JPL CONTRACT
NO. 952023
(NAS 7-100)

TRW REPORT NO.
68.4712.2-024
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FINAL REPORT
PRODUCING HOLOGRAMS OF REACTING SPRAYS IN LIQUID PROPELLANT ROCKET ENGINES

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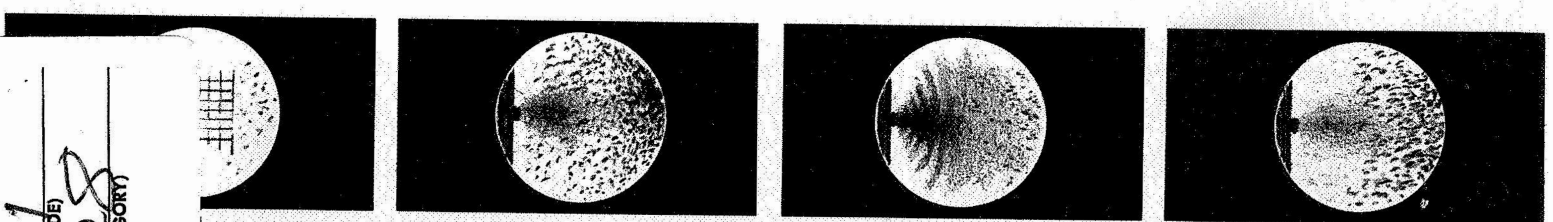

PREPARED FOR
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA
BY
TRW
SYSTEMS GROUP
ONE SPACE PARK · REDONDO BEACH, CALIFORNIA

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Producing Holograms Of Reacting Sprays In Liquid Propellant Rocket Engines

R. F. Wuerker
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"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, as sponsored by the National Aeronautics and Space Administration under Contract NAS7-100"

TRW SYSTEMS GROUP

FOREWORD

This final report was prepared for the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. The report was prepared by TRW Systems Group, TRW, Inc., and is submitted in accordance with the provisions of JPL Contract Number 952023.

The program technical effort was initiated in August 1967 and concluded in June 1968. Technical aspects of the contract were administered by Mr. R.S. Rogero, Senior Research Engineer for the Jet Propulsion Laboratory. The Technology Laboratory of TRW's Power System Division was responsible for implementing the contract. The Program Manager was Mr. B.J. Matthews. Dr. R.F. Wuerker of TRW's Physical Electronics Laboratory developed the pulsed laser holography technology and directed the holographic test activities.

Valuable contributions to the development of the holocamera were made by Dr. L.O. Heflinger, Messrs. C.A. Anderson and R.J. Chouinard. Mr. R.A. Briones was responsible for the operation of the holocamera at the JPL Edwards Test Station site. Rocket engine testing and general support to the holographic studies were provided by various Northrop Corporation staff members at the JPL/ETS facility. In particular, the assistance of Messrs. John Short, Robert McKeon, Charles Mayfield, Thomas Egan and William Tibbitts was greatly appreciated. The authors also wish to acknowledge the suggestions and encouragement provided by Messrs. Jack Rupe and Richard Clayton throughout the entire program.

ABSTRACT

A three-phase 10-month experimental program to demonstrate the feasibility of recording transmission holograms of reacting liquid propellant sprays was conducted at the Jet Propulsion Laboratory's Edwards Test Station (JPL/ETS). Holograms and laser-illuminated photographs were successfully recorded of water sprays and of two different propellant combinations: (1) nitrogen tetroxide (N_2O_4) and a 50 percent (by weight) blend of hydrazine (N_2H_4) and unsymmetrical dimenthyhydrazine (UDMH); (2) fuming nitric acid (FNA) and unsymmetrical dimethyhydrazine (UDMH).

Phase I of the program included the design, construction and verification test of a unique two-beam, pulsed ruby laser holocamera. Water spray and open flame holograms were successfully recorded during Phase I to confirm the feasibility of employing this technique to study combustion phenomena. A single element impinging stream injector was used for all atmospheric water flow and reacting spray tests. Both ambient and elevated temperature propellant tests were conducted.

The second and third phases of the test program were concerned with holography of reacting spray combustion in a confined environment. Phase II dealt with the holography of single element injector sprays reacting in 3-inch-diameter acrylic thrust chambers. A windowed 18-inch-diameter thrust chamber and multiple element impinging stream injector were used for the confined combustion tests in Phase III.

In addition to the prescribed test program, various scene-reference beam ratios were investigated to overcome attenuation of the scene light by the combustion phenomena. Some experimentation with chamber window construction was also accomplished during Phase III to minimize erosion to the internal (chamber) surfaces from the combustion processes.

This report describes the design, development and operation of the laser holocamera apparatus together with a discussion of the results of each test phase. A detailed tabulation of test results is appended to this final report.

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ILLUSTRATIONS (Continued)

1. INTRODUCTION

The technique of pulsed laser holography is particularly adapted to recording high velocity events of moderate to very small size. Further, it reproduces in faithful detail, three-dimensional records of these events within a given scene volume. The recording may be subsequently examined with any classical optical instrument to resolutions approaching that available with high quality camera lenses. In addition, holography is a coherent process and can distinguish information in the presence of a strong background of incoherent radiation.

All of the above unique holographic features stem from the fact that it is based upon the recording of a portion of the stationary optical interference pattern which occurs when two beams of coherent light pass through one another. The recorded interference pattern (called a hologram) can then be used to recall the complete scene whenever it is illuminated by a beam which closely approximates one of the original beams. As a result, the recording and examining steps are separated.

Through the years, studies of liquid rocket combustion have been accompanied by a continuing evolution of optical systems designed to further the investigator's understanding of events occurring within the combustor. The application of pulsed laser holography is a natural extension in the development of such instrumentation systems. Toward this end, an experimental program to demonstrate feasibility of producing pulsed ruby laser holograms of reacting liquid rocket propellant sprays was initiated. This program, under the sponsorship of the Jet Propulsion Laboratory, California Institute of Technology, consisted of three phases of work:

- Phase I was concerned with designing and constructing a laser holocamera system and utilizing this apparatus to record holograms of single element impinging stream water sprays and open flame combustion.

- Phase II involved the recording of combustion holograms of single element impinging stream injector elements operating in 3-inch-diameter acrylic combustion chambers.

- Phase III recorded holograms of the combustion phenomena in an 18-inch-diameter rocket engine utilizing a multiple element impinging stream injector.

This report presents all aspects of the technical activities and accomplishments of each program phase.

2. PROGRAM SUMMARY

2.1 PHASE I—OPEN FLAME TESTING

The first phase of the JPL reacting spray holography program was initiated in August 1967. During this portion of the program, a unique two-beam pulsed laser holocamera was designed, constructed and successfully demonstrated.* This demonstration consisted of recording the very first holograms of reacting liquid rocket propellants during open flame tests conducted at JPL's Edwards Test Station (JPL/ETS).

Design, construction and initial checkout of the laser holocamera system was accomplished during the initial four months of the program. In late November 1967, the apparatus was delivered to the JPL-ETS and installed on Test Stand "B". Water flow tests commenced on 30 November and concluded on 6 December 1967. During this period, 24 tests were run outdoors—under full daylight ambient winter desert conditions ($21^{o}F$ minimum). Both holograms and laser-illuminated photographs were recorded of water spray fans from a single impinging stream injector element.

These water flow experiments served as a functional checkout of the holocamera system and provided an opportunity to integrate the camera shuttering and laser output with the rocket test sequence of events. In addition, the water flow spray patterns recorded on the holograms and the laser-illuminated photographs allowed qualitative comparative observations to be made with the subsequent open flame test results.

At the conclusion of the cold flow test program, a total of 14 holograms and 10 laser-illuminated photographs had been attempted. The majority of these recordings were successful in that droplet distribution could be observed in detail.

The open flame portion of the test program began on 21 December 1967 and was completed 7 February 1968. During this period, 49 hologram recordings were made. Two laser-illuminated photographs were

*Design criteria for the holocamera were established by the Phase III requirement to record combustion phenomena in an 18-inch rocket engine.

also attempted; however, equipment malfunctions resulted in the loss of the photographic record in each instance. The test injector for the combustion studies was the same as that used for the water spray holography.

The open flame holographic studies were made of two propellant combinations operating at both ambient and elevated temperatures. The propellant combinations were: (1) Nitrogen Tetroxide (N_2O_4) and a 50 percent (by weight) blend of Hydrazine and Unsymmetrical Dimethylhydrazine (50/50 N_2H_4 - UDMH), and (2) Fuming Nitric Acid (FNA) and Unsymmetrical Dimethylhydrazine (UDMH).

The open flame test holography using N_2O_4 and 50/50 N_2H_4 - UDMH was conducted at ambient propellant temperatures ranging from 46° to 58°F. With the use of propellant conditioning equipment, another series of test firings was made wherein the propellants were conditioned to elevated temperatures of from 81° to 98°F prior to firing. In addition, holograms were recorded of single propellant stream flow (both oxidizer and fuel) from the test injector orifices.

Further open flame holography was accomplished using the FNA-UDMH propellants. A total of 19 holograms were recorded with this propellant combination. Ambient propellant temperatures varied between 35° and 64°F during these tests. With the temperature conditioning equipment in use, elevated propellant temperatures ranged between 94° and 100°F.

Holographic recordings were made from two different viewing stations with respect to the reacting sprays. For the majority of the open flame tests, the reactants were viewed in the region of stream impingement. From this vantage point, it was possible to record the droplet spray pattern from the injector face to a point approximately 7 inches downstream. In addition, several recordings were made of the droplet dispersion at a viewing station about 12 inches downstream of the injector face.

From the viewing station at the impingement point, three different viewing angles were used. In a predominate number of tests, the major axis of the resultant spray fan (fan plane) was observed. Additional tests were run, however, where the viewing angle was that of the minor axis (or edge view) of the resultant spray fan. And finally, a few oblique viewing angles of the spray fan were recorded.

In general, those holograms made at the impingement station of the fan plane and fan edge resulted in the best quality recordings. Holograms made of the downstream droplet dispersion failed to reveal much information. It is not known whether the lack of droplet dispersion detail in the downstream region was due to limited quality of the holograms or simply the nonexistence of liquid droplets at this distance from the injector face.

A detailed review of the Phase I effort is presented in Reference 1. A summary of Phase I, the cold flow and open flame test conditions and holographic results are presented in Tables A-1 and A-2, respectively. Phase I test results for the cold flow and open flame holography are presented in Sections 3.2.1 and 3.2.2, respectively.

2.2 PHASE II—3-INCH CHAMBER TESTS

Phase II involved the holography of reacting liquid propellants in 3-inch (inside) diameter acrylic combustion chambers. The laser holocamera used during Phase I was again used for the 3-inch chamber test program. The apparatus was slightly modified to accommodate the small (acrylic) thrust chambers and to optimize performance (discussed in Section 3.1).

Phase II consisted of 50 separate engine firings, numbered consecutively from B1123-B1172. A total of 33 firings were made using N_2O_4 - 50/50 blend propellants. All but four firings were made with ambient temperature propellants (ranging from approximately 38° to $80^{\circ}F$, depending upon the desert environment). The four elevated temperature propellant runs (conditioning equipment installed) with this propellant combination were made with inlet propellant temperatures between 98° and $106^{\circ}F$.

The remaining tests (17 in number) were made using FNA and UDMH. Ambient and conditioned propellant temperatures for these propellants approximated those tests made with N_2O_4 and 50/50 blend.

In addition to using two propellant combinations and operating at different propellant temperatures, thrust chamber operating conditions (mass flow, mixture ratio and chamber pressure) were varied in an attempt to evaluate the effect of these changes and to improve hologram quality.

Experimentation with the holocamera scene-reference beam ratio was imperative to successful hologram recording. The scene beam was attenuated by as much as a factor of 200 due to heavy erosion of the acrylic chambers.

The Phase II test effort also included two direct laser-illuminated photographs of an open flame test, and one hologram of open flame combustion. Also, two true double-exposed holograms were attempted. Both failed for lack of stability.

The first successful hologram of confined combustion was Run No. B1141. After this, 25 holograms of excellent to satisfactory quality and content were recorded under a wide variety of adverse operating conditions (i.e., run numbers B1141 to B1164, and B1166). Of all the holograms recorded, the following are singled out as being of exceptional quality: B1141 (historically important since it was the first successful recording and served to demonstrate feasibility), B1149, B1150, B1154, B1157, B1158, B1161, B1162, and B1163. The last (B1163) was one in which two 1-inch-diameter flat pyrex windows in a steel chamber were used instead of the normal acrylic cylinders. In addition to the 25 holograms, two photographs (i.e., Runs B1168 and B1169) of combustion within an acrylic chamber were recorded, along with one open flame photograph (B1172) and one open flame hologram (B1171). The latter was almost ruined by fogging (sun, flame-light, or both) caused by the deactivation of the electronic capping shutter. A Fastex camera recording was made prior to the open flame hologram and photographs (Run B1170). For this test, the holocamera capping shutter was deactivated. It was not restored, leading to the fogging of the plate on the subsequent open flame run (B1171).

Documentation of the 50 Phase II firings and holographic test results are summarized in Tables B-1 and B-2. Test results and reconstruction photographs for Phase II are presented in Section 3.2.3 of this report.

2.3 PHASE III—18-INCH CHAMBER TESTS

The Phase III effort began on 7 May 1968 with the installation of the holocamera astride the JPL 18-inch inside diameter rocket test engine. The injector consisted of twenty-four impinging stream unlike doublets arranged in a circular pattern. The test engine was fitted with 3-1/2-inch thick acrylic side windows of 4- x 12-inch aperture. These were internally capped with Pyrex glass plates to minimize erosion and mottling of the unprotected acrylic surfaces by the combustion phenomena.

Twenty runs (numbers B1173 to B1192) were made, of which 15 yielded holograms. Quality of the reconstructed scenes varied from faint to moderately good. The quality was limited in part by the poor surface finish of some of the windows and their condition at the time that the holograms were recorded. Heavy turbulence and/or convection was another reason for poor quality or lack of definition in the reconstruction. A summary tabulation of the Phase III tests is contained in Appendix "C" to this report.

The best holograms were made through the Pyrex-capped windows. The best capping material was Vycor; it neither melted nor cracked under the severe environment of the combustion process. Only one such window configuration was tested due to its cost—an order of a magnitude greater than the same size Pyrex plate. Pure acrylic was, on the other hand, completely useless for viewing purposes due to the heavy erosion and consequent light attenuation.

The engine was fired both with N_2O_4 and 50/50 N_2H_4 - UDMH and with FNA - UDMH a propellant. The best holograms were made with the former, in spite of a tendency for the combustion process to oscillate unstably.

Initial firings of the engine (N_2O_4 and 50/50 N_2H_4-UDMH) showed instabilities so violent that accelerations of 300 g's were measured on the main support column of the holocamera. The mirror mounts of the ruby laser illuminator in the holocamera indicated 30 g's acceleration. The vibration was so severe that proper alignment of the laser could not be satisfactorily maintained. The laser could not be made to emit coincidentally with the engine firing.

Efforts to stabilize the engine lowered the vibration of the holocamera by a factor of 3. In addition, the ruby laser's end mirror mounts were strengthened with some "Dux" wax available at the test site, and by the addition of more mass (in the form of sand bags) to the holocamera. Also, the support frame was modified so that none of the cross braces protruded into the engine exhaust. This combination of improvements made it possible at least to record holograms through the 18-inch-diameter engine. Test firings with Acid-UDMH produced much less combustion roughness and facilitated operation of the holocamera system.

Rocket engine instability conditions imposed vibration and shock loads on all parts of the holocamera as well as the laser. The effect was so severe that roof prism mirrors were chipped along the roof ridge where the two mirror surfaces meet. The second problem was the laser. During this phase (in contrast to Phase I) desert weather became so hot (compared to Phase I and II) that the refrigeration unit could not adequately cool the laser head. As a result, laser performance (and hence, hologram quality) was affected.

In spite of the aforementioned problems and operational difficulties, Phase III demonstrated that transmission holograms could in fact be made of combustion phenomena in an 18-inch-diameter liquid rocket engine.

Reconstruction of the Phase III holograms showed the scenes to be characterized by the extreme turbulence. Looking at a reconstruction, the far edge of the combustion chamber window no longer appears straight, but instead looks ragged and uneven due to thermal convection in the intervening space. The effect was similar to looking across a desert landscape during the heat of the day. Small particle resolution was greatly reduced. In addition, dense and largely opaque clouds were observed near the injector end; these were regions of high attenuation of the laser light.

3. TECHNICAL DISCUSSION

3.1 TEST APPARATUS

In Phase I, a laser illuminated holocamera was constructed for use during all phases of the test program. Some relatively minor modifications were made to the equipment both in the field and between phases to optimize the holocamera operation and accommodate the diverse test hardware. Essentially, the holocamera system as originally designed successfully demonstrated the feasibility of recording liquid rocket combustion phenomena under a variety of conditions. These conditions included the ability to:

- Accomodate and record the unconfined combustion of a single impinging stream injector element, as well as the combustion phenomena within windowed chambers of 3-inch and 18-inch diameters.
- Survive the vibrational loads, thermal environment and corrosive atmosphere encountered in typical rocket test stand operations with earth storable propellants.
- Withstand prolonged exposure to extremely variable desert weather conditions, since the rocket test stand was not enclosed or sheltered.
- Be operated remotely from a console in a blockhouse 500 feet from the rocket test stand.
- Be operated from a "sequence timer" which automatically programmed the events in each test firing.
- Permit alignment and adjustment as well as general maintenance and parts replacement in the field.

The ruby laser holocamera system used throughout the program is shown schematically in Figure 3-1. Critical component design and operation characteristics of the system shown in Figure 3-1 are described in succeeding paragraphs. Installation and system operation at JPL/ETS are also documented. Reconstruction techniques and equipment are presented in the latter portion of this section.

3.1.1 Pulsed Ruby Laser

The investigation carried out during the JPL reacting spray holography program utilized an illuminator constructed at TRW under the

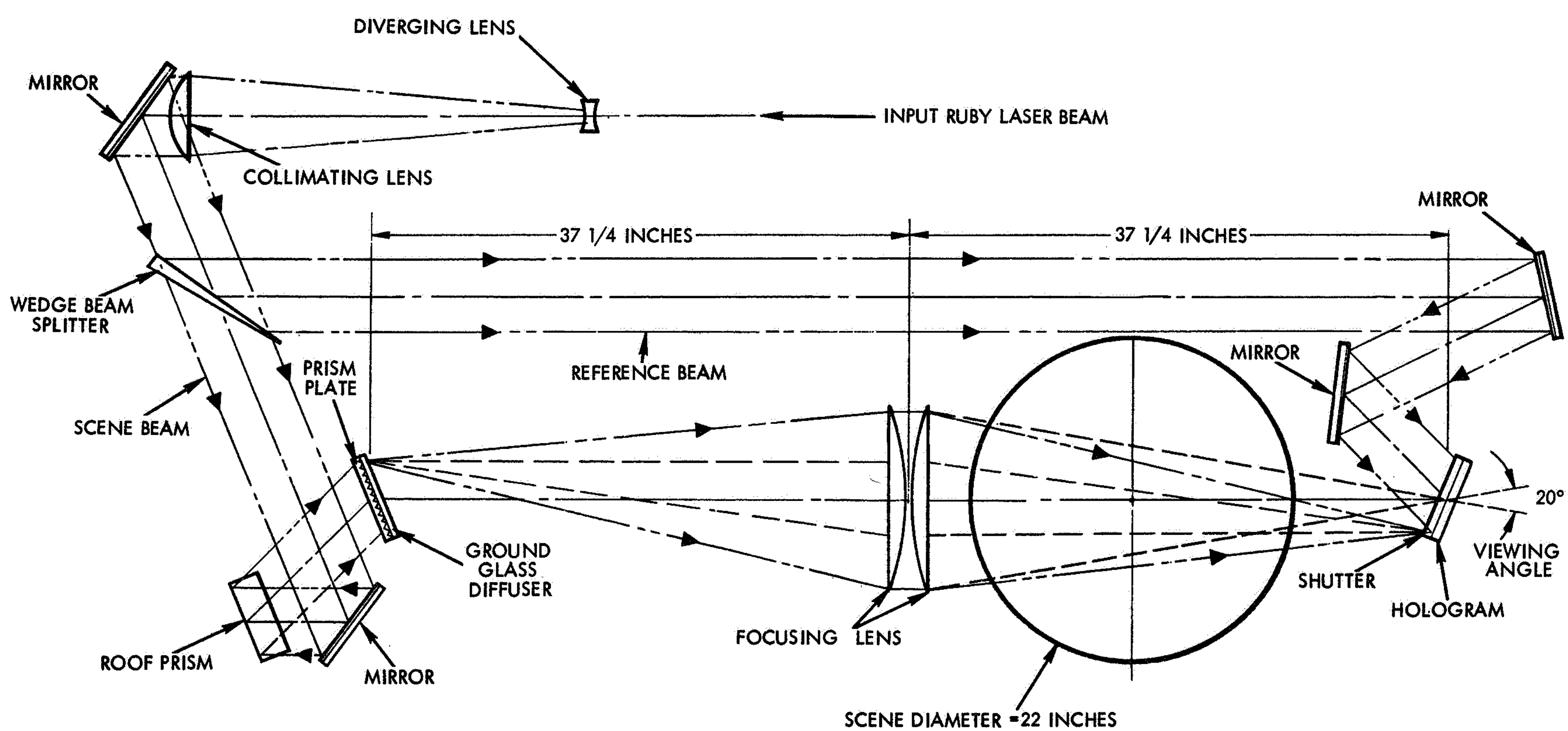


Figure 3-1. Schematic diagram of TRW focused ground glass transmission holocamera design for producing reacting spray holograms

sponsorship of the TRW Independent Research Program. Flexibility, economy, and reliability were major considerations in the design. A schematic of the system is shown in Figure 3-2. The illuminator consists of a Q-switched ruby laser oscillator with flat end mirrors (a 99 percent dielectric coated mirror and a sapphire resonant reflector), a nitrobenzene Kerr cell Q-switch, a Glan polarizing prism, and a 1/2-inch diameter by 3-3/4-inch long 60 degree ruby rod of the highest optical homogeneity.* An aperture was placed within the laser cavity to select the best and most homogeneous area of the laser rod. The laser rod and helical flash lamp are mounted in a water-tight housing and are both cooled by water circulated from a modified drinking fountain chiller. The end mirrors are separated by a distance of ~1.5 meters, the distance being chosen to limit the peak power as well as moderate off-axis mode oscillation which could reduce the spacial coherence. The mirror separation determines the ~30-50 nanosecond pulse duration.

The output of the laser oscillator is directed into a second identical rod which serves as a power amplifier. The water cooling of this unit is in series with the oscillator. The flash lamp is driven from a separate but identical -5KV -375 μF capacitor.

The combination ruby oscillator-amplifier result in a system which emits a single ~1-3 joule - 30-50 nanosecond pulse of 0.69 micron radiation. Spacial coherence has been estimated as ~20 percent of the cross section of the beam, while the temporal coherence is ~4-10 centimeters, depending upon the energy emitted from the system. The combination of an oscillator and an amplifier gives a system which will provide more than enough energy to expose a 4- x 5-inch hologram on Agfa film plate in the holocamera described in the succeeding section.

The extra amplifier provides a reserve of intensity which has been shown to be important. As a result, one can operate the oscillator at reduced levels of power, thereby gaining coherence. In the case of combustion, the phenomena was found to be quite absorptive of the laser beam.

*Union Carbide Corporation, Linde Division, Select Grade Laser Ruby.

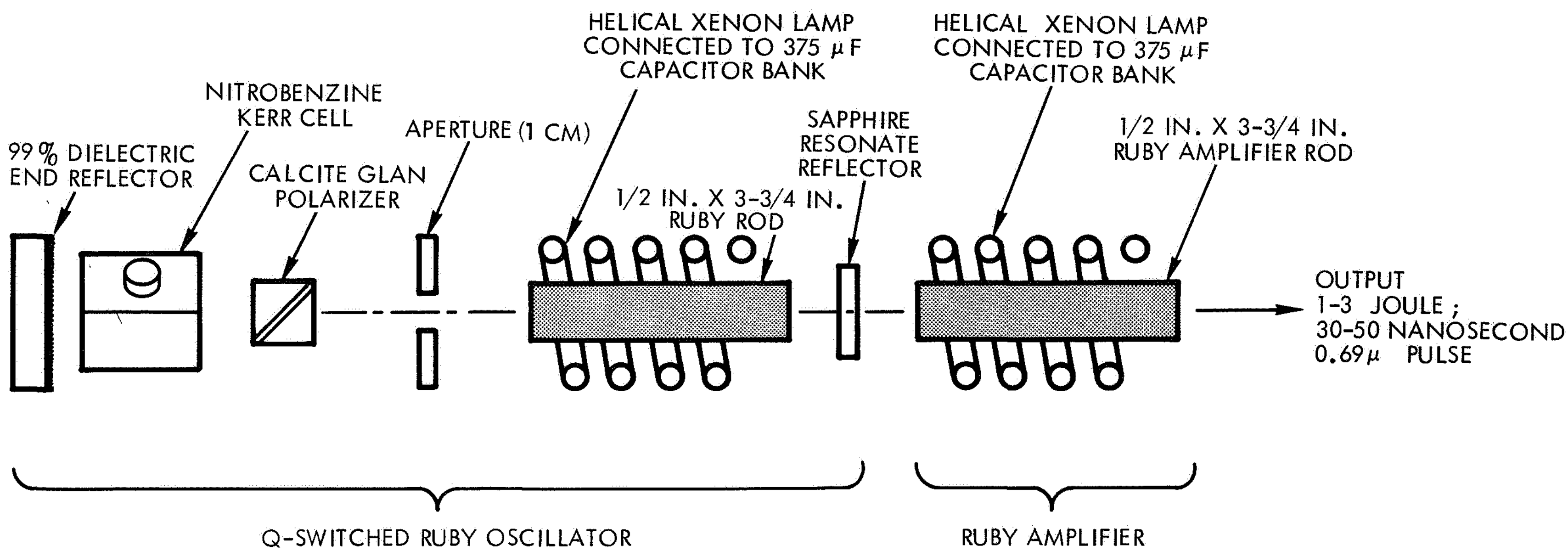


Figure 3-2. Schematic of the ruby laser illuminator used to record holograms of liquid rocket combustion phenomena

The amplifier again provides sufficient reserve to effectively deal with attenuation from the combustion light.

The ruby laser illuminator is operated from a single console which contains two 5 KV - 375μF capacitor banks (for the oscillator and amplifier pump), the Kerr cell electronics, the Kerr cell delay generator, the amplifier delay generator, the capacitor bank charging supply, and the charging controls, and safety interlocks.

The amount of light emitted from the ruby laser illuminator is controlled by the voltage to which the individual capacitor banks are charged. The laser may be fired either manually off a button or by an external trigger input. The current through the helical xenon lamp in the amplifier is started ~0.2 milliseconds after the initiation of current through the oscillator's lamp. This has been proven to optimize the energy gain by the amplifier. The Kerr cell is opened ~1.0 milliseconds after the initiation of oscillator pump current, this time being chosen to minimize the generation of second pulses (~1 percent of the Q-switched pulse). These will follow the "giant pulse" if current still flows through the lamp.

Work under this program led to the development of a remote control console from which functions of charging, stop charge, discharge, and laser firing could be done from another location away from the test stand area (i.e., the block-house at JPL-ETS), a distance of ~500 feet from where the laser was located.

For the tests at JPL-ETS, the ruby laser illuminator was mounted in a galvanized pipe which was attached in turn to the main support column of the holocamera used in the program. The laser functioned throughout the whole program in a relatively trouble-free manner. The original flash lamps were also used throughout.

3.1.2 Holocamera Design

The holocamera has two spacially and temporally matched scene and reference beams as shown in the schematic of Figure 3-1. Spacial matching is achieved by proper use of reflectors, a roof prism, and a large pair of 15-inch diameter condensing lenses. The latter pair of elements takes the light scattered by a ground glass screen and focuses it back onto the hologram. The mirrors and the roof prism insure that each scene ray combines once again with the equivalent reference ray at the plane of the hologram. Temporal matching is achieved by arranging the distances of the mirrors so that after division by the beam splitter, both scene and reference beams travel over the same optical path lengths; the accuracy of the path match is to better than 1/4 inch, well within the temporal coherence limits of the laser illuminator.

Examining the schematic of Figure 3-1 in more detail shows that the beam from the laser is first expanded by a Galilean telescope to a diameter of approximately 5 inches. It is then deflected by a mirror and directed onto a wedge beam splitter. The beam splitter divides the original laser beam into two beams: a horizontally propagating reference beam and a direct beam which propagates at approximately 22 degrees with respect to the vertical. The angle of the wedge is chosen so that the beam reflected from the back surface misses the far mirror, upon which the reference beam (from the front surface) is incident.

The reference beam, after traversing the full length of the holocamera, strikes a mirror which deflects it at approximately 40 degrees relative to the horizontal onto a second mirror. The second mirror then deflects the reference beam into the hologram. The mirror is set so that the reference beam and axis of the condensing lens system are at 45 degrees in respect to one another.

