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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	29
page range	17-31
year	1980
URL	http://hdl.handle.net/10097/28133

A Two-Stage Light Gas Gun for Shock Wave Research*

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(Received July 31, 1980)

Synopsis

A two-stage light gas gun of 9 m length is constructed for shock wave research. The apparatus consisted of a 60 mm inner-diameter and 3.6 m long pump stage and a 20 mm inner-diameter and 3.4 m long launch stage. A flyer plate bearing 10 g projectile is accelerated to 4.1 km/s using 120 g propellant charge. Using tungsten flyer plate, shock pressure of 2.5 Mbar is generated. For the velocity range between 2 to 4 km/s, the reproducibility of the muzzle velocity is proved to be within 3 %. Details of the projectile and piston design, target alignment procedure and projectile velocity measuring system are described.

I. Introduction

Shock compression technique has been used for generation of ultrahigh pressure up to several Mbars[1,2] where static high pressure apparatus hardly reaches even with the recent rapid progress in technology. The technique has extensively been adopted for the equation of state study of various substances at high pressures through the determination of shock compression curve. Shock compression technique has an advantage that the shocked state is unambiguously computed on the basis of conservation relations of mass, momentum and energy across the shock front and is determined with a sufficient accuracy of ±1 %. The experimental results have revealed that the state achieved by shock compression is characterized as if the material were fluid and is favorably compared with purely hydrostatic compression, since the stress generally exceeds the yield strength of materials, bringing shear stress negligible. Furthermore, various interesting phenomena including shock-induced phase transformations, have been noticed under extreme shock loading, which sometimes resulted in synthesis of useful substances stable only at very high pressure.

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* The 1714th report of the Research Institute for Iron, Steel and Other Metals.

In shock experiments, stress loading is accomplished by explosion or impact. Explosives are certainly a feasible means for shock wave research. Actually the research activity in shock wave experiments at RIISOM[3-9] first began in early 1970's using explosive techniques at Michikawa Laboratory for Explosive Experiments at Iwaki-machi, Akita Prefecture, where flux compression experiments for production of very intense magnetic fields were also conducted concurrently.[10,11] Small explosive lens system has been developed by ourselves and both determinations of the shock compression curve and measurements of electrical conductivity under shock compression were carried out. The results have been reported elsewhere.[3-9]

As the development of our shock wave research, needs for higher pressures and more precise measurements were invoked. The impact method using a gun came into our scope as more advanced means for production of ideal plane shock waves for our research purpose. After a few years deliberate examination, we have decided to introduce a two-stage light gas gun which is now believed to be one of the best devices for production of shock pressures up to several Mbars and widely used for research purpose in many shock wave laboratories.

II. Principle and Design

The design of the two-stage light gas gun was first made by Crozier and Hume[12] in 1957, which covers a new range of muzzle velocities up to 3 ∿ 4 km/s which cannot be attained by a single stage propellant gun.

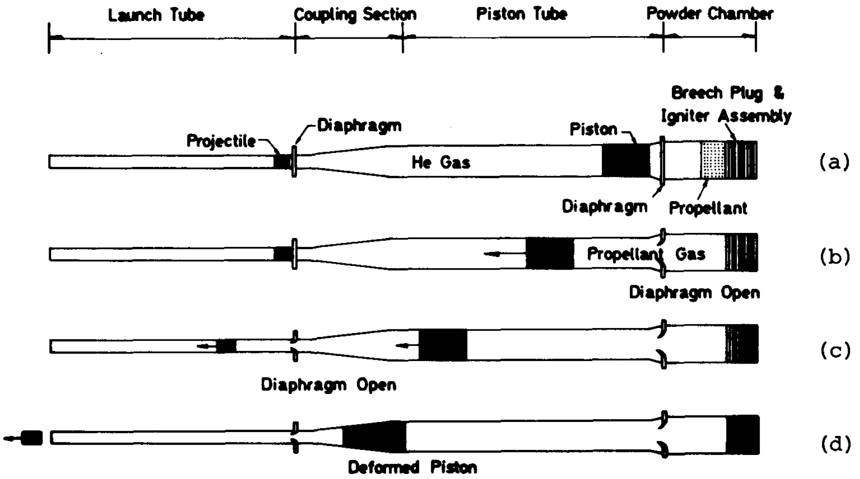


Fig. 1. Illustration of operation cycle of the two-stage light gas gun.
(a) Operation configuration.
(b) Acceleration of the piston by propellant gas (First stage).
(c) Acceleration of the projectile by compressed helium gas (Second stage).
(d) Final stage; The projectile is getting out of the muzzle and piston is stopped at the tapered section of the coupling.

