APPLICATION OF
HOLOGRAPHIC INTERFEROMETRY TO THE
EXTERIOR BALLISTIC FLOW FIELD IN THE
MUZZLE ENVIRONMENT OF A
TWENTY MILLIMETER CANNON

Robert Gene Bettinger
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**Application of Holographic Interferometry to the Exterior Ballistic Flow Field in the Muzzle Environment of a Twenty Millimeter Cannon**

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Naval Postgraduate School  
Monterey, California

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Holographic Interferometry  
Exterior Ballistic Flow

The technique of holographic interferometry was applied to the study of the gas core characteristics in the muzzle environment of a 20 mm cannon. Experimental measurements were made of the muzzle velocity and of gas core pressures at the cannon breech to verify prediction of these parameters in a numerical technique using standard hydrodynamic equations. Holographic interferograms were made of the projectile and its associated flow field during launch.
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Exterior Ballistic Flow Field in the Muzzle Environment
of a
Twenty Millimeter Cannon

by

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Lieutenant, United States Navy
B.S., Case Institute of Technology, 1964

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ABSTRACT

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## LIST OF SYMBOLS

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<tr>
<td>A</td>
<td>cross-section area</td>
</tr>
<tr>
<td>$C_o$</td>
<td>constant specifying thickness of shock region</td>
</tr>
<tr>
<td>d</td>
<td>projectile nose diameter</td>
</tr>
<tr>
<td>E</td>
<td>specific internal energy</td>
</tr>
<tr>
<td>j</td>
<td>mass point number</td>
</tr>
<tr>
<td>M</td>
<td>mass</td>
</tr>
<tr>
<td>n</td>
<td>cycle number</td>
</tr>
<tr>
<td>p</td>
<td>pressure</td>
</tr>
<tr>
<td>q</td>
<td>artificial viscosity</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>u</td>
<td>velocity</td>
</tr>
<tr>
<td>V</td>
<td>specific volume</td>
</tr>
<tr>
<td>x</td>
<td>Eulerian position</td>
</tr>
<tr>
<td>$\Delta S$</td>
<td>shock standoff distance</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
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ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. D. J. Collins for his invaluable guidance and considerable personal involvement during the course of this study, to Dr. D. W. Netzer for his constructive suggestions and counsel, and to the technical staff of the Department of Aeronautics, particularly P. Hickey and N. Leckenby, for their assistance in the construction and operation of the equipment of this investigation.

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I. INTRODUCTION

A thorough knowledge of the physical characteristics of the internal gas flow field is essential in ballistic design. The flow field that is created and exists ahead of the projectile external to the barrel of any ballistic device also plays an important role in the performance of the projectile. The projectile must traverse this unsteady flow field prior to entering a freestream environment and may therefore have its trajectory altered by this field. Projectile design then may be highly dependent on an understanding of the properties of this flow field existing at the muzzle face. Design of muzzle devices intended to control this environment must also stem directly from knowledge of these characteristics.

A number of experimental and theoretical studies of this external field have been conducted and have shown it to be a complicated structure of mixed supersonic and subsonic flow with a network of shock and expansion areas.

Oertel [Ref. 1] has examined the development of the field using a muzzle flow simulator and a multiple pulse laser to produce a sequence of laser interferograms. The luminosity of this field has been studied by Schröder and Klingenberg [Ref. 2] using small caliber guns of low muzzle velocities with spectroscopic techniques. Theoretical studies have included the development of a numerical scheme which simulates
the blast field and introduces the projectile into the field to determine the effects of the field on the projectile [Ref. 3].

Holographic interferometry has been successfully applied in the study of a wide range of aerodynamic flow problems because of its capability of allowing the investigator to store transient wavefront information for later recall. This aspect of the technique is particularly appealing to the inherently short duration ballistic flow fields. Recent advances in the area of fringe data reduction have greatly reduced the time and energy involved in obtaining density distributions from the interferometric data.

This investigation was conducted in three separate segments:

1. Application of the holographic interferometry technique to the study of the gas core characteristics in the muzzle environment of a 20-millimeter cannon.

2. Experimental measurement of the gas core temperatures and pressures at the breech of the cannon using high frequency pressure transducers and thermocouples, and muzzle velocity measurements taken with a precision chronograph triggered by projectile passage through optical velocity screens.

3. Analytical prediction of muzzle velocities and pressure histories using standard inviscid theory.
II. HOLOGRAPHIC INTERFEROMETRY

The utility of holography as an interferometric tool was recognized in the mid-1960's, shortly after the introduction of the laser as a coherent light source for wavefront reconstruction. Interferometry is the technique of combining two beams of coherent light, that is, beams with a well-defined and non-varying phase relationship. The resulting light and dark interference bands or fringe pattern may be used to measure displacements, density variations and wave characteristics. The use of holography greatly enhances the interferometric technique. The unique property of holography is that it permits photographic storage of a transitory wavefront, which is then available for later reconstruction at the convenience of the investigator. This property then permits interferometric comparison of beams of short duration or beams not simultaneously available.

Two techniques of holographic interferometry are of particular importance. The first of these is called "real time" interferometry. Figure 1 provides an illustration of this technique. In this process, a hologram is first produced of the subject in its unperturbed state. After processing, the photographic plate containing the hologram is replaced in its exact exposure location relative to the original subject and all optical equipment. The subject is then placed in its perturbed state. The hologram and subject are then re-illuminated with the
original subject and reference wavefronts. The original undisturbed subject wavefront is reconstructed and interferes with the perturbed subject wavefront, producing a fringe pattern. Changes in the fringe pattern resulting from varying perturbations may then be continuously monitored.

The second method with numerous applications is the double exposure technique. The hologram is exposed twice prior to processing, with the subject in both the perturbed and unperturbed states. Upon reconstruction, both waves are simultaneously reproduced and interfere, creating the desired fringe pattern. This technique has several advantages over the "real time" technique. More flexibility of observation is attainable and distortion due to emulsion shrinkage is eliminated. Additionally, optical components of lower quality may be used, since the double exposure cancels optical component defects. Unfortunately, the technique permits analysis of only a single distorted state per hologram.

If the optical path between exposures is unchanged, and no disturbance is introduced into the field, the resultant fringe pattern is referred to as the "field of infinite fringe" and consists of a single fringe of infinite width. With the disturbance introduced on the second exposure, small phase shifts in the subject field produced by changes in the optical path length result in a limited number of fringes. If a slight displacement or translation of the scene beam is initiated between exposures, a
framework of sharply defined parallel fringes of selectable spacing is introduced into the hologram. This "finite fringe field" represents lines of constant differences in optical path length. The spacing and clarity of the finite fringe pattern is dependent on the amount of translation or rotation of the scene beam. A quantitative relationship between fringe spacing and rotation or displacement is provided by Floyd & Collins [Ref. 6]. If the subject is then perturbed for the second exposure, density gradients are indicated by fringe shifts often more easily analyzed than the infinite fringe field, particularly for small gradients. Measurement of fringe shifts then allows determination of the density field.

The two most commonly employed schemes for illuminating the object are diffuse lighting and non-diffuse or direct lighting, each of which are illustrated in Figure 2.

Direct illumination is particularly useful for flow visualization of two-dimensional and axi-symmetric flow fields and is generally simpler to set up and use, requiring less intensity for subject illumination. When a diffusing glass is placed in front of the subject, significant changes occur. If the subject is a phase object, each point in the field receives illumination from an infinite number of directions. Thus, each point on the hologram plate receives scattered light from every point in the subject. The entire subject may then be viewed by illuminating any part of the hologram. Different views of the subject are
obtainable by re-illuminating different portions of the hologram plate with the reference beam. Three-dimensional diffusely reflecting objects scatter light in a similar manner as the diffusing glass and thus the glass may be omitted when producing holograms of these subjects. Three-dimensional images of opaque objects may be reconstructed and photographed from different viewing angles using a single hologram.

Diffusely illuminated subjects produce holograms with light field backgrounds which are easier to view than the dark background of direct illumination. A problem arising with diffuse lighting is that the loss of spatial coherence between the interfering waves often causes localization of the fringe system in a plane other than that of the subject. If this separation is too large, it may become necessary to use a lens system with a large depth of field to image both the subject and fringes. Such a system may place limits on the resolution obtainable.

A primary consideration in the technique of holographic interferometry of flow fields is the source of coherent light. In order to maintain the stability of the flow field necessary for high resolution holograms, it becomes necessary to shorten exposure times to the point where changes in the optical path length are restricted to less than the wavelength of light.

The Q-switched pulsed ruby laser has proved to be an excellent light source for these applications. It provides the high power
necessary to expose the plate in a time frame suitable for freezing the motion of the flow field. The wavelength of this laser is compatible with certain commercially available holographic film plates. An additional advantage of this system is that it provides a coherence length of approximately 1 meter, thus eliminating the need to precisely match the path lengths of the reference and scene beams. The short pulse length of this laser makes it mandatory to provide a secondary continuous wave laser beam coincident with the ruby beam for alignment of the optical components. A description of the common technique for placing these beams in coincidence is available in Ref. 7.
III. EXPERIMENTAL LAYOUT

A. GENERAL PHYSICAL ARRANGEMENT

The 20-mm cannon was mounted muzzle end facing outward on a steel rocket test stand within a test cell at the Naval Postgraduate School Rocket Laboratory. These test cells measured 12' x 17' with reinforced concrete walls 12 inches thick. The barrel was secured horizontally to the test stand via two steel mounts at a height of $6\frac{3}{4}$ inches from the stand to the barrel centerline. Two large wooden tables were constructed the length of the test stand and placed parallel to it, one on each side for housing the optical system. These tables were rigidly fastened together and isolated from the test stand to maintain stability and minimize vibrational effects from the cannon blast. Plywood covers were constructed for the tables to protect the optical components and provide the necessary light shield for the holography. The tops to these plywood covers were hinged to allow easy access to the optical components. The general layout of the cell can be seen in Figure 3.

The electrical firing mechanism for the cannon was placed on the test stand at the breech end. All controls for firing the cannon were located remotely in a control room directly behind the back wall of the test cell. The projectile was fired into a bullet trap located 13 feet outside the cell. The trap was designed for the bullet to first impact
on an 18" x 18" x 1\frac{1}{2}" armor plate tilted 45° from the path of the projectile. This first contact shattered the shell and deflected the fragments into a steel-encased sand trap measuring 5' x 5' x 2\frac{1}{2}'. The sand trap itself was again shrouded with sand bags for additional safety. The entire trap was housed in a steel turret for a 5" gun mount measuring approximately 15' x 20' x 10'. Figure 4 shows the front of the turret and projectile path.

The ruby laser and all of its components were placed in the test cell adjacent to the cannon. This was done partly for space considerations and also for protection of the ruby laser components. The rail containing the laser cavity was mounted on a specially constructed table and faced normal to the wall separating the cells. A 2-inch hole was drilled through the concrete wall to allow beam passage. The cell was provided with a water source for the laser head and output etalon cooling system. The laser was equipped with a remote control unit so that it could be fired either from the test cell or the remote control room.