The scene beam, after emerging from the far side of the wedge beam splitter, is incident upon a front surface mirror set at approximately 60 degrees relative to the horizontal. This mirror reflects the light into a roof prism which inverts the beam and directs it onto the "prism plate", set also at an angle of 45 degrees relative to the axis of the condensing lens system. This prismatically-cut plate bends the scene light into the horizontal direction onto a frosted glass plate, which scatters the light into the forward direction into the condensing lens system. The condensing lenses refocus the light (at a 1 to 1 image magnification) onto the hologram. Both the prism plate and the ground glass are canted at 67-1/2 degrees relative to the axis of the condensing lenses.

The hologram itself is a 4- x 5-inch glass photographic plate oriented at 67-1/2 degrees. This angle was chosen so that the normal to the photographic plate bisects the angle between the direction of the reference beam and the axis of the condensing lens system. As a result, the interference pattern between scene and reference beam is perpendicular to the emulsion. Holograms made in this manner are believed to be freer of distortion than those wherein the "blazing" is not perpendicular to the plate.

Since the hologram itself is tilted, the ground glass screen must also be tilted, but in the opposite direction, to insure that the optical path length between the ground glass screen and the hologram is everywhere the same.

The original wedge beam splitter was an uncoated piece of glass. Scene-reference beam ratio was a 1:4. Later in the program it was discovered that this was a fallacious choice. A 1:1 ratio was better. In addition, it was necessary to watch attenuation of the scene beam by the scene. The reference beam had to be adjusted accordingly.

The 4 x 5-inch photographic plate is mounted in a standard photographic plate holder, which is inserted behind a focal plane shutter taken from an antique Graflex camera. The focal plane shutter is a "window shade" shutter arrangement which spans a 4- x 5-inch plate. It was modified for solenoid operation.* A Wratten No. 70 gelatin filter is mounted before the plate to protect it against exposure by the background light, as well as the light generated by the combustion. These filters have a transmission of approximately 75 percent at the 0.694 micron ruby wavelength, and a transmission of 63 percent at 0.65 micron, while at shorter wavelengths (into the visible), the filters are essentially opaque.

In addition to the "window shade" focal plane shutter previously described, a second mechanical shutter was installed. This shutter, termed a "capping shutter", is mounted externally to the viewing window

*Later in the Phase I effort, the stop action was removed, thus keeping the 4- x 5-inch open frame in continuous motion. This cut the ambient exposure of the film by 1/20, but also made tearing of the cloth shutter more probable.

leading to the focal plane shutter and film plate. The capping shutter is solenoid operated and is opened via the sequence timer approximately 0.2 second before the laser is fired. This shutter eliminated all ambient daylight which leaked through the window shade shutter resulting in film fogging. This modification was particularly important for the hot firing tests. During these tests, the dark slide on the film cassette was pulled before all personnel departed the test stand area for the firing. The slide was not replaced until after the test had taken place and the area cleared for personnel to return to the test stand. Typically, this time interval was in the order of twenty minutes. Without the capping shutter, this was a sufficient amount of elapsed time to fog the film plate if the day was bright and clear.

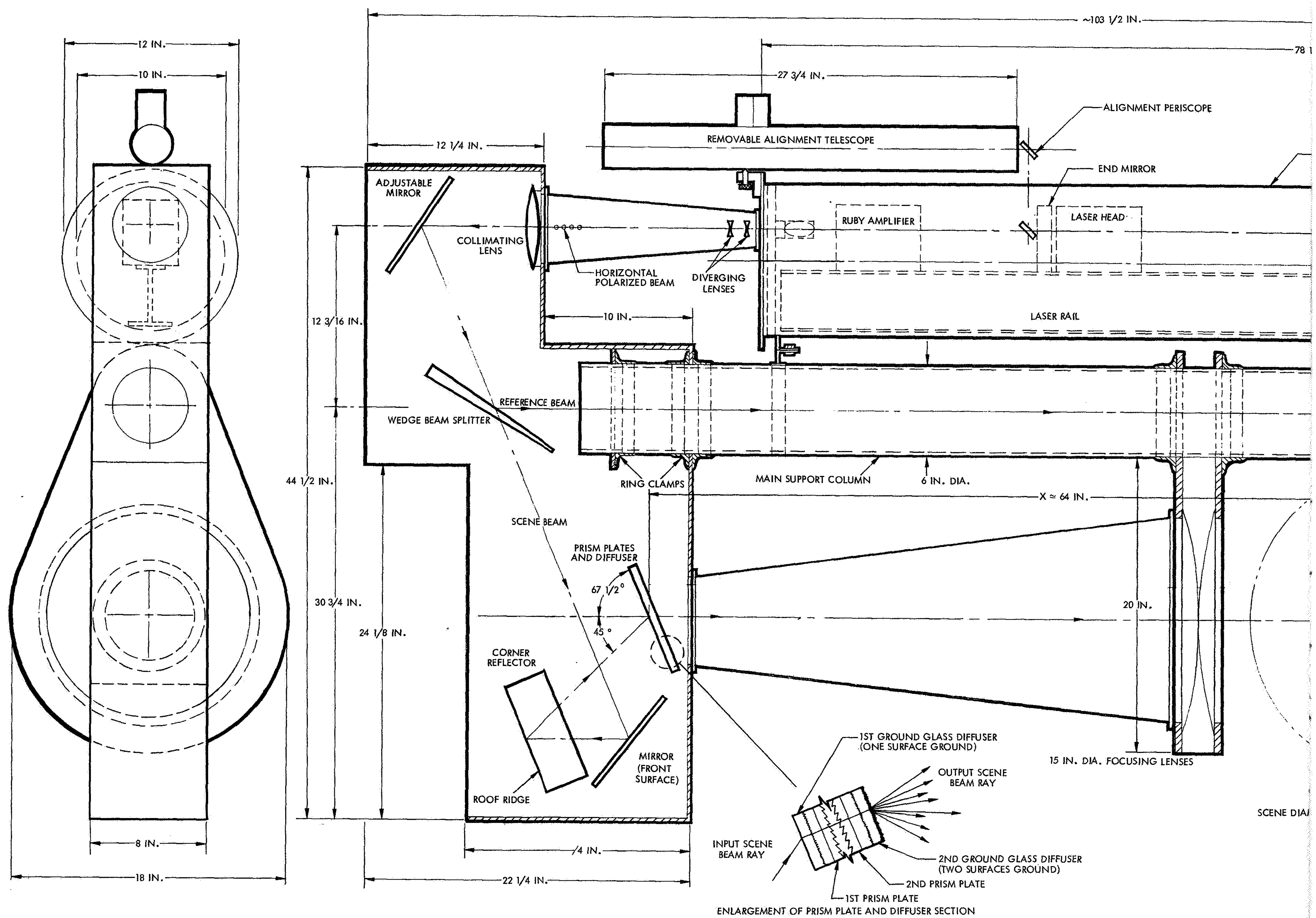
As can be seen from the schematic diagram of Figure 3-1, the reference beam of the holocamera is parallel to the scene beam. This design approach was selected because it eliminates the uncertainties related to the reference beam to be used in reconstructing the hologram. Further, it makes possible the projection of real images (from the hologram) which can then be examined by a high-resolution, short working distance optical microscope. An additional feature of the holocamera design is the ability to replace the condenser lens array by one of shorter focal length, thereby increasing the angular field of the recorded scene at the expense of depth.

3.1.3 Holocamera Construction

Figure 3-3 illustrates the construction layout of the holocamera used for reacting spray holography. The basic structural member of the design is a 6-inch-diameter x 0.125-inch-wall aluminum pipe. This aluminum pipe houses the reference beam. On each end of this aluminum pipe are suspended sheet aluminum housings in which the mirrors, shutter and plate holder, beam splitter, etc., are mounted. In addition, this member supported the 15-inch diameter focusing lenses. These lenses are mounted in an aluminum collar which is attached to the 6-inch-diameter pipe and held in place with clamps.

FOLDOUT FRAME 1

FOLDOUT FRAME 2



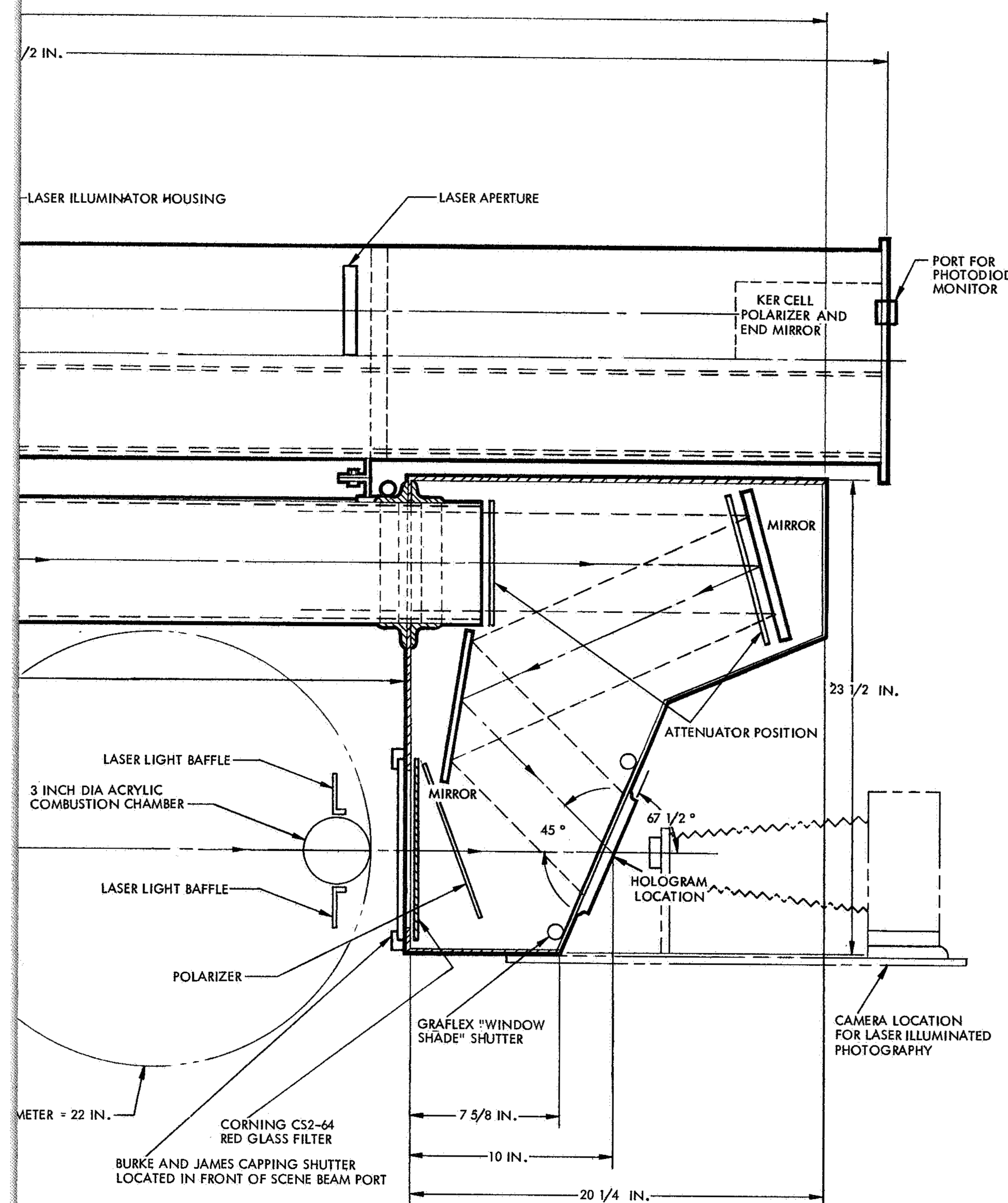


Figure 3-3. Assembly drawing of the laser holocamera used to holograph combustion in a liquid rocket engine

All optical components are precision mounted so that their orientation may be adjusted as required for optical path alignment. In addition, provisions for vibration and shock resistance were incorporated.

This type of construction allows the holocamera to be mounted in a trunion, thus making it possible to rotate the plane of the holocamera parallel to the mounting plates of the injector test element, as it was mounted on the existing JPL rocket test stand. The ability to rotate the holocamera about the axis of the reference beam also minimized the contact of the elements of the holocamera with the products of combustion, particularly during the open flame tests.

The photograph of Figure 3-4 shows the completed holocamera apparatus. This is an overall view of the assembly showing the steel pipe legs used to mount the apparatus in the laboratory. These legs were later modified (at the Edwards Test Site) to position the holocamera at the correct height for each phase of the test program. To the left of the holocamera in Figure 3-4 is the TRW constructed power supply used with the pulsed ruby laser.

Figure 3-5 shows the details of the beam splitter and mirror installations in the left-hand aluminum housing attached to the reference beam 6-inch-diameter pipe. In Figure 3-6 may be seen the right-hand housing with the reference beam mirrors and Graflex shutter assembly. The film plate holder is mounted externally to the housing. The framework extending to the right from the housing (from which a coiled cable is hanging) was used to mount a bellows-type view camera for producing laser-illuminated photographs (see Figure 3-3 and Section 3.2.5).

The laser readily slides in and out of the galvanized steel pipe which was fabricated to protect the optical components of the laser from both the elements as well as from the combustion products. Aluminum end flanges seal off the pipe. The laser beam emerges through windows in the end flanges. The pipe could be pressurized with nitrogen gas (available at the test site) to minimize penetration of foreign elements and propellant fumes into the sensitive surfaces of the laser.

Not shown in Figure 3-3 is the biplanar photodiode used to monitor the relative performance of the Q-switched ruby laser illuminator. This

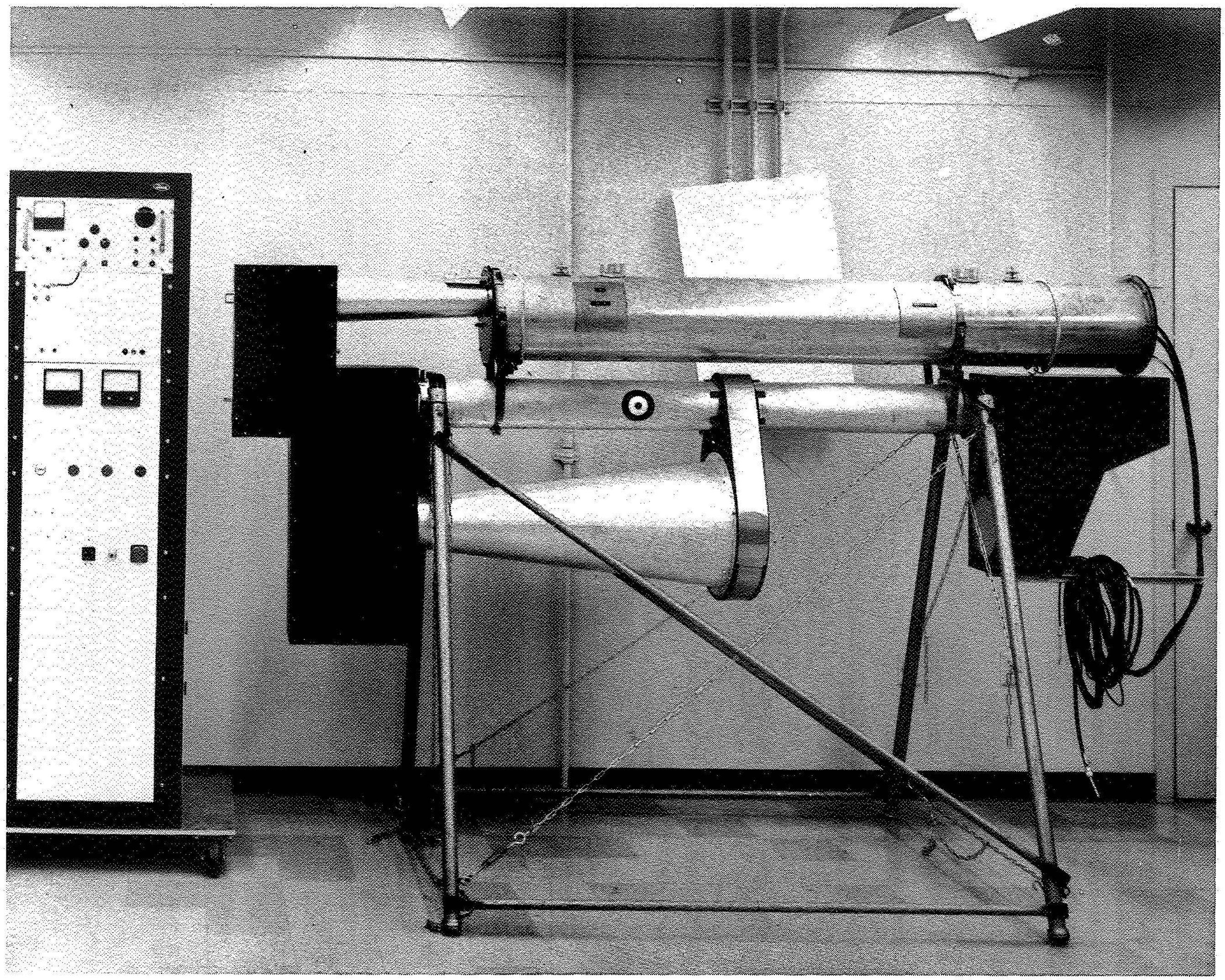


Figure 3-4. TRW laser-illuminated holocamera assembly (The laser power supply cabinet is shown at the left of the photograph.)

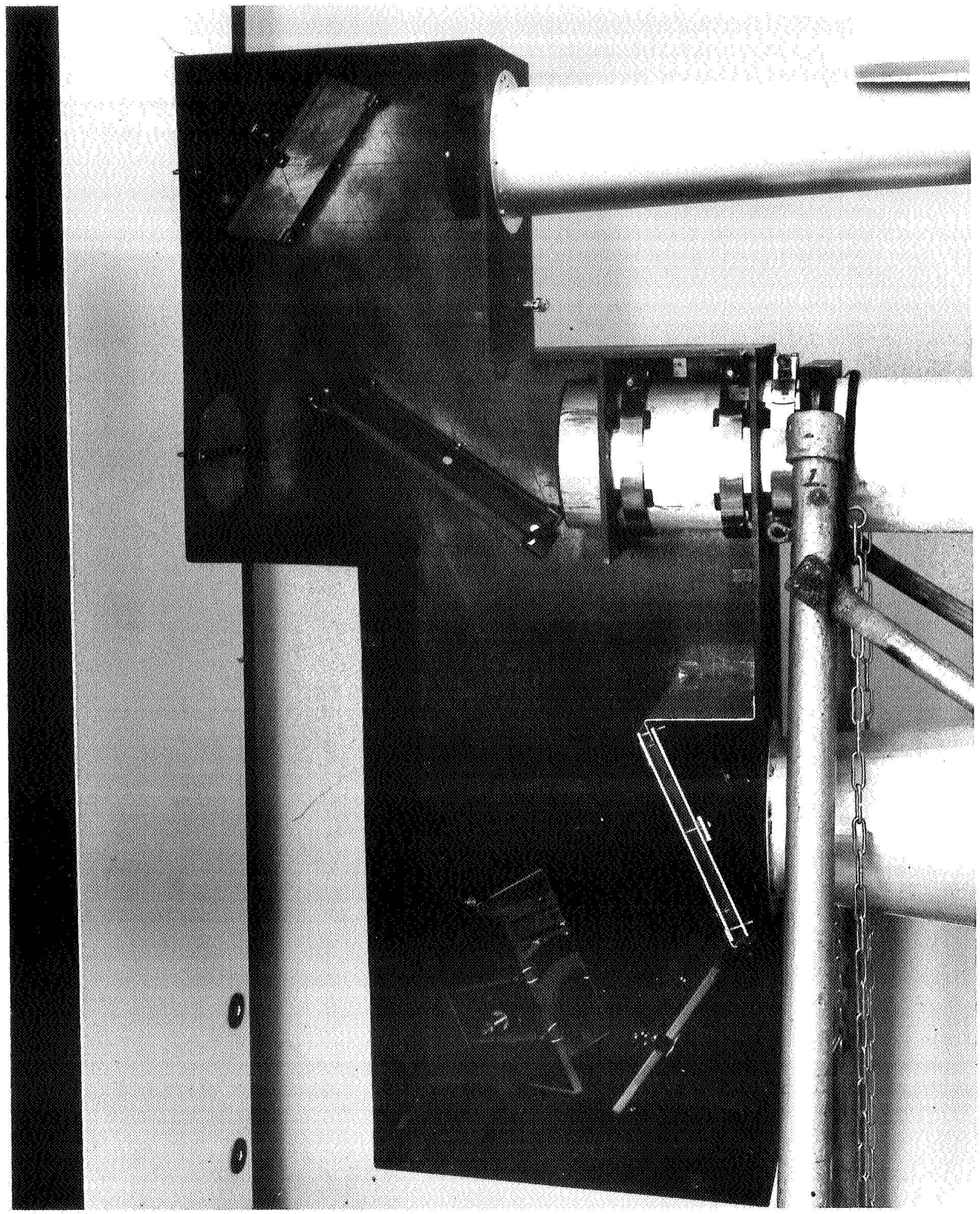


Figure 3-5. Left-hand aluminum housing containing the beam splitter and mirror installations

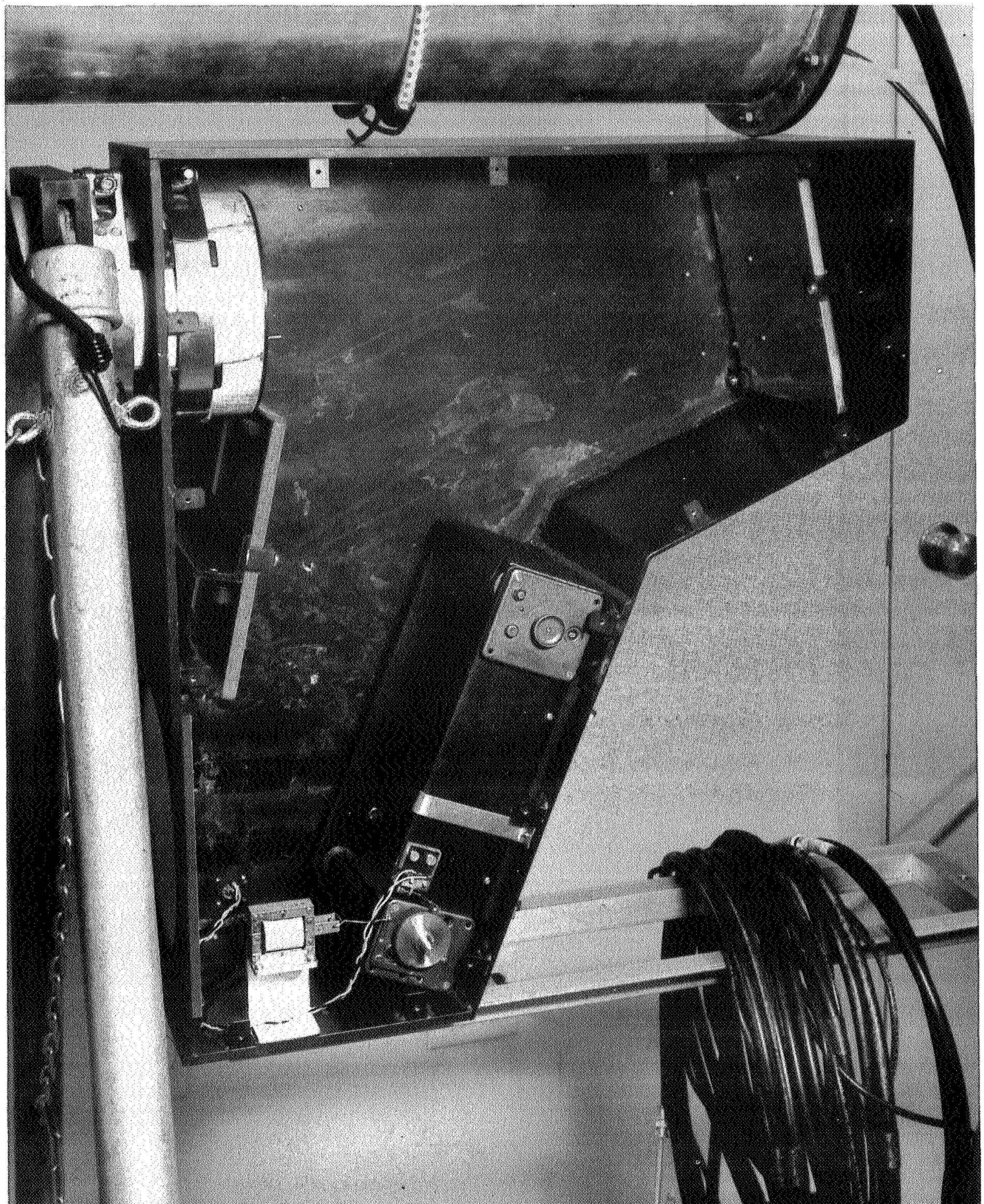


Figure 3-6. Right-hand aluminum housing containing the reference beam mirrors, shutter mechanism and film holder

was mounted in a housing which attached to the rear end flange. The biplanar diode (i.e., an ITT FW 114A) was connected via a 50 Ω coaxial cable to a Tektronix 545 oscilloscope in the main blockhouse at the JPL rocket test site (~500 feet away). The electrical schematic of the photodiode circuit is shown in Figure 3-7. It can be seen that the voltage across C_2 (the oscilloscope input) is proportional to the energy emitted by the Q-switched laser. A single giant pulse thus produces a step oscillogram. Malfunction (caused by laser misalignment) can result in double steps, each of different amplitude. Sample oscillograms are shown in Figure 3-8.

3.1.4 Holocamera Modifications

As work progressed during the test program, modifications were made to the basic apparatus. These changes were necessitated by test operating conditions and experience gained as the system was made operational in the field.

One such field modification (Phase I) was the addition of a "capping shutter" to augment the original focal plane shutter in preventing film fogging by ambient daylight (described in Section 3.1.2).

Another change made during Phase II was increasing the laser beam intensity to help compensate for laser light attenuation by the combustion phenomena and scattering of the laser beam by eroded walls in the 3-inch acrylic chambers. Referring to Figure 3-3, it will seem that the ~1/2 centimeter diameter beam from the ruby laser illuminator is expanded by a Galilean telescope consisting of a 5-inch diameter, 24-inch focal length objective, and two adjacent simple negative lenses of -3 centimeters focal length. Ultimately, one of these 3 centimeter lenses was removed during Phase II permitting an increasing amount of light to be passed by the collimator. The laser beam intensity was increased at the expense of spacial coherence.*

*Spatial coherence of the Q-switch ruby laser used in the tests is thought to be 20 percent of the laser beam cross section, while temporal coherence is thought to be ~10 centimeters.

