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ANALYTICAL AND EXPERIMENTAL STUDY OF THE "GAS BUFFER" CONCEPT

Prepared for:

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SRI Project 6726

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Section 1

INTRODUCTION

The project described in this report grew out of earlier work, performed for NASA's Ames Research Center, on the implosive gun concept. It was thought that the earlier work demonstrated the operation of all the essential features of such guns, but the research had not quite reached the point where an operative combination had been put together. The present project was therefore undertaken with the limited goal of demonstrating that the pieces of the design could indeed be put together as expected. Once this had been done successfully, additional work could be proposed to optimize the design and extend its performance.

Section 2

SUMMARY

Four complete shots were fired without successfully launching an intact projectile. One of the four shots was timed incorrectly and could not have been successful; however, the cause of the failure of the other three is not at all clear. Several possible causes are discussed in this report, but it was not possible within the time constraints of this project to determine which of these was important.

Section 3

BACKGROUND

The results of the two years of work supported by NASA Ames under Contract NAS2-1361 were presented in the final report* on that project. A few of the pertinent points covered there are also included here as background for the present project.

The basic concept of an implosive accelerator is shown in Fig. 1. A tube containing a gas is collapsed by a surrounding cylinder of explosive. The collapse starts at one end and moves along the tube, thus forcing the gas ahead of it as a piston would. Since the velocity of this collapse point or piston is typically higher than the sound speed in the gas, a shock front is formed which moves out ahead of the piston. The growing slug of compressed and accelerated gas between the piston and the shock front can then be used either as a driver for a shock tube or to accelerate projectiles in a gun.

This system was studied in some detail during the NASA Ames work, with the following results:

1. When glass was used as the tube material and helium as the gas, the shock front moved as expected for at least half a meter.
2. Such moving slugs of gas could be used to accelerate Lexan projectiles through a heavy-walled steel tube.
3. The calculated peak pressures on the Lexan projectiles were over 6 kbar and the measured acceleration curve agreed quite well with the calculated one.
4. Short steel tubes could be collapsed into a solid rod without any sign of jetting either on targets or in X-ray pictures of the process.

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* Crosby, John K. and Stephen P. Gill, "Feasibility Study of an Explosive Gun," NASA CR-709, April 1967.

On the basis of this information it appeared possible to design a gun that could use a thin-walled rather than a thick-walled tube for projectile launch, so that it could later be collapsed by explosive. Thus the piston would not need to stop at the beginning of the launch tube but could continue down the tube, chasing the projectile indefinitely.

The last shot fired under the NASA Ames contract was a trial of this continuous piston concept. Although the projectile did remain intact (judging by the crater it formed), it emerged from the barrel quite a bit later than the calculations predicted and was moving at a low velocity. The most likely reason for this behavior seemed to be gas leakage around the projectile due to expansion of the tube during the high-pressure phases of acceleration.