The principle of the two-stage light gas gun can be explained by describing a typical gun cycle, as schematically shown in Fig. 1. The burning propellant produces moderate pressure (first stage) to drive a massive piston down a pump tube which initially contains a pressurized light gas. As the piston moves down the pump tube and into the coupling section, it compresses the light gas to very high pressures (second stage). The opening of a burst diaphragm allows this gas to accelerate a small projectile down an evacuated launch tube to hypervelocity. The piston is stopped by a tapered part in the coupling section.

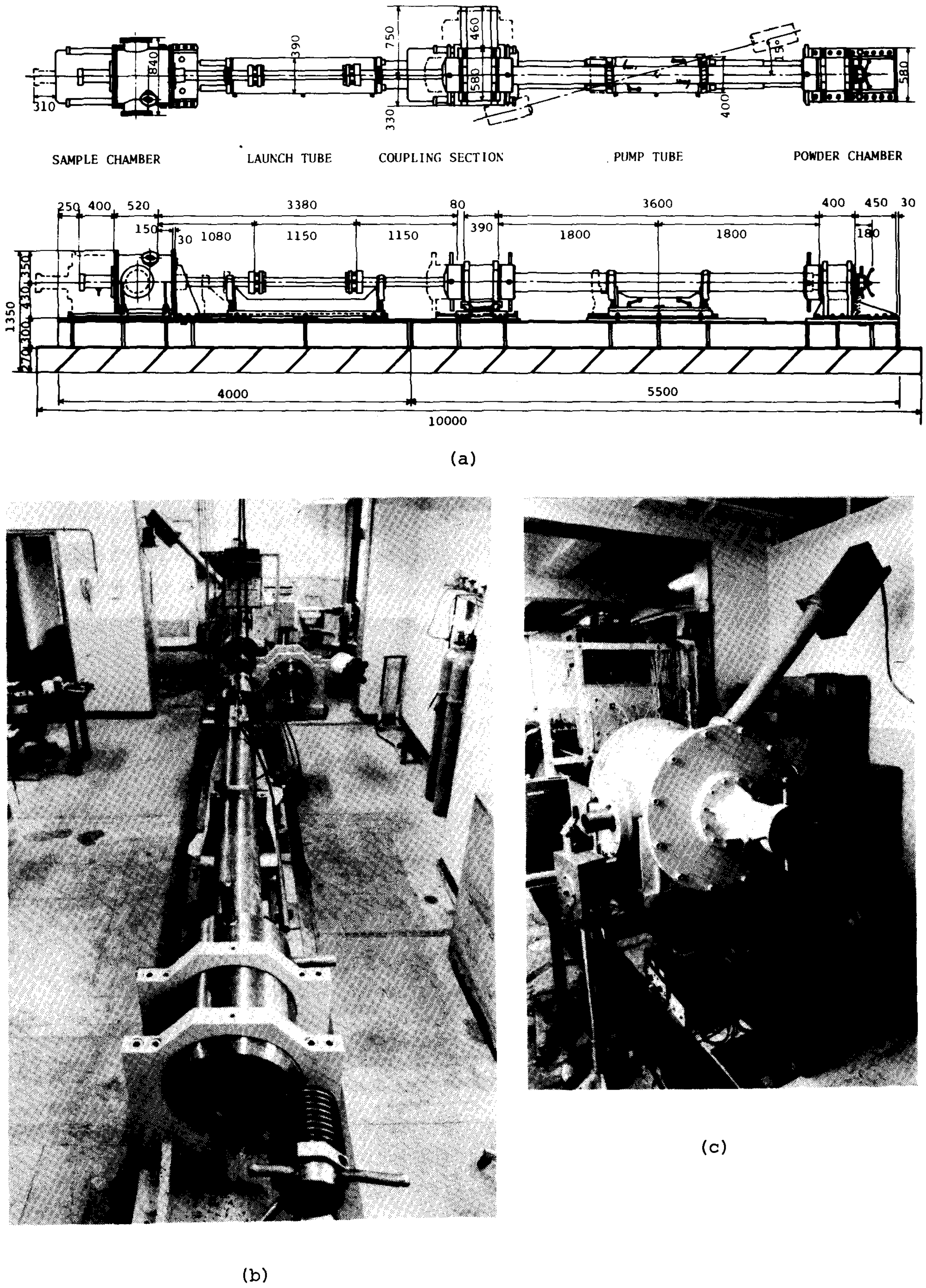
The advantage of the two stage light gas gun is twofold. Firstly the large mass of propellant gas which must be accelerated along with the projectile and limits the muzzle velocity of the one-stage propellant gun is replaced by the small mass of the light gas, helium or hydrogen. Secondly, the light gas is instantaneously pressurized to very high pressure of a few thousand atmosphere which may be awkward to be generated statically, and the reservoir of the light gas in the tapered coupling section is simultaneously accelerated as well as the column of gas in barrel, thereby assuring that the pressure behind the projectile base does not exceeds the strength limit of the projectile material.13)