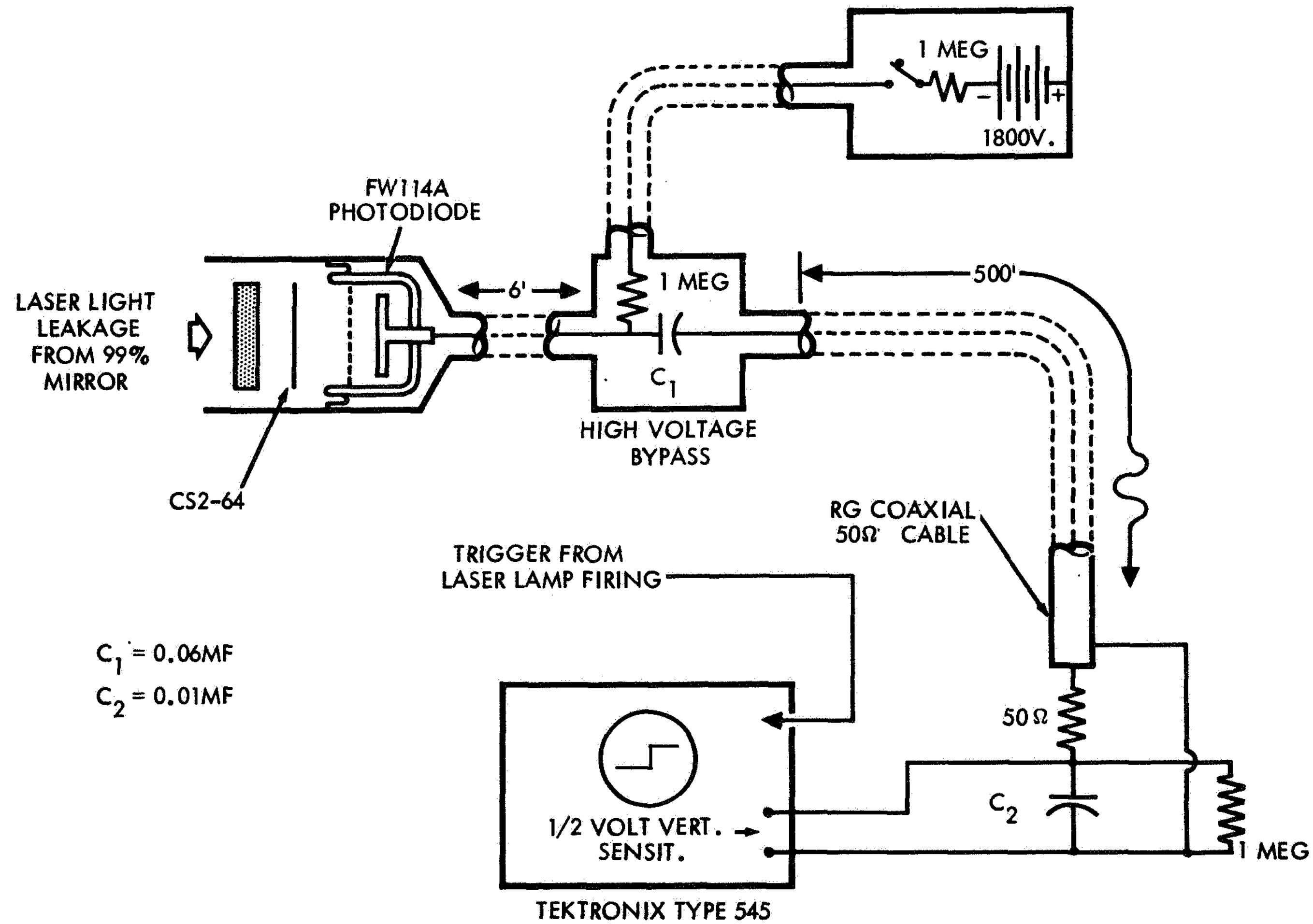
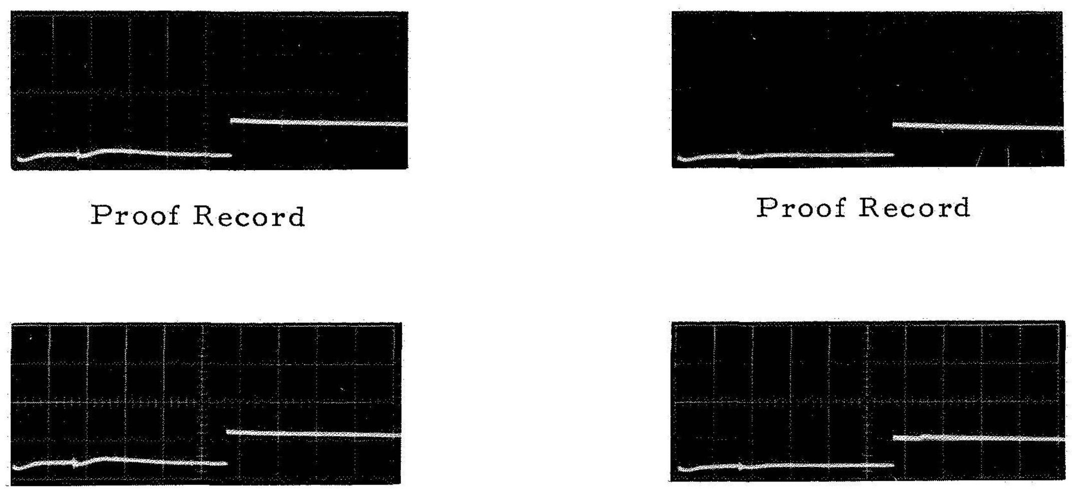


Figure 3-7. Schematic of the Photodiode Circuit; C_1 (0.06 μF) is a high voltage bypass capacitor. C_2 (0.01 μf) serves as an integrator, such that voltage developed across it is proportional to the integral of laser power (i.e., energy emitted by the laser). The photodiode and bypass circuit were designed to drive a traveling wave oscilloscope of 0.3 nanosecond rise time (Tektronix 519). The Tektronix 545 scope shown above was triggered by the initiation of the pump lamp current in the laser oscillator.

B1154 B1162



Proof Record — Proof Record

Combustion Record — Combustion Record

Figure 3-8. Sample oscillograms of the integrated emission from the Q-switch ruby laser oscillator in the combustion holocamera. The upper oscillogram was a proof shot taken ~ 2 minutes prior to the firing of the experimental rocket engine. The lower oscillogram showed the laser emission at the time the hologram was recorded. The two samples corresponds to Runs B1154 and B1162 made during Phase II test program. Vertical sensitivity in all was 1/2 volt/major division. Horizontal sensitivity was 200 μsec/div. B1162 shows the emission of a small unwanted second pulse ~ 0.2 millisecond after the primary pulse.

Still another Phase II alteration to the holocamera involved the diffuser and prism plate assembly (see Figure 3-3 insert). The diffuser and prism plate combination originally consisted (in the following order) of a glass plate ground on one side only, the two prismatically machined acrylic plates, and another glass plate ground on both sides. This combination, used throughout Phase I and the beginning of Phase II, acted to diffuse light so that the reconstructions had the appearance of being illuminated from behind by a random diffuse source of radiation. The diffusion was so good that shading caused by bars in the prismatically cut plate could not be observed. These features of the diffuser are noted, since midway through the Phase II effort, both diffusing plates were removed. This change was necessary because of the severe attenuation of the scene light by combustion phenomena. Later, the plate with the single diffusing surface was replaced behind the prismatically cut beam bender. This was done because, without the diffusion plates, a bright area or "hot sun" effect was produced in the holograms. The single diffuser eliminated the "hot sun" effect. In addition, there was a diffusing effect on the scene light produced by the erosion of the acrylic chamber walls as a result of the combustion.

Figure 3-3 shows the solenoid-actuated capping shutter* (mentioned previously) and the "window-shade" shutter from a Graflex camera. A sheet polarizer was attached to the scene beam port and oriented to transmit only the horizontally polarized laser scene light. The polarized light suppresses one-half the incoherent background light generated by the flame as well as sunlight. Stray light was further eliminated by a large Corning CS 2-64 plate glass red filter.

A final modification effected during Phase II testing concerns the scene-reference beam ratio. The ratio of scene beam light to reference beam light was increased in a further effort to overcome the strong attenuating effects (on the transmitted scene light) of the combustion phenomena. Reference beam intensity was controlled by inserting attenuating glass plates or large Kodak Wratten neutral density filters either just before the

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*Burke and James Inc., Harvard Electric Shutter with 8-inch aperture.

exit side of the support column or just before the first mirror in the shutter housing (see Figure 3-3). The latter location is a doublepass point. It doubles the effective density of the attenuation. The exit port and reference mirrors are accessible by removing the side cover (see photograph in Figure 3-6) of the aluminum housing.

3.1.5 Holocamera Installation

When the laser holocamera construction was complete (Phase I), the apparatus was transported to the JPL Edwards Test Station and installed on rocket test stand "B". The holocamera as installed for the water flow and open flame tests of Phase I is shown in Figures 3-9 through 3-11. The holocamera was positioned (Figure 3-9) such that it straddled the open flame test injector element. The injector element was located laterally at the approximate center of the holocamera scene volume. Rubber vibration isolators were used under the mounting legs of the holocamera.

The photographs of Figure 3-10 and 3-11 are left- and right-hand views of the holocamera installation. For the open flame tests, a special bracket was provided by JPL to mount the injector element on a steel capping plate. This plate, in turn, was affixed to the nozzle exit plane of a large rocket engine already in place on the test stand. The mounting bracket for the injector element was adjustable. It could be adjusted longitudinally so that the injector element could be located at any desired viewing position (over a distance of approximately 12 inches) with respect to the holocamera scene volume. As a result, it was possible to view events taking place in the region of stream impingement, or by relocating the injector element, to view the dispersed droplet patterns 12 inches downstream of the injector.

In addition to the longitudinal adjustment, the injector element could also be rotated or attached to the mounting bracket in one of three radial positions. This permitted holographic recordings of: (1) the resulting spray fan major axis (the major axis oriented normal to the holocamera scene beam), (2) the edge view or minor axis of the spray fan, and (3) a 45-degree oblique view of the spray fan.

The power supply for the laser and the regenerative water cooling system for the laser head were positioned approximately 20 feet behind

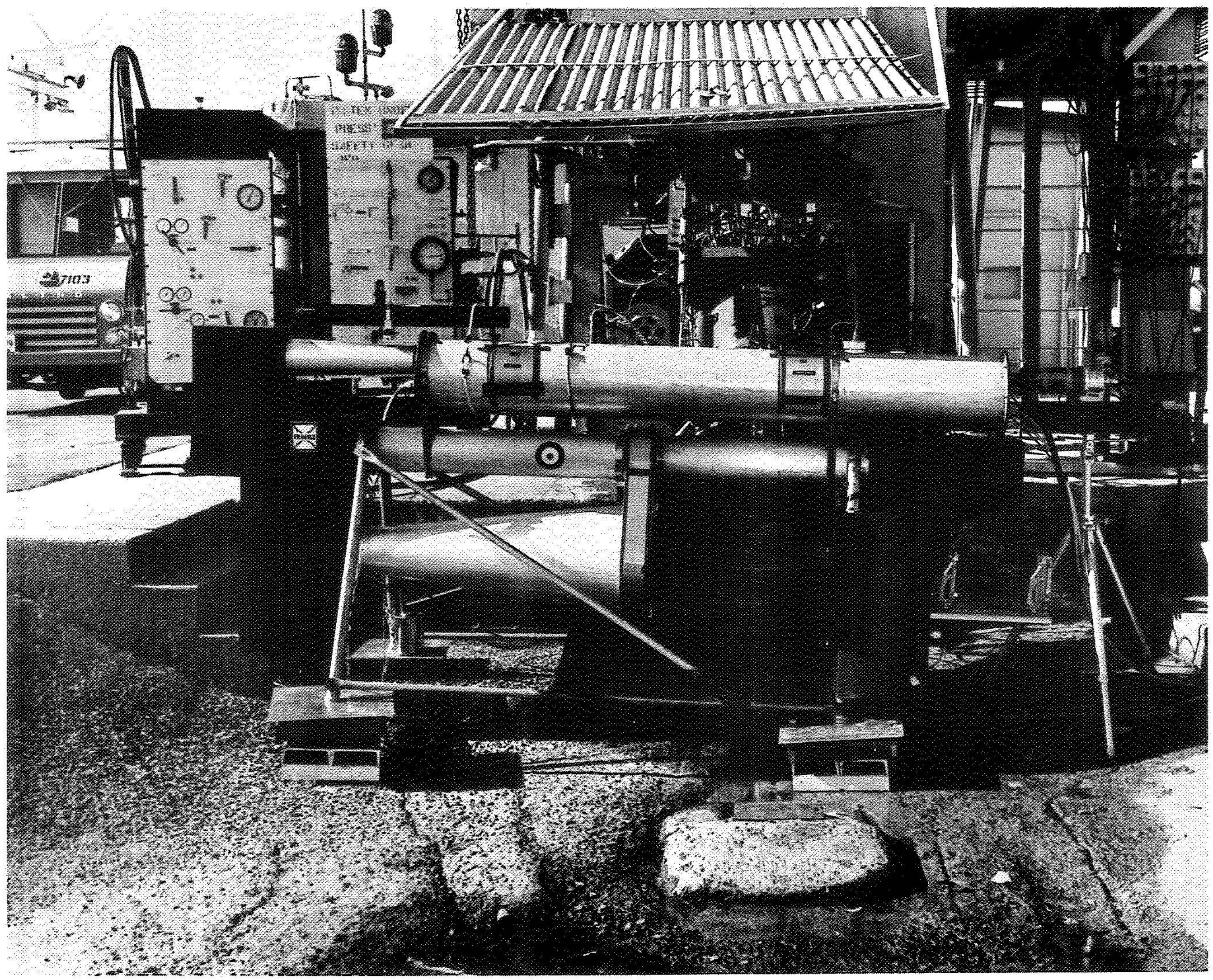

Figure 3-9. Side elevation photograph of the TRW holocamera installed at the JPL-ETS rocket test stand for Phase I open flame testing

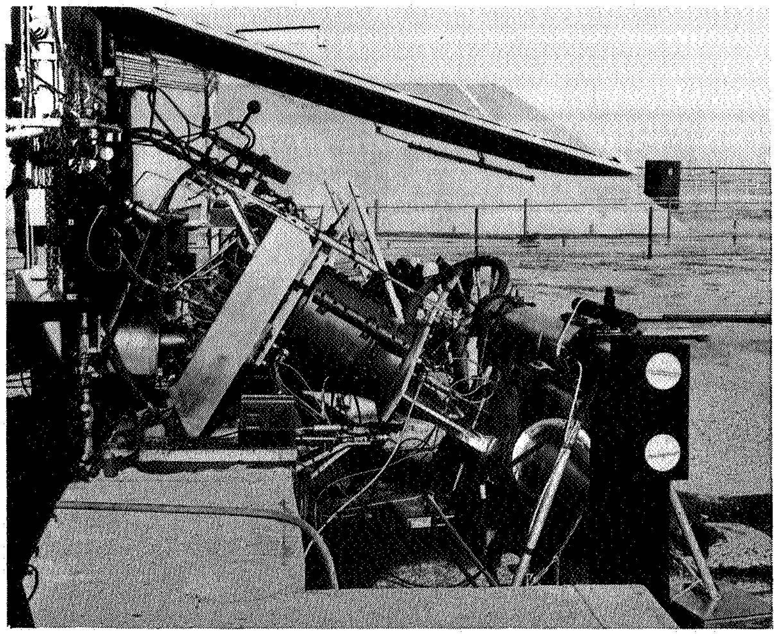

Figure 3-10. Left-side elevation photograph of the holocamera installation at JPL-ETS rocket test stand (Phase I)

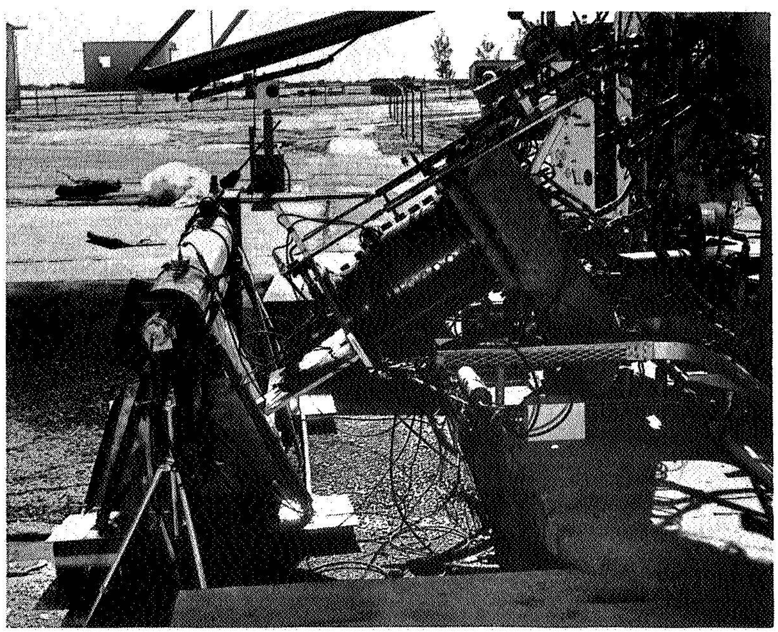

Figure 3-11. Right-side elevation photograph of the holocamera installation at JPL-ETS rocket test stand (Phase I)

the rocket test stand. These units are shown in Figures 3-12 and 3-13, respectively. A plastic cover was slipped over the power supply to protect it from rain and snow.

The installation of the holocamera on the test stand during Phase II was similar to that of Phase I. Figure 3-14 is an overall view of the holocamera installation with the 3-inch-diameter test motor mounted in place. The rocket motor was fired into a 6-inch steel pipe to minimize forces on the holocamera support. Also seen in the picture is the "Saran" window over one of the ports in the laser housing. This was for registering the laser firing on a Fastex camera recording of the combustion phenomena. The Fastex camera is not seen in the photograph since it was to the right of the holocamera. The photographs in Figure 3-15 show a closeup view of the acrylic chamber (test motor) in relation to the scene volume. An approximate positioning of the 3-inch diameter motor may also be seen by referring to the assembly drawing of Figure 3-3.

The original design of the entire holocamera was essentially based upon Phase III requirements to record combustion in an 18-inch-diameter thrust chamber. The choice of the intermediate focusing lens and the angular viewing range of the hologram was set by the requirement of this final program phase.

Installation of the holocamera at the test stand with the 18-inch-diameter windowed engine mounted in place is shown in Figures 3-16 and 3-17. These photographs show that the entire setup was a relatively close fit with the holocamera astride the large test engine. To replace the combustion chamber windows seen in Figure 3-17 (without removing the holocamera) it was necessary to change the location of the large 15-inch-diameter focusing lenses from the original design position. This slightly defocused the ground glass diffusers at the hologram. The coherence of the ruby laser, however, was sufficient to accommodate this change.

Some rework of the holocamera support framework was necessary (for Phase III) to properly position the apparatus in relation to the viewing ports on the 18-inch combustion chamber. The legs of the frame which mounted the holocamera were attached to wooden boxes which incorporated rubber innertubes. These innertubes isolated the holocamera from ground vibration.

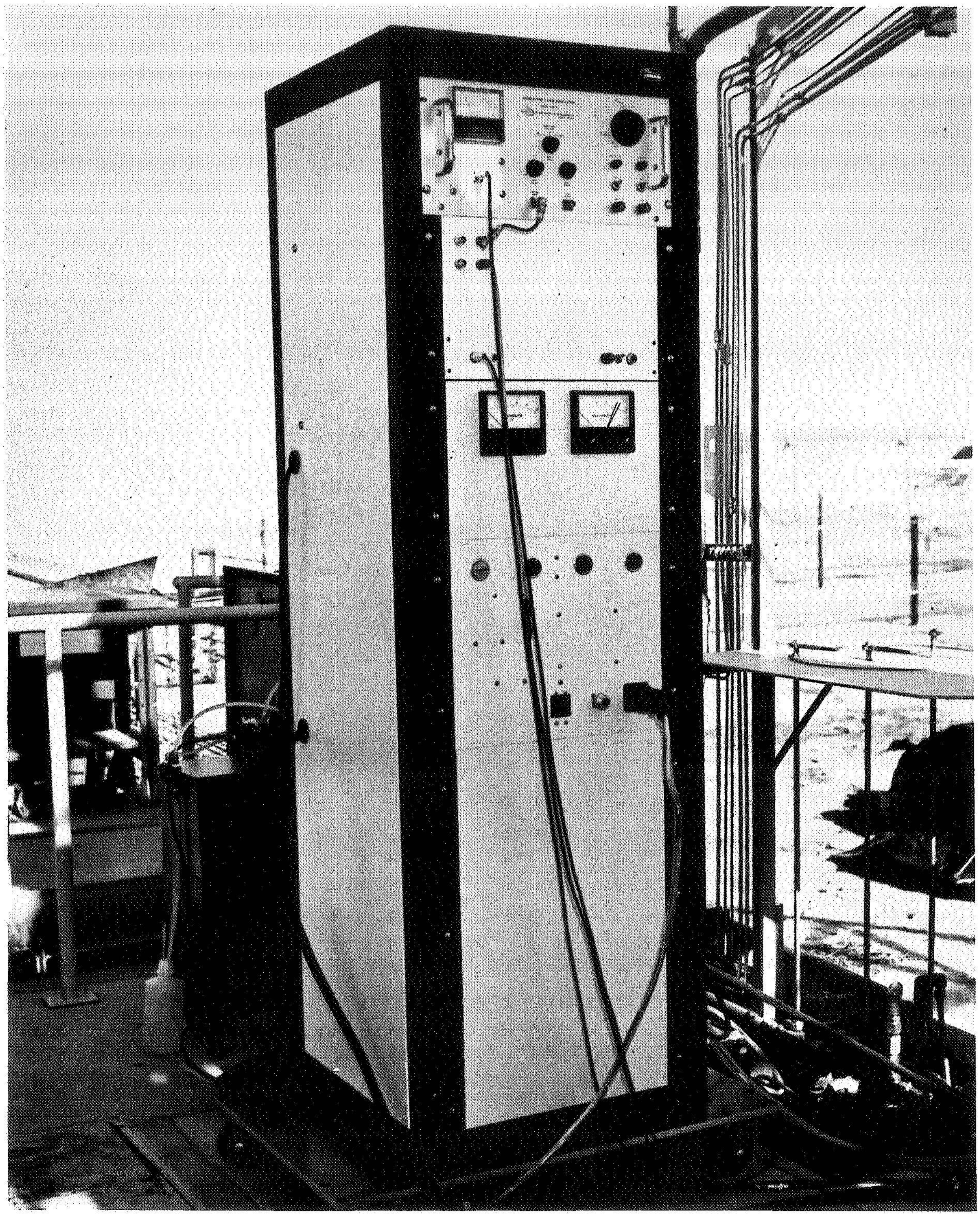

Figure 3-12. TRW power supply unit located at the rocket test stand

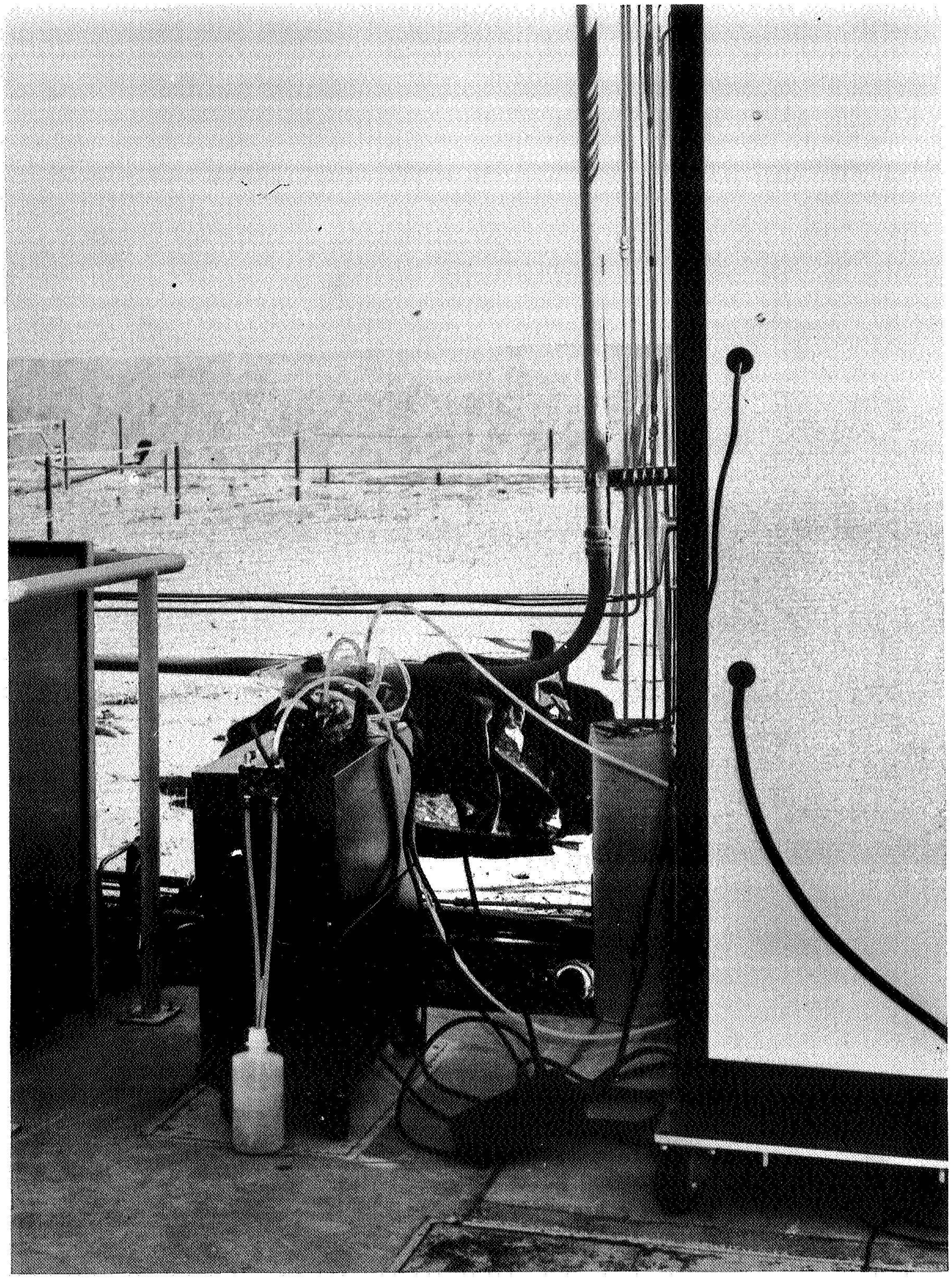

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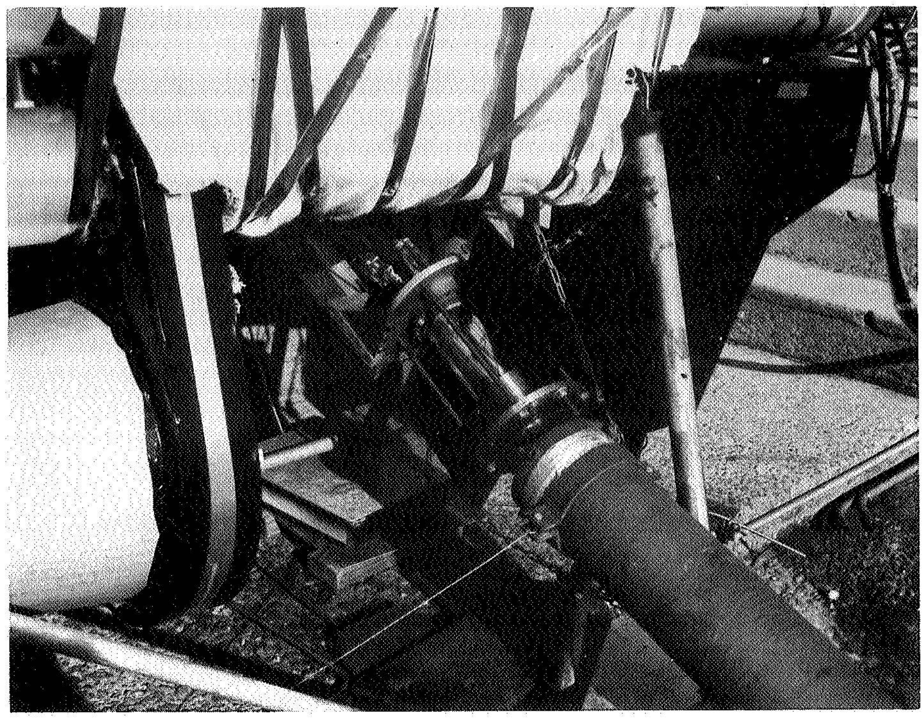
Figure 3-13. TRW portable cooling system for the laser head

Figure 3-14. Photograph of the TRW laser holocamera installed at the JPL-ETS for the Phase II recording of combustion in a 3-inch inside diameter liquid rocket test engine



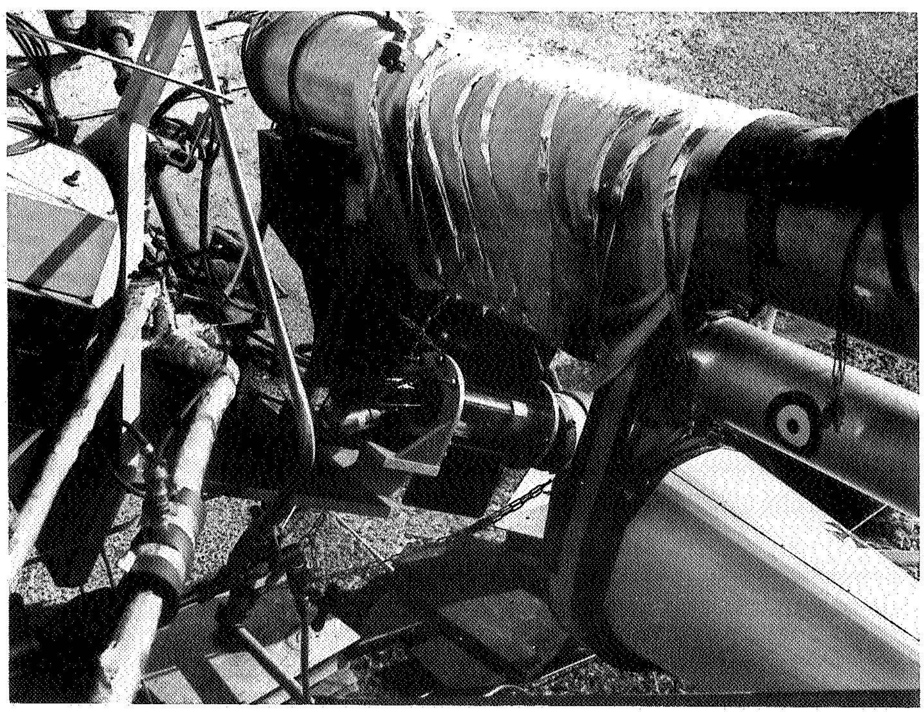


Figure 3-15. Front and rear photographs of the Phase II tests rocket engine with acrylic walls. The engine is mounted in the scene beam of the holocamera just before the electric capping shutter. Note the metal shields attached adjacent to the motor and parallel to its axis. These shields blocked excess scene light not passing through the combustion region.