B. OPTICAL SYSTEM

The holographic optical schematic is shown in Figure 5. The laser system used for the actual holography was the Korad K-1 pulsed ruby laser. This system is capable of delivering high power, single transverse mode output in the Q-switched mode of operation. A Pockels cell was used to provide the Q-spoiling necessary for peak
power output. When operated in the TEM$_{00}$ mode, typical values for pulse energy and pulse width are 0.050 joules over 20 nanoseconds, yielding a peak power of 2.5 megawatts. The output beam is approximately 2 mm in diameter with a wavelength of 6943 Å and a coherence length in excess of one meter. The laser head was equipped with a high optical quality holographic ruby rod. Figure 6 provides a photographic view of the laser installation.

After first passing through the holes in the wall and plywood cover, the beam then passed a narrow-band filter which served to remove the undesired light from the Xenon flash tube. After next passing a series of neutral density filters used to control intensity, the beam then contacted a 2-inch round beam splitter which divided it into two wavefronts of approximately equal intensities. The subject beam was reflected down the centerline of a 2.5 meter optical bench through a series of expanding, collimating lenses to mirror #1. These lenses were designed to expand the subject beam to a size compatible with the field of interest and the 4" x 5" hologram plate. Mirror #1 was secured to a precision gimbal mount which allowed rotation about both the vertical and horizontal axes. This mount provided the precise beam rotation necessary to produce the finite finite field for interferometry. Mirror #1 directed the beam through the test section and a dual grid system in a direction normal to the axis of the cannon.

The beam was then reflected from mirror #2, which directed it along a 1.5 meter optical bench through a set of imaging lenses with
a focal length of 22 inches. The purpose of this set of lenses was to image the test section closer to the hologram plate providing a sharper image with greater fringe contrast. This set of lenses converged the beam to a point at which a second narrow-band filter was placed to remove the flash from the muzzle blast. The beam then passed to mirror #3 which directed it to the hologram plate.

After passing the beam splitter, the reference beam contacted mirror #4 on a 2.0 meter optical bench which allowed adjustment of the reference beam path length to that of the subject beam. From mirror #5 the beam was directed to the hologram plate through two series of expanding-collimating lenses which enlarged the beam to approximately a 4" diameter at the plate. All mirrors in the system were provided with screw type adjustments for vernier-scale movement about their horizontal and vertical axes, thereby greatly simplifying alignment procedures.

The optical benches were bolted to the tables on specially designed crossfeet which allowed the benches to be leveled with two knob adjustments provided on each crossfoot.

For alignment the system was equipped with a Coherent Radiation 3 milliwatt helium-neon continuous wave laser. This laser was mounted on a stand perpendicular to the axis of the ruby laser cavity. By placing a mirror at a 45° angle in the ruby laser cavity, this CW beam could be placed in coincidence with the ruby laser beam.
The overall performance of the optical system was measured through the use of the USAF 1951 resolution test target (Figure 26). The target was placed in the test section and a hologram taken. Examination of the reconstruction of this hologram (Figure 27) reveals a minimum resolution of 3.5 lines per mm which is more than adequate for the fringe shift measurements necessary in the conduct of the interferometry. Figure 7 is a photographic view of the optical arrangement.

C. BARREL INSTRUMENTATION

For measurement of the pressure-time history at the breech end, the barrel was equipped with Kistler 607A pressure transducer installed 5½ inches from the breech end of the barrel. This location was just ahead of the tip of the projectile prior to firing. The signal from the transducer was passed to a Kistler Model 504 Universal Charge Amplifier in the control room and then displayed on a Textronix storage oscilloscope.

Gas core temperature measurements were made at the breech with a special Nanmac tungsten-rhenium thermocouple mounted directly opposite the Kistler transducer. The output from this thermocouple was displayed on a Hewlett-Packard OS 209 (P) oscilloscope.

For muzzle velocity measurements, the projectile was fired through two Oehler Model 55 Ballistic Velocity Screens placed in the path between the muzzle and the sand trap. These screens can be seen in Figure 4. As the bullet passed through each screen, a 12-volt pulse
with an adjustable 2-8 millisecond pulse length was produced and sent to an Oehler Model 21 Chronograph. These pulses provide start and stop signals for the chronograph. This provides a time of passage between the two screens. The screens are placed a known distance apart and thus an average velocity between the two can be calculated. These velocities are tabled for various screen separations. It was found that the first screen had to be placed at least 4 feet from the muzzle to prevent the blast from pre-triggering the screen prior to projectile passage. Figure 8 is a photograph of the control room instrumentation including the fire control panel.
IV. FIRING SEQUENCE

After optical system alignment and warm-up of all electrical components, the test cell was closed and a hologram plate installed in its holder. The laser was fired from its direct control for the first plate exposure of the unperturbed field. This first exposure creates the hologram of the static test section which will later be used to interfere with the second hologram of the flow field. For the finite fringe holograms, mirror #1 was then rotated to produce the desired fringe field for the reconstruction process. Mirror #1 mount was equipped with two micrometer adjustments which provided 20 arc seconds of beam rotation for each unit of micrometer movement. Beam rotation of approximately 100 arc seconds between shots provided the fringe field desired. For infinite fringe holograms mirror #1 was not moved.

After producing the reference hologram the cannon was loaded. The individual who was loading the cannon and connecting the firing mechanism carried with him a safety key which breaks the firing circuit at the control panel to prevent accidental firing prior to his clearing the test area. The laser was then charged remotely from the control room and a horn was sounded to provide final warning of the impending shot. The firing sequence was then initiated. A schematic of this sequence is shown in Figure 9.
While the laser capacitor bank was charging, the safety key was installed in the fire control panel and power supplied to the firing mechanism. When the laser was ready, the firing mechanism capacitors were charged and the cannon then fired. The process could be observed through two glass viewing windows connecting the control room and the test cell.

To provide accurate timing for firing the laser coincident with projectile passage through the test area, it was necessary to use the pulse from the Kistler transducer to initiate the laser firing sequence. After a number of measurements, it was found that for the studies outside the barrel, projectile passage through the test area occurred at approximately 1600 microseconds after the triggering of the Kistler. The laser system has an inherent delay of about 1020 microseconds between discharge of the capacitor bank and lasing action with Pockels cell Q-switching. Additionally, the output voltage from the Kistler charge amplifier was not sufficient for triggering the laser. It was therefore necessary to delay and increase the voltage of the Kistler pulse to provide an accurate reliable trigger for the laser system. To do this, the Kistler pulse was displayed on a Textronix storage oscilloscope and simultaneously used as an input to a Hewlett-Packard USM-310(V) signal modulator. This unit permits the input of a variable signal delay which was changed periodically to adjust to point of exposure on the projectile. The delayed Kistler output was routed through an
ILC PG-10 pulse generator which provided the voltage necessary to trigger the laser.

Additionally, two electronic timers, a Monsanto Model 101 B and a Dynasciences CP-929 were integrated into the system at various locations to provide checks on intervals of interest. These are shown in typical locations in the firing sequence schematic.

After firing, the test cell was closed and the hologram plate removed for processing. The armor plate was checked for damage and repositioned when necessary. The cannon was unloaded and the barrel was periodically cleaned with a standard 20-mm bore brush. The pressure and temperature traces were photographed with a Polaroid C-5 oscilloscope camera.
V. HOLOGRAPHIC FILM AND PROCESSING TECHNIQUE

The wavelength of the coherent light source used in the holography is 6943 Å. It was desirable to use a photographic emulsion with narrow-band sensitivity centered in this region of the spectrum to minimize the effect of extraneous light leakage into the system. The most suitable commercially available emulsion for this purpose was found to be Agfa-Gevaert 10E75 holographic plates. This film has a resolution capability of 2800 lines per mm which is approximately the maximum required film resolution for transmission holograms produced with 6943 Å light. A spectral sensitivity curve for this emulsion may be found in Ref. 4.

Processing of the exposed hologram plates consisted of a five-minute bath in Kodak D-19 Developer followed by five minutes in a standard fixer. The plate was then washed for five minutes in flowing water and then allowed to air dry prior to reconstruction.

It was not possible to control time of exposure for these plates while using the 20-nanosecond ruby pulse. Therefore, exposure was controlled by using a suitable combination of neutral density filters in the beam to produce the intensity desired at the hologram plate.

For the double pulsed holograms a problem was encountered due to the fact that the projectile was not in the field for both exposures as is normally the case when utilizing this technique to observe flow.
fields around opaque objects. For single exposure holograms the bullet appears as a dark object in a light background, while for double exposure holograms the bullet was a light object on a light background. This lack of contrast was improved appreciably by halving the intensity of the first exposure. This provided a grey background for the bullet upon reconstruction, while yielding good fringe contrast.
VI. RECONSTRUCTION

In reconstruction of the holograms, two different techniques were employed using different sources of coherent light for the reconstructing reference wave. For the first of these, illustrated in Figure 10, a 15-milliwatt Spectra-Physics continuous wave, helium-neon laser was used for the reconstructing wave. This laser was equipped with an integral lens system which produced a 50-millimeter collimated beam. This beam was expanded and collimated with a secondary set of lenses to the approximate size of the hologram plate. The converging real image was then photographed with a single lens reflex 35-millimeter camera, using Kodak Panatomic-X (ASA 32) fine grain black and white film.

The second reconstructing procedure used is illustrated in Figure 11. A one-watt continuous wave argon laser was employed to reconstruct overexposed holograms requiring a more intense reference beam. To minimize the possibility of accidentally viewing the powerful reference beam during photography, the reconstructed scene beam was reflected away from the reference beam with a high quality first surface mirror. As suggested by Trolinger [Ref. 11], the actual imaging lens used in the construction of the hologram was placed in the reconstructed scene beam to eliminate spherical aberrations produced by this lens during construction. This lens then served to recollimate the scene
beam. In practice, little or no improvement was observed in the quality of the reconstructed beam. Thus this lens was not used in the first technique.

The real image was again photographed with the single lens reflex camera and Kodak film.
VII. COMPUTER PROGRAM FOR PREDICTION OF FLOW PARAMETERS

The computer program used for the prediction of the muzzle velocity and pressure history of the flow field was an adaptation of a program developed at the Naval Ordnance Laboratory to analyze the performance of hypervelocity model launchers [Ref. 8]. The analysis was essentially a one-dimensional, Lagrangian scheme in which the field was divided into six regions, each of which then was subdivided into zones. Each region had specified its own equation of state which, depending upon the material characteristics of the region, could be either solid, ideal, or non-ideal gas equations. At the interface of each zone were inserted mass points, each of which was assumed to consist of one-half of the mass of the adjacent zone. The analysis successively applied the hydrodynamic equations in finite difference form to each mass point over the time interval of interest. The method employed was the "q" method of Von-Neuman and Richtmyer [Ref. 9 and 13].