Since Jones et al.14) reported the construction of a huge two-stage light gas gun in 1965, similar big devices have been installed competitively in most shock wave laboratories in U. S. They are generally more than 25 m in length and are capable for accelerating the projectile to 10 km/s range. However, mostly due to economical reasons and considerations of research efficiency, much smaller gun was chosen for our case as a first step.

Following points, among other things, are considered to be essential in designing the apparatus; 1) The maximum projectile velocity is at least 4 - 5 km/s range, which produces the shock pressure of 1.5 Mbar range for copper or iron. 2) The diameter of the projectile is sufficiently large so as to allow Hugoniot measurements using conventional optical technique such as inclined mirror method. 3) Easy operation. As a model which seems to satisfy the above requirements, geometry of the two-stage light gas gun was patterned from the device originally developed by Sawaoka and his colleagues at Tokyo Institute of Technology.15)

III. General description

Figure 2(a) shows the construction of our two-stage light gas gun



(a)

(b)

(c)

Fig. 2. (a) Construction of the two-stage light gas gun (2SG-TH1).
(b) Whole view of the two-stage light gas gun.
(c) Sample chamber viewed from the optical window side.

(2SG-TH 1). The apparatus consists of five main parts; a powder chamber, a pump tube, a high pressure coupling section, a launch tube and a sample chamber. These parts are assembled together on a 9.5 m base made of H-shaped steel frame, which is clamped on a steel-framed concrete base. Heavy duty rubber plate of 10 mm thickness is inserted between the concrete base and the floor for the purpose of reduction of shot vibration. The total length of the apparatus is about 10 m. The height of the center axis of the gun is taken to be 1 m above the floor level. The whole view of the apparatus is shown in Fig. 2(b).

1) Powder Chamber

Figure 3 shows a cross sectional view of the powder chamber. The powder chamber is designed for maximum loading of 150 g propellant. The gun uses a cartridge case for charging powder. The inner diameter and the volume of the cartridge case is 70 mm and 0.67 ℓ respectively. The case with powder charge is loaded by hand and supported by a massive breech plug. Gun powder is to be fired by electrical heating of a fusehead inserted in contact. For the sake of safety, the cartridge case and an igniter assembly are separately mounted into the powder chamber. The igniter assembly consists of a fusehead and its holder. It is to be loaded onto the cartridge case through a hole of the breech plug.

