table 4 in Section 6). Similarly, research classes include penetration/perforation mechanics (PM), planar impacts (PI), hypersonic/aerotherophysics (HA), and nuclear/pellet injection (N) (see Fig. 19 and Table 3 in Section 5.2).

56

No.	Facility	Organization Type	Diagnostics	Research Class	Range Tankage Configuration
1	Mississippi State University - I	Academic	PH	PM	Closed
2	Drexel University	Academic	HSI	PI, PM	Closed
3	Caltech	Academic	HSI, VISAR, PH	PM	Closed
4	Commissariat a l’Energie Atomique - I	Government	HSI, LVS	PM	Closed
5	National Defense Academy	Academic	LVS	PM	Closed
6	Commissariat a l’Energie Atomique - II	Government	...	N	...
7	NASA MSFC - I	Government	HSI, LVS	PI, PM	Closed
8	University of Kent	Academic	LVS	PM	Closed
9	Rice University	Academic	...	PM	...
10	NASA WSTF - I	Government	ACC, FXR, HSI, LVS, SG SY	PI, PM	Closed
11	Oak Ridge National Lab	Government	...	N	Closed
12	The Open University	Academic	...	PM	Closed
13	NASA JSC	Government	FXR, HSI, LVS	PM	Closed
14	PERC, Chita	Academic	HSI	PI	Closed
15	NASA MSFC - II	Government	...	HA, PM	Closed

Table 6: Aeroballistic range features available in the literature. Here, key reported diagnostic instruments and methods include high-speed imaging (HSI), flash X-ray (FXR), laser velocimetry (LVS), velocity interferometer system for any reflector (VISAR), shadowgraphy (SY), accelerometers (ACC), strain gauges (SG), streak cameras (SC), photon doppler velocimetry (PDV), shorting pins (SP), schlieren (SL), load cells (LC), photodiode (PH), digital image correlation (DIC), microwave reflectometers (MR), laser doppler vibrometers (LDV), X-ray velocimetry (XV), and high-speed spectroscopy (HSS) (see Fig. 21 and Table 4 in Section 6). Similarly, research classes include penetration/perforation mechanics (PM), planar impacts (PI), hypersonic/aerotherophysics (HA), and nuclear/pellet injection (N) (see Fig. 19 and Table 3 in Section 5.2).

No.	Facility	Organization	Diagnostics	Research Class	Range Tankage
		Type			Configuration
16	Mississippi State University - II	Academic	HSI	PM	Closed
17	University of Nevada, Las Vegas	Academic	PDV, LVS,	PI	Closed
18	Fraunhofer EMI - I	Government	ACC, HSI, LC, LVS, PH, SY, SC	PM	Closed
19	University of Padua	Academic	ACC, LVS, SY	PM	Closed
20	Japan Aerospace Exploration Agency	Government	HSI, PH	PM	Closed
21	Johns Hopkins University	Academic	FXR, HSI, LVS	HA, PI, PM	Closed
22	Cranfield University	Academic	FXR, HSI, SG	PI	Closed
23	Hypervelocity Aerodynamics Institute - I	Government	FXR, HSI, LVS, MI, SL, SY	PM	Closed
24	Denver Research Institute	Academic	...	PI, PM	...
25	Brookhaven National Lab	Government	...	PM	Closed
26	KAIST	Academic	...	PM	Closed
27	National Research Tomsk University - I	Academic	FXR	...	...
28	Corvid	Government	...	PM	...
29	Fraunhofer EMI - II	Government	ACC, HSI, LC, LDV, SC, SY	PM	Closed
30	University of New Brunswick - I	Academic	DIC, HSI	PM	Closed
31	Imperial College London	Academic	...	PI	...
32	Kyushu Institute of Technology	Academic	LVS	PM	...
33	TiTech	Academic	VISAR	PI	Closed
34	Thiot Ingenierie	Private	FXR, HSI, LVS	PI, PM	Closed
35	Texas A&M University	Academic	FXR, HSI, LVS, SL, SY	HA, PM	...
36	NASA WSTF - II	Government	ACC, FXR, HSI, LVS, SG, SY	PI, PM	Closed
37	First Light Fusion - I	Private	HSI, SC, SL, SP, SY	HA, N	Closed
38	Argonne National Lab	Government	PDV	PI, PM	Closed

Table 6: Aeroballistic range features available in the literature. Here, key reported diagnostic instruments and methods include high-speed imaging (HSI), flash X-ray (FXR), laser velocimetry (LVS), velocity interferometer system for any reflector (VISAR), shadowgraphy (SY), accelerometers (ACC), strain gauges (SG), streak cameras (SC), photon doppler velocimetry (PDV), shorting pins (SP), schlieren (SL), load cells (LC), photodiode (PH), digital image correlation (DIC), microwave reflectometers (MR), laser doppler vibrometers (LDV), X-ray velocimetry (XV), and high-speed spectroscopy (HSS) (see Fig. 21 and Table 4 in Section 6). Similarly, research classes include penetration/perforation mechanics (PM), planar impacts (PI), hypersonic/aerotherophysics (HA), and nuclear/pellet injection (N) (see Fig. 19 and Table 3 in Section 5.2).

