An Efficient and Effective Light Gas Gun Design for Millimeter-scale Hypervelocity Testing

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Abstract

This paper serves to document a design for a light gas gun that was used for 3 decades at NASA's Langley Research Center. By adapting readily-available equipment and supplies, this apparatus was capable of accelerating projectiles at up to 9 kilometers per second. The lack of a projectile-carrying sabot sacrifices some adaptability in projectile size, but results in a design that can be cleaned and cycled with far less labor input. Overall limitation on the projectile impact energies attainable effectively limit the applications to assessing the relatively thin shields employed for robotic spacecraft (less useful for those used for manned missions). The original gun has been decommissioned, but it is believed that this design has application for robotic spacecraft shield testing in the modern world, allowing cost-effective generation of larger sample sizes than with conventional sabot-based light gas guns.

1 Introduction

Assuring the robustness of hardware to be used in space includes assessing the potential vulnerability of spacecraft surfaces to hypervelocity space debris, both human-made orbital debris and naturally-occurring meteoroids. Orbital debris particles tend to be larger and slower than meteoroids, though more numerous in Low Earth Orbit environment. For either species of particles, it is necessary to test the spacecraft surfaces and candidate shielding designs at a variety of particle velocities and mass, in order to establish a ballistic limit equation that represents the penetration threshold.

Such ballistic limit equations can benefit from collecting the maximum practical number of data points near the penetration threshold. Some natural variation occurs, so that nearly identical tests near the penetration threshold can yield different results. Unfortunately, most Hypervelocity Impact (HVI) testing is relatively expensive, limiting the quantity of tests performed on each shielding design. A large portion of the cost of such tests is labor to set up the test, collect and distill data, and clean the apparatus between tests. In the early 1970s, a design for a light gas gun (LGG) was developed using readily available equipment and supplies, capable of producing HVI tests with a minimum of labor input – resulting in relatively modest cost per test. Most modern LGGs have been developed to allow greater flexibility and capability in terms of projectile size and mass, but at considerably higher cost per test (thus fewer tests). It is felt that this simpler design still has application in terms of generating larger quantity of results at lower cost.

2 History

The Langley Miniature Light Gas Gun was designed by Don Humes at NASA's Langley Research Center in the early 1970's. It was first used for a space flight mission in February 1971 to test the potentially brittle case surrounding a Radioisotope Thermoelectric Generators (RTG). Representative samples were impacted at 6.8 to 8.3 km/s, with no evidence of perforation or cracking. In early testing, the gun used helium gas in the second stage compression section to prevent suspected safety issues using hydrogen. Later, hydrogen was used for most tests, and it functioned safely for its entire lifetime. Aside from the hunting rifle, all other components were custom-made at Langley.

The gun was used as needed for over 30 years, and hundreds of test shots. There were long stretches during which no tests were performed, and other occasions when 30-40 tests were performed per week. After a period of disuse, the gun was disabled by welding the bolt closed, and it was donated to the Smithsonian Institute as a historical example of hardware used for testing in the early days of space flight.

3 Unique Characteristics

The Langley Miniature LGG had a unique set of characteristics, some of which are shared by other LGGs currently in use at other facilities. The main difference from most other LGGs is that the gun did not require a sabot to hold and deliver the projectile. As a result, it could use a smaller powder charge than conventional LGGs. The design was considerably smaller than most guns, occupying one modest sized room, and had a relatively short cycle time between tests. From the start, it was designed to use readily available supplies and spare parts, generally available for high pressure laboratories and hunting equipment providers.

The lack of a sabot in this LGG design effectively meant that nearly all of the force from the second stage was imposed on the projectile itself. There was no energy lost in accelerating a bulky sabot which usually has greater mass than the projectile itself. In addition, there was no energy lost in rotating the sabot, necessary to ensure that it separated from the projectile. On the other hand, the projectile must be strong enough to withstand the rapid application of so much force to the projectile without the sabot to act as a buffer. The lack of a sabot also means that the projectile diameter must be matched to the inner diameter of the launch tube, whereas a sabot accommodates a variety of projectile diameters.

Because the LaRC LGG accelerated a smaller mass than most guns, it could use less powder in the first stage. That allowed for reduced safety precautions relative to most other guns with similar capability. Safety was still, of course, extremely important – but easier to attain. For example, the guide tube that held and positioned the launch tube would also serve to contain any rupture – though that was never necessary.