A grooved diaphragm made of stainless steel, 110 mm in diameter

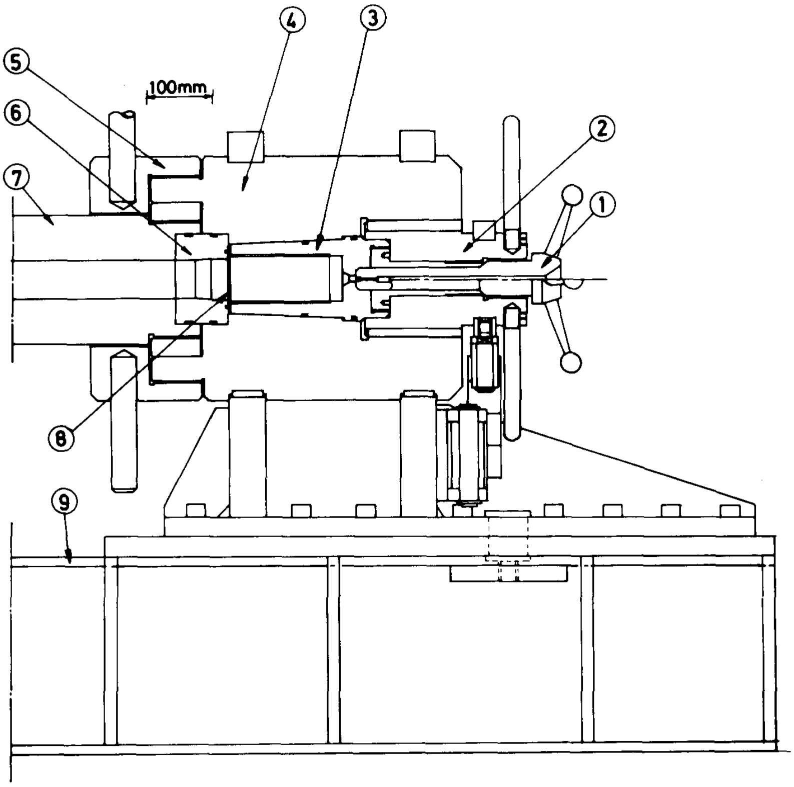


Fig. 3. Cross section of the powder chamber.
1: Fuse-head holder.
2: Breech plug.
3: Cartridge case for powder.
4: Powder chamber.
5: Cap.
6: Transition plug.
7: Pump tube.
8: Burst diaphragm.
9: Base.

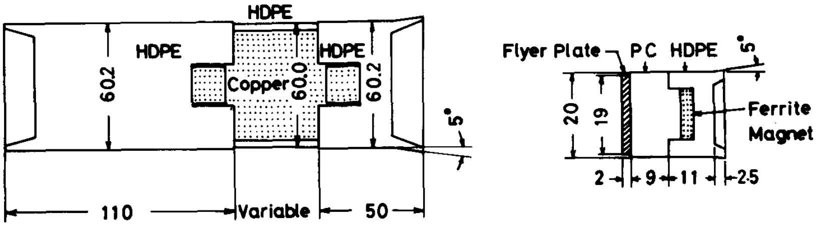
and 1.5 mm in thickness, is placed between the cartridge case and the rear end of the pump tube. A cross groove is engraved on one surface of the diaphragm in order to avoid rugged rupture. Burst pressure which determines initial motion of the piston is controlled by changing the depth of the groove on the diaphragm.

Single-base smokeless powder* (NY-500, Nippon Oil and Fat Co.) is used for propellant. A small amount of black powder is used around the fusehead to help rapid and homogeneous burning of the smokeless powder.

2) Pump Tube and Piston

The pump tube is made of a single, chrome-molybdenum steel (SCM-3) tube, whose dimensions are 60 mm in inner diameter, 200 mm in outer diameter and 3.6 m in length. Various types of plastic pistons made of high density polyethylene (HDPE) have been used. A typical example of the piston is illustrated in Fig. 4(a). In order to change the weight of piston, cylindrical block made of copper is placed inside the plastic piston. The weight of piston is changed from 570 g to 2,230 g. The leading part and the tail of the piston are shaped into a sleeve valve for the purpose of sealing during movement. The diameter of the leading part of the piston is chosen to be greater by 0.2 mm than the inner diameter of the pump tube at 20 °C. Smooth insertion of the over-sized piston into the pump tube is easily made by cooling the piston in the refrigerator down to about -5 °C.

The pump tube is connected with the powder chamber and the high pressure coupling and tightly supported by large screwed caps. When the pump tube is decoupled, it is allowed for an axial displacement and subsequent rotation around a vertical axis up to 15°, for the purpose



(a) (b)

Fig. 4. Design of the piston (a) and the projectile (b)

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* The burning characteristics provided by the manufacturer are as follows: Force of propellant, $f = 9500$ kg·m/kg; Explosion temperature, $T = 2690$ K; Heat of explosion, $H = 800$ kcal/kg; Volume of burned gas, $V_b = 930$ ℓ/kg; Vivacity, $A = 0.559$ cm^3/kg·s; Geometry function, $\varphi(Z) = (1 - z)^{0.6}$ where z is the ratio between the burnt volume to the initial one during the burning process.

of convenience for removing the piston when it accidentaly stopped in the midst of the pump tube.

3) High Pressure Coupling

The high pressure coupling connects the pump tube and the launch tube with a tapered section whose cone angle is selected to be 12° as shown in Fig. 5. It is composed of an inner and outer tube, both of which are made of SCM-3. The outer diameter of the inner tube is 230 mm. Similar burst diaphragm, as used in the powder chamber, inserted between the high pressure coupling and the launch tube determines the initial pressure of the projectile motion.