The equations applicable to the scheme were the following:

Isentropic Flow energy equation:

\[
\frac{\partial E}{\partial t} = -(p + q) \frac{\partial V}{\partial t}
\]

Equation of motion:

\[
\frac{\partial u}{\partial t} = -\frac{\partial (p + q)}{\partial x} \frac{1}{M} A(x)
\]
Equation of state:

\[ p = p(E, V) \]

with

\[ M = \int_0^x \rho(x) A(x) \, dx \]

\[ q = \begin{cases} \frac{C_o^2}{V} \left( \frac{\partial u}{\partial j} \right), & \frac{\partial u}{\partial j} < 0 \\ 0, & \frac{\partial u}{\partial j} \geq 0 \end{cases} \]

The artificial viscosity term "q," which was added to the pressure term in the energy and motion equations, essentially spreads variable changes created by the shock over a finite region. This facilitates computation by allowing the equation variables to be continuous across the shock. The constant \( C_o \) permits adjustment of this shock "thickness."

For computation purposes these equations were written in finite difference form. Initial values of \( E_o, p_o, \) and \( V_o \) are provided for each region. Stability was maintained during the process by recalculating a new time increment for every cycle in the process.

During each cycle, the pressure at each mass point was calculated using the equations of state and energy. From the pressure differential at these interfaces the acceleration and velocity of each mass point were obtained using the equation of motion.

Required data inputs included initial temperatures, pressures, and molecular weights for each region, along with a series of variables.
describing the geometry of each region. Additional inputs describing burning characteristics were required for each region containing powder.

The program was written in FORTRAN and a listing along with the input format is given in Appendix A.
Considerable trial and error was involved in the initial attempts to capture the projectile and its associated flow field at the muzzle of the barrel. The optics of the system were initially designed primarily for investigation of the interior flow behind the projectile and thus the available size of the scene beam was limited. The average view of the test section was circular of 4-cm diameter centered 2.5 cm outside the muzzle. Initially a barrel-mounted dual grid system (one grid on each side of the test section) was installed on the barrel. These grids were removed and replaced with a central vertical wire for viewing orientation when it was discovered that grid movement due to the blast introduced undesirable noise into the system for the double-pulsed holography.

Prediction of the pulsing instant of the Q-switched laser was reliable to within ± 10 microseconds. The time of projectile passage through the test section after triggering the transducer varied by as much as 50 microseconds. This variability was reflected in the range of projectile velocities obtained from the velocity screens and was probably a result of differences in powder charge and projectile weight. Because of this unpredictability and also experimentation with relative beam intensities, many shots were fired before meaningful holographic results were obtained.
Among the first successful holograms were a series of single exposures taken while attempting to refine the timing of the laser pulse to coincide with projectile passage through the test area. Figure 12 is the reconstruction of one of these single exposure holograms containing a shadowgraph of the projectile. As an indication of the size of the projectile, the grid in the photograph is \(\frac{1}{2} \times \frac{1}{3}\) centimeter. In this particular hologram, the detached bow shock wave is actually discernible. For easier viewing, the projectile and shock are redrawn in Figure 13.

The standoff distance of the shock at the nose of the projectile was 2.7 mm. The approximate nose radius of the projectile was 3.8 mm, yielding a standoff distance to nose diameter ratio of 0.355.

Van Dyke [Ref. 12] provides theoretical values of this ratio for a sphere as a function of Mach number. His values are obtained through an inverse method in which a marching technique is used to integrate numerically the flow equations from the shock to the sphere. Experimental measurements provided excellent agreement with these theoretical results.

A \(\Delta s/d\) ratio of 0.355 indicated that the projectile Mach number was 2.2 in the region of elevated temperature just outside the muzzle. The precursor traveling shock, well ahead of the projectile at this point, is outside the view of this hologram.

The measured muzzle velocity for this particular shot was 3364 feet per second for a freestream Mach number of 3.0.
After resolving as well as possible the problem of timing the laser firing, double pulsed holography was conducted. Figure 14 is a finite fringe hologram of the precursor traveling shock emerging from the barrel ahead of the projectile. This shock was created by rapid expulsion of the gases within the barrel ahead of the projectile. At the point of exposure, this shock was 1.75 cm from the muzzle along the barrel axis and appears nearly spherical with a radius of 2.25 cm. The steep density gradients across the shock are evident by the extremely closely packed fringe pattern visible across the shock.

Figure 15 is another finite fringe hologram with the precursor traveling shock at a distance of 3.2 cm from the muzzle. At this point the shock radius had increased and had weakened appreciably as indicated by the wider spacing of the fringes. This hologram also reveals a second shock of smaller radius behind the first at 2.6 cm from the muzzle. This inner shock could have been a recompression wave due to overexpansion behind the outer shock wave. Further examination of this hologram also revealed the radial development of the Prandtl-Meyer expansion fan around the rim of the muzzle face. The precursor shock from Figures 14 and 15 are redrawn together in Figure 16. As seen in this figure the limited size of the field makes fringe analysis difficult.

Figure 17 is a double-pulsed hologram taken with the nose of the projectile 2.4 cm into the field. The grid system is still in place and
its adverse effects are evident. In this figure a marker on the grid indicating the central portion of the test section is evident on the nose of the projectile.

Holograms of the projectile at increasing degrees of penetration of the flow field may be seen in Figures 18 through 21. Each of these holograms is a finite fringe hologram with varying degrees of fringe separation. The boundary layer was visible in Figures 18 and 21 in the sharp fringe shifts at the projectile surface. As the bullet progressed through the field, less of the field around the projectile was visible due to the limited view of the test area.

In Figure 21 nearly 2/3 of the projectile had passed the center of the test section indicated by the vertical reference wire. With approximately one inch of projectile remaining, the field became blurred and the image of the bullet as well as the fringe pattern disappeared. The beginning of this process was also shown clearly in Figure 20. It is probable that the loss of image at this point was due to leakage of the high pressure combustion gases around the projectile. The flow of these gases is turbulent and tends to obscure the field. Additionally, the combustion effluents caused the gases to become opaque and difficult to observe holographically.
IX. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

Sample outputs from the computer program are illustrated in Figures 22 and 23. Figure 22 summarizes the major inputs including initial conditions in the approximate program output format. As seen in this figure, the time increment between printout of calculated flow parameters may be selected arbitrarily. The print interval for this particular run was .2 milliseconds. Figure 23 illustrates the output from the final cycle as the projectile leaves the barrel. The mass point, \( j \), for the projectile is 6 and its velocity (muzzle velocity at this point) is 1064 meters per second. The \( X \) position is distance from the breech end to the mass point. Using printout from each cycle, the projectile velocity was plotted as a function of \( X \)-distance in Figure 24.

The mean experimental projectile velocity measured with the Oehler velocity screens over a series of 53 shots was 1032 meters per second for an average Mach number of 3.03. The velocities ranged from 1020 to 1056 meters per second and had a standard deviation of 10.7 meters per second. The measurement was taken at a distance of 2.68 meters from the muzzle. Assuming a projectile drag coefficient of .28 [Ref. 10], the average muzzle velocity was approximately 1033 meters per second. This measurement was within 3% of the predicted value.
From Figure 23, the computed time of projectile arrival at the test section was 1884 microseconds after the firing pulse. Actual average time of arrival based on holographic evidence of the projectile in the test section was 1600 microseconds after triggering of the Kistler pressure transducer 14.0 centimeters from the breech end. This required a projectile travel of nearly 7 centimeters. From the computer program this estimated time of travel was 378 microseconds for a total of 1978 microseconds. Agreement between predicted and measured values is within 5%.

The computer pressure history at the transducer location was plotted using the zone pressure at the 14-centimeter location for each print cycle. This pressure trace is plotted in Figure 25 along with the actual measurements from the Kistler pressure transducer. Very good agreement was obtained between the actual and numerically obtained pressures. The experimental results show, after an initial overshoot, a peak pressure of 4966 bars at approximately .62 milliseconds after the firing pulse. The predicted pressure history rises and falls somewhat more rapidly than the actual trace, with a peak pressure of 5624 bars at .475 milliseconds after the firing pulse. Excellent agreement is seen between the actual and theoretical pressures after these initial peak values.
X. SUMMARY AND RECOMMENDATIONS

The numerical solution of the one-dimensional hydrodynamic equations has provided excellent agreement with experimentally measured flow parameters including muzzle velocity, pressure history, and projectile launch time. This program may be used in predicting these parameters under a wide range of initial conditions including variations in powder characteristics, and projectile and launcher size.

The feasibility of the use of holography in the visualization of exterior ballistic flow fields has been demonstrated. Several excellent holograms of the projectile and its associated flow field have been obtained. Interferometric analysis was restricted, however, due to the limited field of view obtained with the present optical arrangement which was initially designed to study interior ballistic flow fields. Currently, the optical arrangement is being modified to provide this enlarged field of view necessary for the interferometry. Additionally it is felt that imposition of a horizontal fringe field rather than the vertical field used in this study would be easier to analyze interferometrically because of the axi-symmetric nature of the flow field. This entails only vertical rather than horizontal rotation of the scene beam between exposures and requires no modification of the current optical arrangement.
FIGURE 2.
FIGURE 3. TEST CELL LAYOUT
FIGURE 4. PROJECTILE PATH AND TURRET
FIGURE 5. OPTICAL ARRANGEMENT
(b) CANNON AND OPTICS TEST CELL

(b) LASER INSTALLATION

FIGURE 6.
FIGURE 9. FIRING SEQUENCE
Figure 10. Reconstruction
FIGURE 11. RECONSTRUCTION
FIGURE 12. SINGLE EXPOSURE HOLOGRAM OF PROJECTILE
FIGURE 14. HOLOGRAPHIC INTERFEROGRAM OF PRECURSOR TRAVELING SHOCK
FIGURE 15. HOLOGRAPHIC INTERFEROGRAM OF PRECURSOR TRAVELING SHOCK
FIGURE 16. REDRAWN SHOCK SYSTEMS OF FIGURES 14 AND 15
FIGURE 17. DOUBLE PULSED HOLOGRAM OF PROJECTILE
FIGURE 18. HOLOGRAPHIC INTERFEROGRAM OF PROJECTILE
FIGURE 19. HOLOGRAPHIC INTERFEROGRAM OF PROJECTILE
FIGURE 20. HOLOGRAPHIC INTERFEROGRAM OF PROJECTILE
FIGURE 21. HOLOGRAPHIC INTERFEROGRAM OF PROJECTILE
GUN BARREL PROJECT

Computer Run Number: 3  Date: 5/10/75

Dimensions: 6 Regions, 6 Zones

<table>
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<tr>
<th>Regions</th>
<th>Zones</th>
<th>Length (cm)</th>
<th>Area (cmsq)</th>
<th>Volume (cc)</th>
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<td>1</td>
<td>1.47</td>
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INITIAL CONDITIONS

Powder Conditions: Grams Powder = 38.23
TBURND = 1.000 Millisec

Materials:

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<th>Region</th>
<th>NEQST</th>
<th>Pressure (psi)</th>
<th>Temp. (Deg. K)</th>
<th>Molec. Wt. (gm/mole)</th>
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<td>125.00</td>
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Print out every 0.20 milliseck up to 10.00 milliseck
Print out every 0.050 milliseck up to break
Print out every 0.200 milliseck up to launch