No.	Facility	Organization Type	Diagnostics	Research Class	Range Tankage Configuration
39	NASA AVGR	Government	HSI	HA	Closed
40	Naval Surface Warfare Center - I	Government	FXR, HSI, SG, VISAR	PI, PM	...
41	Royal Military College of Science	Academic	FXR, HSI	PM	Closed
42	Tohoku University - I	Academic	HSI	PM	...
43	Hypervelocity Aerodynamics Institute - II	Government	FXR, HSI, LVS, MI, SL, SY	PM	...
44	China Academy of Space Technology - I	Government	...	PI	Closed
45	AEDC - I	Government	...	HA, PM	...
46	Tohoku University - II	Academic	FXR, SC	PM	...
47	UDRI - I	Academic	ACC, FXR, HSI, LC LVS, SG	PI, PM	...
48	University of British Columbia	Academic	SP, LVS	PI	Closed
49	University of New South Wales	Academic	HSI, LVS, PDV	PI, PM	...
50	Commissariat a l'Energie Atomique - III	Government	FXR, HSI, TH, VISAR	PI, PM	Closed
51	National Research Tomsk University - II	Academic	...	PM	...
52	University of California, Davis	Academic	LVS, SP, VISAR	PM	...
53	China Academy of Space Technology - II	Government	...	PI, PM	...
54	Hypervelocity Aerodynamics Institute - III	Government	...	HA	Closed
55	Seoul National University	Academic	HSI, FXR	PM	Closed
56	University of New Brunswick - II	Academic	HSI, DIC	PM	...
57	National Institute for Material Science	Government	VISAR, SG, SC, FXR	PI	...
58	NASA WSTF - III	Government	ACC, FXR, HSI, LVS, SG, SY	PI, PM	...
59	Engineering Research Development Center	Government	HSI	PM	...
60	Wuhan University	Academic	...	PI	Closed
61	Lawrence Livermore National Laboratory - I	Government	FXR, VISAR	PI	Closed

Table 6: Aeroballistic range features available in the literature. Here, key reported diagnostic instruments and methods include high-speed imaging (HSI), flash X-ray (FXR), laser velocimetry (LVS), velocity interferometer system for any reflector (VISAR), shadowgraphy (SY), accelerometers (ACC), strain gauges (SG), streak cameras (SC), photon doppler velocimetry (PDV), shorting pins (SP), schlieren (SL), load cells (LC), photodiode (PH), digital image correlation (DIC), microwave reflectometers (MR), laser doppler vibrometers (LDV), X-ray velocimetry (XV), and high-speed spectroscopy (HSS) (see Fig. 21 and Table 4 in Section 6). Similarly, research classes include penetration/perforation mechanics (PM), planar impacts (PI), hypersonic/aerotherophysics (HA), and nuclear/pellet injection (N) (see Fig. 19 and Table 3 in Section 5.2).

No.	Facility	Organization Type	Diagnostics	Research Class	Range Tankage Configuration
62	Sandia National Labs	Government	HSI, HSS, PDV, ORVIS, VISAR	HA, PI	...
63	Los Alamos National Lab - II	Government	...	PI	...
64	Chinese Academy of Sciences	Government	...	PM	Closed
65	UDRI - II	Academic	ACC, FXR, HSI, LC, LVS, SG	PI, PM	...
66	Northwest Institute of Nuclear Technology - I	Government	...	PM	Closed
67	Swedish Defence Research Agency	Government	FXR	PI, PM	Closed
68	Eglin Air Force Base	Government	...	PM	Open
69	Southwest Jiaotong University	Academic	...	PI	...
70	University of Alabama - I	Academic	...	HA, PM	Closed
71	Institute of Saint-Louis	Government	FXR, SL, SY	HA, PI, PM	Closed
72	Lawrence Livermore National Laboratory - II	Government	FXR, HSI, SP, LVS, VISAR	PI, PM	...
73	University of Alabama - II	Academic	...	HA, PM	...
74	Southwest Research Institute	Private	...	HA, PM	...
75	First Light Fusion - II	Private	HSI	N	Closed
76	New Mexico Tech - EMRTC	Academic	...	PM	...
77	NASA Ames HFFAF	Government	HSI	HA	...
78	Naval Surface Warfare Center - II	Government	FXR, HSI, SG, VISAR	FPI	...
79	TBRL	Government	FXR	PM	Closed
80	Los Alamos National Lab - I	Government	...	PI, PM	...
81	Hypervelocity Aerodynamics Institute - IV	Government	...	PM	...
82	AEDC - II	Government	...	HA, PM	...
83	Lawrence Livermore National Laboratory - III	Government	FXR, HSI, SP, VISAR	PI, PM	Closed
84	Fraunhofer EMI - III	Government	ACC, HSI, LC, SC, SY, XV	HA, PM	...

Table 6: Aeroballistic range features available in the literature. Here, key reported diagnostic instruments and methods include high-speed imaging (HSI), flash X-ray (FXR), laser velocimetry (LVS), velocity interferometer system for any reflector (VISAR), shadowgraphy (SY), accelerometers (ACC), strain gauges (SG), streak cameras (SC), photon doppler velocimetry (PDV), shorting pins (SP), schlieren (SL), load cells (LC), photodiode (PH), digital image correlation (DIC), microwave reflectometers (MR), laser doppler vibrometers (LDV), X-ray velocimetry (XV), and high-speed spectroscopy (HSS) (see Fig. 21 and Table 4 in Section 6). Similarly, research classes include penetration/perforation mechanics (PM), planar impacts (PI), hypersonic/aerotherophysics (HA), and nuclear/pellet injection (N) (see Fig. 19 and Table 3 in Section 5.2).

No.	Facility	Organization Type	Diagnostics	Research Class	Range Tankage Configuration
85	TAMU Ballistics Aero-Optics and Materials	Academic	...	HA, PM	...
86	University of Alabama - III	Academic	...	HA, PM	Closed
87	AEDC - III	Government	...	HA, PI, PM	...
88	Agency for Defence Development	Government	HSI, LVS, PDV	PI	Closed
89	Harbin Institute of Technology	Academic	...	PM	...
90	Northwest Institute of Nuclear Technology - II	Government	...	PM	...
91	Beihang University	Academic	...	PM	...
92	Shenyang Ligong University	Academic	HSI	PM	...

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