The LaRC LGG design was shorter than that used by most other LGGs, resulting in a more compact overall design. The pump tube was cleaned quickly in the same manner as a hunting rifle, and the launch tube could be replaced outright, for rapid cycling to a subsequent test. When used for consecutive tests, hypervelocity impacts could be simulated by one person in about an hour per test, compared to 4-6 person-hours or more per test with some other guns. Since labor is a main expense for such testing, reduced labor can result in a greater sample size.

4 Description Of The Design

The LaRC LGG was a two stage light gas gun. An explosive first stage fired a piston through the pump tube (rifle barrel), which compressed the gas as the second stage of compression. The compressed gas, controlled by a burst disk, then pressed directly onto the projectile, accelerating it through the launch tube and into the test chamber. Figure 1 shows a detailed drawing of the portion of the gun from the first stage through the end of the launch tube. There is an excellent YouTube video online [1] in which Don Humes demonstrates the setup and triggering of a test with this gun.

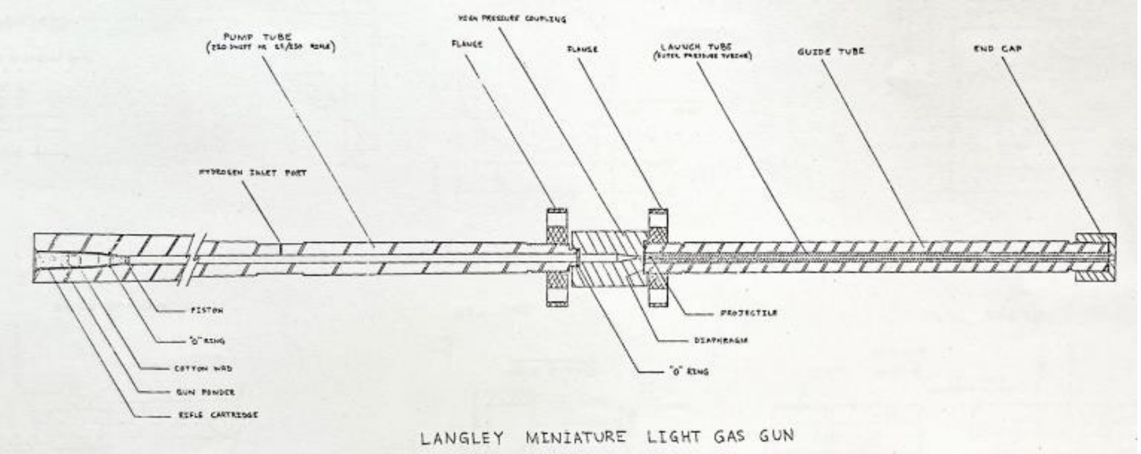

Fig. 1. Detailed drawing of the first and second stages of the LARC LGG

The compression section of the LaRC LGG used a modified .220 caliber Swift bolt action hunting rifle. Other rifles were considered, but the .220 Swift had the highest muzzle velocity at the time (and is still among the highest). The chamber of the rifle was unchanged, so that it accepted a standard cartridge, reloaded for each shot with a fresh primer cap. Pistol powder was used due to its fast burn rate, filled to a precisely measured mass (typically 0.4 to 1.3 grams), and held in place in the cartridge using cotton wadding. The amount of powder used was one of the main determinants of the projectile speed. The bullet in the cartridge was replaced with a high density polyethylene piston machined to match the 0.22 inch (5.59 mm) barrel/pump tube inner diameter. The barrel of the hunting rifle was modified by omitting the rifling, drilling a gas port along its length, and threading the muzzle to interface to a high pressure flange. The loaded cartridge is shown in Fig. 2.

Fig. 2. Prepared cartridge

The piston traveled down the pump tube to lodge in a tapered high pressure coupling. This coupling, bolted in place between two flanges, constituted the final volume of compressed gas before expanding to press on the projectile. A thin Mylar (polyethylene terephthalate) diaphragm in the downstream end of the coupling was selected to rupture at a preset pressure, giving some control over the projectile velocity. Diaphragm thickness varied from 0.001 to 0.010 inch, with most tests using 0.003 to 0.005 inch thick film stock. Figures 3 and 4 show the diaphragm and the installation of it into the pressure coupling.