Mass of Projectile = 90.0 gm
Break Valve Strength = 690.0 Bars
Number of Pressure Points: 1
Location of Pressure Points: 14.0 cm

FIGURE 22. COMPUTER OUTPUT FORMAT
## GUN BARREL PROJECT

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<th>T(Millisec)</th>
<th>DT(Millisec)</th>
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<table>
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<tr>
<th>j</th>
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<th>VELOCITY (CM/MS)</th>
<th>PRESSURE (BARS)</th>
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<tr>
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<td>1.01004E+02</td>
<td>8.52849E+02</td>
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<td>3.98267E+02</td>
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**FIGURE 23. COMPUTER OUTPUT FORMAT**
FIGURE 24. PROJECTILE VELOCITY vs. POSITION
FIGURE 26. USAF 1951 RESOLUTION TEST TARGET
FIGURE 27. HOLOGRAM OF USAF 1951 RESOLUTION TEST TARGET
**APPENDIX A**

**GUN PROJECT**

**C**

```c
COMMON PCON3, SLOPE, RADIUS, CALPGM, TURBAND, GMSDPD, GASPRS, IHEL
COMMON AREA1, AREA2, AREA3, Area, CSQX4, CMAPR, CSQ, CSQMAX, CP, CV, DLMAX
1, DTMIN, DUTD, DLAMDA, DTSQ, DTLAST, DJLAST, DNZONE, DELX, DMU, DPDE, HVMN0030
2DPDMU, DQ1, DQ2, DS, EZERO, EINSUM, ESUM, EINT, EKIN, E, ETOT, ETENT, HVMN0050
3ERONG, E, FORCE, GAMMA, HALFW, HALFRO, HYDRD1, HYDRD2, HYDRD3, HYDRD4, HVMN0060
4OUTBDY, OUTDT1, OUTDT2, PCCN1, PCCN2, PPLUSQ, P, PL, Q, ZERO, SHPR, HVMN0070
5SIGMAX, SIGMIN, SKIN, TMAX1, TMAX2, TVDT1, TVDT2, TMAX, TSIGS0, TNEXT, HVMN0080
6TPRINT, TVNEXT, TMINSQ, TVFREQ, UZERU, USQ, TBAP, TVRE1, THEA, TAWAL, HVMN0090
7VZERO, V, VOLUME, VISCOS, X, X1, XGRID1, XMIN, XMAX, ZMASS, EMIN, JSTOP, HVMN0100
COMMON IMAX, INU, J, JSTOP, JMAX, J, JMAX, J, JMAX, J, HVMN0110
1JPLHAF, JMNHAF, JLAST, JLAST, JMIN1, JMAX1, K, L, MACHSQ, NDAT1, NDAT2, HVMN0120
2NDATE3, NUMBER, NTV, NCHKE, NQST, NZONE, NCYCLE, N, MNHAF, NPPLUS1, HVMN0130
3NPLHAF, NN, NPL3HAF, NP, IQUIT, JPROJ, JSTOP, R, REMPIST, PO, TO, AMOL, DUMVAR, HVMN0140
DIMENSION AREA(200, 2), CSQX4(30), CMAPR(30), CS1(200), CP(30), CV(30), HVMN0150
1DTMAHDA(200), DTSQ(200), DELX(30), DQ1(200), DQ2(200), DS(200), HVMN0160
2EZERO(30), E(200, 2), EINT(30), EKIN(30), FORCE(30), GAMMA(30), HVMN0170
3HALFW(30), HALFRO(30), HYDRD(200), INTERJ(30), MACHS0(200), NEQST(30), HVMN0180
4NZONES(30), OUTBDY(30), PPLUSQ(200), Q(200, 2), PZERO(30), HVMN0190
5SKIN(200), TSIGS0(200), TMINSQ2, TVRE1(30), THEA(200), UZERU(30), HVMN0200
6U(201, 2), USQ(201), VZERO(30), WC0(200, 2), VISCOS(200), X1(201, 2), X2(201, 2), HVMN0210
7MASS(200), PO(30), TO(30), AMOL(30), DUMVAR(500, 5), HVMN0220
DIMENSION XP1(500), XP2(500), PP1(500), VP2(500), XP3(500), PP3(500), HVMN0230
DIMENSION XPO(10), STOPX1(10), NPTPLEX1(10), TPOX(500), HVMN0240
1P(300, 2), TPLT(500), HVMN0250
1DIMENSION ISTOFM(500), STORM(100), AVEL(100), ALCAD(100), AGAS(100), HVMN0260
DIMENSION XP4(500), PP4(500), HVMN0270
DIMENSION DATA(150), PRSTAB(90), HVMN0280
DIMENSION PDMAX(200), TDMAX(200), PDMMIN(200), TDMIN(200), HVMN0290
NAMELIST/READ1/AMOL, AREA1, AREA2, AREA3, CALPGM, CSQX4, EMLEAD, HVMN0300
1EMPIS, EMPROJ, FRAC, GAMMA, GASPRS, GMSDPD, HYDRD1, HYDRD2, IHEL, HVMN0310
2INU, IPCX, JPROJ, NCHKE, NDAT1, NDAT2, NDAT3, NEQST, NPOX, NUMBER, HVMN0320
3NZONE, OUTBDY, OUTDT1, OUTDT2, PCCN1, PCCN2, PCCN3, PO, PERK, PWANT, HVMN0330
4RADIUS, SHPR, SLCEP, TURBND, TMAX1, TMAX2, TO, UZERO, XPQ, XPV1, XPV2, HVMN0340
5JSTOP, HVMN0350
C
INITIAL CONDITIONS FOR PRGPAM
T=0.0
1DATA=0
HVMN0370
HVMN0375
HVMN0380
```
123 NI = 0
   M = 6
   NPVTR = 1
  1 CALL ZECAB
       CALL ZEROA(500, XP1, XP2, PP1, VP2, XP3)
       CALL ZEROA(500, PP3, PP1, PP1, PP1, PP1)
       CALL ZEROA(10, ISTOPX, ISTOPX, ISTOPX, ISTOPX, ISTOPX)
       IRL = (31) = M
       CPMAX = 0.0
       PRTMAX = 0.0
       AMPMAX = 0.0
       NTMPT = 0
       IP = 0
       NPUNCH = 1
       IPNCHX = 0
       LN = 0
       IPV1 = 1
       IPV2 = 2
       HYDRD1 = 13.3
       HYDRD2 = 0.1
  C END INITIAL CONDITIONS FOR PROGRAM, BEGIN INPUT FOR RUN, NEW OR IRE
  620 IF (NPVTR.EQ.1) GO TO 41
       IF (NPVTR.EQ.1) GO TO 41
  C INPUT FOR ITERATION FROM STORAGE
       CALL STORE (ISTORM, STORM)
       EMHEAD = STORM(97)
       HYDRD1 = STORM(98)
       HYDRD2 = STORM(99)
       NEOST(30) = ISTORM(100)
       IF (IDATA) 8, 8, 698
       continue
  41 INPUT FOR NEW RUN, STORAGE OF INPUT
       READ(5, 604) IDATA, IPRMTZ, ITRNSF, IPUNCH, DTSQ(199)
       READ(5, 604) IDATA, IPRMTZ, ITRNSF, IPUNCH, DTSQ(199)
       IF (ITRNSF.EQ.0) GO TO 619
       M = 6
       IRL = (31) = M
       IF (IDATA) 606, 606, 620
       READ(5, REA1)
       IDATA = 0
       GO TO 619
       READ(5, 606) IPOS, NPX, (XPX(K), K = 1, NPX)
       READ(5, 606) IPOS, NPX, (XPX(K), K = 1, NPX)
       READ(5, 606) IPV1, IPV2, PVEK, PVKMT
       READ(5, 606) IPV1, IPV2, PVEK, PVKMT
       READ(5, 606) P1MPTS, FRAC, EMHEAD
       READ(5, 606) P1MPTS, FRAC, EMHEAD
  66 FORMAT(6(E10.4, 3F10.0)
       READ(5, 606) (PO(I), I = 1, IMAX)
       READ(5, 606) (PO(I), I = 1, IMAX)
       READ(5, 606) (PD(I), I = 1, IMAX)
       READ(5, 606) (PD(I), I = 1, IMAX)
READ (5,49) (AMOL(I),I=1,IMAX)
49 FORMAT (7F10.0)
610 CONTINUE
C initial conditions and constants for run
8 NPTN=NZONES(1)+NZONES(2)+NZONES(3)+1
XSST = FRAC * OUTBDY(5)
NEQST(20) = IPX
616 CALL CALCUL (EMLEAD)
IF (NI,NE,0) GO TO 603
CALL PRINTC (EMLEAD,FRAC,XPV1,XPV2, PVWANT,NPOX, IPOX,XPO)
IF (IPRN,NE,0) GO TO 603
READ (5,11) ILASTK
IF (ILASTK) 123,12,1
603 CALL SETUP
DO 706 IMP=1, JLAST
PMDMIN(IMP) = PPLUSQ(IMP)
706 PMDMAX(IMP) = PPLUSQ(IMP)

C MAIN LOOP OF PROGRAM - DYNMEQ, LFOVER, AND OUTPUT
2 CALL DYNMEQ
CALL LFOVER(IPNCHX)
DO 710 IMP=1, JLAST
IF (PPLUSQ(IMP), GT, PMDMIN(IMP)) GO TO 705
PMDMIN(IMP) = PPLUSQ(IMP)
705 IF (PPLUSQ(IMP), LT, PMDMAX(IMP)) GO TO 710
PMDMAX(IMP) = PPLUSQ(IMP)
TDMDXM(IMP) = T
710 CONTINUE
IF (IPUNCH, NE, 0, OR, JPROJ, NE, 300) GO TO 627
PRSTAB(IPUNCH) = T - DTSQ(200)
NPNP1 = IPUNCH + 1
JPLHAF = INTERP(6)
J = JPLHAF
JMNHAF = JPLHAF - 1
DUD1 = 26. / 18. * PPLUSQ(JMNHAF) - 1. / 9. * PPLUSQ(JMNHAF - 1)
707 PRSTAB(NPNP1) = DUD1
IF (.GT. (DTSQ(200) + DTSQ(199))) GO TO 647
PRSTAB(NPNP1) = PRSTAB(NPNP1) * (T - DTSQ(200))/ DTSQ(199)
647 NPUNCH = NPUNCH + 2
IF (91 - NPUNCH) 625, 625, 627
625 PUNCH 641, PRSTAB
641 FORMAT (3(F12.8,E12.8))
627 CONTINUE
630 M=6
72. CONTINUE
C STORAGE CF, MAXIMUM PressURES
INER51 = INTERJ(6) -1
CPMAX=AMAX1(CMAX, PPLUSQ(NPTN))
NPTMAX=AMAX1(PTMAX, PPLUSQ(NPTN-1), PPLUSQ(NPTN-2), PPLUSQ(NPTN-3))
AMPMAX=AMAX1(AMPMAX, PPLUSQ(INER51))
C DETERMINATION IF MODEL HAS BEEN LAUNCHED
IF(XSTOPX(XJLAST, NPLUS1) 0, 3, 3
C ROUTINE STORAGE OF POINTS TO BE PLOTTED
3 IF(IP0X.EQ.5) GO TO 2
IF (X(NPTN, N) = LT - XSST ) GO TO 2
KN=NCYCLE/6
CN = KN
SN=NCYCLE
TN=SN/6.
4 IF(LN GT 498) GO TO 7
LN = LN+ 1
IF (IP0X.EQ.6) GO TO 75
XP3(LN)=T
XP4(LN)=PPLUSQ(NPTN)
PP4(LN)=PPLUSQ(NPTN-1)
IF(IP0X.EQ.1) GO TO 51
DO 60 INPOX=1, NPOX
IF(IP0X INPOX) .GE. 1 GO TO 60
MTXPTL=LN
DO 59 INPTN=2, JLAST1
IF(XPO(IPOX), L*XI(INPTN)) GO TO 59
58 CONTINUE
DVAR(LN, INPOX)=PPLUSQ(INER51)
NPTPL(INPOX)=LN
GO TO 60
59 DVAR(LN, INPOX)=PPLUSQ(INPTN-1) + (PPLUSQ(INPTN-1) - PPLUSQ(INPTN))
1/(XI(INPTN-1)-XI(INPTN)) * (XPQ(INPOX)-XI(INPTN-1))
NPTPL(INPOX)=LN
IF(LN.EQ.1099)GO TO 55
GO TO 60
55 ISTPOX(INPOX)=2
NPTPL(INPOX)=LN
60 CONTINUE
IF (IP0X.NE.6) GO TO 78
75 DVAR(LN,1) = PPLUSQ(INER51)
78 TPOX(LT)=T
IF (IP0X.EQ.6) GO TO 2
51 IF(IP0X.EQ.2) GO TO 52
C PROGRAM TO FIND MAX IN REGION TO GO HERE