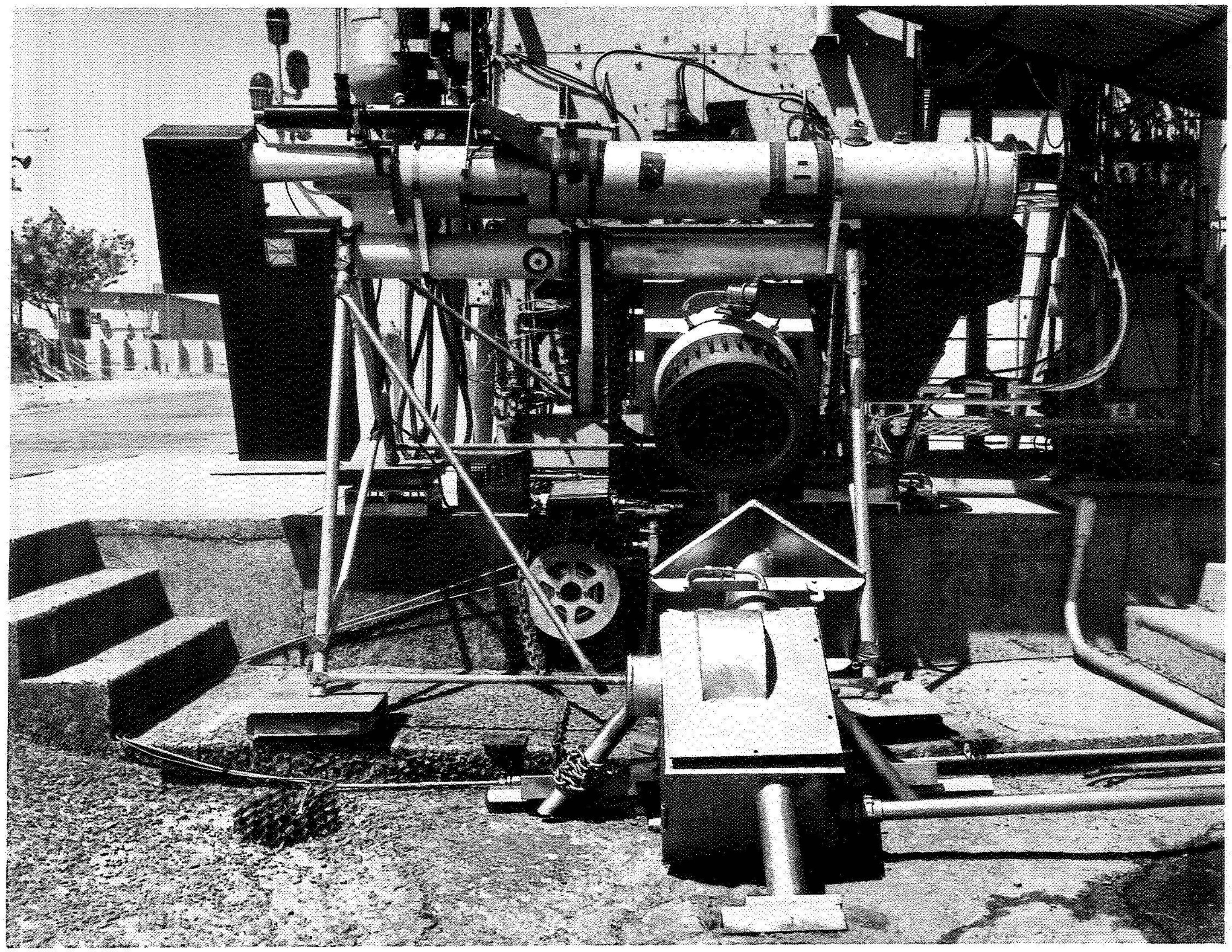


Figure 3-16. Photograph of the holocamera and 18-inch rocket test engine at the beginning of Phase III

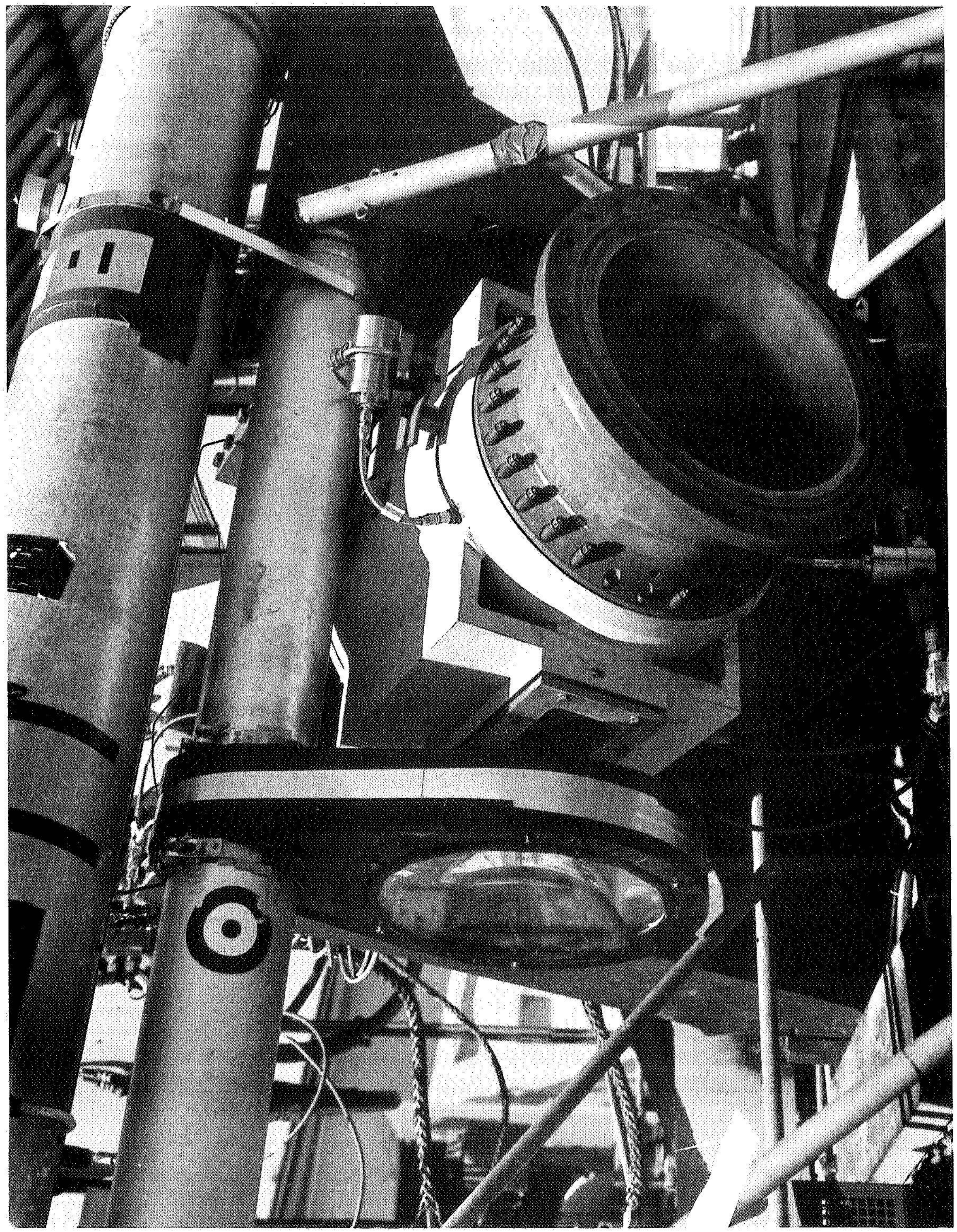


Figure 3-17. Close-up photograph of the 18-inch Phase III rocket engine with slab windows. The lens of the holocamera is on the left. Also visible is the accelerometer attached to the central support column of the holocamera (in line with the vertical axis of the motor).

Referring again to Figure 3-16, a large steel enclosure is seen mounted in the path of the engine exhaust. This steel enclosure housed a high speed movie camera for filming engine firings. The camera housing was later removed from the test stand vicinity to minimize coupling of the engine exhaust with the holocamera.

3.1.6 Holocamera Operation

Operation of the holocamera system was essentially the same for all three test phases of the program. During the second and third phases, it was necessary to replace or clean the acrylic windows as required. Essentially, however, operation of the holocamera system was reduced to a routine procedure. The succeeding text documents system operation and is generally applicable for the entire test program.

As already noted in Section 3.1.3, the laser power was monitored by a biplanar photodiode which could easily drive the 500 foot length of 50Ω coaxial cable, between the detector housing and the oscilloscope in the blockhouse. The photodiode was mounted in the housing attached to the end flange which sealed the steel shroud containing the laser illuminator. Light transmitted by the 99 percent dielectric mirror on the end of the laser passed through a plexiglass window and struck several ground glass diffusing screens, as well as a Corning CS2-64 red filter before being registered by the photodiode. The electrical current pulse (proportional to the laser light intensity) was transmitted by coaxial cable to either a Tektronix 519 high frequency traveling wave oscilloscope (0.3 nanosecond rise time) or to an integrator and a conventional Tektronix Type 545 oscilloscope (see Figure 3-7). The latter measured the relative energy in terms of the charge passed by the photodiode in terms of the voltage across a capacitor (see Figure 3-8). This monitoring was considered most important, since it provided information on whether the laser emitted a clean single pulse or whether it emitted a series of pulses due to misalignment. The latter resulted in holographic interferograms, rather than the desired single exposed holograms.

A water cooling system (a part of TRW's inventory) with a circulating centrifugal pump served to cool both the oscillator and amplifier rubies. The cooling system was set to maintain 13°C water temperature.

The Tygon water lines were insulated to minimize water heating between the cooling system and the laser housing during the high temperature days experienced on the desert in the latter part of the program. During Phase I, the cold desert weather necessitated that ethyl alcohol be added to the circulating water to prevent freezing.

The ruby laser could be fired either at the power supply unit at the test stand, from the remote control console in the ETS blockhouse, or by the automatically programmed sequence timer. The laser was fired when the focal plane (window shade) shutter was activated. This was accomplished through the use of a microswitch which sensed the open position of the focal plane shutter. In addition, approximately 400 milliseconds prior to activating the focal plane shutter, the solenoid operated capping shutter was opened in the automatic sequence of events.

The integrated laser emission was monitored on an oscilloscope (as previously indicated and shown in Figure 3-8). The output of the oscilloscope (vertical amplifier output) was also connected to the recording oscillograph used to monitor all of the operating parameters of the injector test element. As a result, the precise time of the hologram recording could be related to the other measured parameters of the test operation.

In order to make holograms, it was necessary only to align the laser and check to see that the holocamera had not been disturbed.* Alignment of the laser was achieved by mounting the dark field autocollimator into position (see Figure 3-3), inserting periscope into the mounting hole (thereby deactivating the ruby laser trigger), removing the $\lambda/4$ bias from the Kerr cell and adjusting the mirror alignment screws. The front mirror was adjusted until one perceived (through the autocollimator eyepiece) the superposition of light returned from the resonate reflector and from the far 99 percent rear mirror. The periscope was then withdrawn, the laser capacitor banks charged, and the laser fired.

*Alignment of the holocamera meant that the scene and reference beams overlapped, and that scene and reference beam optical path lengths were equal.

The output from the laser was monitored with a photodiode. The operation of the laser was considered satisfactory when an oscillograph sweep consisting of a single step of proper amplitude (approximately 0.6 volts) was recorded (see Figure 3-8).

If the holocamera or the position of the laser illuminator relative to the axis of the holocamera had to be aligned, one then removed the negative diverging lens (just before the output of the ruby laser amplifier) and taped a piece of unexposed and developed Polaroid film before the collimator lens, charged the banks, and fired the laser. The emitted energy marked the film. The small gas laser (Radiation Physics) was placed in its holder, a periscope inserted in the second mounting hole, and the leveling screws adjusted until the gas laser beam passed centrally through the aperture in the ruby laser oscillator and the mark in the photographic film. The gas laser beam was thus coincident with the pulse laser beam. The marked film could be removed and the diverging lens replaced. The cover was removed from the side of the housing on the holocamera, and the capping and focal plane shutters were opened. An old 4- x 5-inch photographic plate, upon which had been cemented a white paper, was placed in one of the wooden 4- x 5-inch holders and inserted into the mount in the holocamera. The superimposed scene and reference patterns could be observed (after the sun had set) on the white surface. A wire cross at the entrance to the holocamera cast a single shadow if the two beams were properly superimposed. Proper (1:1) scene-reference beam intensity ratios were checked by eclipsing the opposite part of either beam and comparing it against the other.

Temporal matching was essentially a laboratory alignment which could be verified by making a hologram in which a large stair-step block of Plexiglas was set in the scene beam of the holocamera.

With both the laser illuminator and the holocamera aligned, it was then necessary to check the programming of the laser and shutter functions relative to the firing of the injector. Verification of the proper sequencing of events was done by recording all parameters of interest on a highspeed recording oscillograph. When the desired sequencing was achieved, the apparatus was ready to record holograms.

A loaded film cassette was inserted in the holocamera, the focal plane shutter cocked manually, and the dark slide removed. Rocket test safety operations dictated that all personnel clear the immediate area of the test stand. Once the film was loaded in the holocamera, the operation of the equipment was done from the blockhouse instrument room used to conduct the firing. Prior to the actual injector test firing, the laser was pulsed and monitored from the remote control panel in the blockhouse. If the laser emission was satisfactory, the test firing proceeded.

After the test firing was complete and test stand area reopened, the dark slide was reinserted in the cassette, the cassette withdrawn from the camera, and either stored or immediately taken to the "darkroom" for development.

The exposed holograms were developed as soon as possible, particularly to check on the test results and to verify the quality and nature of the recorded scene.

3.1.7 Reconstruction Apparatus

Holograms produced with the apparatus and techniques described in preceding sections were subsequently developed, rinsed and fixed. When the holographic film plates were dried, they were reconstructed with the light of a continuous wave (CW) gas laser.*

In the period between the end of Phase I and the beginning of Phase II, a simple apparatus was built to view the holograms produced with the holocamera built under the program. Basically, the apparatus is little more than a wooden box which contains a helium neon laser (either a Spectra Physics Model 124 or a Radiation Physics Model RPI-7S), a diverging lens (a Spectra Physics Model 332 Spacial Filter or a 25X Microscope Objective), two front surface mirrors to redirect the gas laser beam, and a 5-inch diameter, 24-inch focal length collimating lens. One of the redirecting mirrors is spring-mounted so that the illuminating beam can be centered on the hologram. The 4- x 5-inch hologram is mounted far enough from the optics so that the observer does not see distracting reflections. The reconstruction, therefore, appears in a very dark region of the box.

*Approximately 20 milliwatts emission at 0.63 microns wavelength.

A photograph of the assembled reconstructor is shown in Figure 3-18. The observer sees the reconstructed scene within the box at an angle of 45 degrees relative to the horizontal.

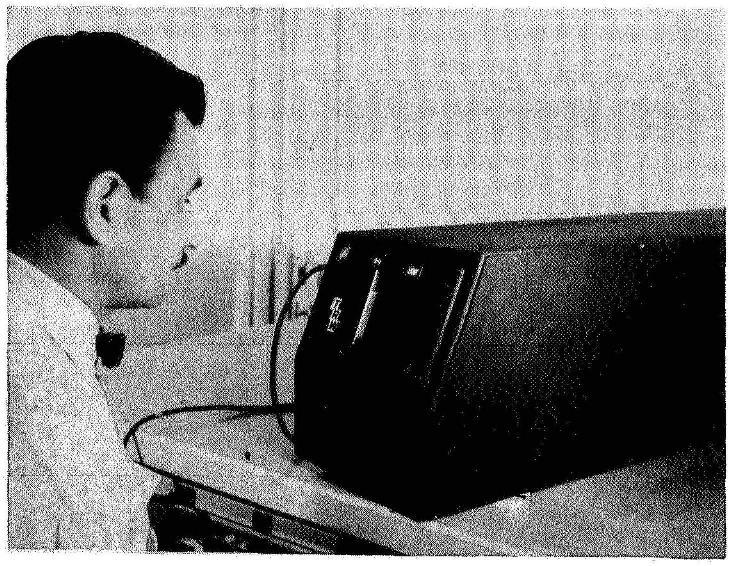


Figure 3-18. Photograph of the apparatus used to reconstruct holograms recorded in the JPL holocamera with a 45° scene-reference beam angle

Figure 3-19 shows photographs of the reconstructor with the side panels removed. In the lower photograph, the Spectra physics laser is shown mounted inside the box along with the power supply.* In the upper photograph, one sees the collimating lense.

The reconstructor is simple in construction and greatly facilitates the systematic viewing of a large number of holograms. It can only be used for holograms made in the apparatus shown in Figure 3-3. A universal hologram reconstructing appartus is not possible.

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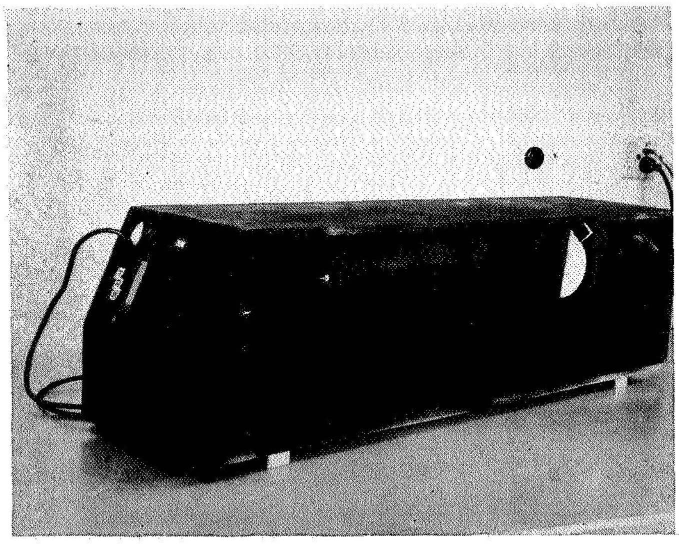
*The internal mounting of the power supply was found unsatisfactory due to lack of sufficient circulating air.

3.1.8 Test Hardware

Injector and rocket engine test hardware for all test phases was furnished by JPL. The single exception were the windows furnished by TRW for Phase II and III.

The first phase (water flow and open flame testing) required only a single element impinging stream injector. This element, shown in the photographs of Figure 3-20 and 3-21, consists of two impinging stream orifice tubes mounted in an aluminum block. The included angle of impingement is 45 degrees. The inside diameter of each tube is 0.173 inch.

The same injector was also used in Phase II, together with single impinging stream elements of smaller diameters. (See Tables B-I and B-II).



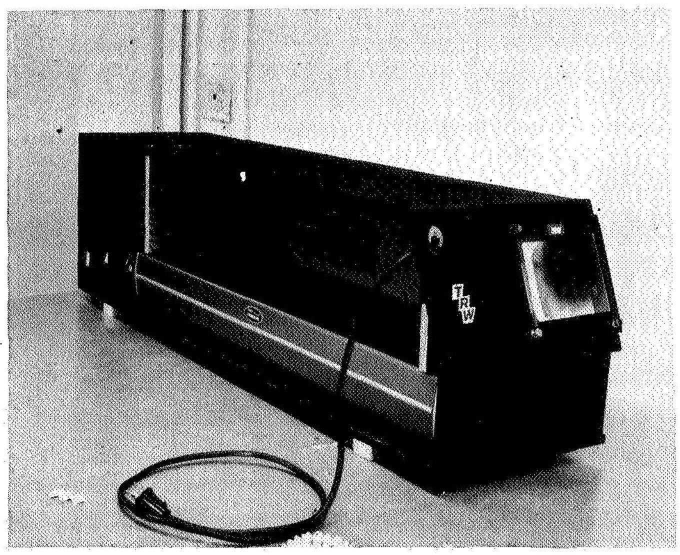


Figure 3-19. Photographs of the reconstruction apparatus with the sides removed showing the internal mounting of a Spectra Physics Model 124 helium-neon gas laser and beam-forming optics

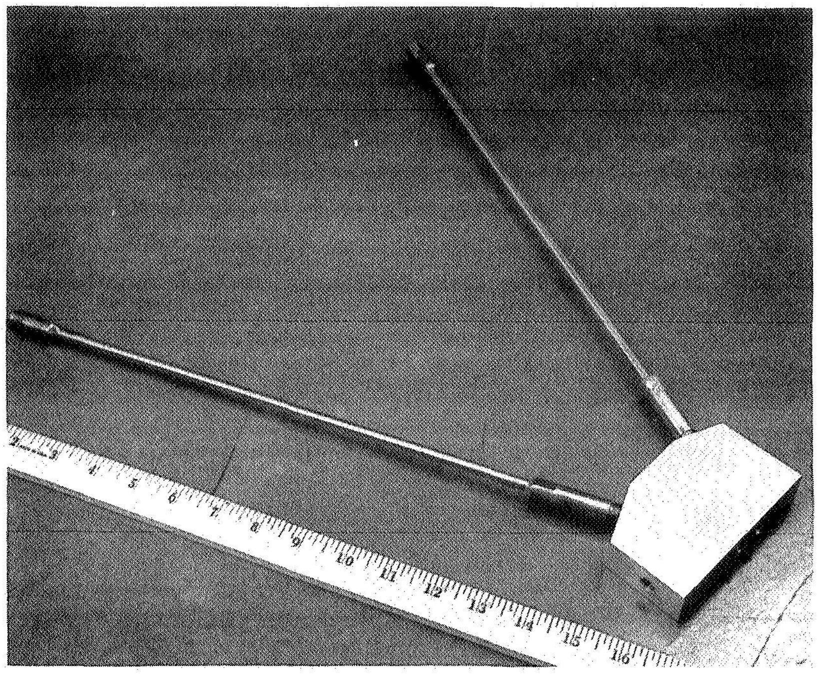


Figure 3-20. Photograph of the JPL single element impinging stream injector used for the Phase I open flame tests

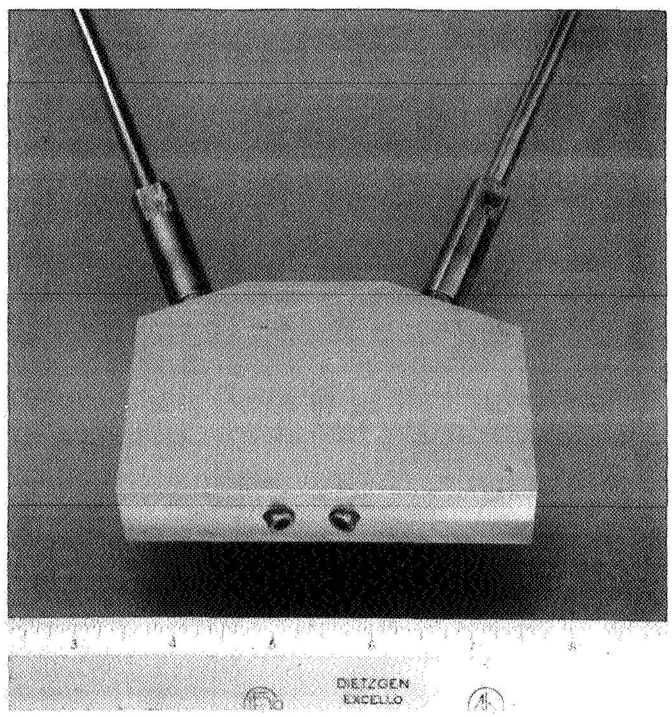


Figure 3-21. Closeup view of the JPL single element injector showing the 0.173-inch-diameter tubes extending slightly beyond the face of the aluminum injector block

The chambers used in the Phase II tests consisted of acrylic chambers of 3-inch inside diameter x 6-inch length. A drawing of these chambers is shown in Figure 3-22.

At the downstream end of the acrylic combustion chamber, heat sink steel throats were bolted in place. Two different size throat sections were used. The nozzle throats employed were 1.60 and 0.919 inches in diameter. Photographs of a typical engine assembly installed on the test stand are shown in Figure 3-15. The two parts of this figure show a front and rear view of the acrylic chamber installation. As may be seen from these photographs, the engine is centrally located with respect to the holocamera scene beam and in addition, positioned adjacent to the capping shutter covering the scene beam port of the housing structure.

The photograph in Figure 3-23 shows an alternate test engine configuration. In this instance, the combustion chamber consists of a steel cylindrical section (in place of the acrylic) with a porting arrangement for the accommodation of (TRW furnished) 1-inch-diameter Pyrex windows. This engine test configuration was used for a limited number of firings and demonstrated the superiority of Pyrex over acrylic. However, the view of the combustion phenomena was greatly restricted in comparison with the all-acrylic chamber.

For maximum viewing, the acrylic cylindrical section between the injector plate and the steel throat was used. TRW provided 24 acrylic cylinders as shown in the drawing of Figure 3-22. The 0.4-inch wall was chosen on the basis of the tensile strength of Plexiglas at a temperature of 180^{o}C and a chamber pressure of 300 lb/in^2.

Windows for the 18-inch-diameter combustion chamber testing (Phase III) were furnished by TRW to the design shown in Figure 3-24. Material of construction for these large windows was originally all acrylic.

Experience gained during Phase II indicated that internal surface melting and erosion of the acrylic cylinders (refer to the drawing of Figure 3-22) were very severe even after only 500 milliseconds of engine operation. A typical example of the effect of N_2O_4 - 50/50 blend combustion on one of the Phase II acrylic cylinders is seen in Figure 3-25.

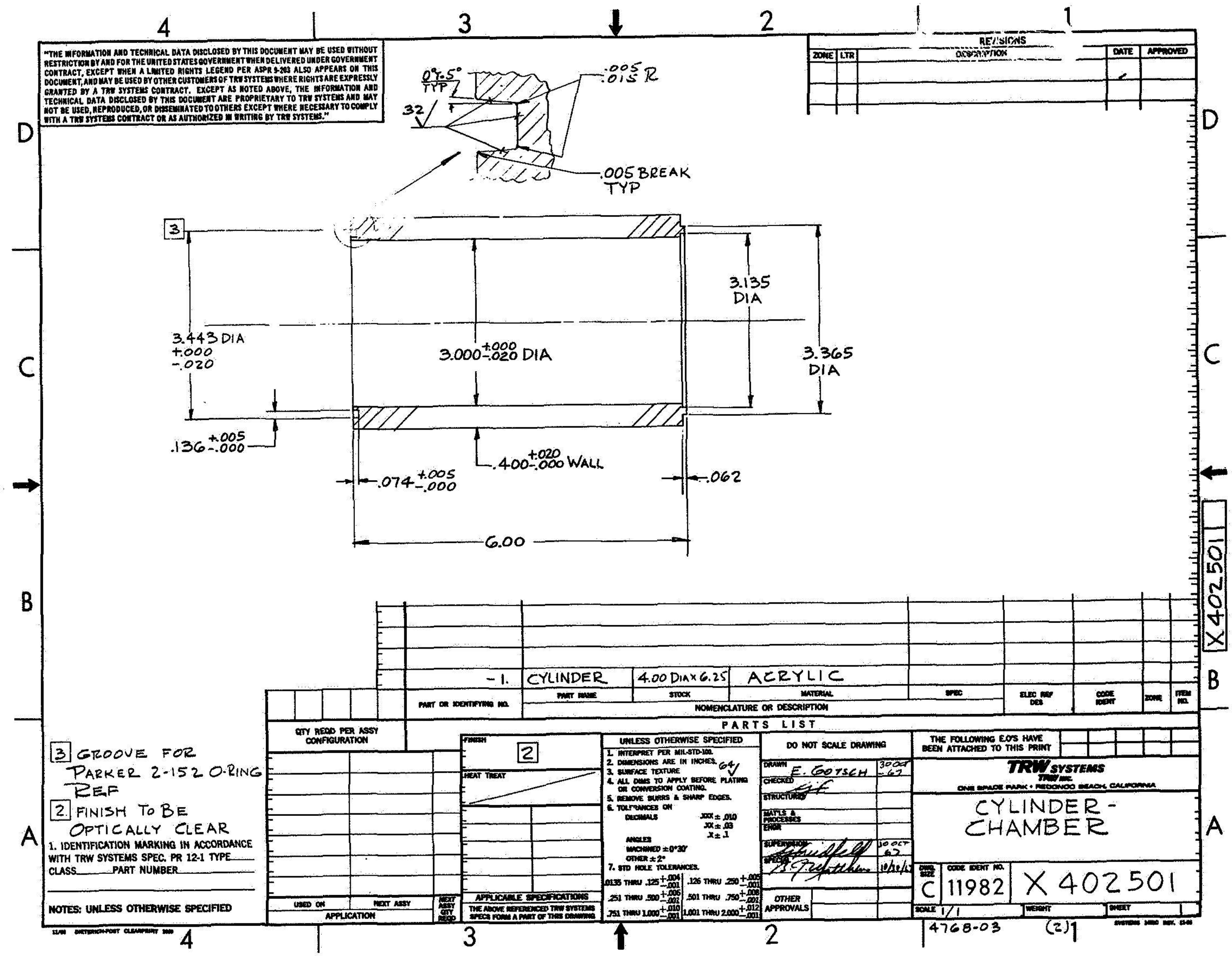


Figure 3-22. Shop drawing of the transparent acrylic chambers within which rocket engine combustion was holographed

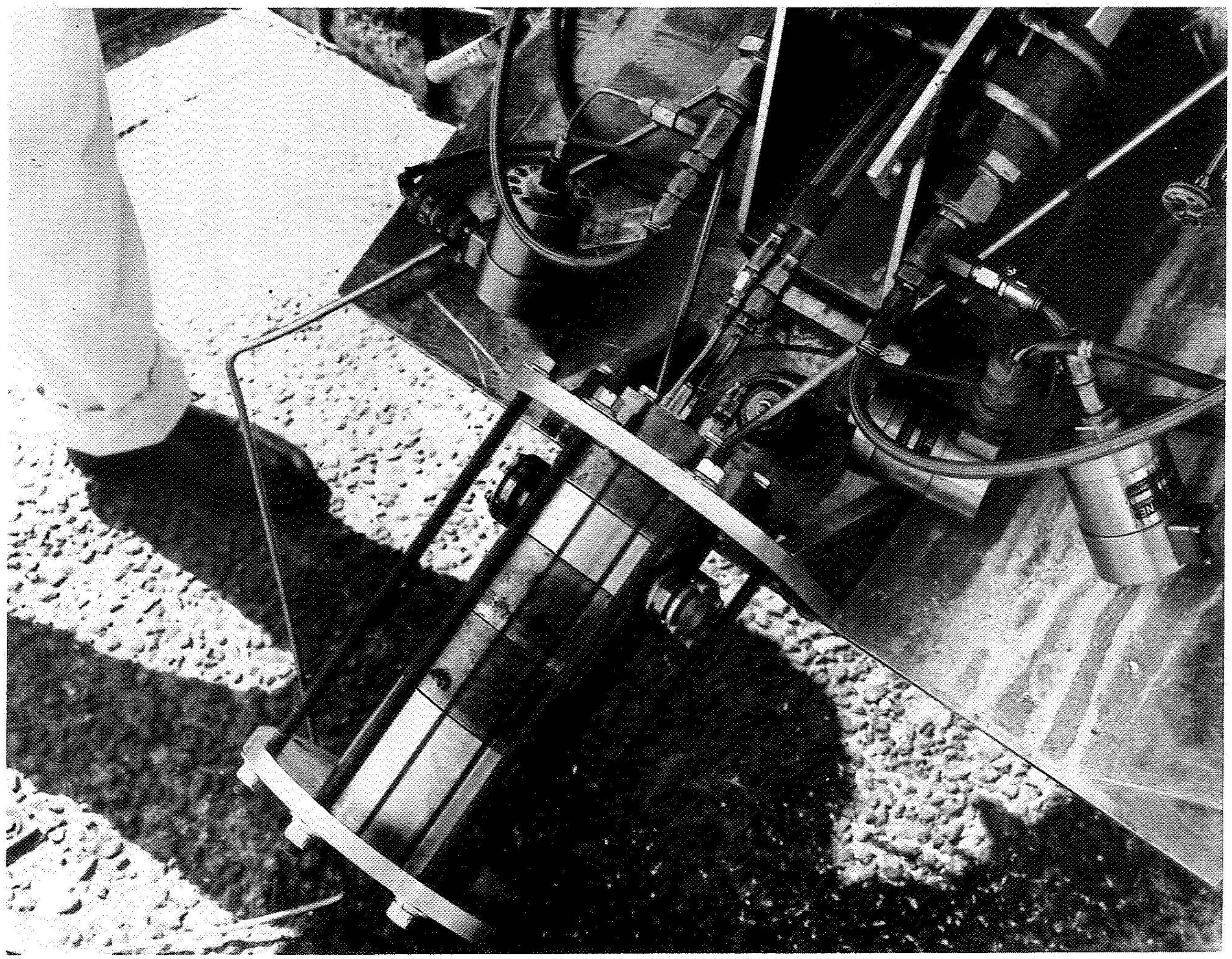


Figure 3-23. Photograph of the JPL test engine within which combustion was holographed. The engine consisted of a single doublet injector mounted within a 3-inch diameter, 6-inch long combustion chamber, followed by a nozzle throat section. In this photograph the engine had all steel walls, one section of which was fitted with bosses for 1-inch-diameter Pyrex windows.