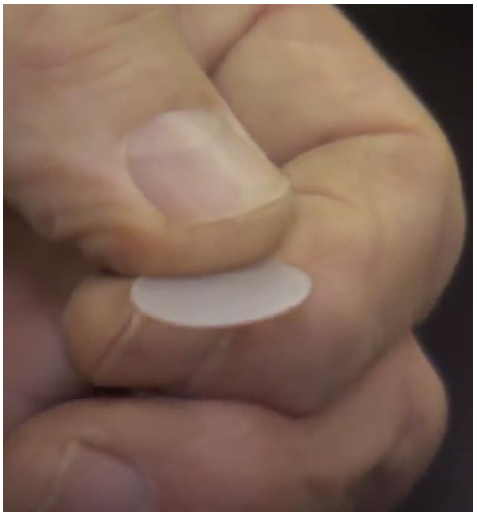

Fig. 3. Mylar diaphragm

Fig. 4. Installing the diaphragm into the high pressure coupling

The gas used in the second stage could be hydrogen or helium. Initial testing was performed using helium, but the gun was transitioned to hydrogen gas at approximately 90 psi initial pressure for the majority of the tests. Slower velocity impacts are also important to the generation of a ballistic limit curve, and it was found that using helium for the compression gas and a very thin diaphragm produced tests in the range of 2 to 3 km/s projectile velocities.

The projectile next traveled into the launch tube, a piece of ¼ inch outer diameter super high pressure stainless steel tubing selected to match the diameter of the projectile. There were four different inner diameter choices between 1/16 (0.0625) inch and 1/8 (0.125) inch, to allow different diameter projectiles to be used. The launch tube was aligned and supported by a guide tube, threaded for a flange on the upstream end and an end cap on the downstream end. The guide tube used a rubber stopper as the interface to the test chambers, which sealed between the two surfaces when the chamber was evacuated with a vacuum pump. Figures 5 and 6 show assembling and installing the guide tube assembly.

Fig. 5. Inserting the launch tube into the guide tube assembly

Fig. 6. Installing the guide tube assembly

There were two test chambers in series that the projectile would encounter after leaving the launch tube, both of which would have been evacuated to approximately 50 millitorr with a roughing pump. The first of these chambers was used to measure the projectile velocity. The chamber included a set of four optical ports through which a laser beam would pass, reflected by right angle mirrors opposite the He-Ne laser source. The projectile broke the beam twice, a known distance about 10 cm apart. A recording oscilloscope monitored the output of an optical sensor, so that the time between the breaks could be measured accurately, and the projectile velocity calculated. In addition, an optical sensor near the sample was monitored to detect light released by the impact, as a confirmation of the projectile velocity. Figure 7 shows the velocity measurement chamber.

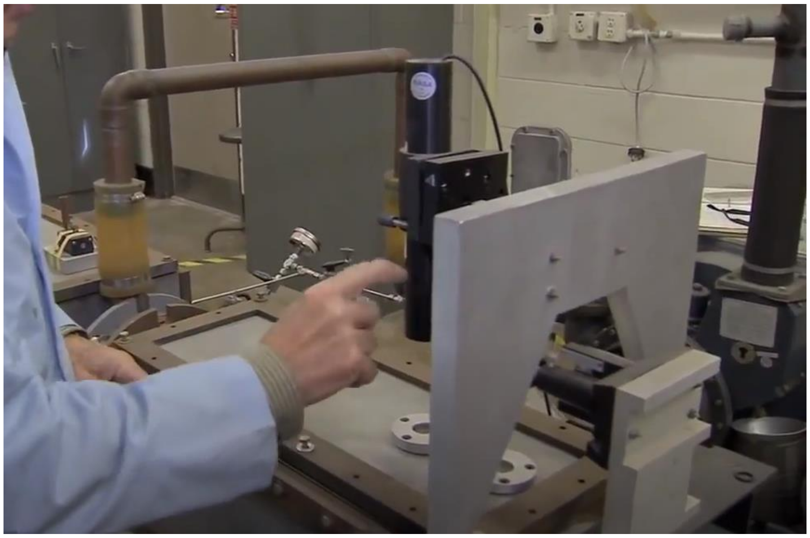

Fig. 7. The velocity measurement chamber

The second chamber, much like the first in dimensions, held the sample which was to be impacted. Containing it in a separate chamber helped to contain secondary debris, protecting the velocity-measuring laser setup. There was also a third larger sample chamber available for testing larger samples, but most tests were performed with the smaller sample chamber. The sample chamber is shown in Fig. 8.