C STORAGE OF MODEL PLOTS AFTER BREAK VALVE
52 CONTINUE
7 IF (JPC=300) 13, 5, 13
5 IF (IP.GT.498) GO TO 2
10 IF (XSTOP.EQ.3000.) GO TO 76
XP1(IP)=X(JLAST,N)
XP2(IP)=X(JLAST,N)
PP1(IP)=PPLUSQ(INER51)
PP2(IP)=U(JLAST, NMNHA)
13 GO TO 2

C FINAL STORAGE OF POINTS TO BE PLOTTED, AND WRITING OF ALL PLOT TAP
9 IF (IPCX.EQ.5) GO TO 25
9 IF (IPCX.EQ.6) GO TO 76
35 NPOX=1
36 DO 70 IPLTX=1,NPOX
NPTT=NPTPL(IPLTX)
70 CONTINUE
76 DO 93 ITXP=1, NPLTX
TLP(IITX)=TPOXI(TITX)
80 PPLT(IITX)=DUMVAR(IITX, IPLTX)
93 CONTINUE

C TERMINATION OF RUN, RETURN FOR NEW INPUT
25 READ(5,11) JLAST
25 IF ((IPUNCH.EQ.0).OR.(NPUNCH.EQ.1)) GO TO 629
NPUNCH=NPUNCH+1
PUNCH 641, (PRSTAB(IPXX), IPXX=1, NPUNCH)
629 CONTINUE
WRITE(6, 45) CPMAX, PTMAX, AMPMAX
WRITE(6, 704) ((IT, PMDMIN(IT), TMDMIN(IT), PMDAMAX(IT), TMAKMAX(IT)),
1=1, JLAST)
704 FORMAT(I3, 2X, E12.6, 2X, E12.6, 2X, E12.6)
15 WRITE(6,44)(I, I, (AVE(I), ALOAD(I), AGAS(I)), I = 1, N1)
16 GO TO 123
13 FORMAT (1000, 16 FORMAT (13,2F10,0))
14 FORMAT (13,2F10,0)
15 END
SUBROUTINE PRINTO(EMLFAD, FRAC, XPV1, XPV2, PWANT, NPOX, IP, XPO)
     COMMON PCON3, SLOPE, RADIUS, CALPGM, TBURNO, GMSPDR, GASPRS, IHEL
     COMMON AREA1, AREA2, AREA3, AREAO, COSQX4, CHAXR, CSQ, CSQMAX, CP, CV, DLAMAX
     COMMON DTMIN, DUDT, DLMANA, DTSQ, DTLAST, DLAST1, DJLAST, DNZONE, DELX, DMU, DPDE,
     COMMON DPDMU, CQ1, DQ2, DS, EZERO, EINSUM, ESUM, EKSUM, EINT, EKIN, E, ETOT, ETENTH,
     COMMON NQBO, NFORCE, GAMMA, HALFM, HALFPROP, HYPERD1, HYPERD2, HYPERD3, HYRAD,
     COMMON CUTOBDY, CUTOBD1, CUTOBD2, PCON1, PCON2, PPLUSO, P, P1, Q, ROZERO, SHPR,
     COMMON IMAX, INU, I, INTERJ, INDEX, LIMIT, JFORCE1, JPROJ2, JMIN, JMAX, J
     1 PLHAF, JMNHAF, JLAST, JLAST1, JMIN1, JMAX1, K, L, MACHSQ, NDATE1, NDATE2,
     2 NDATE3, NUMBER, NTY, NCHECK, NEQUAT, NQBO, NFORCE, NMAX, NPLUS1,
     3 PLHAF, NN, NPL3HF, NP, IQUIT, JPROJ, JSTOP, R, EMPIST, PO, TO, AMGL, DUMVAR
     COMMON AREA(200,2), CQSOX4(30), CHAXR(30), CSQ(200), CP(30), CV(30),
     COMMON DTMIN(3), DLMA(200), DTSQ(200), DELX(30), DQ1(200), DQ2(200), DS(200),
     COMMON EZERO(200), EI(200,2), EINT(30), EKIN(30), EFORCE(200), GAMMA(30),
     COMMON HALFM(200), HALFPROP(200), HYPERD1(200), INTERJ(31), MACHSQ(200), NEQUAT(30),
     COMMON NQBO(200), NFORCE(200), PPLUSO(200), P(200,2), Q(200,2), ROZERO(30),
     COMMON SKIN(200), TSIGSO(200), TMINSO(2), TVRRE1(30), THETA(200), UZERO(30),
     COMMON UZ(201,2), USO(201), VZERO(30), V(200,2), VISCO(200), X(201,2), X1(200),
     COMMON ZMASS(200), PC(30), TO(30), AMGL(30), DUMVAR(500,5)
     DIMENSION XLGTH(30), ZMASS(30), XPO(10), REGVL(30)
     WRITE (6,65)
     FORMAT (131)
     XLGTH(1)=CUTOBDY(1)
     REGVL(1)=AREA1*XLGTH(1)
     IF (IMAX.EQ.1) GO TO 210
     DO 200 QK=2, IMAX
     200 XLGTH(KQ)=CUTOBDY(KQ)-CUTOBDY(KQ-1)
     KQXX=KQ+1
     DO 201 KX=2, KQXX
     201 REGVL(KQ)=AREA2*XLGTH(KQ)
     REGVL(IMAX)=AREA3*XLGTH(IMAX)
     ANGLE=ATAN(SLOPE)
     WRITE (6,100) NUMBER, NDATE1, NDATE2, NDATE3
     WRITE (6,102) IMAX, JPROJ
     WRITE (6,103) I, NZONES(I), XLGTH(I), AREA1, REGVL(I)
     IF (IMAX.EQ.1) GO TO 211
     KQX=IMAX-2
     WRITE (6,104) (I, NZONES(I), XLGTH(I), AREA2, REGVL(I), I=2, KQX)
     WRITE (6,105) IMAX, NZONES(IMAX), XLGTH(IMAX), AREA3, REGVL(IMAX)
     WRITE (6,105) SLOPE, ANGLE
112 FORMAT(1H /5X,10HWEIGHTS --/9X,6HPISTON/13X,23HM ASS OF FIRST SECT
1OCN = ,F13.4,4H LB,8X,1H = ,F13.4,4H GM/13X,24HM ASS OF SECOND SECTI
2CN = ,F13.4,4H LB,8X,1H = ,F13.4,4H GM/9X,5HMODEL/13X,15HM ASS OF M
3ODEL = ,F12.4,4H GM)
113 FORMAT(1H /18X,22HBREAK VALVE STRENGTH = ,F10.2,6H BARS,5X,1H = ,F10
1,2,5H PSI)
114 FORMAT(1H /5X,18HPISTON VELOCITY --/10X,6HXPV1 = ,F10.2,7H CM
110X,6HXPV2 = ,F10.2,7H CM /10X,18HDESIRED VELOCITY = ,F10.2,7H FIT
2/SEC)
115 FORMAT(2H //20X,15HPRINT OUT EVERY,F7.3,11H MSEC UP TO,F7.3,5H MS
1EC/20X,15HPRINT OUT EVERY,F7.3,17H MSEC UP TO BREAK/20X,15HPRINT 0
2UT EVERY,F7.3,18H MSEC UP TO LAUNCH)
116 FORMAT(1H /10X,26HNUMB ER OF PRESSURE POINTS ,14//10X,27HLOCATION OF
1F PRESSURE POINTS)
117 FORMAT(20X,F10.0,5H CM)
118 FORMAT(1H /10X,20HPLOT START FRA CTION ,1PE11.4)
119 FORMAT(1H /5X,8HPLOTS --,10X,6HIP0X = ,13,34H (ALL PLO TS, ALL PRE
1SURE POINTS))
120 FORMAT(1H /5X,8HPLOTS --,10X,6HIP0X = ,13,33H (ALL PLOTS, NO PRES
1SURE POINTS))
121 FORMAT(1H /5X,8HPLOTS --,10X,6HIP0X = ,13,12H (NO PLOTS))
122 FORMAT(1H /5X,8HPLOTS --,10X,6HIP0X = ,13,24H (O NLY PRESSURE P0IN
1TS))
123 FORMAT(1H /5X,8HPLOTS --,10X,6HIP0X = ,13)
124 FORMAT(1H /6X,3HR = ,1PE11.4)
RETURN
END
SUBROUTINE LFT0VR

C DETERMINES DELTA T AND PRINT CYCLE

COMMON PPCCN3, SLOPE, RADIUS, CALPGM, TURBND, GMSPD, GASPRS, IHEL
COMMON AREA7, AREA2, AREAS, AREA, COSQ6X4, CMAXR, CSQ, CSQMAX, CP, CV, DLMAX, FLD00010