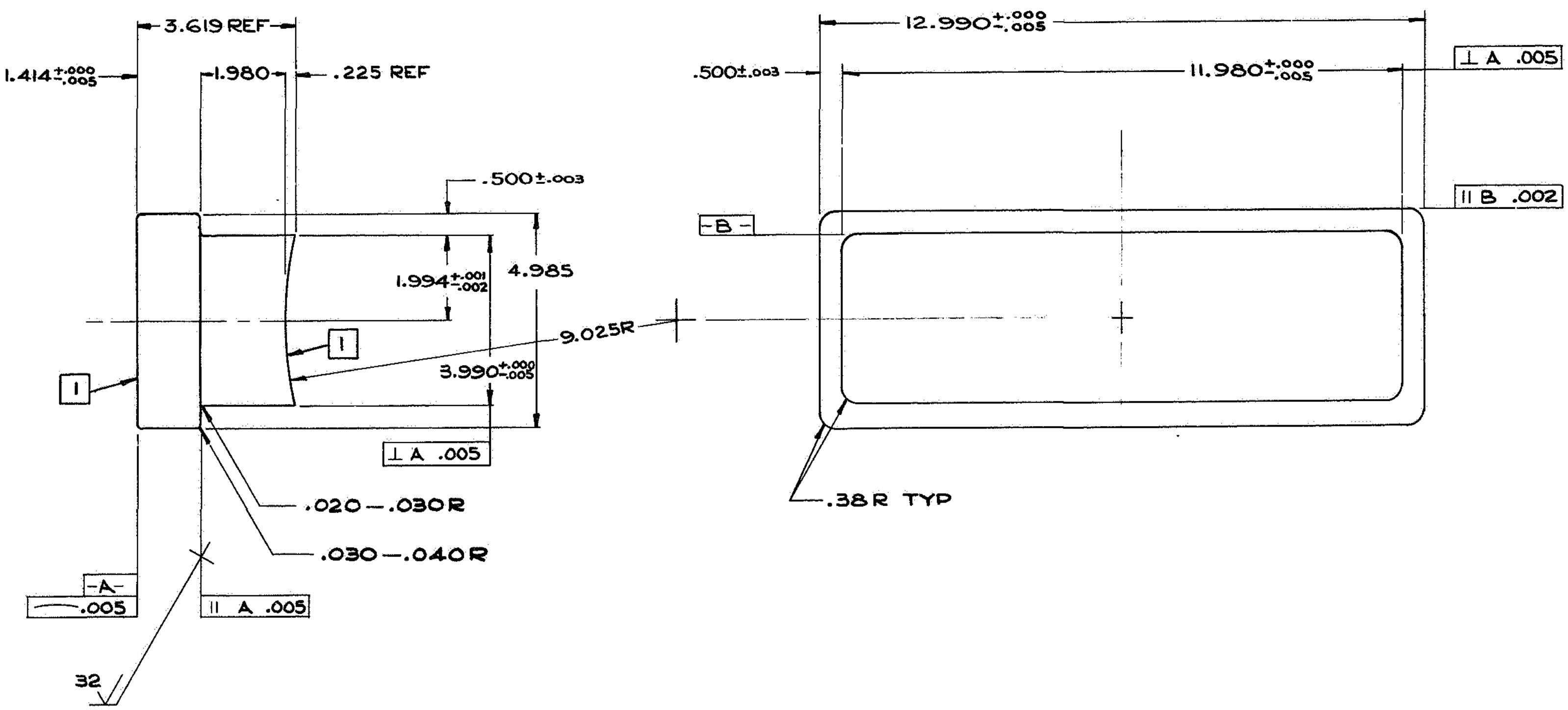


Figure 3-24. Acrylic windows used with the 18-inch-diameter chamber assembly during the Phase III test program. These windows were subsequently modified by capping the internal (chamber wall) surface with Pyrex glass to reduce thermal erosion.

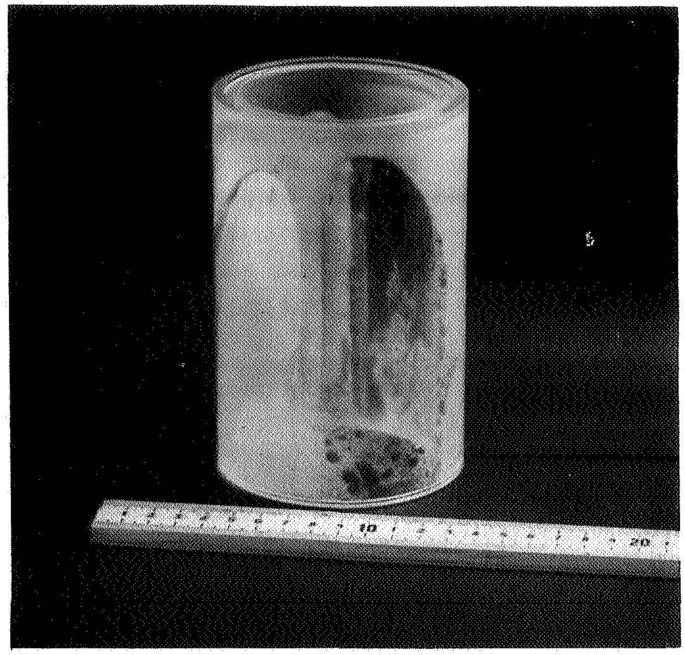


Figure 3-25.

Photograph of one of the acrylic chambers after use. This was Run B1158 in which erosion was mild. The fuel was acid-UDMH precooled, and with the smaller 0.0986-inch orifices. Other chambers were completely translucent.

Erosion of the acrylic chamber walls produced a mottled appearance. This damage to the acrylic severely attenuated the laser scene beam and essentially determined the quality of the resulting holograms.

Earlier testing with Pyrex windows (1-inch-diameter) in a 3-inch inside diameter steel chamber during Phase II demonstrated the superiority of this material to resist high temperature erosion. A composite material, therefore, was desirable, namely one in which the erosion qualities of glass were coupled with the strength of acrylic. To this end TRW built some windows in which Pyrex glass plate was epoxy-bonded to acrylic sheet for the Phase III test program. This was done by machining the inside surface of the original windows (Figure 3-24) to a flat surface and then bonding a piece of 1/8-inch Pyrex to the inside surface of the acrylic window.*

A strong bond was achieved by rough grinding the surface of the acrylic; thus, only the external surface of the acrylic is finish machined. The matching of the refractive indices of glass and acrylic by the epoxy was so good that the roughened acrylic surface could not be observed visually after the bonding process was complete.

*The surfaces of the glass-acrylic bond were rough ground and glued with Rohm and Haas PS-18 cement. The epoxy was allowed to set at room temperature.

The net result was a window with the surface finish of plate glass but with the strength of acrylic. Sandwich constructions also were made with Pyrex on either side of a piece of acrylic. The outer surface of this composite is that of the normally-finished glass plate and does not have to be polished. The result is a window in which all polishing was eliminated and fabrication costs were less than those of either an all-acrylic window, or an all-glass window. A photograph of a preliminary window consisting of 1/8-inch thick Pyrex epoxied to 1-inch acrylic is shown in Figure 3-26.

The original 18-inch-diameter chamber (acrylic) windows were modified as described in the preceding paragraphs. The composite window construction proved very satisfactory. Further, it was found that these laminated windows could be "re-manufactured" whenever the internal Pyrex surface became cracked or damaged. (Damage could occur through handling, rough engine operation and thermal stress). When the Pyrex became cracked, it was chisled away and a new piece bonded to the basic acrylic structure (Figure 3-44 shows some of these surfaces remachined.)

3.2 HOLOGRAPHY TEST PROGRAM

3.2.1 Phase I — Cold Flow Tests

Initial holographic studies at the JPL/ETS site were conducted using water spray fans. These water flow tests were conducted as a convenient means of checking alignment of the laser and holocamera optics, as well as establishing the proper sequence of events preparatory to open flame testing.

A total of 24 water flow tests were conducted in which either a hologram or a laser-illuminated photograph recording was attempted.* The operating conditions for these preliminary water flow tests are tabulated in Table A-1 of Appendix A to this report. Of the 24 tests made, 17 successful recordings were obtained: a total of 9 holograms and 8 laser-illuminated photographs.

*Laser-illuminated photography is described in a subsequent section of this report.

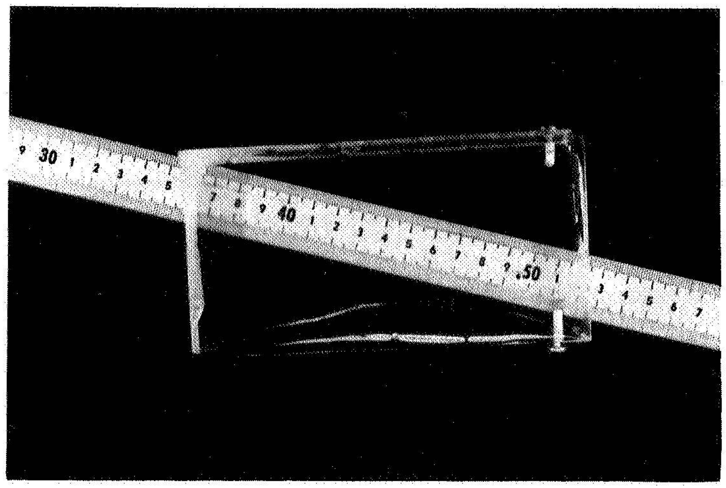


Figure 3-26. Photograph of a composite 1-inch thick acrylic test window capped with Pyrex. The materials are bonded with a clear epoxy, the mating surfaces being rough ground. The rough ground surface can be seen (in an area near the 35-36 cm portion of the scale) where no glue was placed. The windows made by this technique were used on the Phase III test program.

Photographs of the test apparatus with water flowing through the injector element are shown in Figures 3-27 and 3-28. In Figure 3-27, the injector element is installed such that the spray fan is perpendicular to the scene beam of the holocamera. This particular photograph is representative of a relatively low total flow condition (in the order of 1.2 lb-H_2O/sec). Figure 3-27 also clearly shows the installation of the 15-inch-diameter focusing lenses suspended from the 6-inch-diameter support structure through which the reference beam passes.

Figure 3-28 illustrates the installation of the injector element 90 degrees away from the position shown in Figure 3-27. The spray fan is now horizontal within the scene beam. Note that a large piece of acrylic sheet has been placed in front of the window leading to the film

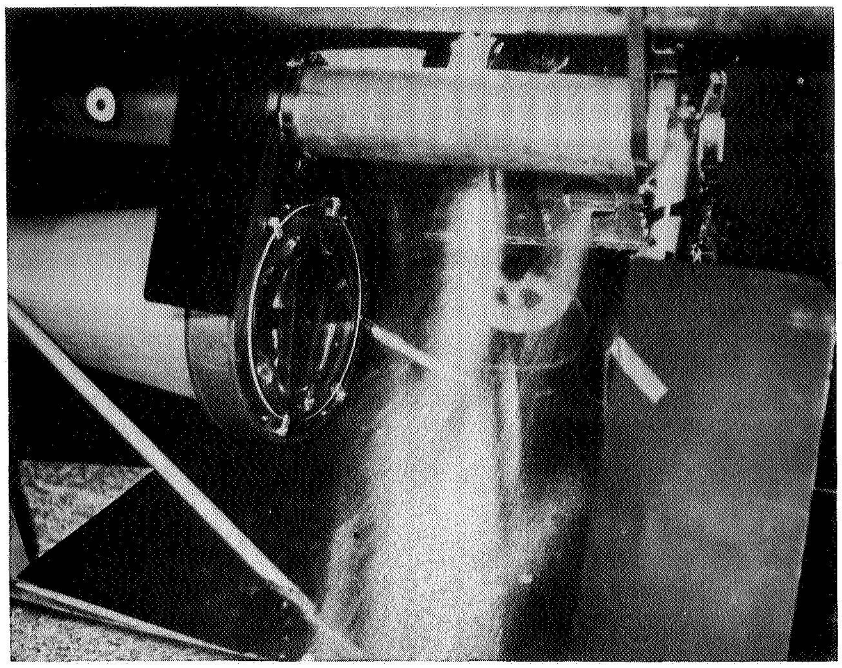


Figure 3-27. Injector water flow test with the spray fan perpendicular to the scene beam of the holocamera

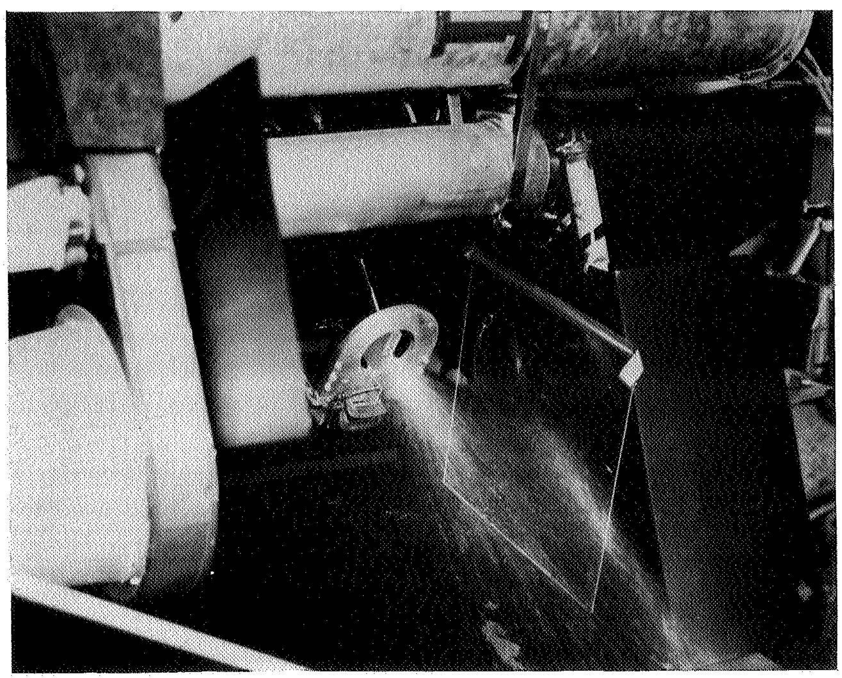


Figure 3-28. Injector water flow test with the spray fan oriented 90 degrees from that shown in Figure 3-27.

plate holder. This was done to obtain a qualitative indication of the amount of impingement upon the window from the spray fan when it is oriented in the horizontal plane. During a 2-second duration flow test, it was determined that a relatively small amount of water impinged upon the acrylic. It was concluded from these experiments that open flame test holograms could be made of the edge view of the spray fan without serious risk to the basic apparatus.

Subsequent open flame testing confirmed this conclusion. The same technique was applied, in that acrylic sheets were placed in front of the 15-inch-diameter focusing lenses and the film holder viewing port opposite. It was noted that with the N_2O_4-50/50 N_2H_4-UDMH propellant combination, there was an almost imperceptible amount of discoloration to the acrylic sheets after several firings. When the FNA-UDMH propellants were fired, however, the deterioration of the protective acrylic sheets became more evident. The acid tended to chemically attack the acrylic, and the sheets had to be replaced periodically. Splatter on the windows appreciably degraded the visibility of the reconstructed scene.

During the initial water flow tests and subsequent early open flame holography studies, a considerable amount of experimentation centered on obtaining correct exposure and development of the Eastman 649F and Agfa 10E75 and 8E75 film emulsions. Coupled with this were tests conducted with and without the ruby amplifier installed in the laser system. This work is described in some detail in Reference 1.

With the holocamera system optimized for the cold flow studies, some reasonably good holograms and laser-illuminated photographs were obtained. An example of a photograph of the reconstruction of a water spray hologram is shown in Figure 3-29. This photograph was made of Run No. B1113I and was recorded on Agfa 10E75 early in the test program. The reconstructed scene was photographed on Polaroid Type P/N55 film with a bellows copy camera, using a Schneider-Kreuznach Componon 300 mm, f/5.6 lens. The copy camera was focused on a plane passing through the impingement point and central portion of the spray fan. This hologram is typical of the various recordings made during the water flow

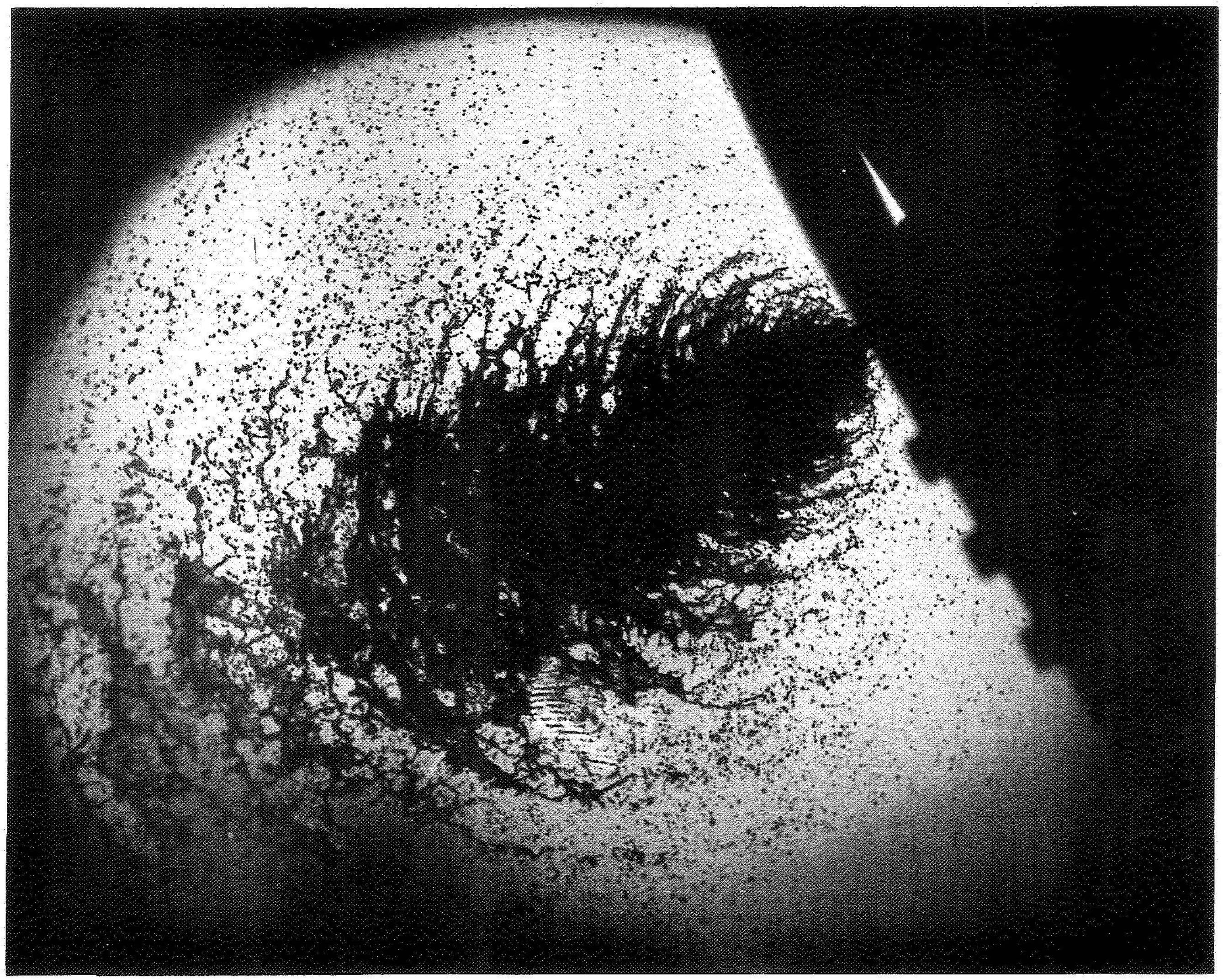


Figure 3-29. Photograph of the reconstruction of hologram B1113I. This photograph illustrates the water flow spray pattern from the single element impinging stream injector operating at a pressure drop of approximately 300 lb/in^2 and a flow rate of 2.35 lb/sec.

test series. In this particular instance, the mass flow was relatively high (2.35 lb/sec) and the view is of the initial coherent water sheet formation. The result is a rather dense fan-shaped mass through which the laser light did not penetrate. It has been seen in other water spray studies[2] that finer diameter impinging streams and lower mass flow rates permit increased laser penetration of this area of the spray fan. Under these latter conditions, as might be expected, better definition of the fan breakup is achieved.

The reconstruction of hologram B-1113I does clearly show the ligament formation development by the disintegrating spray fan. Small shed droplets at the spray fan fringes are also clearly visible.

Figures 3-30 and 3-31 illustrate the results obtained from making laser-illuminated photographs of various water spray fans. To make these photographs, the reference beam of the holocamera was blocked and only the scene beam utilized. A view camera was positioned on a mounting bracket provided adjacent to the film plate holder used for recording holograms. The film plate holder was removed and the view camera focused on the impingement point of the injector element. The laser illuminator was operated with a ruby amplifier during the photography experiments in order to obtain the most emission.

Figure 3-30 is a laser photograph of the spray fan produced during Run B1113L. The total water flow rate for this run was approximately 1.22 lb/sec. The scene was recorded on Agfa 10E75 film plate and developed in HRP developer for about 5 minutes. Note the increased penetration of the laser light (hence greater detail) through the spray fan of this illustration in contrast with the reconstruction photograph of the previous figure. This is primarily attributed to the lower mass flow rate at the time of this recording.

Laser-illuminated photographs were made of the water droplet dispersion approximately 12 inches downstream from the injector element. Figure 3-31 illustrates the droplet pattern of one such test (Run No. B1113U). The photography was made on Agfa 10E75 film plate and developed for 2 minutes in HRP developer diluted 1:8 at 72°F. The

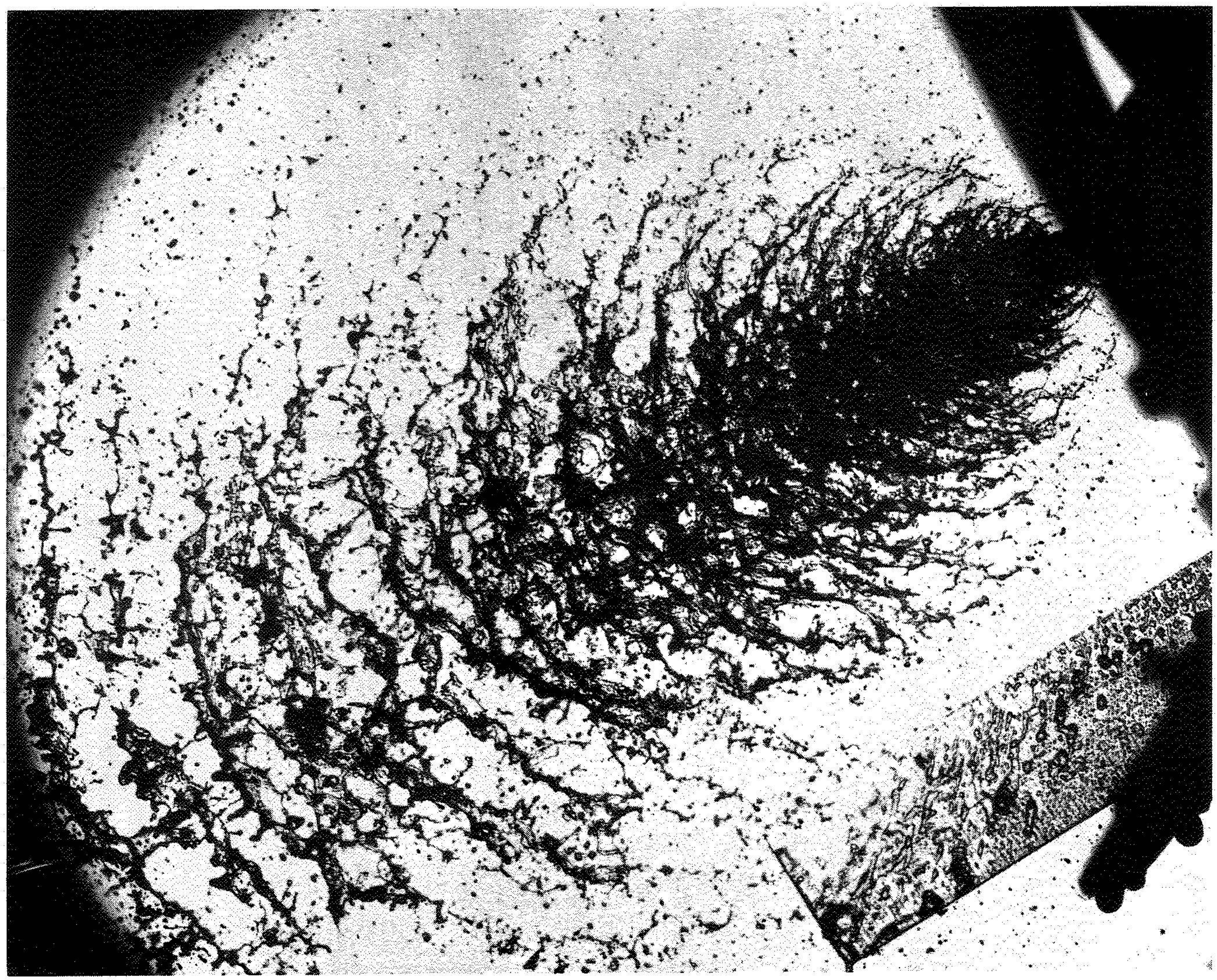


Figure 3-30. Laser-illuminated photograph of the water spray fan produced from a single element doublet during Run B1113L

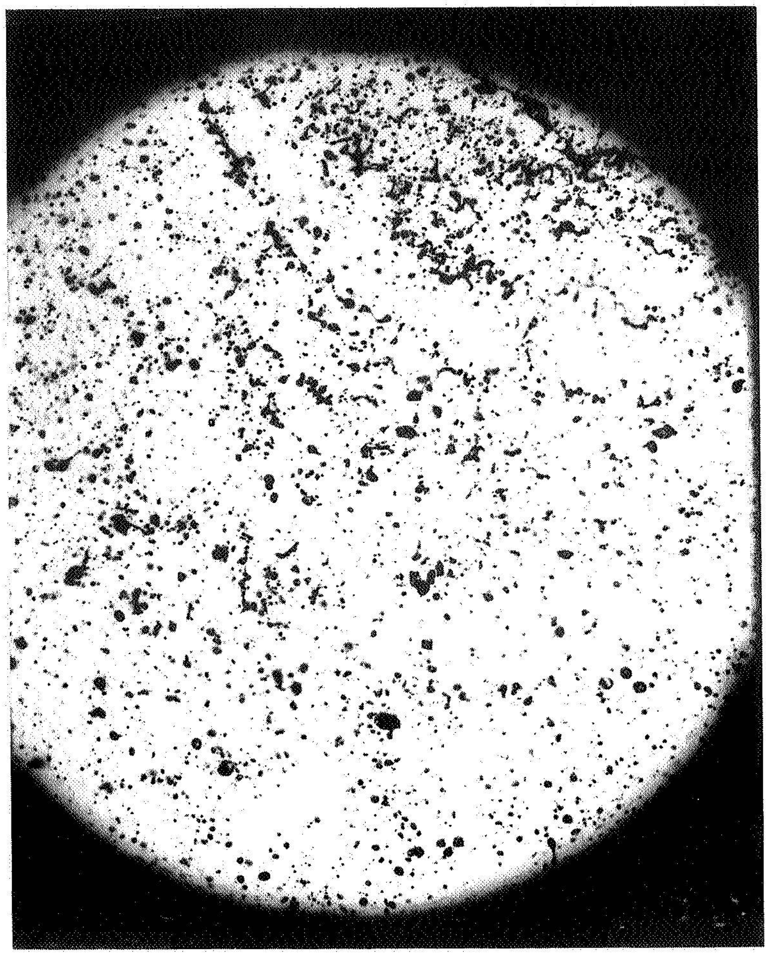


Figure 3-31. Photographic print made from a laser-illuminated photograph taken of the water flow from the JPL single element injector during test number B1113U. Direction of droplet flow is from the upper right-hand corner of the photograph to the lower left-hand portion. Examination of the Agfa 10E75 film plate (from which this print was made), under a microscope, indicated a resolution of around 25 microns.

photograph used for Figure 3-31 was made by contact printing the Agfa film plate using Kodak Velox printing paper. The film plate was subsequently examined with the aid of a microscope, and a preliminary assessment indicated a resolution of about 25 microns.