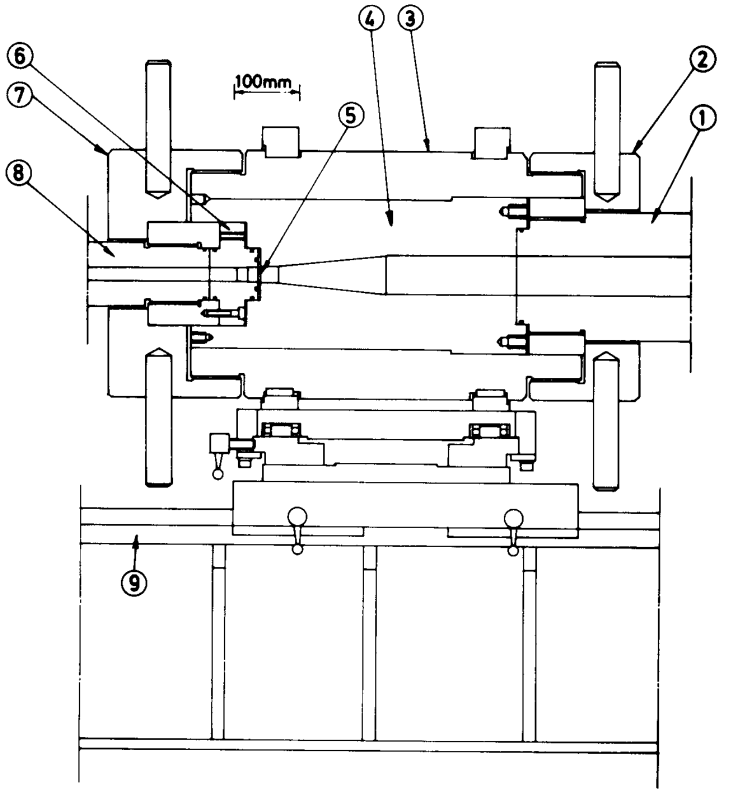

Fig. 5. Cross section of the high pressure coupling.
1: Pump tube.
2: Cap.
3: Outer tube of coupling section.
4: Inner tube of coupling section.
5: Burst diaphragm.
6: Transition plug.
7: Cap.
8: Launcher tube.
9: Base.

The high pressure coupling, when disconnected from the tubes of both sides, is designed to be displaced for an axial and subsequent lateral direction. The mechanism is necessary in order to remove the thrusted piston from the tapered section. Removing of the plastic piston is easily made using a small ram, which is instantaneously fitted to the high pressure coupling. The thrusted piston is pushed back by steel rods with variable length which are mounted in front of a 10-ton ram operated by a hand pump.

4) Launcher and Projectile

The launch tube whose bore diameter is 20 mm consists of three pieces of tubes made of SNCM-8, coupled end to end. The total length of the launcher is 3.4 m. The inner surface of the launcher tube is carefully honed to a precision of ±0.01 mm.

The projectile consists of a metal flyer and a complex body, as shown in Fig. 4(b). The main body of the projectile made of polycarbonate is accurately machined so as to fit the launcher, in order to assure flat impact on the target. The projectile has a tail made of HDPE. In order to eliminate passage of blowby of the light gas ahead of the projectile, it has a thin wing on the trailing edge. Pressure acting normal to the wing forces it against the inside surface of the barrel, thereby effectively sealing the projectile against blowby.

The projectile varies in weight from 10 g to 20 g, depending on its length and the material and dimension of the flyer plate. Various flyer materials such as aluminum (2024 Al), copper, tantalum and tungsten are used in accordance with requirements for shock impedance. The flat flyer plate, polished on both parallel faces, is tightly glued on the front surface of the projectile body. Care is taken to assure that all surfaces are held parallel to each other.

A small magnetized magnet is embedded inside the projectile body for generating induction signals when the projectile passes through a pair of coils placed for velocity measurements.

5) Sample Chamber

The sample chamber into which the muzzle of the launcher extends is 700 mm long and 610 mm in outer diameter, being about 190 ℓ in volume. The photograph of the sample chamber is shown in Fig. 2(c). The sample chamber consists of a muzzle wall and a movable tank mounted on slide bearings which allow a smooth, longitudinal displacement up to 600 mm along two rails. There are two flanges on the muzzle wall for mounting BNC connectors for electrical measurements and an opening for evacuating the sample chamber.

The cylindrical tank section has two optical windows for the observation by a streak camera and a light source. The window is made of 10 mm thick, expendable PMMA (Polymethylmetaacrylate) plate. Access to the target area is made by a 273 mm diameter flap window in the opposite side of the optical windows.

The target assembly is mounted on an steel plate which is supported by a cylindrical alignment system as shown in Fig. 6. The system is accurately manufactured so as to hold the target plate perpendicular to the axis of the launcher in order to assure flat impact of the flyer on to the target. It is directly fixed to the launcher itself by close fitting.