1, DTM0, DUTD, DLAMDA, DTSQ, DTLAST, DLAST, DJLAST, DNLZONE, DELX, DMU, DPDE, FLD00020
2, DPD2U, DQ1, DQ2, DS, EZERO, EINSUM, ESUM, EKIN, EKIN, EMT, ETOT, ETEN0, FLD00030
3, EKRON, E1, FORCE, GAMMA, HALFM, HALFE, HYRDL, HYRDL, HYRD2, HYRD3, HYRAD, FLD00040
4, OUTBDY, OUTDT1, OUTDT2, PCON1, PCON2, PPLUSQ, P, P1, Q, ROZERO, SHPR, FLD00050
5, SIGMAX, SIGMIN, SKIN, TMAX1, TMAX2, TVDT1, TVDT2, TVX, TSIG0, TTEXT, FLD00060
6, TVNEXT, TVNEX, TVFREQ, UZERO, U, USQ, TAP, TAP1, TAP2, TAP3, TAP4, TAp5, TAp6, TAp7, TAp8, TAp9, FLD00070
7, VEPP, VOLUME, VISCONS, X, XI, XGPD, XMIN, XMAX, ZMASS, EMPROJ, XSTOP

COMMON IMAX, INU, I, INTERJ, INDEX, LIMIT, JPROJ1, JPROJ2, JMIN, JMAX, J, FLD00080

1, JPLHAF, JMNHAF, JLAST, JLAST, JMIN1, JMAX1, K, L, MACHSO, NDATE1, NDATE2, FLD00090
2, NDATE3, NUMBER, NTV, NCHECK, NEQST, NZONE, NCYCLE, N, NMNHF, NLUS1, FLD00100
3, NLHAF, NN, NL3HF, NP, IQUIT, JPROJ, JSSTOP, P, EMPIST, PC, TO, AMOL, DUMVAR, FLD00110
4, DIMENSION AREAS(200,2), COSQ6X4(30), CMAXR(30), CQ0(200), CP(30), CV(30), FLD00120
5, DTM0(30), DLAMDA(200), DTSQ(200), DELX(30), DQ1(200), DQ2(200), DS(200), FLD00130
6, EZEF(0,30), E(200,2), EINT(30), EKIN(30), FORCE(200), GAMMA(30), FLD00140
7, HALFM(200), HALFE(200), HYRDL(30), INTERJ(31), MACHSO(200), NEQST(30), FLD00150
8, NZONE(30), OUTBDY(30), PPLUSQ(200), P(200,2), Q(200,2), ROZERO(30), FLD00160
9, SKIN(200), TSIG0(200), TVX(30), TTEXT(30), TAP1(200), TAP2(200), TAP3(200), FLD00170
10, U(201,2), USQ(201), VZERO(30), VI(200,2), VISCONS(200), XI(201,2), XI(200), FLD00180
11, ZMASS(200), PC(30), TO(30), AMOL(30), DUMVAR(500,5), FLD00190
12, DLAMDA=DTMIN(NPLHAF)
13, M=INTERJ(31)
14, IF(SIGMAX.EQ.0.0) GO TO 240

SIGMIN=1./SIGMAX
GO TO 244

240 SIGMIN=0.0
244 IF(SIGMIN-7.41*TMINSQ(NPLHAF)) 270, 270, 250
250 IF(DLAMAX-0.79) 255, 270, 270
255 IF(SIGMIN-11.11*TMINSQ(NPLHAF)) 265, 260, 260
260 IF(DLAMAX-0.65) 270, 270, 265
265 TMINSQ(NPL3HF)=TMINSQ(NPLHAF)
GO TO 205
270 IF(DLAMAX.-0.01) 275, 275, 280
275 TMINSQ(NPL3HF)=SIGMIN/2.25
GO TO 285
280 TMINSQ(NPL3HF)=AMIN1(SIGMIN/9.00, .005184*TMINSQ(NPLHAF)/DLAMAX**2)
285 DTMIN(NPL3HF)=AMIN1(SIG0AT(TMINSQ(NPL3HF)),1.4*DTMIN(NPLHAF))
290 DTMIN(NPLHAF)=(DTMIN(NPL3HF)+DTMIN(NPLHAF))/2.

NP=PLUS1
PLUS1=N
NPLHAF=NPLUS1
N=N
NMMHAF=N
NPLH3F=N
EINSUM=0.
ESUM=0.
EKSUM=0.
USQ(1)=U(1,N)**2
DO 350 I=1,IMAX
EINT(I)=0.
EKN(I)=0.
JMIN=INTERJ(I)
JMAX=INTERJ(I+1)-1
DO 295 J=JMIN,JMAX
JPLHAF=J
USQ(J+1)=U(J+1,N)**2
X1(JPLHAF) = (X(J,N)+X(J+1,N))/2.
EINT(I)=EINT(I)+E(JPLHAF,N)/HALFPO(I)*HALF(JPLHAF)
295 EKN(I)=(USQ(J)+USQ(J+1))*HALF(JPLHAF) +EKN(I)
EKN(I)=.5*EKN(I)
EINSUM=EINSUM+EINT(I)
EKN(6)=.5*EMPROJ*U(JLAST;NMHAF)**2+EKN(6)
EKSUM=.5*EMPOJ*U(JLAST;NMHAF)**2*EKSUM
300 EKSUM=EKSUM+EKIN(I)
ESUM=EINSUM+EKSUM
IF(NCHEKE) 301,305,301
301 IF(ABS(ETOT-ESUM)-ETENTH) 305,305,302
302 EWRCNG=1.
CALL OUTPUT
305 IF(JPRJ=400) 306,306,307
307 JPRJ=300
PRINT=TMAX2
TNEXT=T+TPRINT
CALL OUTPUT
GO TO 121
306 IF(TNEXT-T) 315,315,121
315 CALL OUTPUT
316 TNEXT=TNEXT+TPRINT
IF(TMAX-TNEXT+CO1)320,121,121
320 TNEXT=TNEXT-TPRINT
TPRINT=OUTDT2
TNEXT=TNEXT+TPRINT
TMAX=.5*TMAX
121 IF(XSTEP-X(JLAST,NPLUS1)) 556,555,555
556 CALL OUTPUT
557 RETURN
END
SUBROUTINE OUTPUT

PRINTS OUTPUT PARAMETERS

COMMON PCON3, SLOPE, RADIUS, CALPgm, TBURND, GMSpDR, GASpRS, IHEL
COMMON AREA1, AREA2, AREA3, AREA, COSX4, CAXX, COS, COSMAX, CP, CV, DLAMAX OUTP 0030
1, DTMIN, DUTD, DLMADA, DSQ, DLTAIL, DLAST1, DJLAST, DNZONE, DELX, DMU, DPDE, OUTP 0040
2, DPDMU, DQ1, DQ2, DS, EZERFO, FINSUM, ESUM, EKSUM, EINT, EKIN, E, ETOT, ETENTH, OUTP 0050
3, JERONG, EL, EXCE, GAMMA, HALFM, HALFRO, HYRD1, HYRD2, HYRD3, HYRAD, OUTP 0060
4, OUTD1, OUTD2, PCON1, PCON2, PLUS0, P, P1, P2, RZERFO, SPMR, OUTP 0070
5, STGMAX, SIGMIN, SKIN, TMGIN, TMAX, TMAX2, TVD2, TMAX, TSIGSO, TNEXT, OUTP 0080
6, TPFINT, TVNEXT, TMINSQ, TFREQ, UZERFO, USQ, TBAR, TVREL1, THETA, TWALL, OUTP 0090
7, VZERFO, V, VOLUME, VISCONS, X, XI, XCRID, XMIN, XMAX, ZMASS, EMPROJ, XSTOP
COMMON IMAK, INU, I, INP, INDEX, LIMIT, JPROJ1, JPROJ2, JMIN, JMAX, J OUTP 0100
1, LPJLHAF, JLJHAF, JLAST, JLAST1, JLAST2, JLAST3, KL, MACHQ, NDATER1, NDATER2, OUTP 0110
2, NDATER3, NUMBER, NT, TV, NCHER, NEQST, NZONES, NCYCLE, NL, NMNHAF, NPLUS1, OUTP 0120
3, NPLHAF, NL, NPL3HR, NP, IQUIT, JPROJ, JSTOP, P, EMPST, PO, TO, AMOL, DUMVAR OUTP 0130
DIMENSION AAREA(200, 2), COSX4(30), DMAX(200), C(200), CP(30), CV(30), OUTP 0140
1DTMIN(3), DLMADA(240), DSQ(200), DELX(301), DQ1(200), DQ2(200), DS(200), OUTP 0150
2EZERFO(301), EL(200, 2), EINT(301), EKIN(301), FORCE(200), GAMMA(30), OUTP 0160
3HALF(200), HALFR(300), HYRAD(200), INTERJ(31), MAXSQ(200), NEQST(30) OUTP 0170
4, NZONES(30), OUTFDY(30), PPLUSO(200), P(200, 2), Q(200, 2), RZERFO(30), OUTP 0180
5SKIN(200), TSIGSO(200), TMINSQ, TVREL, THET4(200), UZERFO, OUTP 0190
6U(200), V(200), Z(200), VISCONS, X(200), XI(200), OUTP 0200
7VZERFO(200), PO(30), PO(30), AMOL(30), DUMVAR(500, 5) OUTP 0210
DIMENSION XP(200), PP5(200), XP6(200), VP6(200), OUTP 0220
M=INTERJ(31)
LIMIT = IMAX
49 WRITE(K, 11K, NUMBER, NDATER1, NDATER2, NDATER3 OUTP 0230
51 WRITE(K, 12)
52 WRITE(K, 12) NCYCLE, T, DTLAST, ESUM IF(NCYCLE) 53, 54, 400
53 DD 57 JPLHAF=1, JLAST1
57 ZMASS(JPLHAF)=2.*HALFM(JPLHAF) OUTP 0240
60 WRITE(K, 2)
61 WRITE(K, 3)
DO 505 L=1, JLAST1
DO 602 L2=2, LIMIT
62 CONTINUE
WRITE(K, 4) L, X(L, N), U(L, NMNHAF), V(L, N), PPLUSQ(L), Q(L, NMNHAF),
1E(L, N), AREA(L, N), DTSQ(L), ZMASS(L)
GO TO 604
603 WRITE(K, 5) 5556
5556 FORMAT(1H0)
WRITE(K, 4) L, X(L, N), U(L, NMNHAF), V(L, N), PPLUSQ(L), Q(L, NMNHAF),
1E(L, N), AREA(L, N), DTSQ(L), ZMASS(L)
604 CONTINUE
WRITE(K, 4) JLAST, XI(JLAST, N), U(JLAST, NMNHAF) OUTP 0470
GO TO 71
400 NYDRA2 = HYDRD2
IF((NYDRA2, EQ.0) OR((NYDRA2-60), EQ.0) OR((NYDRA2-30), EQ.0))
1 GO TO 100
IF((NYDRA2, GT.30) AND (NYDRA2, LT.60)) GO TO 300
IF(NYDRA2, GT.60) GO TO 600
MN = 1
MZN = INTERJ(NYDRA2 +1) - 1
GO TO 200
300 NYDRA2 = NYDRA2 - 30
MN = INTERJ(NYDRA2)
MZN = INTERJ(NYDRA2 +1) - 1
GO TO 200
600 NYDRA2 = NYDRA2 - 60
MN = INTERJ(NYDRA2)
MZN = JLAST1
200 DO 70 JK = MN, MZN
JKM = JK - MN + 1
XP6(JKM) = X1(JK)
VP6(JKM) = U(JK, NMNHAF) / 100.
XP5(JKM) = X1(JK)
70 PP5(JKM) = PPLUSQ(JK)
100 CONTINUE
WRITE (M, 7)
WRITE (M, 8)
WRITE (M, 5555)
DO 704 L = 1, JLAST1
GO TO 702 IF(L = 1) IL = 2, ILIMIT
702 CONTINUE
WRITE (M, 4) L, X(L, N), U(L, NMNHAF), V(L, N), PPLUSQ(L), Q(L, NMNHAF),
1E(L, N), AREA(L, N), DTSQ(L), X1(L)
GO TO 704
703 WRITE (M, 5555)
5555 FORMAT (1H7)
WRITE (M, 4) L, X(L, N), U(L, NMNHAF), V(L, N), PPLUSQ(L), Q(L, NMNHAF),
1E(L, N), AREA(L, N), DT SQ(L), X1(L)
704 CONTINUE
WRITE (M, 4) JLAST, X(JLAST, N), U(JLAST, NMNHAF)
71 WRITE (M, 9)
75 WRITE (M, 10) (I, NEQST(I), EKIN(I), EINT(I), I = 1, I = MAX)
WRITE (M, 6) NCYCLE, T, DTLAST, ESUM
WRITE (M, 9)
5 FORMAT (1H1)
IF (EVRCNG) 95, 95, 80
80 WRITE (M, 11)
95 RETURN
40 FORMAT (115, 1P7E13.5)
SUBROUTINE ZERO(I1, I2, I3, I4, I5, I6, I7, I8)
C
ZEROS INTEGERS
I1 = 0
I2 = 0
I3 = 0
I4 = 0
I5 = 0
I6 = 0
I7 = 0
I8 = 0
RETURN
END