3.2.2 Phase I – Open Flame Tests

After the completion of the water flow experiments, the open flame combustion tests were initiated. Testing was conducted with two propellant combinations (N_2O_4 and 50/50 N_2H_4-UDMH, and FNA-UDMH) at ambient test cell conditions. Following these tests, propellant temperature conditioning equipment was moved into the test stand area and both propellant combinations were fired at elevated temperatures. For these latter tests, the propellants were conditioned to temperatures of approximately 80° to 100°F prior to each firing. Examples of the holographic results of this part of the Phase I test program are described in succeeding paragraphs. A listing of these tests is contained in the tables of Appendix B. A more complete description of the open flame testing is contained in Reference 1.

Initial attempts at open flame holography resulted in very heavy fogging of the film plates and extremely weak images. Various correctional measures were taken including the installation of Wratten filters, a capping shutter and close attention to sealing the joints of the aluminum housing containing the film holder, etc.[3] In addition, the maintenance of laser alignment had become a critical problem area.[4]

Coincident with the various changes designed to eliminate fogging and increase image strength, the laser rail was mechanically decoupled from the holocamera. This modification completely removed the laser misalignment problem. It, and the other improvements previously mentioned, resulted in the production of the first successful hologram of open flame combustion phenomena.

Figures 3-32 and 3-33 are reconstruction photographs of a hologram made during open flame test Run No. B-1117G. The reconstruction photographs show open flame (atmospheric) combustion of N_2O_4 and 50/50

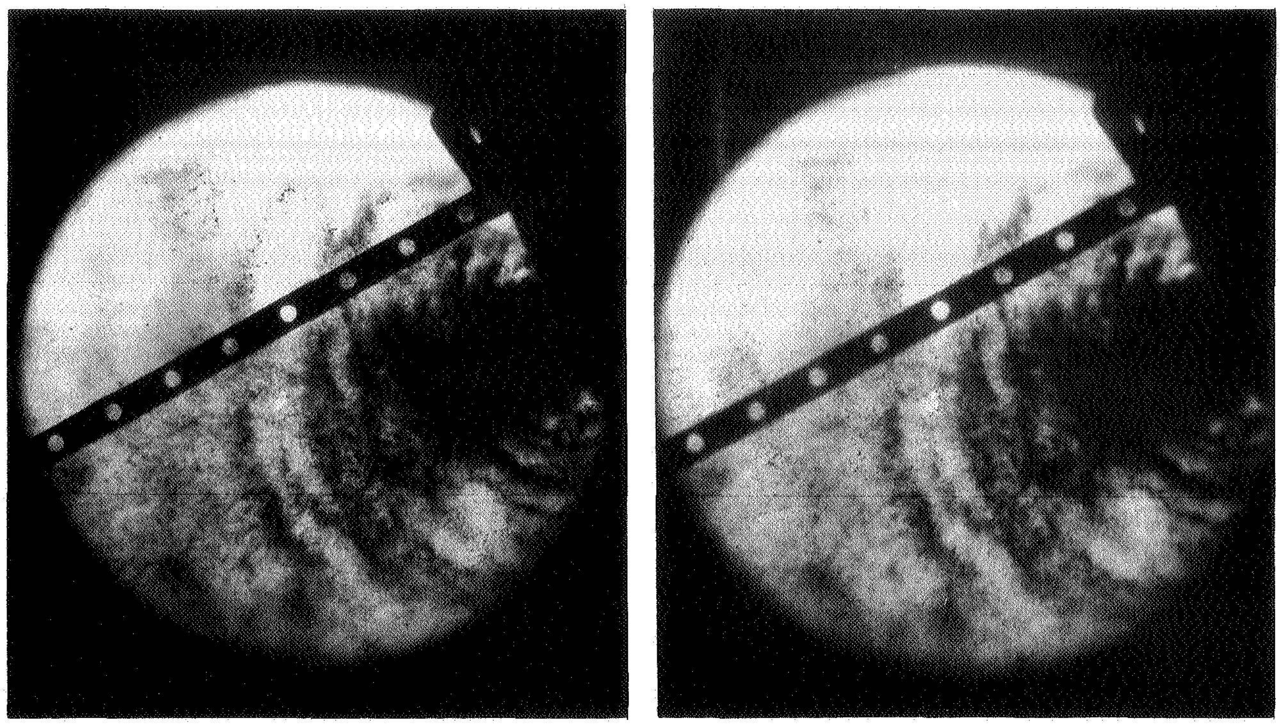


Figure 3-32. Two photographs of the reconstruction of a ruby laser hologram of the open flame combustion of N_2O_4 and 50/50 mixture N_2H_4 and UDMH (Run B1117G). The two differ by a slight change in focus of the f/8 150mm copy camera lens. In the left, the steel strap with 1/4-inch holes on 1-inch centers is in sharp focus. In the right, it is out of focus.

N_2H_4-UDMH. The view is of the major axis (fan plane) of the reacting spray from a single element unlike doublet. Total propellant flow rate was 2.813 lb/sec at an overall mixture ratio (O/F) of 1.25.

The general direction of droplet breakup and flow is from right to left in the illustration. The "viewing station" for this hologram was the impingement point and the region immediately down stream (approximately 8 inches). The viewing angle is that of the major axis of the resultant spray fan.

The hologram (Figure 3-32 and 3-33) was made with Agfa 10E75 film plate and developed for approximately 60 seconds in HRP developer. The hologram was reconstructed with the light from a Spectra Physics

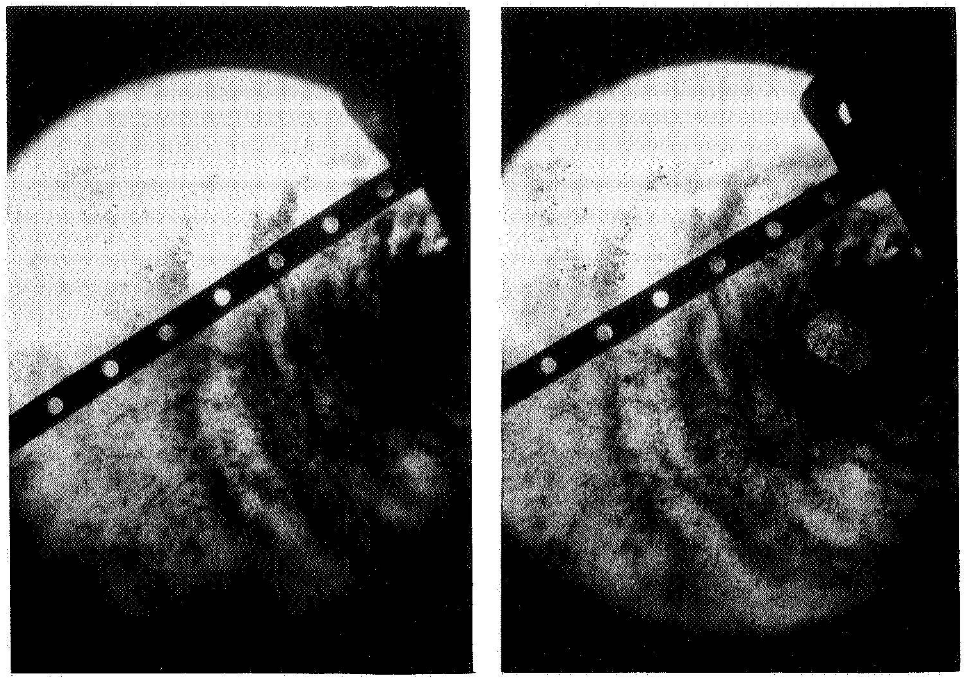


Figure 3-33. Two photographs of the reconstruction of a hologram of open flame combustion (Run B1117G). The pictures differ by the viewing angle of the copy camera. The pictures are mounted as a stereo pair, and can be so viewed with the aid of a viewer.

helium-neon laser, and photographed with a bellows copy camera using an f/8, 150 mm. lens.*

The first figure (3-32) illustrates the reacting propellant spray at slightly differing focal planes within the scene and illustrates photographically the three-dimensional characteristic of holography. The second figure (3-33) shows a given focal plane from two differing viewing angles (by the copy camera). With the aid of a viewer, this pair of reconstruction photographs can be viewed stereoptically.

Figure 3-34 is a photographic reproduction of the high speed recording oscillograph trace from Run B1115Q. This oscillograph trace is representative of the various tests of all phases of the test program and shows graphically the sequence of events which took place.

*Schneider-Kreuznach Componon lens.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

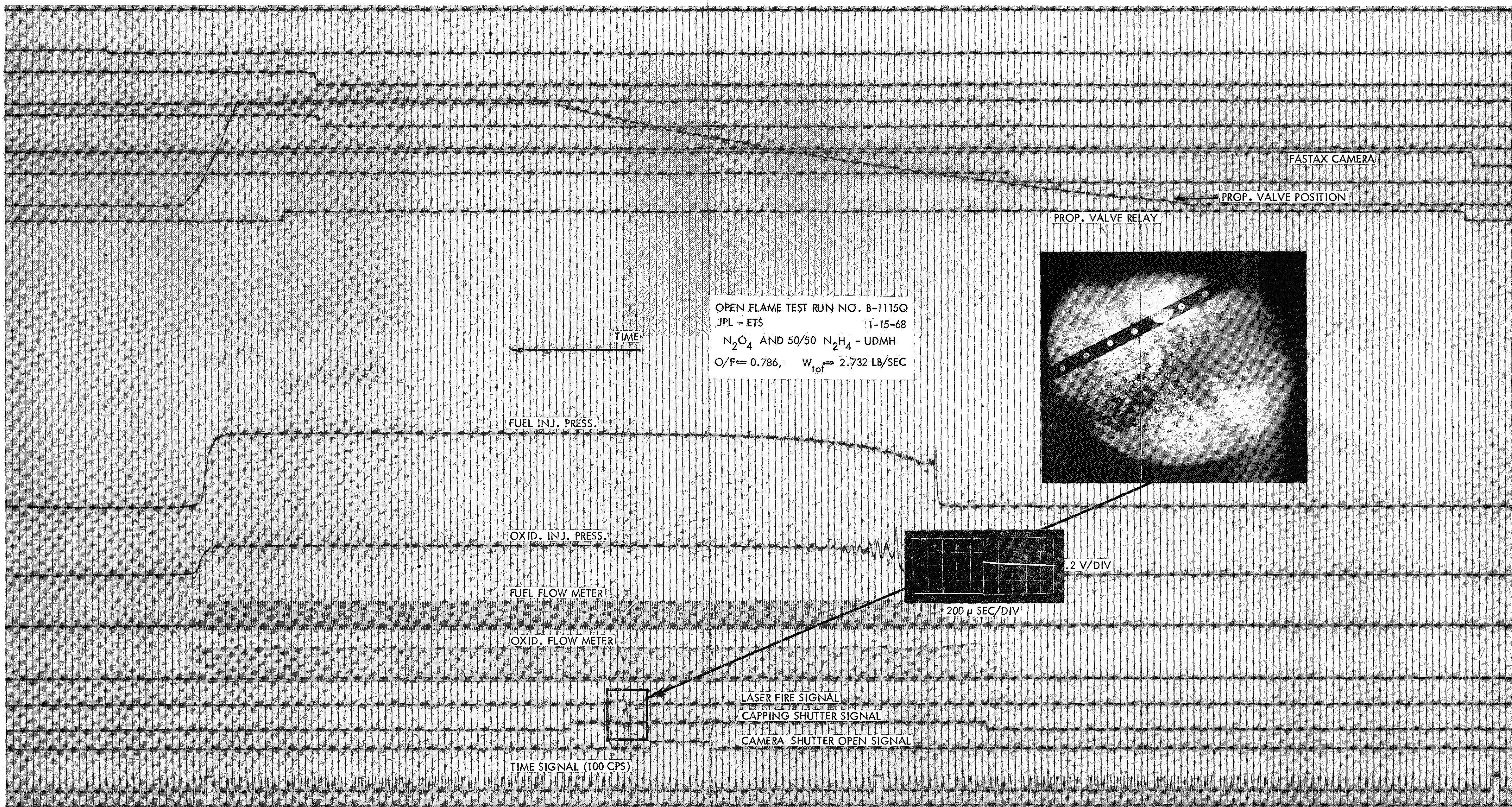


Figure 3-34. Photographic reproduction of the high speed recording oscillograph from open flame test Run No. B1115Q

The oscillograph trace shows that 300 milliseconds following the first indication of the propellant valve opening, the holocamera capping shutter was opened. Approximately 400 milliseconds later, the focal plane shutter was actuated which, in turn, triggered the laser (via a microswitch). The laser pulse occurred some 30 milliseconds after the focal plane "shutter open" signal was completed. The focal plane shutter signal trace indicated that approximately 90 milliseconds were required to fully open the shutter.

Several other open flame reconstruction photographs are presented and discussed in Reference 1. The illustrations of Run No. B-1115Q, and B1117G, however, are representative of these results. Two additional open flame hologram reconstruction photographs are presented here (Figured 3-35 and 3-36) since they are of particular interest.

The photographs of Figures 3-35 and 3-36 are interesting to compare because of the strikingly different events taking place. Both illustrations show views of the reactants along the minor axis or spray fan edge. The propellants were N_2O_4 and 50/50 N_2H_4-UDMH.

Figure 3-35 illustrates what appears to be a rather orderly combustion process, in that approximately 2 inches downstream of the impingement zone, droplet formations are readily discernible and somewhat uniformly distributed. In marked contrast with this photograph is the photograph shown in Figure 3-36. Examination of this photograph reveals a significant disruption of the mass of burning propellants into two separate and distinct regions. Note also the wave patterns formed in the lower divergent mass flow. For convenience, the operating parameters associated with these two test runs have been extracted from the complete listing of the open flame tests found in Appendix A. The operating parameters and conditions were as follows:

Parameter	Run No. B1115I	Run No. B1115R
Oxidizer	N_2O_4	N_2O_4
Fuel (50/50 Blend)	N_2H_4 - UDMH	N_2H_4 - UDMH
Mixture Ratio, O/F	1.359	1.219

Parameter	Run No. B1115I	Run No. B1115R
Oxidizer Flow Rate, lb/sec	0.893	1.576
Fuel Flow Rate, lb/sec	0.657	1.292
Injector Velocity, Ave. ft/sec	65.4	122.5
Oxidizer Temperature, ^{o}F	57	49
Fuel Temperature, ^{o}F	55	56

The reconstruction photographs for both illustrations were made by focusing the copy camera on a plane passing through the propellant impingement zone. The irregular shaped pattern or spot seen in Figure 3-36 is due to a reflection of the reference beam by windows protecting the film and mirror in the right assembly housing of the holocamera in the original scene which was recorded.[5]

Figure 3-37 is another illustration of the three-dimensional characteristics of a hologram. Three reconstruction photographs of the same hologram were made by selecting different focal planes within the scene. Referring to the figure, it may be seen that the photograph in the center was made by focusing the copy camera on the central portion of the reacting spray. In this instance, the viewer is looking at an edge of the spray fan recorded during Run No. B1115I. A reconstruction photograph of this firing was discussed previously (see Figure 3-35).

The photograph on the right in Figure 3-35 was made by focusing a copy camera on droplets located in a plane adjacent to the acrylic window protecting the film plate housing on the right side of the holocamera scene volume. The central opaque portion of the initial part of the reacting spray fan appears as a blur located behind these droplets. Conversely, the photograph on the left was made by focusing the copy camera on the droplets at the extreme opposite side of the scene volume. In this photograph, the opaque part of the spray fan is again blurred and out of focus, since it is now in the foreground of the scene. Also in sharp focus in this photograph is the 1/2-inch grid which was scribed on the acrylic plate attached to the 15-inch-diameter field lenses.

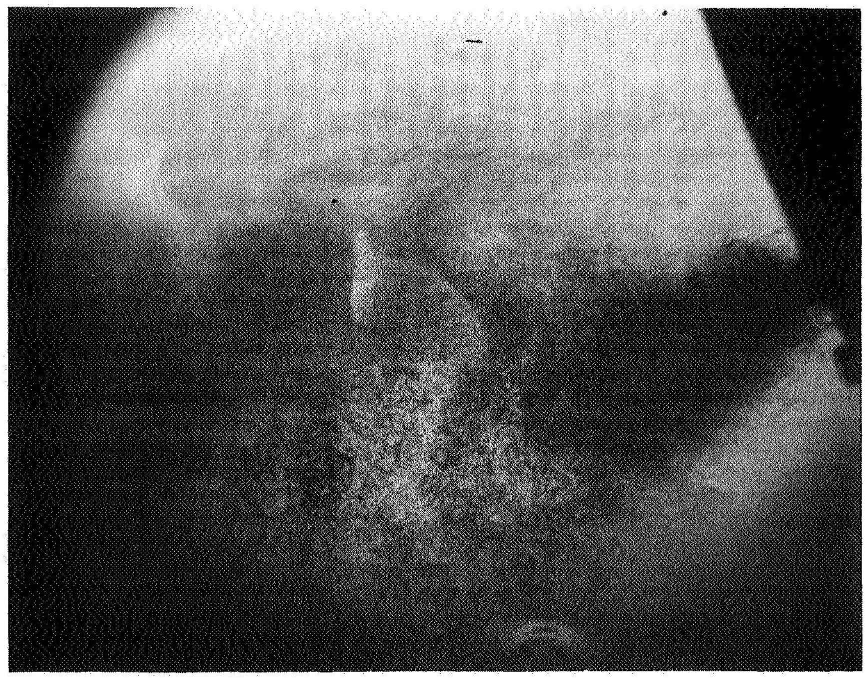


Figure 3-35. Reconstruction photograph of the edge view of the combustion spray fan recorded on N_2O_4-50/50 N_2H_4-UDMH firing No. B1115I

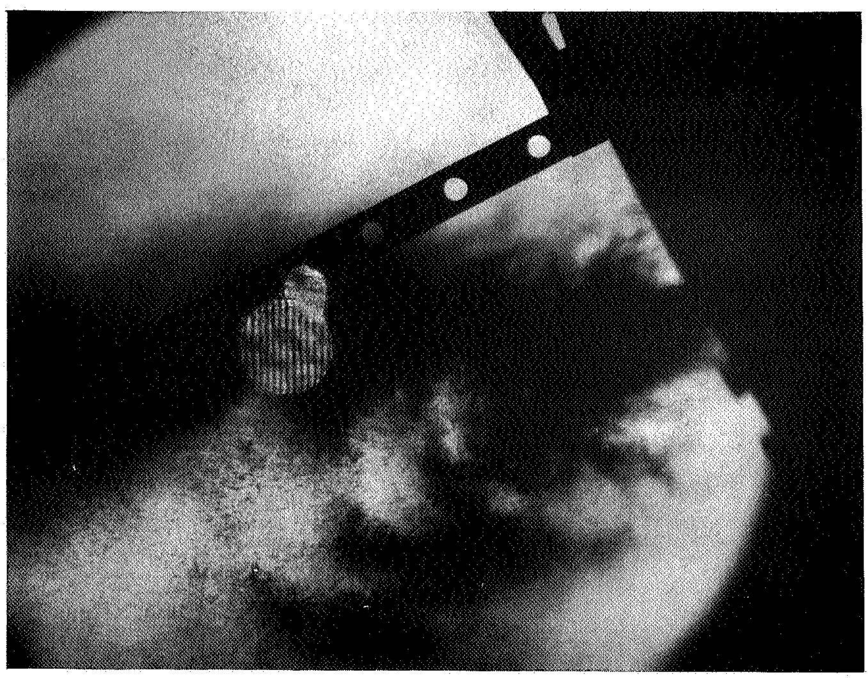


Figure 3-36. Reconstruction photograph of the edge view of the combustion spray fan recorded on N_2O_4-50/50 N_2H_4-UDMH firing No. B1115R

FOLDOUT FRAME 1

FOLDOUT FRAME 2

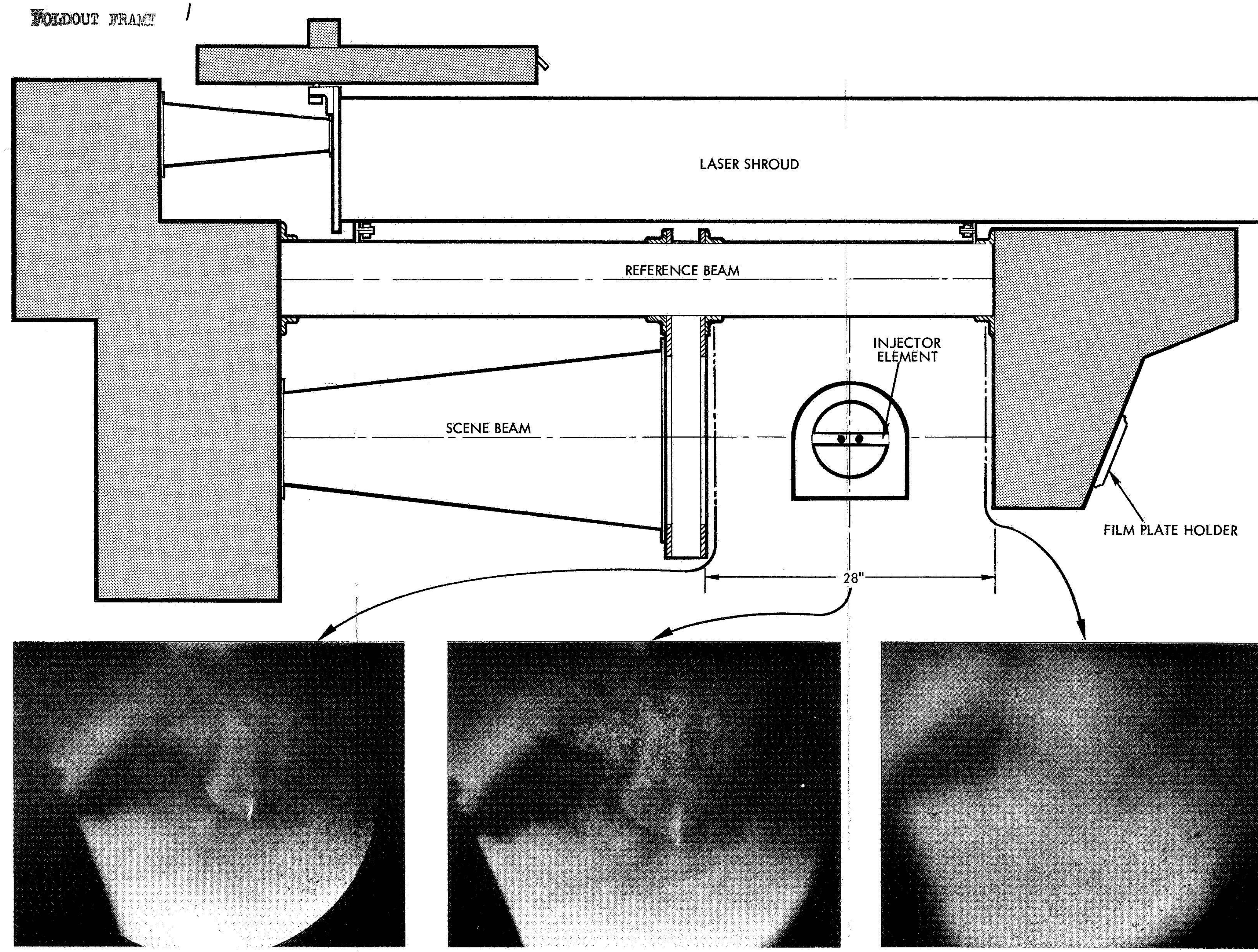


Figure 3-37. Reconstruction photographs made from open flame test B1115I illustrating three-dimensional characteristics of a hologram

3.2.3 3-Inch Chamber Tests

The Phase II holography studies involved the recording of reacting liquid propellant sprays in 3-inch-diameter combustion chambers. The test chambers consisted of 3-inch I. D. x 6-inch long acrylic cylinders attached to steel heat sink nozzles. Propellant was introduced into the transparent chamber section via a single element unlike doublet injector. A complete tabulation of the Phase II test results is given in Appendix B to this report.

All testing was conducted at the JPL/ETS site, test stand B. The test engine was fired at ambient test cell conditions. Initial testing utilized ambient temperature propellants. Later, tests were made with the propellant conditioning equipment installed. Elevated temperature propellants ranged between 98^{o} and 111^{o}F. Due to the changing desert test site weather conditions, ambient propellant temperatures varied between 33^{o} and 80^{o}F. As in Phase I, both N_2O_4 - 50/50 N_2H_4 - UDMH and FNA-UDMH propellant combinations were fired.

In general, the best quality holograms were recorded during the FNA-UDMH firings. Erosion of the acrylic chambers seemed less severe with this propellant combination. In addition, the holocamera scene-reference beam ratio had been optimized (by the time this series of tests were conducted) to diminish the ever-present problem of scene light attenuation.

Initial Phase II testing (reported in Reference 6) was concerned with calibration testing of the rocket engine and resolving holocamera equipment problems. The first several holographic recording attempts were unsuccessful.[7] Adjustment of the scene-reference beam ratio continued. The diffuser plates from the prism plate assembly were removed in a further effort to concentrate the laser light and penetrate the combustion volume. Severe erosion of the acrylic chambers continued to be a very serious problem in that the scene light was greatly attenuated by the chambers as well as the combustion reactions.

Test firing No. B-1149 (N_2O_4-50/50 N_2H_4-UDMH at P_c=102 psia) produced the first really successful hologram in the Phase II program. Prior to this run, smaller diameter injection orifices (0.0986-inch diameter) were installed in the chamber head-end. Most of the previous runs had been made using the 0.173-inch diameter orifices (used for the Phase I open flame tests). The smaller injection orifices together with adjustments to the beam intensity and ratio combined to produce an excellent reconstruction. Reconstruction photographs of the hologram made during this run are shown in Figure 3-38. The reconstruction of this hologram had one defect. It reproduced the "bright sun" effect caused by the undiffused scene beam. This effect tended to obscure most of the downstream* detail of ligament breakup and droplet formation. Further obscuring the combustion detail is the melting and erosion of the acrylic chamber walls which is also apparent in this figure.