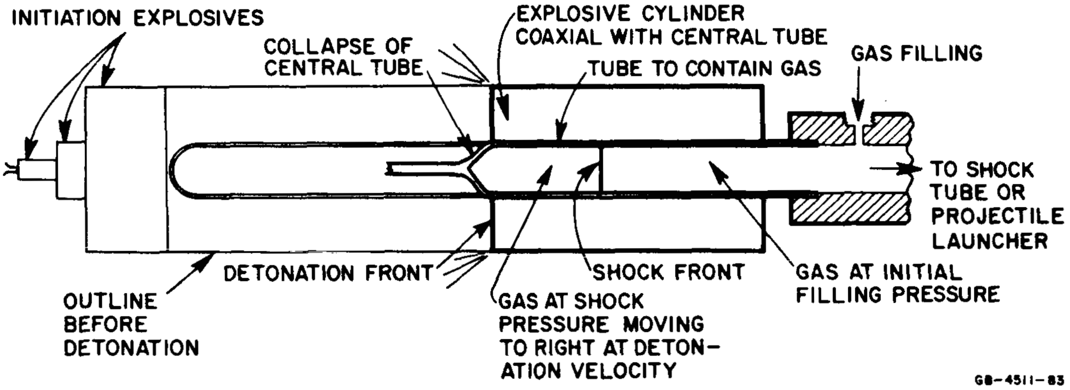

FIG. 1 SCHEMATIC OF EXPLOSIVE ACCELERATOR

Section 4

WORK PERFORMED UNDER CURRENT CONTRACT

The fair success of the final shot under the Ames contract and the basic knowledge gained earlier concerning the behavior of imploding systems suggested that with only minor modifications the continuous piston design could produce results closely conforming to those predicted by calculations. In such calculations it is seen that the gas between the piston and the projectile does not act as the energy source for the projectile as it does in a more conventional light gas gun. Instead, it is merely a buffer between the two, helping to even out acceleration peaks which would otherwise be too much for the projectile to withstand. In order for the gas to act in this way it must remain in the buffer and not leak away past the projectile or the collapse point or through any breaks in the tube wall. If this could be assured, it might be possible to continue using this buffer during acceleration to higher and higher velocities without being limited by the properties of the gas itself.

The contract covering the work reported here called for a minimum of four complete shots to attempt to demonstrate that a gas buffer can indeed be made to operate as outlined above.

PRELIMINARY WORK

Computer Simulation of First Shot

Calculations were performed to determine the theoretical behavior of the explosive gun under idealized conditions. The helium driver gas was assumed to be an ideal gas, losses due to viscosity and heat conduction were ignored, and the explosive tube collapse was treated as an ideal piston driving a shock into the driver gas. Projectile acceleration, multiple shock reflections, and the complicated high-energy gasdynamics in the driver were taken into account by a highly accurate computer code developed at SRI. The accuracy of the calculations was checked by rerunning the code with twice the number of computational zones. The results of the computer calculation for the chosen gun configuration are shown in Fig. 2. Computational inaccuracies due to the finite difference approximation are appreciable only in the vicinity of the shock reflections, where there is overshoot of perhaps 10% in the pressure, followed by a highly damped ringing.

The initial pressure of the driver gas, the detonation velocity of the explosive, and the length of the driver were chosen to provide approximately equal projectile base pressures at the first and second shock reflection. A third reflection is shown, but its magnitude is greatly diminished because of the high projectile velocity and the expansion of the driver gas. The magnitude of the third reflection can be increased to maintain an approximately constant base pressure only by increasing the piston velocity.

Launch Tube Collapse Experiments

To prevent loss of driver gas due to expansion and cracking of the launch tube at high internal gas pressures (approximately 8 kbar peak pressure), the tube was originally designed to withstand the expected pressures statically. The design called for high-strength, 4130 alloy steel, drawn tubing, 4.75 mm i.d. by 12.7 mm o.d.

An experimental investigation was initiated to determine the behavior of this high-strength tubing under conditions of explosive loading. A 60 cm section was tested with sufficient explosive to provide a ratio of explosive charge mass to tube mass equal to 1.3. The tube collapse was observed using a 300 kV Field Emission Corporation flash X-ray source, and the collapsed tube was recovered for terminal observation.

The tube did not collapse fully, a result which was subsequently shown to be caused by the fact that the energy given to the tube walls during the impulsive acceleration by the explosive was not sufficient to overcome the long-duration resistance to motion due to plastic yielding of the high strength tube material. The importance of this resistance phenomenon, which had not previously been recognized since relatively low-strength tubing had been used in earlier experiments, led to a theoretical reappraisal of the tube collapse and tube expansion problems for a more refined prediction of explosive gun operation.