SUBROUTINE ZERO(Z1, Z2, Z3, Z4, Z5, Z6, Z7, Z8)
C
ZEROS NCN-Integers
Z1 = 0.
Z2 = 0.
Z3 = 0.
Z4 = 0.
Z5 = 0.
Z6 = 0.
Z7 = 0.
Z8 = 0.
RETURN
END

SUBROUTINE ZEROA(ZA1, ZA2, ZA3, ZA4, ZA5)
C
ZEROS VECTORS
DIMENSION ZA1(300), ZA2(300), ZA3(300), ZA4(300), ZA5(300)
DO 1 IZZ = 1, IZA
ZA1(IZZ) = 0.
ZA2(IZZ) = 0.
ZA3(IZZ) = 0.
ZA4(IZZ) = 0.
ZA5(IZZ) = 0.
1 CONTINUE
RETURN
END

SUBROUTINE ZEROB(ZAB, IZA, JZB)
C
ZEROS APAYS
DIMENSION ZAB(300, 10)
DO 2 IZZ = 1, IZA
X(JMAX+1,N)=OUTBOY(I)
U(JMAX+1,NMNHAF)=UZERO(I)
E(JMAX,N)=EZERO(I)
55 V(JMAX,N)=VZERO(I)
DO 132 J=1,JLAST
132 CALL ARCCMP
65 DO 130 I=1,IMAX
JMIN=INTERJ(I)+1
JMAX=INTERJ(I+1)
DO 125 J=JMIN,JMAX
120 CALL VCOMP
HALFM(JMNHF)=HALFRO(I)/V(JMNHF,N)*VOLUME
125 CONTINUE
HALFM(JLAST)=HALF(JLAST)+EMPROJ
INDEX=NEQST(I)
IF (INDEX.EQ.1) CALL EQUEST
IF (INDEX.EQ.2) CALL EQUEST2
IF (INDEX.EQ.3) CALL EQUEST3
130 CONTINUE
DO 135 JMNHF=1,JLAST1
135 PPLUSQ(JMNHF)=P(JMNHF,N)
150 DK=1.
DK1=2.
155 EINSUM=0.
EKSUM=0.
ETOT=0.
USQ(I)=U(I,N)**2
DO 165 I=1,IMAX
EINT(I)=0.
EKIN(I)=0.
JMIN=INTERJ(I)
JMAX=INTERJ(I+1)-1
DO 160 J=JMIN,JMAX
JPLHF=A
USQ(J+1)=U(J+1,N)**2
EINT(I)=EINT(I)+E(JPLHF,N)/HALFRO(I)*HALF(JPLHF)*DK
160 EKIN(I)=(USQ(J)+USQ(J+1))*HALF(JPLHF)*DK+EKIN(I)
EKIN(I)=.5*EKIN(I)
EINSUM=EINSUM+EINT(I)
165 EKSUM=EKSUM+EKIN(I)
ETOT=ETOT+EKSUM
ETX=ETOT+ETOT
ETX=1.*ETOT
175 XGRID=.125*(X(JMAX,N)-X(1,N))
XMN=X(1,N)-XGRID
XMAX=X(JMAX,N)+XGRID
180 CALL OUTPUT
SUBROUTINE DYNMEQ
C CALCULATES MASS POINT VELOCITY AND ZONE SPECIFIC VOLUME AND
C BOUNDARIES
COMMON PCGN3, SLOPE, RADIUS, CALPCH, TBUPN, GMSPDR, GASPR, IHEL
COMMON AREA1, AREA2, AREA3, AREA4, CSQX4, CMAXR, CSQ, CSQMAX, CP, CV, DLAMA
COMMON DTMIN, DUDT, DLAMDA, DTSQ, DTLAST, DLAST1, DTLAST, ONZONE, DELX, OMU, DPE
COMMON DODU, DDT, DDO1, DDO2, DDT2, DZER0, DZER, EINSUM, ESUM, EINT, EKT, EUT, ETENTH
COMMON C2, C3, XMAX, YMAX, ZMAX
DATA D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11, D12, D13, D14, D15, D16, D17, D18, D19
10 D1 = 0.0, D2 = 0.0, D3 = 0.0, D4 = 0.0, D5 = 0.0, D6 = 0.0, D7 = 0.0, D8 = 0.0, D9 = 0.0, D10 = 0.0, D11 = 0.0, D12 = 0.0, D13 = 0.0, D14 = 0.0, D15 = 0.0, D16 = 0.0, D17 = 0.0, D18 = 0.0, D19 = 0.0

C 120 I = 1
C 125 DLAMA = 0.0
C 126 SIGMAX = 0.0
C 127 NCYC1 = NCYC1 + 1
C 128 DO 245 T = 1, TMAX
C 130 N2 = N2 + 1
C 131 CMAXR(I) = 0.
C 132 CSQX4(I) = 0.
C 133 JMIN = INTERJ(I) + 1
C 134 JMAX = INTERJ(I) + 1
C 135 DO 230 J = JMIN, JMAX
C 136 IF(JLAST = J) 155, 155, 1700
C 137 IF(JPDRJ = EQ, 300) Go to 1755
C 138 IF(J = EQ, INTERJ(6)) Go to 901
C 139 IF(J = GT, INTERJ(6)) Go to 902
C 140 GO TO 1755
C 141 IF(PPLUSQ(JMNHAF) = -SHPR) 902, 903, 904
C 142 GO TO 245
C 143 IF(JPDRJ = EQ, 300) Go to 1755
C 144 IF(J = EQ, INTERJ(6)) Go to 901
C 145 IF(J = GT, INTERJ(6)) Go to 902
C 146 GO TO 1755
C 147 IF(PPLUSQ(JMNHAF) = -SHPR) 902, 903, 904
C 148 GO TO 245
VOLUME = (X(J, NPLUS1) - X(J-1, NPLUS1)) * AREA3
RETURN
END
SUBROUTINE EQST1
C CALCULATES PRESSURE AND ENERGY FOR IDEAL GAS ZONES
COMMON PCOND, SLOPE, RADIUS, CALPGM, TBURND, GMSDOR, GASPRS, IHEL,
COMMON AREA1, AREA2, AREA3, APEA, COSQX4, CMAR, CSQ, CSQMA, CP, CV, DLAMAX,EQS10030
1, OTMIN, ODINT, DLAMDA, DTSQ, DTALAST, DLAST1, DJLAST, DNZONE, DELX, DMU, DPDE, EQS10040
2DPDMU, DQ1, DQ2, DS, EZERO, EINSUM, ESUM, EKSUM, EINT, EKIN, E, ETCT, ETENTH,
3EWRONG, EI, FORCE, GAMMA, HALFM, HALP0, HYDRD1, HYDRD2, HYDRD3, HYDRAD,
4OUTBDY, OUTDT1, PCON1, PCON2, PLUSO, P, P1, Q, ROZERO, SHPR,
5SIGMAX, SIGMIN, SKIN, TMAX1, TMAX2, TVD1, TVD2, T, TMAX, TSIGSO, TNEXT,
6TPRINT, TVNEXT, TMINSO, TFREQ, UZERO, V, USO, TBAP, TVCRE1, THETA, TWALL,
7VZERO, V, VCLUME, VISQOS, X, X1, XGRID, XMIN, XMAX, ZMMASS, EMPROI, XSTOP,
COMMON IMAX, INU, INTERJ, INDEX, LIMIT, JPR0J1, JPR0J2, JMIN, JMAX, J,
1JPLHAF, JMNNHAF, JLAST, JLAST1, JMIN1, JMAX1, K, L, MACHSO, NDATE1, NDAT2,
2NDATE3, NUMBER, NT, V, NCHEKE, NEQST, NZONES, NCYCLE, N, NMNHAF, NPLUS1,
3NPLHAF, NN, NPL3HAF, NP, QUIOT, JPR0J, JSSTOP, E, EMPIST, PD, TC, AMOL, DUMVAR,
DIMENSION AREA(200,2), COSQX4(30), CMAR(30), CSQ(200), CP(30), CV(30), EQS10140
1DIM(3), DLAMDA(200), DTSQ(200), DELX(30), DQ1(200), DQ2(200), DS(200), EQS10150
2EZERO1(30), EI(200,2), EINT(30), EKIN(30), FORC(200), GAMMA(30),
3HALF(200), HALP0(30), HYDRAD(30), INTER(31), MACHSO(200), NEQST(30), EQS10160
4NZONE(30), OUTBDY(30), PLUSO(200), P(200,2), Q(200,2), ROZERO(30),
5SIGMA(200), SIGMIN(200), SKIN(30), TMAX1(30), TFREQ(30), THETA(200), UZERO(30),
6USO(201,2), USO(201), VZERO(30), V(200,2), VISQOS(200), X(201,2), X1(201,2),
7ZMMASS(200), PO3(30), PO3130), AMOL(30), DUMVAR(500,5)
JMIN1=JMIN-1
JMAX1=JMAX-1
10DO 10 JMNHAF=JMIN1, JMAX1
E1=E(JMNHAF,N)-(P(JMNHAF,N)+Q(JMNHAF,NPLHAF))*(V(JMNHAF,NPLUS1)-
1V(JMNHAF,N))
11P1=E1*GAMMA(1)-1.0)/V(JMNHAF,NPLUS1)
12E(JMNHAF,NPLUS1)=E1+5*(P1-P(JMNHAF,N))*V(JMNHAF,NPLUS1)-
1V(JMNHAF,N))
13P(JMNHAF,NPLUS1)=E(JMNHAF,NPLUS1)*GAMMA(1)-1.0)/V(JMNHAF,NPLUS1)
14RETURN
END
SUBROUTINE EQST2
CALCULATES PRESSURE AND ENERGY FOR NON-IDEAL GAS ZONES
COMMON PCCN3, SLOPE, RADII, CALPGM, TBURND, GMSDP0, GASPRS, IHELO
COMMON AREA1, AREA2, AREA3, AREA4, CQSQX4, CMAXP, CSQ, CSQMAX, CP, CV, DLAMAXEQ
1, DTHIN, DUDMA, DTSQ, DTLAST, DLA1ST, DDLAST, DKZONE, DELX, DMU, DPDE, EOS20040
2, DPDMP, E01, D02, DS, EZERO, EINSUM, ESUM, EKSUM, EINT, EKN, ETOT, ETENTH, EOS20050
3, EWRONG, E1, FCCE, GAMMA, HALFM, HALFQ, HYDRD, HYDR2, HYDPD, HYDRA, EOS20060
4, OUTBDY, OUTD1, PCON1, PCON2, PLLUSQ, PI, Q, ROZERO, SHPR,
5, SMAX, SMIN, TMAX1, TMAX2, TSVOL, TWD', TMAX, TSIG, TNEXT, EOS20070
6, TPINT, TVNEXT, TINSQ, TVFREQ, UZERO, USQ, TBAR, TOFREI, THEA, TWALL, EOS20090
7, TVZERO, VOLUME, VISCO, X, XI, XGRID, XMIX, XMAX, XMMASS, EMPROJ, XSTOP, EOS20100
COMMON IMAX, INU, I, INTERJ, INDEX, ILIMIT, IPROJ, IPROJ2, JMIN, JMAX, J, EOS20110
1, IPQLAF, JMNHAF, JLAST, JLAST1, JMIN1, JMAX1, K, L, MACHSQ, NDATE1, NDATE2,
2, NDATEx3, NUMBER, KT, NCHKE, NEST, NzONES, NCYCLE, N, NMNHAF, NPLUS1,
3, NPLHAF, NUM, NPL3HF, NP, NQUIT, JSTOP, P, EMPLST, PD, TO, AMOL, DUMVAR, EOS20130
4, DIMENSION AREA(200, 2), CQSQX4(30), CMAXR(30), CSQ(200), CP(30), CV(30), EOS20150
1, DTMIN(3), DLAMDA(200), DTSQ(30), DELX(30), D01(200), D02(200), DS(200), EOS20160
2, EZEFO(30), E(200, 2), EINT(30), EKIN(30), FORCE(20), GAMMA(30), EOS20170
3, HALFIP(200), HALFPF(301), HYDRD(200), INTERJ(31), MACHSQ(200), NEQST(30), EOS20180
4, NPOINTS(30), OUTBDY(30), PLLUSQ(200), P(200, 2), Q(200, 2), ROZERO(30), EOS20190
5, SFLXN1(200), TSIGSQ(200), TINSQ(20), TVFREQ1(20), THEA(200), UZERO(30), EOS20200
6, U(201, 2), USQ(201), VZERO(30), V(200, 2), VISCO(200), X(201, 2), X1(200), EOS20210
7, MA3S(200), P(30), T(30), AMOL(30), DUMVAR(500, 5)
IF (NCYCLE.EQ.0) T = 0.0
IF (T.GT. 0.999999) GO TO 3
IF (INTERJ(30) .LT. 1) GO TO 3
1 NCHKE = 0
2 TBURND = 0
3 TOLD = 0.
4 INTERJ(30) = 2.
5 ZMAS(200) = 2.
6 GASPRS = GASPRS/14.5
7 PVOL = GMSDP0/1000.
8 GVOL = PCCN1*AREA1*0.01-PVOL
9 GMOLK = GASPRS*GVOL/24.61
10 PMOLEK = GMSDP0/125.
11 PRESUR = (GMOLK+PMOLEK)*24.61/(GVOL+PVOL)*1.0136
12 IF (THERM.EQ.0) GO TO 35
35 GAMMA(I) = (GMOLK*1.667+PMOLEK*1.23)/(GMOLK+PMOLEK)
36 WGTOL = GMOLK*4.0026+PMOLEK*125.0)/(GMOLK+PMOLEK)
37 GO TO 50
40 GAMMA(I) = (GMOLK*1.4+PMOLEK*1.23)/(GMOLK+PMOLEK)
41 WGMOLK = GMOLK*2.4+PMOLEK*125.0)/(GMOLK+PMOLEK)
42 GO TO 50
50 SPCVOL = 83.17300.0/(PRESUR*WGMOLK)
51 ROZERO(I) = WGMOLK/22400.
52 VZERO(I) = SPCVOL*ROZERO(I)
53 JMIN1 = JMIN-1
54
INPUT FORMAT