A pair of two coils for projectile velocity measurements are also embedded in this system; one in the target holder plate and the other

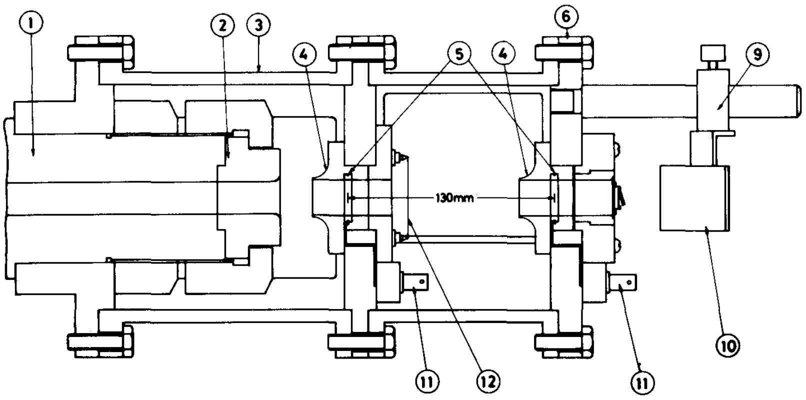

Fig. 6. Target assembly supported by the cylindrical alignment system.
1: Launcher tube, 2: Muzzle extension, 3: Target alignment system, 4: Gas stripper, 5: Pickup coil for velocity measurement, 6: Target holder plate, 7: Target holder, 8: Target and specimen assembly, 9: Mirror holder, 10: Mirror, 11: BNC terminal of pickup coil, 12: Breakage wire.

in the plate inserted between subdivided cylinders. The distance between two coils is selected to be 130 mm. The coil parts are backed up with gas strippers for the purpose of diminishing ablation due to high velocity gas.

The sample chamber is also designed to allow x-ray flash-radiography of the flying projectile; Two flanges for 2 mm thick aluminum window are attached along a direction which makes 45° with respect to the vertical direction. The upper flange is used for holding the flash x-ray source through a 860 mm long tube. The lower flange is used for mounting a x-ray film cassette.

The catcher section is 320 mm long and 100 mm in inner diameter. The projectile-stopping mechanism consists of a heavy casing with holes in the side wall, stuffed with rags and a 10 mm thick steel plate. The rear of the casing is supported by a screw cap via a strong spring and a thick rubber plate.

A steel, cylindrical protector, 270 mm in outer diameter, and 210 mm in length, which has two holes in the side for optical path, is placed around the target area for the purpose of diminishing the destruction due to debris. This is particularly effective in the case of recovery experiments.

The entire sample chamber including catcher and both barrels are evacuated to pressures of 1 mmHg or less using a rotary pump whose pumping speed is 500 ℓ/min. The evacuation is important not only to eliminate the possibility of an air shock preceding the projectile, but also to secure safe and quiet operation.

IV. Instrumentation

Details of instrumentation, in particular related to optical measurement system, will be described in the succeeding paper.16) Here the description is limited to those which are necessary for elucidating the gun performance.

1) Velocity measurement

The magnetoflyer method is adopted in measuring the projectile velocity. The method is based on detecting electromagnetically induced signals when the projectile containing a small magnetized magnet passes through a pair of pickup coils which are placed close to the inner rim of the coil holder. Since the two coils are accurately positioned with a certain distance, 130 mm in our case, measurement of the time interval between two signals picked up by them which is recorded by means of a transient recorder (Biomation, type 8100, 100 MHz time base, 8 bit) yields the average velocity of the projectile between them. The transient recorder is triggered by the signal generated by wire breaking. Accuracy of velocity measurements is less than 0.2 %. An example of the recorded signal is reproduced in Fig. 7.

2) Monitoring projectile in flight

The projectile is also monitored in flight by taking a shadow graph by means of a flash x-ray system. A portable type flash x-ray generating system (Hewlett Packard, model 43501 B) is modified so as to meet the requirement for taking high-speed phenomena. The system is modified so as to be externally triggered by the pulse signal produced by wire breaking. Details will be described in the succeeding paper.16)

The x-ray source is energized to 150 kV. The focal size of the

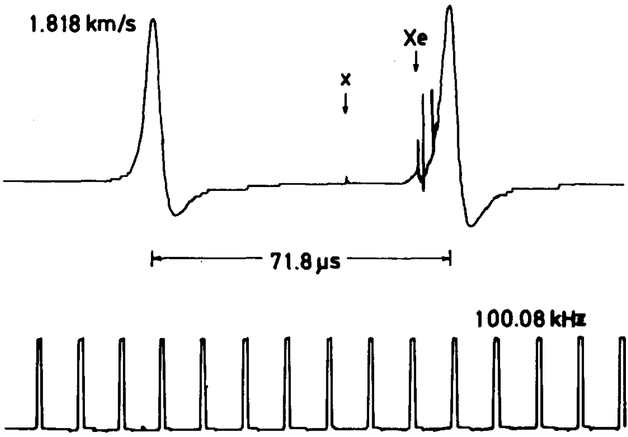

Fig. 7.