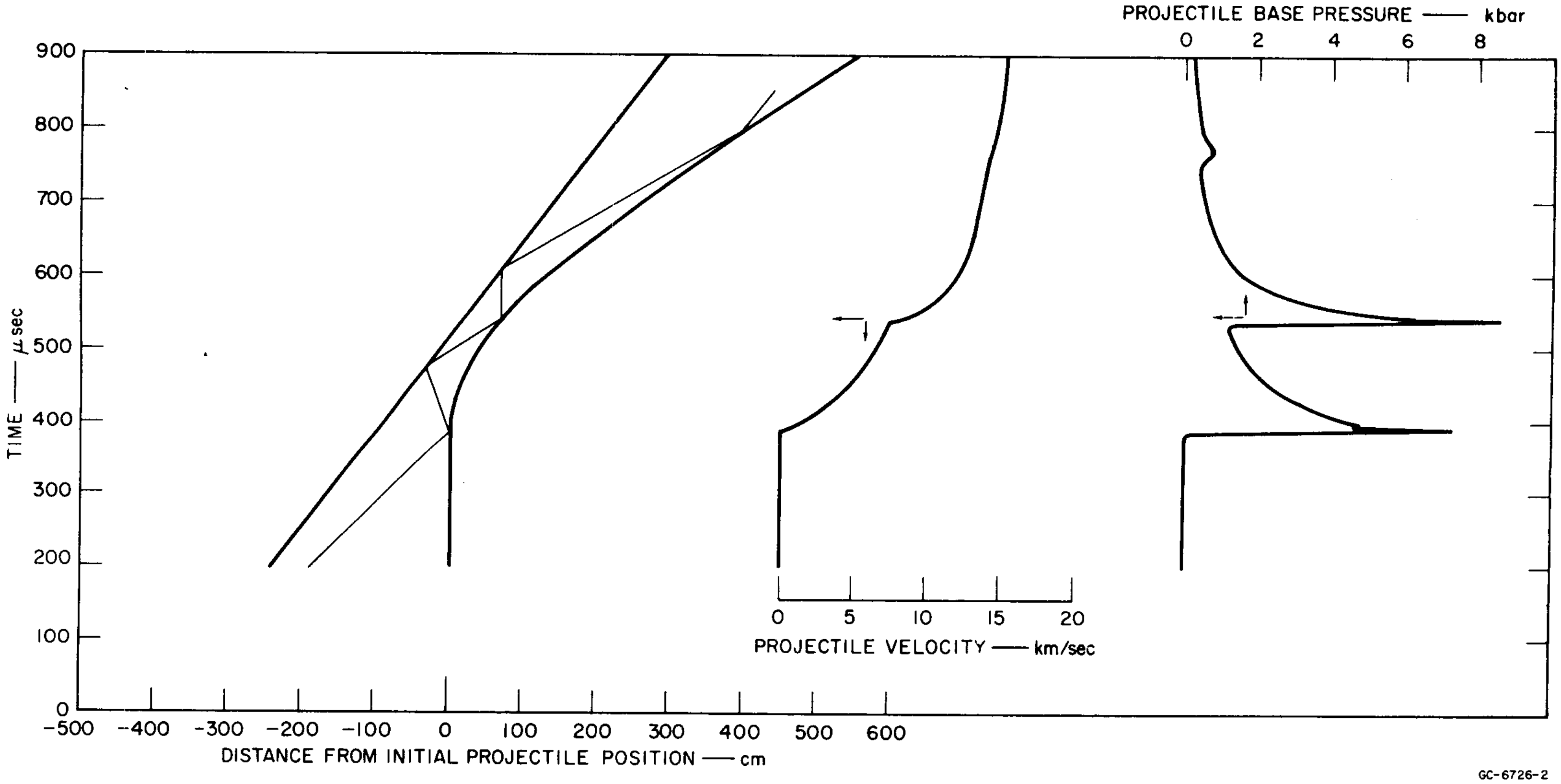

FIG. 2 COMPUTER SIMULATION OF FIRST SHOT

Theory of Tube Collapse and Tube Expansion

It was found that exact analytical predictions of the motion of a metal tube under uniform internal or external loading could be made by disregarding reverberation effects within the tube wall. The wall material was assumed to follow the von Mises yield criterion; i.e., the shear stress in fully developed plastic flow is constant and related to the von Mises tensor stress invariant. The equations of motion were found to be analytically integrable for a condition of constant internal or external stress. Numerical integration is required for more complex situations.

The theory shows that the mechanisms of tube expansion and tube collapse are closely related and that the explosive gun tube must be carefully chosen to minimize undesirable tube expansion resulting from high internal pressures while at the same time allowing the tube to be fully closed by the impulsive loading of high explosives.

As a result of these theoretical calculations, the design of the explosive gun tube was modified to include a high-pressure breech section and to replace high-strength 4130 steel with more ductile 1015 steel. The breech section, which consists of local strengthening of the tube in the vicinity of the initial projectile position, is designed to prevent excessive tube expansion in the vicinity of the accelerating projectile. By considering the time scale of shock-pressure pulses at the base of the projectile, the additional strengthening was found to be necessary over 10 cm of the length of the tube centered at the initial projectile position.

The tubing was carefully chosen to provide for effective tube collapse and minimum tube expansion, but the design is based on limited data concerning the behavior of alloy steels under dynamic loading. The 1015 alloy (cold-rolled) was chosen as the best compromise in terms of strength, behavior under conditions of plastic yielding, and commercial availability. Some further research will be necessary, especially if the gun is to be used with more sophisticated explosive arrangements in which a tubing closer to optimum may be required.