Additional holograms were recorded of N_2O_4-50/50 N_2H_4-UDMH firings with only moderate success.[8] Subsequently, the propellants were changed to FNA-UDMH. At this time, the glass plate with a single ground surface was placed after the prism plate to result in more diffuse scene light. The reference beam intensity was increased by a factor of two.**

During the FNA-UDMH test firings, the best hologram of the entire Phase II effort was recorded (Run No. B1162, Figure 3-39). The accompanying laser oscillogram indicated that the laser produced a double pulse during the recording sequence. The reconstruction showed no fringes, however, indicating that in the interval between the two pulses (80 μsec) the optical path length must have changed more than several hundred wavelengths. The second pulse was much smaller than the first.

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*Below the coherent portion of the reacting spray fan.

**This scene-reference beam combination was used throughout the rest of the Phase II program.

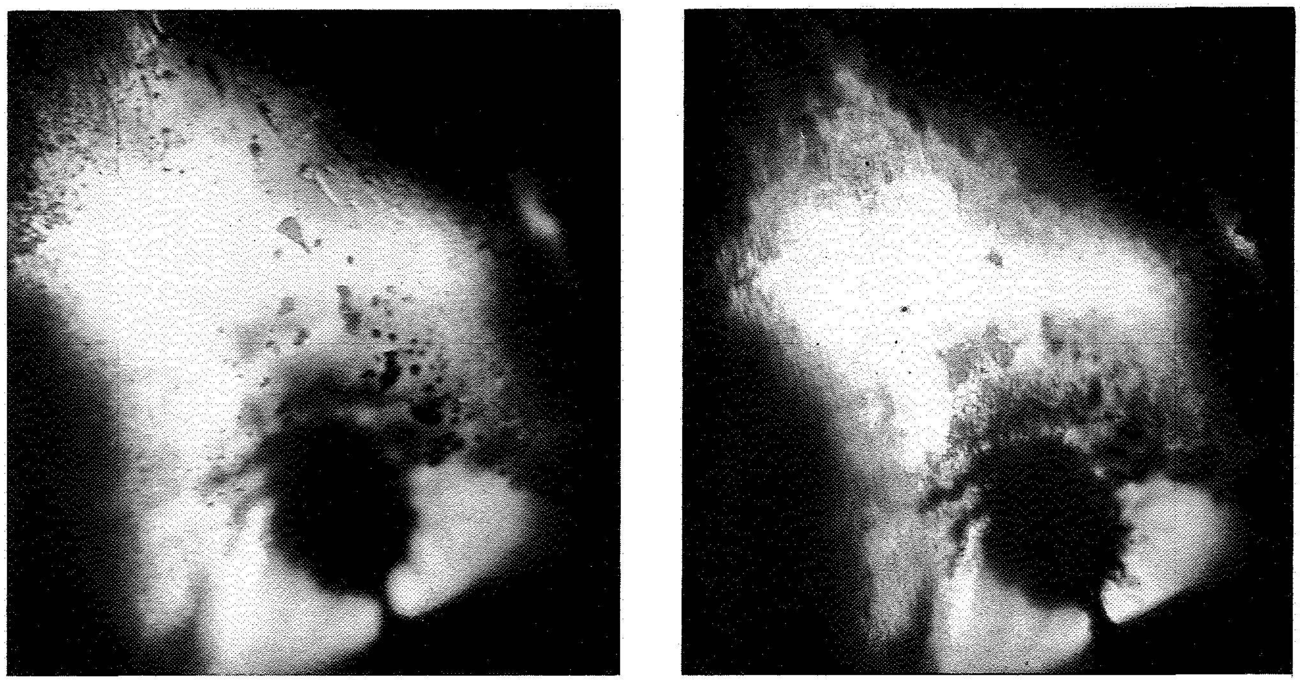

Figure 3-38. Two photographs of the reconstruction of a hologram of hypergolic propellant combustion in a 3-inch inside diameter combustion chamber with 0.099-inch injector orifices. The photographs correspond to different focal settings of the copy camera. The photographs are of Run B1149 using N_2O_4 and 50/50 N_2H_4-UDMH propellants

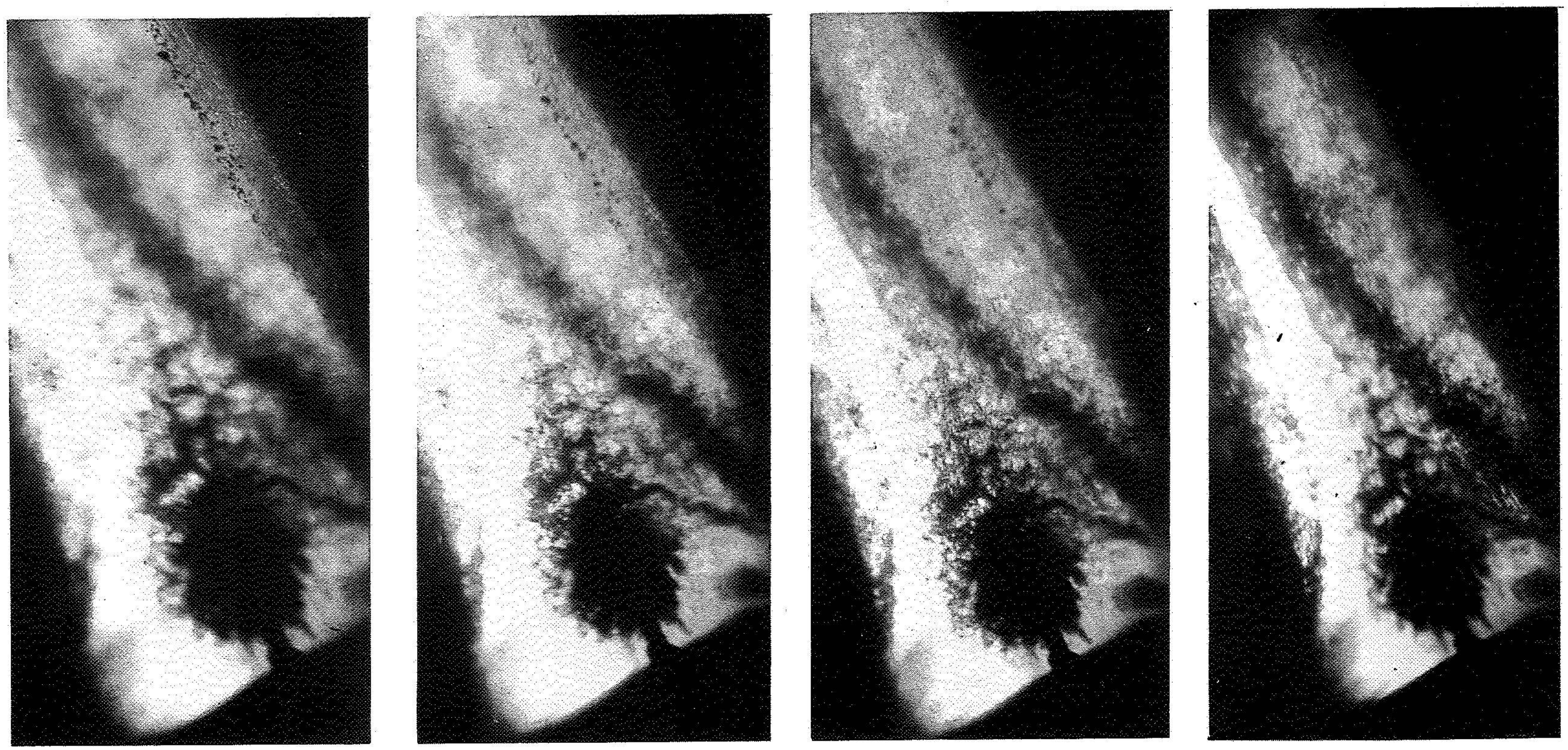

Figure 3-39. Four photographs of the reconstruction of a hologram of combustion within a rocket engine. The four photographs correspond to different focusing of the camera throughout the reconstruction volume. For the left picture, the camera is focused on the near inner wall. For the right picture, the camera was focused on the far inner wall. The other photos were at intermediate locations in the region of the fan. The hologram was No. B1162 and was the best of the Phase II series. The propellant was FNA and UDMH.

Figure 3-39 is a series of four reconstruction photographs of firing B1162. This is a fanplane view of FNA-UDMH combustion using the 0.0986-inch-diameter orifice injector. The copy camera was focused on the near side chamber wall in the left-hand photograph. In the extreme right-hand photograph, the camera was focused on the opposite or far side chamber wall. The intermediate photographs were made at different planes within the combustion scene. This series of reconstruction photographs serves to illustrate the depth-of-field feature of holography. As experienced throughout Phase II, definition in this series of photographs is degraded by the mottled condition of the eroding acrylic chamber.

The photographs of Figure 3-40 were also made from the reconstruction of hologram B1162. In this instance, the photographs were taken at different viewing angles of the hologram with respect to the copy camera. Adjacent photographs can be viewed stereoptically.

As indicated previously, run B1162 was made with FNA-UDMH propellants. Chamber pressure (P_c) in the 3-inch I. D. chamber was 106 psia and the overall mixture ratio was 1.40. Propellant inlet temperatures were in excess of 100^oF.

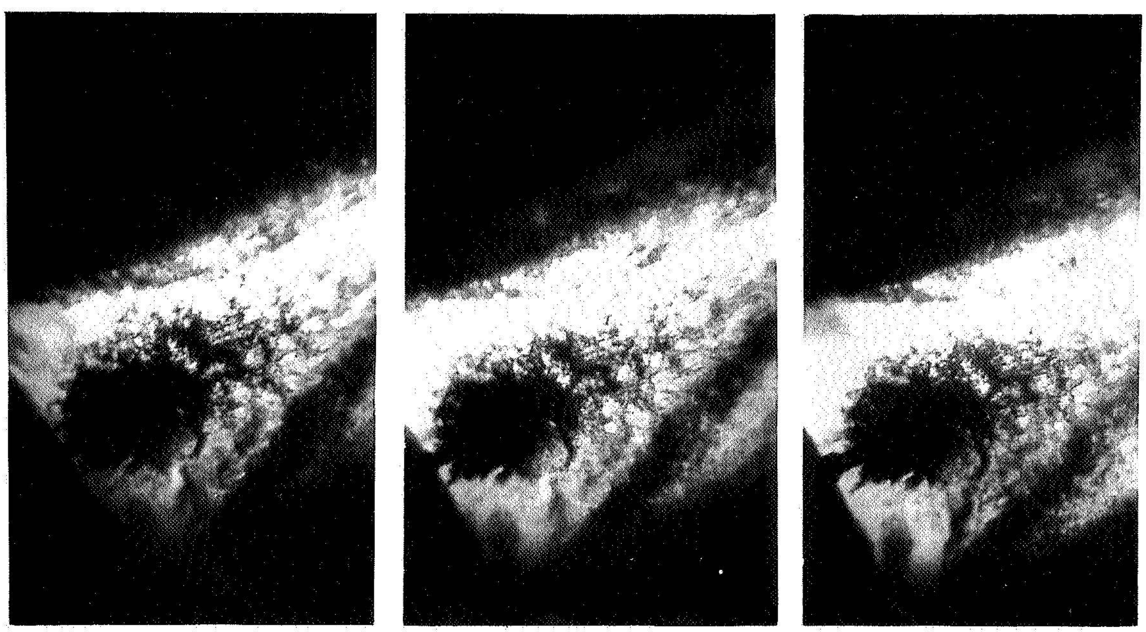

Figure 3-40. Three photographs of the B1162 hologram taken at different viewing angles. Adjacent photographs can be viewed stereoptically.

As may be seen from the illustrations of Figures 3-39 and 3-40, chamber wall erosion was again significant.* In spite of the overall attenuation of scene light (due to the eroded chamber and the combustion phenomena) a fair amount of detail may still be observed in the reconstruction and via the copy photographs. Some ligament formation is apparent although the initial part of the spray fan remains opaque. Under moderate magnification there appears to be discrete droplet formations about the fringes of the fan. This is, of course, a matter of interpretation at this time.

Also during Phase II, some true holographic interferograms were attempted, both of combustion and of air. For these holograms, the plate was exposed before, and coincident with, the event. In B1165, the attempt failed; either because of vibration or because the scene-reference beam intensity ratio between the two expanses was too great.

In B1167, the fan could be seen, but fringes were indistinct. Some tests were also attempted in which air was blown out of the orifices between the two exposures. Fringes could be seen in one, but they were not centered on the orifice. Vibration was thought to be the possible difficulty.

One other hologram (B1171) was attempted of an open flame. The hologram was fogged because the capping shutter was not reactivated. Fogging produced a weak reconstruction. A laser-illuminated photograph was also made during Phase II. This work is discussed in Section 3.2.5.

3.2.4 Eighteen-Inch Chamber Tests

As in the previous portions of the program, testing was initiated in the eighteen-inch diameter engine using N_2O_4 and 50/50 N_2H_4-UDMH propellants. Severe combustion instability was experienced in many of these firings with this propellant combination. The attendant shock and vibration loads imposed on the laser holocamera system (due to rough engine operation) were the source of many problems related to obtaining satisfactory holograms during Phase III. Much of the effort in this phase

*Note the sweeping and generally longitudinal dark streaks and mottled appearance near the edges of the acrylic chamber.

was devoted to reducing engine roughness and simultaneously making the holocamera operable under a more severe test environment.

The first attempt in Phase III to make a hologram was on 16 May 1968 (Run B1173). This attempt failed because of vibrations in the holocamera system. The cause of the vibrations was attributed to combustion roughness.

A second recording was made on 20 May 1968 (Run B-1174). The emission of the laser was not a single pulse, but rather a series of multiple pulses which persisted for about 50 microseconds. An accelerometer attached to the main support column of the holocamera (see Figure 3-17 in Section 3.1.5) indicated that the holocamera was being subjected to violent oscillations — accelerations of 300 g's — during the engine firing. Further, another accelerometer located on the end mirror of the laser showed accelerations of 30 g's.

In spite of vibration problems, the hologram recorded during Run B-1174 could be reconstructed. The reconstruction was dim; however, it showed at least that holography of combustion in relatively large engines (18-inch diameter) was, in fact, possible.

Hologram No. B-1174 was thought to be fortuitous. Subsequent attempts to make holograms failed because of the vibration problem which misaligned the laser. In addition to attempting to smooth the test engine operating characteristics, efforts were made to stiffen the holocamera structure. These efforts included the addition of supports to the laser end mirror mounts, and the addition of mass to the holocamera. The latter was in the form of small plastic sand bags inside the cannister which held the ruby laser. The holocamera support framework was also modified to avoid any direct impingement of the exhaust plume.

The attainment of smoother combustion in the engine proved to be the most significant factor in ultimately obtaining holograms which could be reconstructed. Several moderately good holograms were produced. Photographs of two are shown in Figures 3-41 and 3-42. The first figure corresponds to Run B1178, and is abnormal. During this run, the engine went unstable and the automatic water-nitrogen gas purge was subsequently actuated. The laser was fired, however, and recorded the engine in the process of being shutdown. The hologram shows a field of droplets suspended in the exhausting chamber gases. The droplets were millimeter size and were presumably water.

Figure 3-42 is a photograph of the reconstruction of the test engine during Run B-1184. This recording was one of the best recorded during the Phase III effort. The copy photograph was difficult to record and does not do justice to the reconstruction. Part of the difficulty was the unexpected nature of the scene. Droplets could not be seen; rather, the event was characterized by turbulence and the presence of dark clouds in the intervening space. This is illustrated by the ragged appearance of the edge of the far window when observed through the combusting cases. The opaque clouds were in the region closest to the injector plate and were presumed to be the fuel and oxidizer still in the unburned state. The turbulence of the gases prevented the observation of droplets smaller than a millimeter.

A comparison of Figure 3-41 with 3-42 shows that the out-of-focus edge of the rear window is sharp in one case, but diffuse in the other. This diffusion is attributed to the turbulent high-temperature burning gases. The dark cloud on the left of the photograph is thought to be an interference fringe resulting from optical length changes during the ~0.1 microsecond laser pulse.

To test or at least verify the resolution of the holograms, some tests were made after one of the runs. For this test, a transparent scale was mounted inside the engine along the midplane. Photographs of one of these holograms are shown in Figure 4-43. Very thick slab optical windows were used in this test. The finish on these windows could and did affect resolution of objects within the chamber.

The 18-inch-diameter engine was also fired with FNA and UDMH propellants. The combustion was noticeably smoother with these propellants. During this time, other capped windows were tested. In addition, attempts to improve the scene-reference beam ratio and reference beam diameter were made. Also, it was discovered that the roof reflector had been chipped along the edge where the two glass surfaces join. Despite this deficiency, further combustion holograms were recorded.

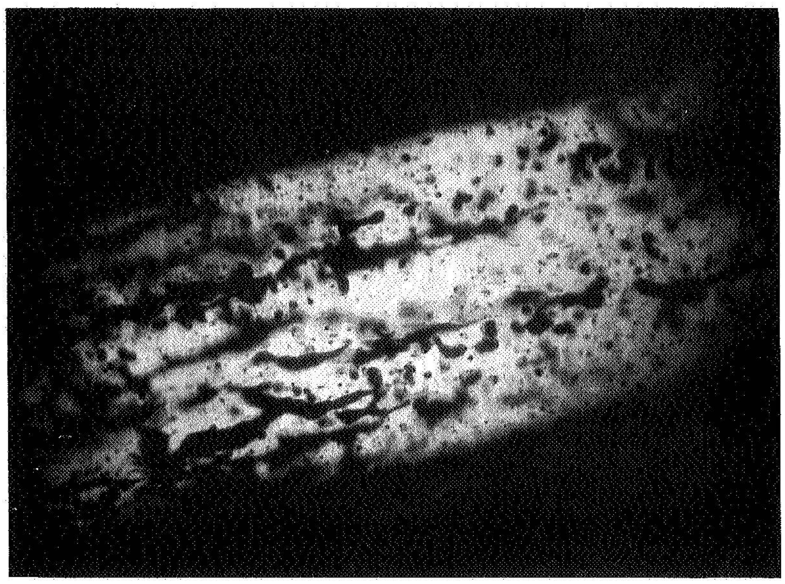

Figure 3-41. Photograph of the reconstruction of a ruby laser hologram made during the Phase III effort. The hologram corresponded to Run B1178, and is a recording of the engine shutdown with the air-nitrogen purge in operation.

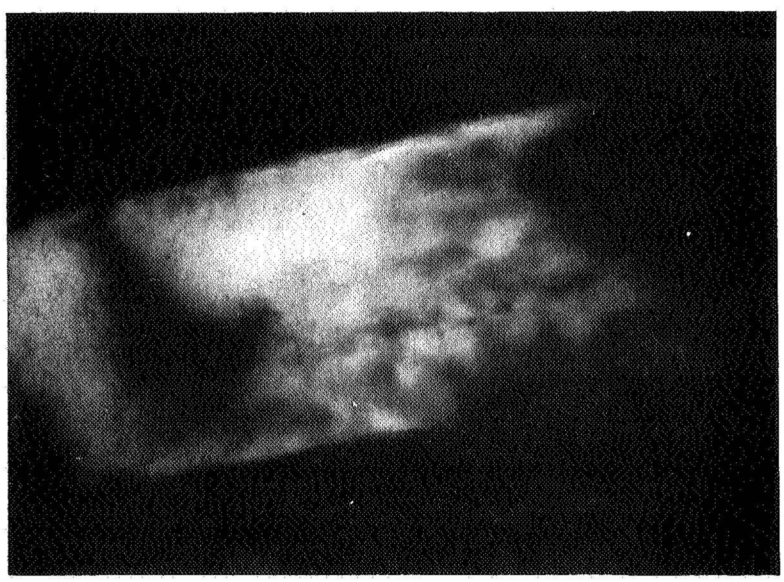

Figure 3-42. Photograph of the reconstruction of a hologram of the 18-inch engine combusting N_2O_4 and 50/50 mixture. The photograph corresponded to Run B1184.

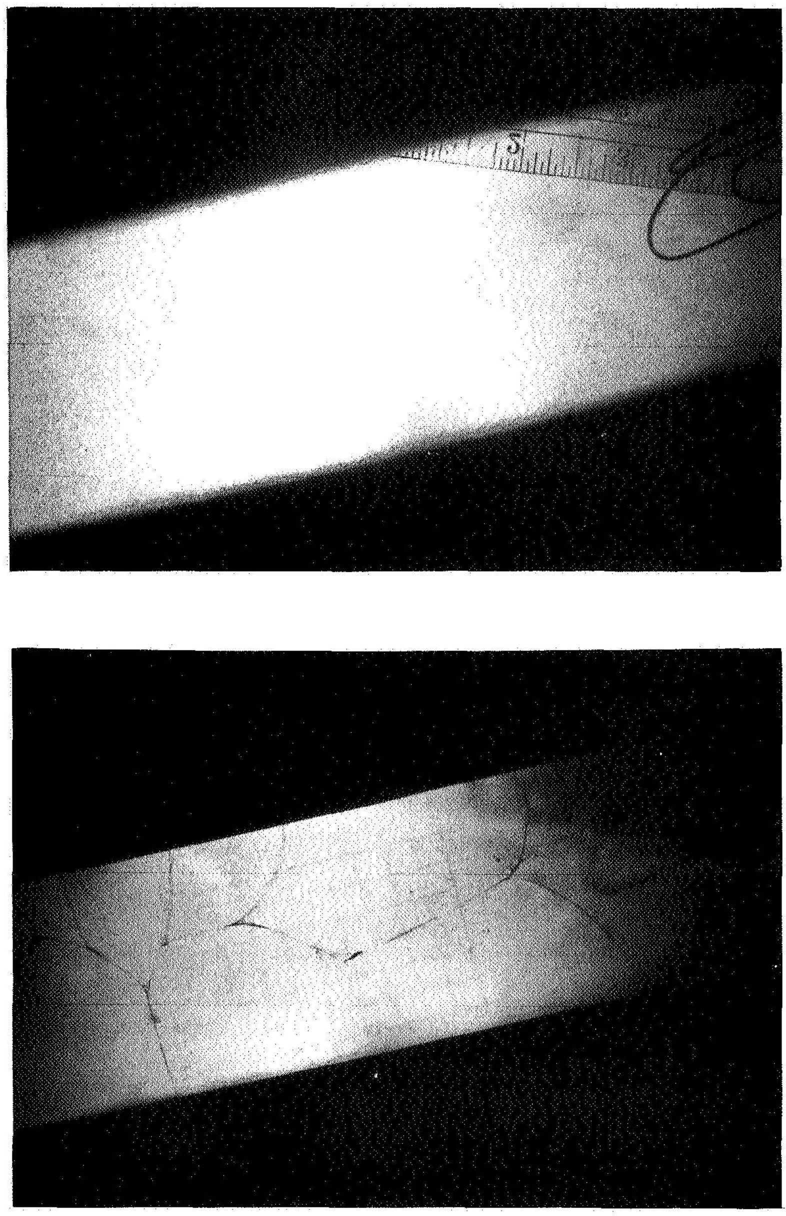

Figure 3-43. Photographs of the reconstruction of a test hologram made between firings of the engine. A transparent scale was mounted on the midplane of the holocamera. In the upper photograph, the copy camera was focused on the ruler; in the lower, on the cracked surface of the rear window. The size of the previous figures can be estimated from these two photos.

The refrigerator used to cool the ruby rod did not have the capacity to cope with increasing ambient temperatures. As a result, the laser emission became erratic. In spite of these difficulties, six holograms were recorded of the acid-UDMH combination. Hologram quality was not as good as others made previously. Time was not available to work out the deficiencies.

As indicated previously (Section 3.1.8), laminated acrylic-glass viewing windows were developed for the Phase III combustion testing. When N_2O_4-50/50 N_2H_4-UDMH propellants were fired in the 18-inch-diameter engine, the local combustion temperature adjacent to the inside window surface was sufficiently high that some Pyrex glass surface melting occurred. The post-fire water-nitrogen purge tended to quench the glass and produce cracking.* Combustion temperatures with the FNA-UDMH propellants were (apparently) lower in the vicinity of the window and damage was less severe. Some blistering of the glass was still noted.

One test was made with a window capped with Vycor (synthetic quartz). This did not melt, but was too thin to prevent internal blistering of the cement. A 3/8-inch-thick glass window had surface blistering, but no internal blistering. It, therefore, appears that a thick Vycor window would be optimum and could be used repeatedly. Vycor, however, is several times more expensive than Pyrex. A photograph of the two types of windows used during Phase III is shown in Figure 3-44.

3.2.5 Laser Illuminated Photography

A limited amount of laser illuminated photography work was conducted during the Phase I effort. Test photographs were recorded of water spray fans (reported in Section 3.2.1) using the single element 0.173-inch-diameter impinging stream injector. Open flame laser photography was also attempted during Phase I but without success.[9]

At the conclusion of the Phase II test program, laser photography tests were again conducted in an effort to get quality photographic recordings.

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*The glass portion of the laminated window could be replaced as described in Section 3.1.8, thus allowing the window assemblies to be reused.

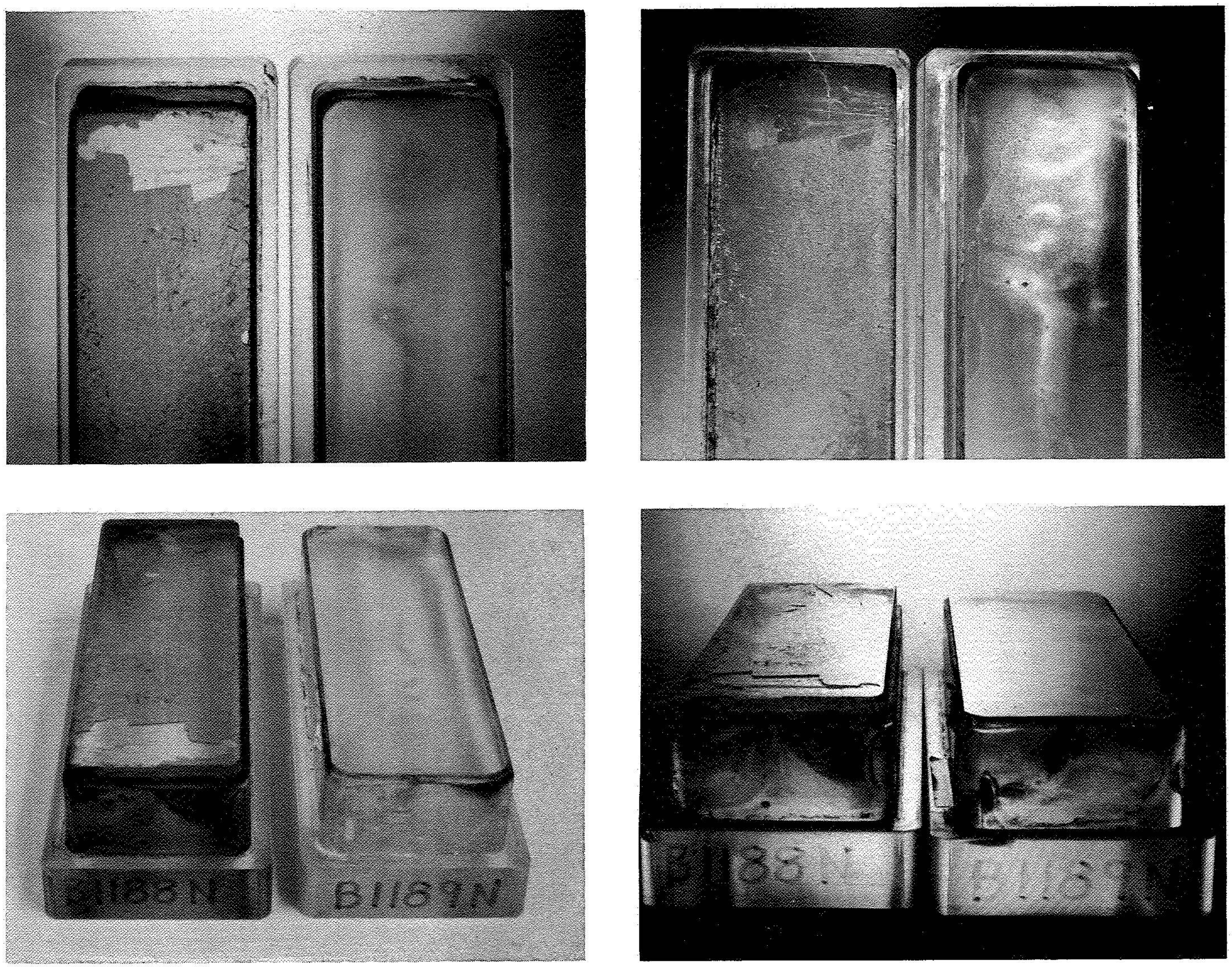

Figure 3-44. Four photographs of the Pyrex and Vycor capped acrylic window after use. The surface of the glass was blistered but did not fail in the bond. The Vycor surface survived, but the bond blistered.

As noted, the holocamera was fitted with brackets so that a bellows-type copy camera could be positioned to make conventional photographs of the flow phenomena. The camera thus used the laser and beam forming optics as a high-grade transmission type illuminator.

For laser photography, the reference beam was blocked and only the scene beam was used. The camera was mounted before the plate holder; the shutter was opened (i.e., on time exposure) and focused on the midplane of the combustion zone. The regular capping shutter and focal plane shutter in the holocamera were used to shutter the copy camera. The photographs were recorded on Eastman S0243 film using a Schneider Kreuznack Xenar f/1.4, 150 mm lens.* The resolution of the film (~400 lines/mm) was greater than that of the camera lens.