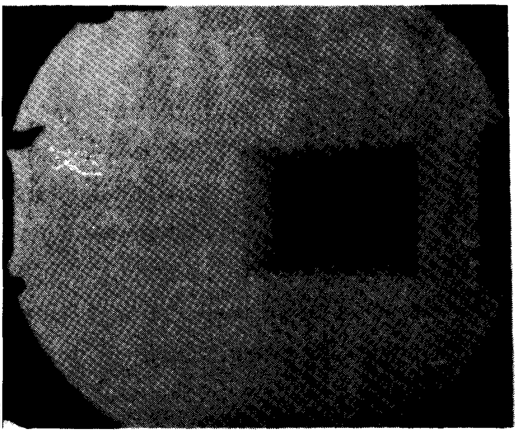

Fig. 8.

Fig. 7. Picked-up signals produced by the flying magnet and recorded by transient recorder. x: Triggering noise due to flash x-ray system, Xe: Discharge noise due to Xe flash lamp.

Fig. 8. x-ray flash-radiograph of the projectile in flight.

x-ray source is 2.5 mm in diameter and the half-width of pulse x-ray is 30 ns. The x-ray source is mounted on the tube holder about 1.2 m apart from the center of the gun axis while the cassette holder for polaroid film is placed beneath the flange attached to the sample chamber. This geometry gives only 0.12 mm of blurring in the shadowgraph of the projectile even with 4 km/s velocity. On the ports for the x-ray path in the sample chamber 2 mm thick aluminum plates are placed for the purpose of vacuum sealing. An example of x-ray shadowgraph of the projectile is shown in Fig. 8.

The projectile tilt observed here is generally within an acceptable range of 0.5° for the projectile velocity up to 3 km/s. This is further confirmed by measuring the flatness of shock arrival on the target surface by means of streak photography as will be described in the next paper.

V. Operation and Safety

Operation of the gun is strictly followed after the check list for the purpose of security. Operation room is separated by a thick concrete wall or steel-plated wall in a corner of the main gun room, 12 m × 6 m wide. Firing of the two-stage light gas gun and operations of all the instruments are carried out remotely in the operation room. Interlock system using proximity-type magnetic switch is installed at the doors; Unless two doors between the operation room and the main room are closed, the line to the firing system cannot be connected. Before firing, warning is made by flashing red light and buzzer which simultaneously begins to sound with turning on of the key switch of the firing system.

VI. Performance

There have been many attempts for determining optimum operation condition of the two-stage light gas gun by computer simulation of the gun cycle. The analysis based on the constant driving pressure is most widely accepted.17)

Since many factors such as mass of projectile, of piston, and of burning propellant, burst pressures of two diaphragms which determine the initial motion of the projectile and piston, species and pressure of light gas, the lengths of the launcher and pump tube, etc. are involved in the gun cycle, the analysis often becomes very complex. Therefore, the optimum condition for operation was determined empirically. It is well known that the mass ratio of projectile to propellant, among other things, is most essential in determining the muzzle velocity of the projectile, when the geometry of the gun is given.[18)] Other parameters such as piston mass and burst pressures of diaphragms have only secondary effect on the performance of the gun. Generally the mass of projectile and piston are kept to be constant and helium gas pressure in the pump tube and rupture pressures of the diaphragms are selected to be increased with increasing propellant mass. Under these circumstances, the velocity characteristics of the projectile as a function of the propellant mass is summarized in Fig. 9, projectile mass being taken as parameter.

With the standard projectile of 14 g in weight where 2 mm copper or 1 mm tungsten flyer is used, the maximum velocity attained is 3.9 km/s with 140 g propellant. If the weight of the projectile is decreased to 10 g, the maximum velocity is increased to 4.1 km/s with 120 g propellant. Although the gun has not been tested under limiting condition, possible maximum velocity for this model will be 4.5 km/s.