FIRST TWO COMPLETE GUN SHOTS

Configuration

The configuration of the gun for the first two shots is shown in Fig. 3. It coincides with the parameters chosen for the first computer simulation. The 396 cm driver (containing 7.9 bars of helium) and the 300 cm evacuated launch tube were constructed from 1015 alloy steel drawn tubing, 6.27 mm i.d. by 11.1 mm o.d. The driver and launch tube were connected by a 10 cm strengthened breech section containing the necessary vacuum seals. The 0.155 g projectile was made of Lexan plastic, and was held in place by a shear tab. Launch tube length for the first two shots was 300 cm, so that only the first two shock reflections would be effective in accelerating the projectile. The calculated velocity of the projectile at 300 cm was 13.9 km/sec.

The launch tube was straightened to within 0.025 mm in 30 cm by means of a rigid H-beam construction. Final alignment was performed with an alignment telescope. The driver and the launch tube for the entire length of the gun were surrounded by a sleeve of Composition C-2 explosive.

Instrumentation

The launch tube was connected to an evacuated observation chamber terminated by a witness plate. The 122 cm observation chamber was constructed of Lucite and contained baffles for minimizing optical interference resulting from contaminated driver gas. The observation chamber was backlighted with an argon-bomb light source and viewed with a Beckman and Whitley Model 189 framing camera. A slab of 6061 TO aluminum 5 cm thick, backed by a spall plate, was provided for terminal observations.

Instrumentation was included in these first shots to measure the locations of both the projectile and the explosive collapse region as a function of time, using a proprietary technique developed at SRI. This technique had worked well in low-velocity guns (1 km/sec or less) and was expected to improve in performance at high velocities.