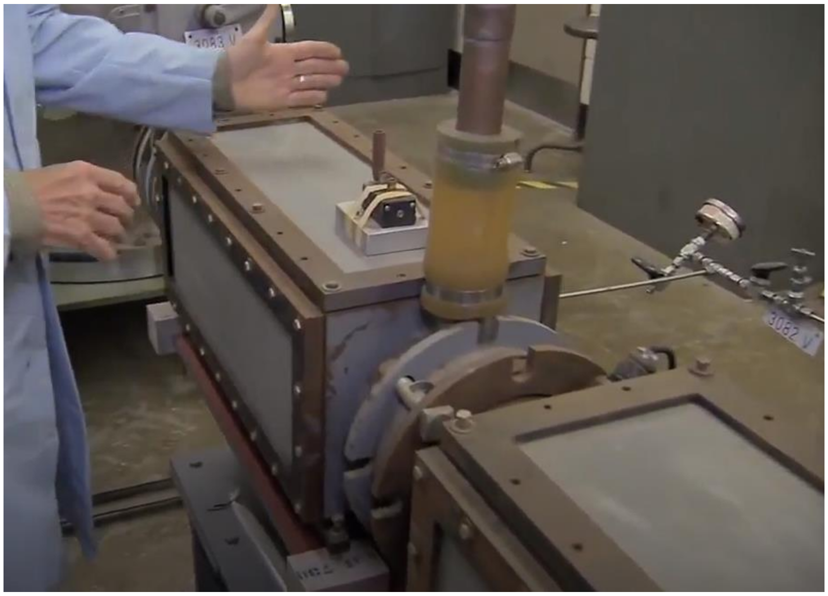

Fig. 8. The sample chamber

5 Results

This Miniature Light Gas Gun was used off and on for over 30 years, testing a wide range of projectiles and shield materials for a diverse set of missions. While the majority of tests were performed in the range of 5 to 7 km/s, this gun was capable of up to 9.2 km/s when it was new. By the end of its life, the gun was capable of only about 5 to 6 km/s projectile speeds. Aside from age, the main factors affecting the projectile velocity were the quantity of powder used and the diaphragm thickness selection.

Projectiles were typically spherical, but cylindrical projectiles were also used. Projectile materials ranged from nylon to glass to steel, as the test conditions called for. For projectiles smaller than the launch tube inner diameter, a sabot was used, but more commonly the projectiles were matched to the launch tube. It was feared that the glass projectiles might be damaged by the directly applied force, but they were shown to remain intact until impacting the sample.

Expendable supplies for each test included the projectile, diaphragm, piston, pistol powder, and a primer cap. The 220 Swift cartridge could often be reloaded, but occasionally would sustain damage and need to be replaced. Similarly, the launch tube might be reusable for several shots, but was typically replaced if the highest velocities were needed. It has been estimated that the expendable costs in the 1990's were about $1.25 per shot.

Tests were performed in support of a diverse set of missions, both crewed and robotic. Among the missions supported were Pioneer and Voyager 1. Tests were also performed in order to re-create impact damage identical to that observed on returned panels from the LDEF mission. Other tests confirmed that the multilayer thermal blanket used on the Lunar Orbiter spacecraft would act as an effective bumper shield to project the spacecraft during its 90 day mission. Some testing was also performed in support of the International Space Station.

6 Conclusion

An effective and elegant design for a miniature light gas gun has been described. By incorporating easily and inexpensively replaced components in portions of the gun, it was possible to perform tests more efficiently than with most other designs. Limitations of the gun have been discussed as well as advantages. This instrument was used for over three decades, firing a wide variety of projectiles in support of a diverse set of missions. This piece of history has now been retired, but elements of the design still have value for modern equipment.

References

[1] NASA Langley Cultural Resources, "Don Humes: Developing the Light Gas Gun", November 2012, https://www.youtube.com/watch?v=7-7dVrTcgmg,