The reproducibility of the gun performance is very good for the velocity region between 2 - 4 km/s. This is essential for a research-

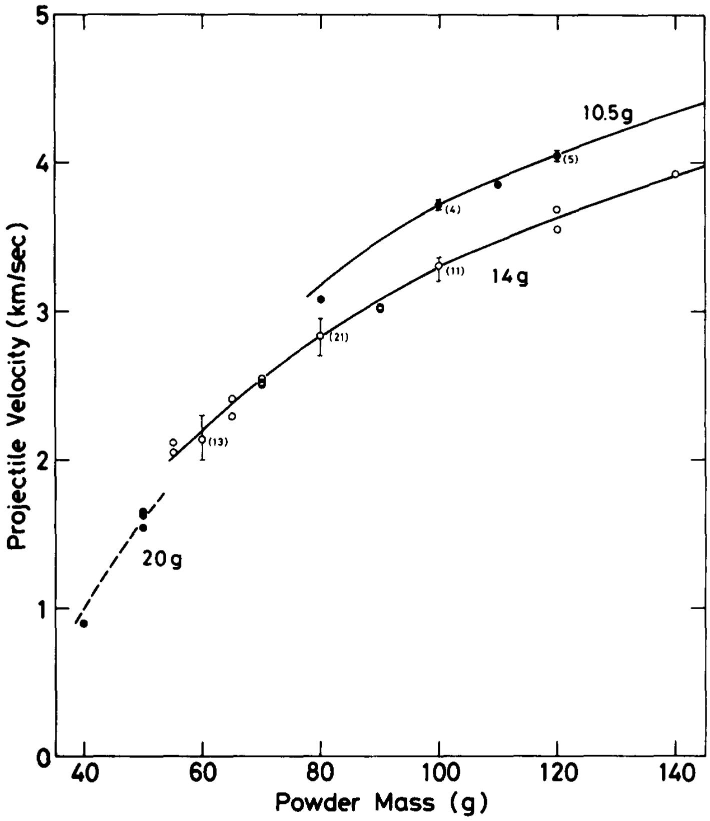

Fig. 9. Performance characteristics of the two stage light gas gun (2SG-TH1). Projectile mass is taken as a parameter. The mean value together with the velocity range is indicated, when the number of experimental runs (shown in brackets) is greater than 3.

type gun, since uncertainty of the muzzle velocity makes timing margin for triggering very narrow. Below about 1.5 km/s, considerable scatter in the achieved projectile velocity is encountered, probably due to unstable operation condition.

The post-shot cleaning is also very important to assure the reproducibility of the projectile velocity. The pump tube and coupling section is rather easily cleaned up with rags. Extensive cleaning is necessary for the launcher, particulary, for the part near the coupling section. Scraping by rotary blush made of brass wire, driven with a drilling motor is useful. Then the whole launcher is cleaned up by stuffing, squeezing and pushing a lump of toilet paper by a 4 m long brass rod. The procedure has to be repeated for several times. Considerable ablation of the launcher immediately forward of the coupling section has been observed particularly for the shots with higher projectile velocities. The part is designed to be replaced easily as shown in Fig. 5, since continued use of a severely ablated launcher tube may lead to erratic muzzle velocities.

Summary

For one year's testing period, about 100 shots have been conducted for various types of experimental conditions. As was described in the present paper, our two-stage light gas gun has been proved to be of quite high performance from the consideration of the availability of the high velocity range up to 4 km/s, reproducibility of the projectile velocity and flatness of the impact of the flyer plate on to the target. By taking account of relatively economical, easy and quiet operation, the present model could be regarded as one of the ideal model of the two-stage light gas gun for the velocity range of 2-4 km/s designed for research purpose.

Various types of shock wave experiments are now being carried out, including Hugoniot measurements with the inclined mirror technique and time-resolved spectroscopy under shock compression by means of streak photography, and microscopic investigation of the shock residual effects of the recovered materials. These results will be shortly released elsewhere.

Acknowledgements

The authors would like to express their hearty gratitude to Professor Akira Sawaoka and his colleagues at Tokyo Institute of Technology, who kindly permitted us to pattern our gun after their apparatus and gave many helpful comments in designing our gun. They are also deeply indebted to Professor Thomas J. Ahrens and Mr. Harold A. Richeson of California Institute of Technology, from whom a great deal of things have been learned. They are pleased to acknowledge Mr. Hitoshi Ozaki, Nippon Research and Development Co. (Now at Toho Seisakusho Co.) who kindly offered us invaluable suggestions in designing the apparatus. They are grateful to Professor Syun-iti Akimoto, University of Tokyo, and Professor Ichiro Sunagawa for their interest in this work. They also wish to thank Professor Yasuaki Nakagawa for continued support and Mr. Hiroshi Moriya for preparation of the manuscript. Many expendable parts necessary for gun operation are mainly manufactured in Machine Shop of RIISOM. The work is supported by the Grant in Aid for Special Project Research (Grant No. 321503 and 420902) given by the Ministry of Education, Science and Culture.

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