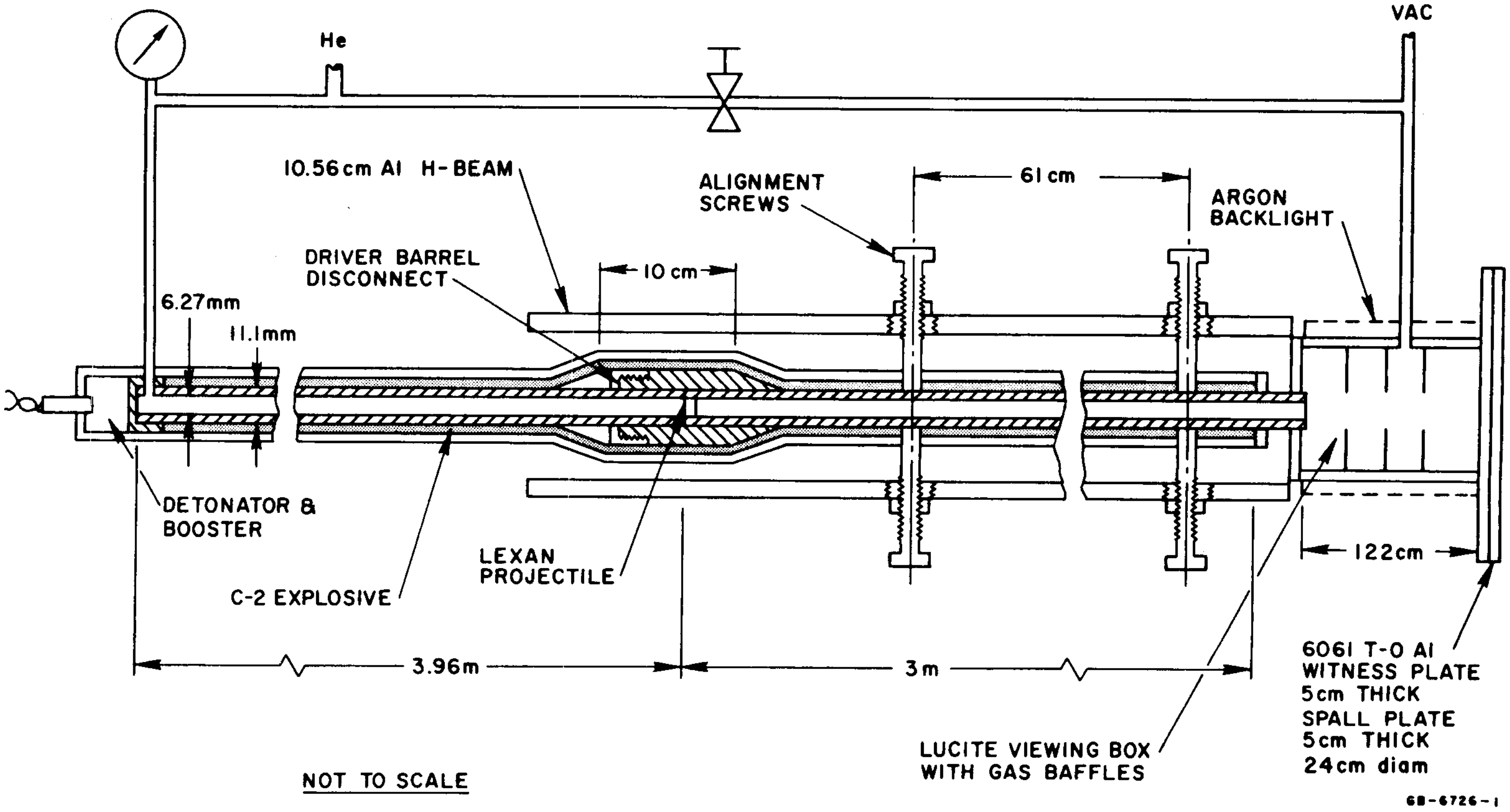

FIG. 3 MECHANICAL CONFIGURATION OF FIRST SHOT

Results

Because of an error made while computing the delay times required for the shot and the light sources, the light sources were fired several hundred microseconds sooner than they should have been on the first complete shot. The blast from this charge (about seven pounds of C-2 explosive) would be expected to disrupt the viewing chamber and to bend the end of the launch tube severely before the projectile arrived. It would also disrupt the sensors for the systems to measure the projectile and piston positions.

The second shot was timed properly but did not produce an intact projectile. The target plate was hit and showed one large crater in the center surrounded by many smaller pits. The framing camera record showed a cloud of dark gas emerging 58 μsec after the calculated emergence time. The velocity of this cloud was about 8 mm/μsec. The sensor for the projectile position did not show any movement until the time at which the detonation front arrived. All these data suggested that the projectile broke up almost immediately.

THIRD COMPLETE GUN SHOT

Analytical Work

The most likely source of difficulty in the design for the first two shots appeared to be the high peak pressure value of 8 kbar. To reduce this pressure it was necessary to lengthen the gun and to use a lower initial gas pressure. Figure 4 shows the results of a computer run in which the gas reservoir length was doubled and the initial pressure was halved from the values used for the first two shots. As expected, the peak pressures were also halved and the launch tube length for a given projectile velocity was doubled.

Although a shot based on the second computer run would subject the projectile to a pressure which it can almost certainly withstand, the final projectile velocity is still very high--higher than any yet achieved in light gas guns. To avoid the unknown dangers which may exist at high velocities, the launch tube was cut off at the point where the projectile base pressure had fallen to a low level just before arrival of the second shock.