CARD 1 (413, F10.0)

IDATA = 0; STANDARD 18 CARD INPUT
        = 1; NAMELIST INPUT OF ALL VARIABLES ON CARDS
IPRINTZ = 0; STANDARD RUN
           = 1; PRINT OUT INITIAL DATA ONLY
INTRNSF = 0; USE DISK SCRATCH FILE AND PRINTOUT ONLY LAST PISTON
           ITERATION
           = 1; PRINT OUT ALL PISTON ITERATIONS (HYPERVELOCITY MODEL ONLY)
IPUNCH = 0; NO PUNCHED OUTPUT
          = 1; PUNCHED OUTPUT OF MODEL BASE PRESSURE VS TIME
DTSQ(199)   FINITE BREAK VALVE OPENING TIME

CARD 2 (2013)

IMAX = NUMBER OF REGIONS (UP TO SIX)
NCATE1 = MONTH
NCATE2 = DAY
NDATE3 = YEAR
NUMBER = RUN IDENTIFICATION NUMBER
NCHKE = 0; NO ENERGY CHECK
        = 1; ENERGY MONITORED AND PROBLEM STOPPED IF THE TOTAL ENERGY
        CHANGES BY MORE THAN 10%
INU = 0; ALL ZONES HAVE ZERO INITIAL VELOCITY
       = 1; ALLOWS INITIAL VELOCITY FOR EACH ZONE TO BE READ
JPROJ = MASS POINT NUMBER OF PROJECTILE
CARD 3 (2013)
NEQST(I) = NUMBER OR INDEX OF EQUATION OF STATE USED IN REGION I

CARD 4 (2013)
NZONES(I) = NUMBER OF ZONES IN REGION I

CARD 5 (7F10.0)
OUTBDY(I) = DISTANCE IN CM TO OUTER INTERFACE OF REGION I

CARD 6 (7F10.0)
GAMMA(I) = RATIO OF SPECIFIC HEATS FOR REGION I

CARD 7 (7F10.0)
CQSQX4(I) = CONSTANT USED IN ARTIFICIAL VISCOITY COMPUTATION (GOOD VALUES ARE 4.0 FOR GAS REGION, 9.0 FOR SOLID REGION)

CARD 8 (7F10.0)
AREA1 = AREA IN SQ CM OF FIRST CONSTANT AREA SECTION (PROGRAM ALLOWS UP TO THREE DIFFERENT CONSTANT AREA SECTIONS AND ONE TAPERED SECTION BETWEEN THE SECOND AND THIRD CONSTANT AREA SECTIONS)
AREA2 = AREA IN SQ CM OF SECOND CONSTANT AREA SECTION
AREA3 = AREA IN SQ CM OF THIRD CONSTANT AREA SECTION
PCON1 = POSITION IN CM WHERE FIRST AREA CHANGE OCCURS
PCON2 = POSITION IN CM WHERE SECOND AREA CHANGE OCCURS
SHPR = PROJECTILE RELEASE PRESSURE IN BARS
EMPROJ = MASS OF PROJECTILE IN GRAMS
OUTDT1 = DELTA T FOR PRINTING UP TO TIME TMAX1
TMAX1 = MILLISECS
OUTDT2 = DELTA T FOR PRINTING UP TO TIME TMAX2
TMAX2 = MILLISECS
XSTOP = POSITION IN CM THAT WHEN THE INTERFACE JSTOP REACHES IT,
THE PROBLEM IS TERMINATED

CARD 9  (7F10.0)  REQUIRED ONLY IF INU = 1
UZERO(I) = INITIAL VELOCITY FOR EACH ZONE

CARD 10  (7F10.0)
PCON = POSITION IN CM WHERE THIRD AREA CHANGE OCCURS
SLOPE = SLOPE OF CONSTANT TAPERED SECTION
RADIUS = RADIUS IN CM OF THE CONSTANT AREA SECTION TO THE RIGHT
OF THE TAPERED SECTION

CARD 11  (4F10.0,I4)
CALPGM = CALORIES PERGRAM OF POWDER
TBURND = TIME TO BURN POWDER
GMSPDR = GRAMS OF POWDER
GASPRS = INITIAL GAS PRESSURE IN POWDER REGION
IHEL= 0  (NOT APPLICABLE TO GPN PROJECT)
CARD 12 (7F10.0)

IPOX = 0  ALL PLOTS, ALL PRESSURE POINTS (PLOT ROUTINE MUST BE INCLUDED)
= 1  ALL PLOTS, NO PRESSURE POINTS
= 5  NO PLOTS, NO PRESSURE POINTS
= 6  ONLY PRESSURE POINTS

NPOX = NUMBER OF PRESSURE POINTS (UP TO FIVE)
XPO(I) = X POSITION IN CM OF PRESSURE POINT I

CARD 13 (7F10.0)  HYPERVELOCITY MODEL LAUNCHER PARAMETERS, (NOT APPLICABLE TO GUN PROJECT)

XPV1 = X POSITION IN CM OF FIRST MEASUREMENT POINT OF PISTON VELOCITY
XPV2 = X POSITION IN CM OF SECOND MEASUREMENT POINT OF PISTON VELOCITY
PVERR = PISTON VELOCITY ERROR IN FT PER SEC
PVWANT = DESIRED PISTON VELOCITY IN FT PER SEC

CARD 14 (E10.0,3F10.0)

R = 0.8317E 08  GAS CONSTANT
EMPIST = MASS OF FIRST PISTON SECTION (HYPERVELOCITY MODEL LAUNCHER ONLY)
FRAC = 1.0
EMLEAD = MASS OF SECOND PISTON SECTION (HYPERVELOCITY MODEL LAUNCHER)

CARD 15 (7F10.0)

PO(I) = INITIAL PRESSURE IN PSI IN REGION I

CARD 16 (7F10.0)

TO(I) = INITIAL TEMPERATURE IN DEGREES KELVIN IN REGION I
CARD 17 (7F10.0)
AMUL(1) = MOLECULAR WEIGHT OF MATERIAL IN REGION I

CARD 18 (I3)
ILASTK = 0; STOP, CONTINUE FOR NEW RUN
LIST OF REFERENCES


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Application of holographic interferometry to the exterior ballistic flow field in the muzzle environment of a twenty millimeter cannon.