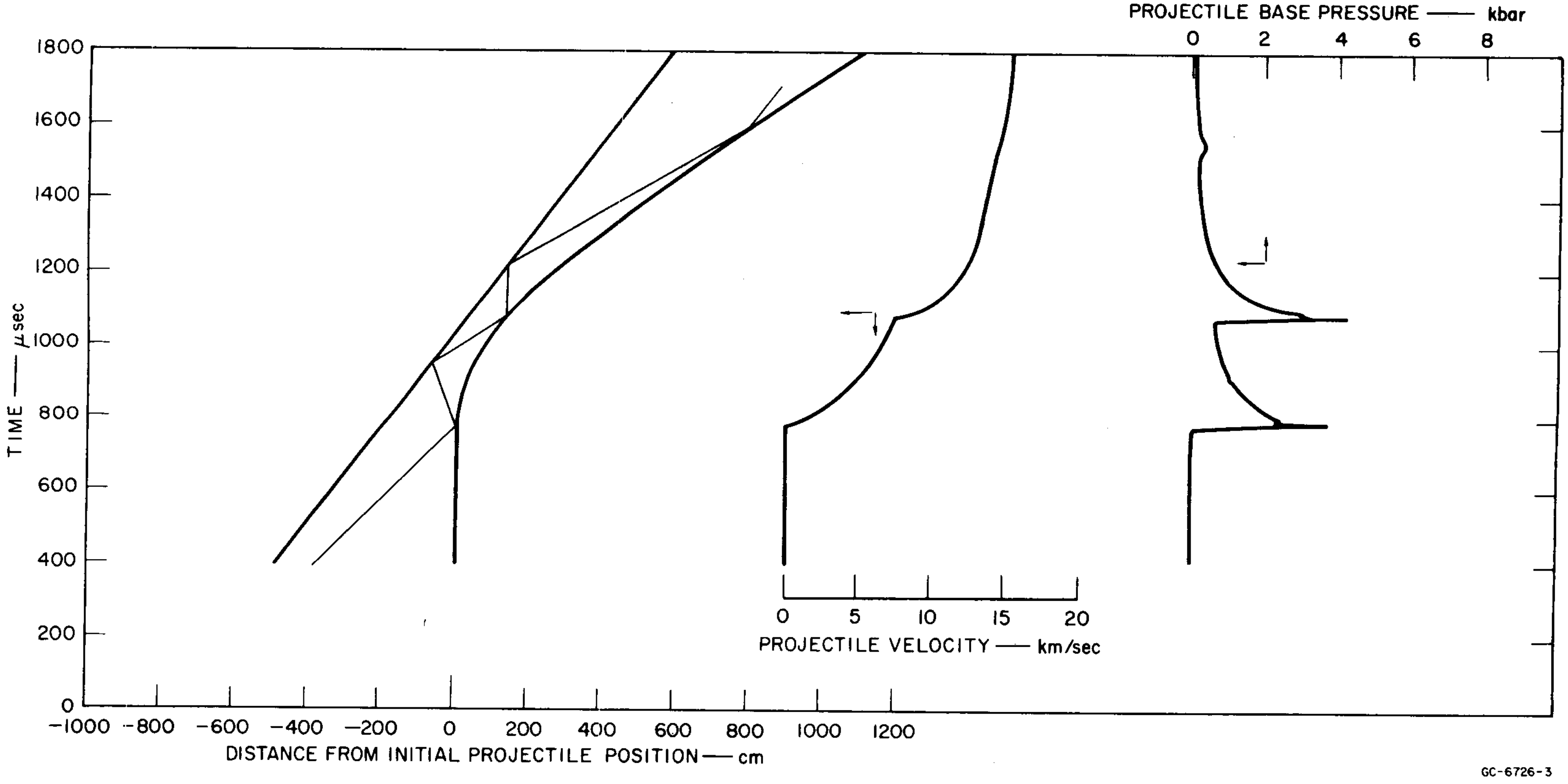

FIG. 4 COMPUTER SIMULATION OF THIRD SHOT

Configuration

In the third shot a 793 cm driver containing 3.95 bars of helium was used; the launch tube was 100 cm long. The length of the reinforced section was 15 cm. Except for these changes, the shot was identical to the first two. The calculated projectile velocity was 6.7 mm/μsec.

Instrumentation

The wire sensor used to measure projectile position was removed from this shot in case it was contributing to projectile breakup. In addition to the other instrumentation listed for the first two shots, a Beckman and Whitley single-frame, image-converter camera was used to obtain a single, short-duration picture of the observation chamber at a time when the projectile should be in view. An exposure time of 10 nsec was used for this camera so that image motion blur would be reduced to a minimum.

Results

No record of the projectile was made by either camera and no craters were formed on the target plate. The piston position indicator showed that the detonation proceeded normally over the entire length of the tube and there was no indication of mistiming of any of the instrumentation.

FOURTH COMPLETE SHOT

Analytical Work

This laboratory is engaged at present in the development of another implosively driven system for producing well-characterized blast waves. In the course of that work it has become clear that the details of the collapse of long metal tubes to make shock drivers may vary considerably from the simple models which had been successfully used before the start of this project. One of the most obvious symptoms of this complication is that the length of the slug of shocked gas does not grow at the expected rate and, indeed, may reach a steady-state length quite soon.

One factor which may play a significant part in this behavior is the growth of boundary layers and their interaction with the collapse process. If this is an important factor a short, high-pressure driver should be less susceptible to degradation in performance than a long, low-pressure one. If the third shot did fail for some reason such as this, it would easily explain the evidence, or lack of evidence. A slug of shocked gas which is too short will result in a very high second shock pressure which would break up the projectile and allow gas to pass by. It is then likely that the projectile fragments would be overtaken by the detonation front before they could leave the launch tube.

A thorough investigation of the shock buildup in metal tubes was obviously beyond the scope of this project. The little already known, however, suggested that the basic design used for the first two shots was less likely to give trouble than that used for the third. Accordingly, the fourth shot was based on the computer run shown in Fig. 2.

Four changes in the design used for the first two shots were planned, to reduce the risk of failure. First, a fiber-filled Lexan material* was used which should have almost doubled the tensile strength of the unreinforced material. Second, the complicated joint at the breech was eliminated and the projectile was simply pressed into a continuous piece of tubing and held by friction. Third, it was planned to hone out the launch tube to provide a smoother flight for the projectile. Honing a 2.5 meter tube only 6 mm in diameter is not routine, however, and even with the assistance of the personnel at Ames Laboratory we were not able to set up the system for doing this in time for the shot.

The final planned modification was to increase the explosive loading slightly to reduce the probability of gas leakage through the collapse point. All the earlier shots using this tubing had been loaded with a concentric explosive cylinder with an outside diameter of 15/16 inch, giving a calculated charge-to-metal ratio (C/M) of 1.061. This design had been tested in short lengths which were found to collapse satisfactorily without jetting. Two other designs were tested before the final shot of this project was assembled. The explosive outside diameters used were 1.0 inch and 1.125 inch, giving C/Ms of 1.256 and

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* Polycarbafil G 50/20/HD, made by Fiberfil, Inc., Evansville, Indiana

1.460. Two-foot lengths of tubing were collapsed by these explosive loadings and witness plates were provided to determine if jetting occurred. Both plates showed considerable cratering and it was concluded that even the slight increase of C/M from 1.061 to 1.256 was enough to cause jetting; the 15/16 diameter charge was therefore chosen for the final shot.

Configuration

The fourth shot had a 420 cm driver containing 7.9 bars of helium; the launch tube was 250 cm long. The projectile mass was 0.5 g/cm^2 as before and its thickness was 0.37 cm. This resulting in a thickness-to-diameter ratio of 0.59. The calculated velocity was 13.8 mm/μsec. The tubing was continuous through the breech and the only joint was 55 cm away, in the driver tube. The breech was reinforced over a 15 cm length.

Instrumentation

The instrumentation used for this shot was the same as that used on the third shot.

Results

The last two frames of the framing camera record show some dark gas emerging from the launch tube. This occurred 130 μsec after the calculated emergence time and only 35 μsec before the detonation front should arrive at the muzzle. The target plate was not pitted.

Section 5

CONCLUSIONS AND RECOMMENDATIONS

The most obvious conclusion to be drawn from this project is that a continuous piston gun cannot be assembled by simple extension of the techniques and knowledge gained during the earlier work for Ames. The major differences between the designs studied under this project and those studied earlier are that a metal tube was being collapsed and that it was much longer than those studied before. It is likely that the heart of the difficulty experienced during this project is connected with these two changes. If this is so it will be necessary to back up and look at some of the basic behavior of collapsing metal tubes before a rational gun design can be assembled with a good chance of success.

The following program is suggested as one which should yield the information required for a good continuous-piston gun design.

1. Measure the shock front motion in long metal tubes to determine if significant deviations from calculated behavior are taking place.
2. If required, investigate the details of the collapse process and make design modifications to eliminate or reduce gas leakage through the collapse region.
3. Accelerate a stable, heavy projectile to a low velocity with a shock of known characeteristics, and compare the velocity history with calculations.
4. Repeat Step 3 but lengthen the launch tube so that two shocks accelerate the projectile. If possible, this should still be done at a low velocity provided satisfactory low detonation rate explosives are available.
5. Work up gradually to higher pressures and higher velocities.
6. For all shots the launch tube should be honed and all parts of the tube should be monitored to make sure that nothing comes apart at the wrong time.

The major unknown in such a program is the difficulty that may be encountered in Step 2. It now seems likely that a slight increase in the explosive loading should be sufficient to eliminate leakage at the collapse point after boundary layers begin to form. This may not be true, however, and other, more complex, schemes may be required. The potential performance of such a gun, once developed, is so much higher than any now available that we feel that the effort is well justified.