Two laser illuminated photographs (Runs B-1168 and B-1169) were attempted of combustion phenomena in 3-inch-diameter acrylic chambers. The results are reported in Reference 6. Unfortunately, the S0243 negatives were over developed and the results were marginal. The resulting photographic prints were flat and lacked definition.

One open flame laser photograph was also made during Phase II. This test, Run No. B-1172, produced an excellent quality photograph as shown in Figure 3-45. The propellants for this test were FNA-UDMH. The overall mixture ratio was approximately 1.4 with a total flow rate of about 0.92 lb/sec. Ligament formation and droplet dispersions are clearly visible.

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*Courtesy of William Tibbitts of JPL-ETS (lens No. 7287318).

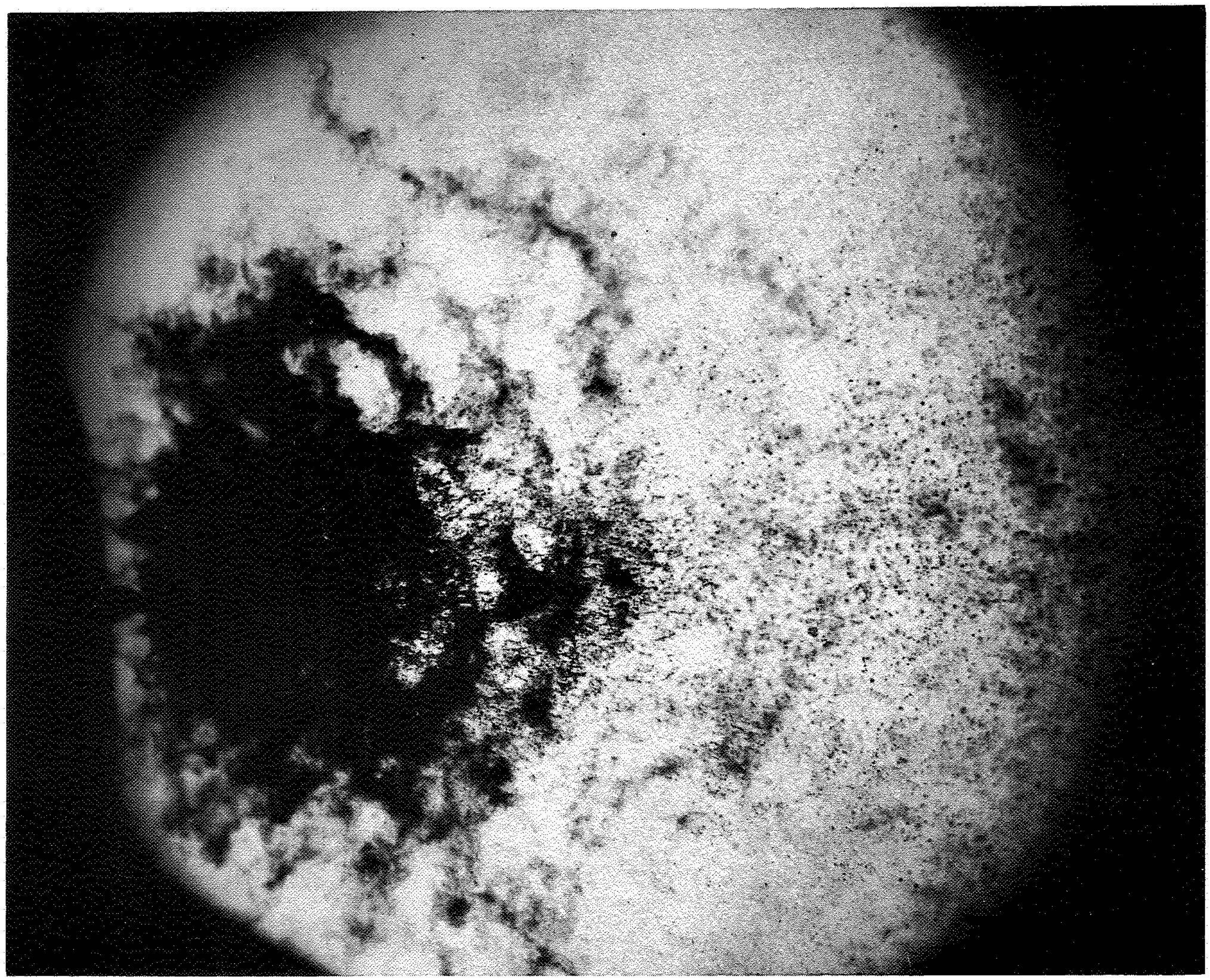

Figure 3-45. Direct laser photograph of open flame combustion using FNA and UDMH (Run B1172). The camera used a Schneider Kreuznack Xenar f/1.4, 150 mm lens.

4. CONCLUSIONS

The feasibility of producing pulsed ruby laser holograms and laser illuminated photographs of reacting liquid propellant sprays has been demonstrated as a result of this program. Feasibility of making this type of recording was specifically demonstrated for open flame tests, for small 3-inch-diameter (acrylic) thrust chambers, and for large 18-inch-diameter windowed thrust chambers.

Phase I resulted in the design, construction, and verification of a new and unique pulsed ruby laser holocamera. The feasibility of the holocamera design concept was tested and found satisfactory. More specifically, the feasibility of:

- Producing transmission holograms of burning propellant droplets in the presence of strong background radiation from the combustion flame was conclusively demonstrated
- Making holograms of a test scene volume 14 inches in diameter by 26 inches wide (scene volume depth) was demonstrated
- Routinely recording holograms under adverse field operating conditions and within the environment associated with liquid rocket engine testing was achieved

From the Phase II test program work using 3-inch-diameter acrylic chambers, it was concluded that:

- The combustion process of the two propellant combinations tested resulted in severe attenuation of the 0.69 μ ruby illumination light
- Holograms could be recorded by increasing the scene and reference beam ratios to compensate for the scene beam attenuation
- Erosion and melting of the acrylic chamber walls significantly degraded resolution of the events taking place within the combustion chamber as well as contributed to a loss of scene light
- Pyrex glass proved greatly superior to acrylic for use as window material in the investigation of reacting sprays via holography

The test work during Phase III demonstrated that transmission laser holography through an 18-inch-diameter combustion chamber was possible. The degradation of resolution because of window erosion experienced in Phase II was solved by the use of acrylic windows internally capped with Pyrex glass. Detailed resolution of the events within the large combustion chamber was, however, almost totally destroyed.

This loss of resolution in the large chamber was caused by refraction of the scene light caused by combustion gas turbulence.

5. RECOMMENDATIONS

The feasibility of using pulsed laser holography to record liquid rocket combustion phenomena has been demonstrated as a result of this program. Qualitative judgements regarding the hologram and the recorded phenomena are possible at this time. There is a need to extend further the techniques and application of combustion holography to a point where meaningful quantitative data may be routinely gathered. Toward this end, the following additional work is recommended:

- Review and analyze systematically the holographic results of all phases of the feasibility demonstration test program.
- Ascertain the resolution of the holocamera and modify this equipment as required to improve overall hologram quality and resolution.
- Conduct critical definition tests to determine the physical state or nature of the recorded phenomena and to establish standards of reference for additional combustion holography.
- Explore, on a preliminary basis, the feasibility of applying various data acquisition and reduction techniques to holographic recordings of reacting and nonreacting sprays.
- Construct and demonstrate a reflected light holography technique in an effort to identify the physical state of the reactants.
- Construct and demonstrate apparatus designed for lens-assisted holography to specifically investigate the small droplet size range of the reacting sprays.

6. NEW TECHNOLOGY

The following new technology items have been reported in compliance with the contractual requirements for this program.*

1) Title: Laser Holocamera

   Name of Innovator: R. F. Wuerker

   Reported In: "Producing Holograms of Reacting Sprays in Liquid Rocket Engines," Phase I Interim Report No. 68.4712.2-017, 24 February 1968, pp. 5-26.

   Date Reported to NASA: 2 August 1968

2) Title: Ground Control Approach by Holography

   Name of Innovator: R. A. Briones

   Reported In: Letter to Mr. Monte F. Mott, Technology Utilization Officer, Jet Propulsion Laboratory, Pasadena, California.

   Pages: Second attachment to above letter.

   Date Reported 2 August 1968

3) Title: Glass-Acrylic Windows for Combustion Test Cells

   Name of Innovator: R. F. Wuerker

   Reported In: "Producing Holograms of Reacting Sprays in Liquid Rocket Engines," Final Report, TRW Report No. 68.4712.2-024, July, 1968.

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*JPL Contract No. 952023 (NAS7-400), "Producing Holograms of Reacting Sprays in Liquid Propellant Rocket Engines."

APPENDIX A

SUMMARY OF PHASE I TEST RESULTS

Table A-I. Water Flow Test Summa

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} psi	P_{TF} psi	Total Flow $\dot{\omega}$ lb/sec	Type of Record	Remarks
B1113A	11-30-67	Impingement Pt.	Fan Plane	125	125	1.37	Hologram	Holograms were not recorded for tests A, B & C. For test C, TRW power supply was disconnected and only ETS power supply used. Shutter open micro-switch to be used to fire laser. Sequence timer fire signal removed by setting "offtime" to zero.
B	"	" "	" "	125	125	1.40	"	
C	"	" "	" "	128	128	1.42	"	
D	12-5-67	" "	" "	83	96	1.19	"	Holograms and photographs were not recorded on tests D, E & F. Laser may be firing too soon. For Test G, a new electrical cable was used from TRW control con-sole to camera to isolate fire signal from shutter solenoid signal.
E	"	" "	" "	94	99	1.25	"	
F	"	" "	" "	85	85	1.17	Photograph	
G	"	" "	" "	90	94	1.21	Hologram	
H	"	" "	" "	107	107	--	"	
I	"	" "	" "	275	320	2.35	"	
J	"	" "	" "	285	330	2.40	"	
K	"	" "	" "	293	338	2.42	Photograph	Lost photograph - Laser out of alignment
L	12-6-67	" "	" "	85	94	1.22	"	
M	"	" "	" "	270	312	2.34	"	
N	"	" "	" "	280	326	2.38	"	
O	"	" "	Fan Edge	96	96	1.23	"	
P	"	" "	" "	80	87	1.17	"	
Q	"	" "	" "	95	95	1.227	Hologram	
R	"	" "	" "	95	95	1.227	"	
S	"	" "	Oblique-10°	91	92	1.19	"	
T	"	" "	" "	91	92	1.19	Photograph	
U	"	12" Downstream	Fan Plane	92	93	1.21	"	
V	"	" "	" "	99	100	1.264	Hologram	
W	"	" "	" "	277	323	2.39	"	
X	"	" "	" "	279	322	2.39	Photograph	

Table A-II. Phase I Open Flame Test Summary: N_2O_4 and 50/50 N_2H_4–UDMH Propellant Combination

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} Psi	P_{TF} Psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_f$ Lb/Sec	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp., °F Ox/Fuel	Type of Record	Remarks
B1114F	12-21-67	Impingement Pt.	Fan Plane	145	132	0.863	0.60	1.44		35/40	Hologram	Film plate was fogged
G	"	" "	" "	145	132	0.796	0.623	1.28		35/40	"	" " " "
H	12-22-67	" "	" "	145	132	0.80	0.61	1.31		35/40	"	" " " "
I	"	" "	" "	135	132	0.786	0.618	1.24		35/40	"	Very weak image - plate fogged
B1115A	1-8-68	Impingement Pt.	Fan Plane	137	134	0.945	0.619	1.526	64.7	46/45	Hologram	No hologram obtained
B	"	" "	" "	135	135	0.938	0.629	1.491	65.1	46/46	"	" " "
C	"	" "	" "	136	133	0.943	0.626	1.506	65.1	47/47	"	" " "
D	1-10-68	" "	" "	131	133	0.916	0.625	1.465	64.5	53/53	"	Poor holocamera position
E	"	" "	" "	135	130	0.939	0.618	1.357	65.7	52/53	"	Hologram unsatisfactory
F	"	" "	" "	108	175	0.780	0.764	1.021	67.3	52/52	"	Recording of fuel jet only
G	1-11-68	" "	" "	138	130	0.874	0.659	1.326	65.1	57/58	"	Good hologram
H	"	" "	" "	109	174	0.793	0.763	1.039	67.8	57/50	"	" "
I	"	" "	Fan Edge	139	132	0.893	0.657	1.359	65.4	57/49	"	" "
J	1-12-68	" "	" "	166	76	0.967	0.496	1.949	59.3	54/54	"	Adjusted capping shutter, hologram very hazy
K	"	" "	15° Oblique	106	114	0.778	0.609	1.277	59.1	54/56	"	Hologram very hazy
L	"	Downstream	Fan Plane	107	114	0.770	0.606	1.270	58.6	54/54	"	Good hologram - few droplets visible
M	1-15-68	"	" "	428	460	1.688	1.281	1.317	125.6	52/50	"	" " - more droplets visible
N	"	Impingement Pt.	" "	377	434	1.574	1.269	1.240	121.4	54/54	"	Double laser pulse - hologram dark
O	"	" "	" "	373	433	1.576	1.269	1.241	121.4	55/55	Photograph	No photograph obtained
P	"	" "	" "	372	428	1.572	1.258	1.249	-	55/58	Hologram	Weak hologram

Table A-II. Phase I Open Flame Test Summary: N_2O_4 and 50/50 N_2H_4 – UDMH Propellant Combination (Continued)

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} Psi	P_{TF} Psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_f$ Lb/Sec	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp., °F Ox/Fuel	Type of Record	Remarks
B1115Q	1-15-68	Impingement Pt.	Fan Plane	220	593	1.203	1.529	0.786	120.8	56/58	Hologram	Very good hologram
R	"	" "	Fan Edge	429	375	1.576	1.292	1.219	122.5	55/56	"	" " "
S	"	" "	" "	572	285	1.948	1.037	1.878	121.5	54/55	"	Hologram weak and hazy
B1117A	1-30-68	" "	Fuel Stream	-	131	-	0.621	-	-	--/46	Hologram	Single orifice flow only
B	1-31-68	" "	Oxid. Stream	144	-	0.737	-	-	-	46/--	"	Single orifice flow only
C	2-2-68	" "	Oxid. Stream	147	-	0.712	-	-	-	47/--	"	Single orifice flow only
D	"	" "	Fan Edge	148	130	0.602	0.633	0.951	56.2	92/92	"	Good hologram
E	"	" "	Oxid. Stream	232	-	0.858	-	-	-	96/--	"	Single orifice flow only
F	2-6-68	" "	Fan Edge	442	450	1.400	1.450	0.965	137.6	87/91	"	
G	"	" "	Fan Plane	547	451	1.565	1.248	1.254	122.6	95/98	"	
H	"	" "	" "	151	125	0.699	0.635	1.035	58.2	97/96	"	Good hologram
I	"	" "	" "	151	123	0.738	0.625	1.180	59.7	81/91	"	Lost photographic record

Table A-III. Phase I Open Flame Test Summary: FNA-UDMH Propellant Combination

Run No.	Date	Viewing Station	Viewing Angle	P_{TO} psi	P_{TF} psi	$\dot{W}_o$ Lb/Sec	$\dot{W}_F$ Lb/Sec	O/F Ratio	V_{ave} Ft/Sec	Prop. Temp, °F Ox/Fuel	Type Of Record	Remarks
B-1115-T	1-16-68	Impingement Pt.	Fan Edge	360	423	1.496	1.225	1.221	122.3	55/54	Hologram	Multiple laser pulse
U	"	" "	" "	206	571	1.104	1.391	0.793	120.3	54/56	"	Hologram poor - acrylic windows etched
V	"	" "	Fan Plane	415	390	1.614	1.167	1.383	122.4	54/56	"	No hologram obtained
W	1-17-68	" "	" "	407	382	1.605	1.163	1.380	121.7	53/52	"	Good hologram - clear but weak
X	"	" "	" "	641	254	2.035	0.943	2.158	121.8	53/56	"	" " " " "
Y	"	" "	" "	102	92	0.784	0.558	1.405	59.0	55/59	"	" " " " "
Z	"	" "	" "	161	64	0.987	0.467	2.113	59.8	56/60	"	" " " " "
B-1116-A	"	" "	Fan Edge	103	94	0.783	0.563	1.391	60.8	57/64	"	Good hologram - acrylic windows were dirty
B	"	" "	" "	62	127	0.607	0.661	0.918	60.0	57/64	"	Good hologram
C	1-18-68	" "	15° Oblique	103	94	0.773	0.558	1.385	58.4	49/51	"	Poor and hazy - dirty windows
D	"	Downstream	Fan Plane	104	94	0.788	0.557	1.414	59.0	54/54	"	Good hologram - not many droplets visible
E	"	"	" "	412	381	1.609	1.161	1.385	121.9	55/56	"	No hologram obtained
F	"	"	" "	414	381	1.619	1.158	1.398	122.3	56/60	"	Good hologram - droplets not visible
B-1117-J	2-8-68	Impingement Pt.	Oxid. Stream	142	-	0.704	-	-	-	90/-	Hologram	Single orifice flow only
K	"	" "	" "	167	-	0.839	-	-	-	101/-	"	" " " "
L	"	" "	Fan Plane	156	135	0.863	0.611	1.412	66.1	94/95	"	Good hologram
M	"	" "	" "	537	449	1.953	1.188	1.650	137.5	98/100	"	" "
N	"	" "	Fan Edge	452	445	1.604	1.156	1.387	124.8	98/100	"	" "
O	"	" "	" "	159	130	0.811	0.594	1.365	63.4	100/95	"	" "

APPENDIX B

SUMMARY OF PHASE II TEST RESULTS

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Run No.	Date	Time	Viewing Angle	P_{t_o}	P_{inj-o}	P_{t_f}	P_{inj-f}	PC-1	Oxidizer Flow lb/sec	Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks		Laser Performar
B1123	4/5/68	2:45	Fanplane cond. "B"	210	184	225	197	41.4 tape	0.772	0.637 r = 1.21 C* = 2519	South	No record	T_o = 76 T_f = 72	0.173 orifice 1.60 nozzle steel chamber, no windows		
B1124	4/8/68	3:36	Fanplane cond. "E"	828	727	835	726	101.1 tape	1.742	1.305 r = 1.33 C* = 2432	South	No record	T_o = 80 T_f = 70			
B1125	4/9/68	2:52	Fanplane	327	326	355	354	64.1 tape	0.234	0.202 r = 1.16 C* = 3808	Fastax and South	No record	T_o = 76 T_f = 72	0.072 orifice 0.919 nozzle steel chamber, no windows		
B1126	4/9/68	3:14	Fanplane	427	426	465	460	70.0 tape	0.271	0.227 r = 1.19 C* = 3587	Fastax and South	No record	T_o = 75 T_f = 75			
B1127	4/10/68	3:01	Fanplane	329	307	330	311	154 tape	0.863	0.577 r = 1.195 C* = 2458	Fastax and South	No record	T_o = 78 T_f = 80	0.173 orifice 0.919 nozzle steel chamber; quartz window south; pyrex north		
B1128	4/10/68	3:35	Fanplane	297	282	363	338	155.6 tape	0.750	0.623 r = 1.204 C* = 2635	Fastax and South	No record	T_o = 74 T_f = 80	0.173 orifice 0.919 nozzle acrylic chamber		
B1129	4/16/68	9:08	Fanplane	301	287	353	299	146 tape	0.770		Fastax and South	H*	T_o = 50 T_f = 56	No laser signal		Failure
B1130	4/16/68	11:00	Fanplane	298	285	351	326	150 tape	0.762	0.612 r = 1.245 C* = 2546	Fastax and South	H	T_o = 61 T_f = 60	No laser signal		Failure
B1131	4/17/68	8:49	Fanplane	300	283	352	330	148 tape	0.806	0.623 r = 1.293 C* = 2418	Fastax and South	H	T_o = 55 T_f = 54	Steel chamber, quartz windows Accelerometers	S	0.30 volts
B1132	4/17/68	11:18	Fanplane	296	280	352	330	153.6 tape	0.788	0.620 r = 1.27 C* = 2539	No	H	T_o = 57 T_f = 55		S	0.08 volts
B1133	4/17/68	1:34	Fanplane	296	280	355	332	164.2 tape	0.788	0.613 r = 1.285 C* = 2713	No	H	T_o = 57 T_f = 56			Failure
B1134	4/18/68	10:59	Fanplane	294	275	351	275	146	0.791	0.614 r = 1.288 C* = 2429	No	H	T_o = 53 T_f = 55		S	0.54 volts
B1135	4/18/68	11:18	Fanplane	297	280	351	330	154	0.786	0.612 r = 1.284 C* = 2563	No	H	T_o = 60 T_f = 57		S	0.44 volts
B1136	4/18/68	1:18	Fanplane	295	297	353	329	151	0.784	0.615 r = 1.274 C* = 2515	South	H	T_o = 55 T_f = 55	Acrylic chamber Accelerometers	S	0.30 volts

Note: Fuel orifice north on fanplane and bottom for fanedge.

H = Hologram

FOLDOUT FRAME 3

Table B-I. Phase II 3-Inch-Diameter Chamber Test Summary: N_2O_4 and 50/50 N_2H_4-UDMH Propellant Combination

ce	Emulsion Type and Development		Hologram Quality	Relative Reference Beam
	8E75		No penetration	1/8 (1:1)
	8E75		No penetration	1/8 (1:1)
	8E75			1/8 (1:1)
	8E75		No penetration	1/8 (1:1)
	8E75		No penetration	1/8 (1:1)
	8E75		Faint penetration near injector plate	1/8 (1:1)

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Run No.	Date	Time	Viewing Angle	P_{t_o}	P_{inj-o}	P_{t_f}	P_{inj-f}	PC-1	Oxidizer Flow lb/sec	Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks	Laser Perfor[m]	
B1137	4/18/68	2:59	Fanplane	295	277	352	325	147	0.806	0.615 r = 1.310 C* = 2416	Fastax and South	H	T_o = 51 T_f = 50	0.173 orifice 0.919 nozzle acrylic chamber—fuel orifice south	S	0.36 volts
B1138	4/19/68	1:03	Fanplane	289	265	356	327	149	0.756	0.615 r = 1.229 C* = 2536	Fastax and South	H	T_o = 54 T_f = 51	Repeat of B1137 odd laser signal, plate not developed		Prelased
B1139	4/19/68	1:58	Fanplane	292	275	356	334	149	0.779	0.622 r = 1.252 C* = 2481	Fastax and South	H	T_o = 54 T_f = 48	0.173 orifice 0.919 nozzle acrylic chamber—fuel orifice north	S	0.40 volts
B1140	4/19/68	3:07	Fanplane	291	272	355	334	150.4	0.767	0.618 r = 1.241 C* = 2532	Fastax and South	H	T_o = 55 T_f = 53	Accelerometers discontinued	S	0.52 volts
B1141	4/22/68	3:14	Fanplane	325	321	351	340	80	0.462	0.395 r = 1.339 C* = 2475	Fastax and South	H 1st good Hologram	T_o = 38 T_f = 40	0.0986 orifice 0.919 nozzle acrylic chamber—fuel orifice north	S	0.66 volts
B1142	4/28/68	10:46	Fanplane	399	395	469	459	103	0.515	0.408 r = 1.263 C* = 2700	No	H	T_o = 42 T_f = 42	0.0986 orifice 0.919 nozzle acrylic chamber—fuel orifice north	S	0.20 volts
B1143	4/23/68	11:20	Fanplane	389	385	456	445	101.6	0.509	0.405 r = 1.256 C* = 2694	No	H	T_o = 45 T_f = 45	Full orifice south		missed
B1144	4/23/68	2:04	Fanplane	290	274	364	336	149	0.777	0.632 r = 1.229 C* = 2467	No	H	T_o = 52 T_f = 54	0.173 orifice 0.919 nozzle acrylic chamber—fuel orifice north	S	0.48 volts
B1145	4/23/68	3:08	Fanplane	290	273	361	337	151.2	0.766	0.626 r = 1.223 C* = 2531	No	H	T_o = 51 T_f = 52	Fuel orifice south	S	0.44 volts
B1146	4/24/68	11:25	Fanplane	292	270	354	331	144	0.784	0.626 r = 1.253 C* = 2390	Fastax and South	H	T_o = 45 T_f = 45	Fuel orifice north	S	0.72 volts
B1147	4/24/68	3:02	Fanplane	296	269	360	331	142	0.790	0.636 r = 1.242 C* = 2333	Fastax and South	H	T_o = 42 T_f = 44	Fuel orifice north	S	0.74 volts
B1148	4/24/68	3:34	Fanplane	392	387	457	446	101.6 tape	0.512	0.408 r = 1.254 C* = 2676	No	H	T_o = 39 T_f = 44	0.0986 orifice Fuel orifice north	S	0.72 volts
B1149	4/25/68	10:48	Fanplane	391	385	455	446	102 tape	0.509	0.400 r = 1.272 C* = 2718	No	H	T_o = 50 T_f = 46	0.0986 orifice Fuel orifice north	S	0.5 volts
B1150	4/25/68	1:07	Fanedge	395	387		445	103.2 tape	0.507	0.401 r = 1.264 C* = 2750	Fastax and South	H	T_o = 42 T_f = 44	Fuel orifice bottom	S	0.4 volts

FOLDOUT FRAME 3

Table B-I. Phase II 3-Inch-Diameter Chamber Test Summary: N_2O_4 and 50/50 N_2H_4- UDMH Propellant Combination (Continued)

...nance	Emulsion Type and Development		Hologram Quality	Relative Reference Beam
	8E75		Better penetration near injector plate	1/16
	10E75		Failed	1/16
	10E75		Barely visible near injector	1/40
	10E75		Only edges of hologram reconstructed	3 cm lens remove from colluator. Also 1/40
	10E75	5 minutes	First real Hologram of combustion in acrylic chamber	1/1600 with one -3 cm lens in collimator
	10E75	15 minutes	Faint	1/1600 with -3 cm lens—recollimated 1 diffuser removed
	10E75	8 minutes	Faint but otherwise satisfactory	1/1600 with -3 cm lens—recollimated 1 diffuser removed
	10E75	10 minutes	Penetration only near injector plate	1/1600 with -3 cm lens—recollimated 1 diffuser removed
	10E75	10 minutes	Penetration only near injector plate	1/1600 with -3 cm lens—recollimated 1 diffuser removed
	10E75	6 minutes	Better penetration	1/800 with -3 cm lens—1 diffuser removed
	10E75	4 minutes		1/400 with -3 cm lens in collimator and all diffuser plates removed
	10E75	3 minutes	Overdeveloped dark reconstruction	1/400 with -3 cm lens in collimator and all diffuser plates removed
	10E75	~4 minutes	Beautiful, has hot sun but excellent	1/200 with -3 cm lens in collimator and all diffusers removed
	10E75	4 minutes	Good hologram	1/200 with -3 cm lens in collimator and all diffusers removed

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Run No.	Date	Time	Viewing Angle	P_{t_o}	P_{inj-o}	P_{t_f}	P_{inj-f}	PC-1	Oxidizer Flow lb/sec	Fuel Flow lb/sec		ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks	Laser Perform	
B1151	4/25/68	2:05	Fanedge	395	367	455	426	180 tape	0.949	0.731	r = 1.298 C* = 2325	Fastax and South	H	T_o = 42 T_f = 45	0.173 orifice Fuel bottom	S	0.52 volts
B1152	4/26/68	10:16	Fanedge	296	280	355	335	158 tape	0.774	0.598	r = 1.294 C* = 2674	Fastax and South	H	T_o = 100 T_f = 106	0.173 orifice Fuel bottom	S	0.7 volts
B1153	4/26/68	10:47	Fanedge	400	398	455	445	112 tape	0.514	0.399	r = 1.288 C* = 2941	Fastax and South	H	T_o = 99 T_f = 104	0.0986 orifice Fuel bottom	M 2 pulses spaced 120	0.43 volts
B1154	4/26/68	12:54	Fanplane	401	397	452	442	112.4 tape	0.502	0.396	r = 1.268 C* = 2999	Fastax and South	H	T_o = 103 T_f = 106	0.0986 orifice Fuel north	S	0.45 volts
B1155	4/26/68	1:19	Fanplane	297	280	354	332	157.6 tape	0.758	0.609	r = 1.245 C* = 2521	Fastax and South	H	T_o = 98 T_f = 103	0.173 orifice Fuel north	S	0.35 volts

FOLDOUT FRAME 3

Table B-I. Phase II 3-Inch-Diameter Chamber Test Summary: N_2O_4 and 50/50 N_2H_4-UDMH Propellant Combination (Continued)

ance	Emulsion Type and Development		Hologram Quality	Relative Reference Beam
	10E75	4 minutes	Heavy erosion of acrylic	1/200 with -3 cm lens in collimator and all diffusers removed
	8E75	8 minutes	Heavy erosion	1/200 with -3 cm lens in collimator and all diffusers removed
μsec apart	8E75	6-1/2 minutes	No fringes seen	1/200 with -3 cm lens in collimator and all diffusers removed
	8E75		Excellent except for bright sun	1/200 with -3 cm lens in collimator and all diffusers removed
	8E75		Heavy attenuation	1/200 with -3 cm lens in collimator and all diffusers removed

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Run No.	Date	Time	Viewing Angle	P_{to}	P_{inj-o}	P_{tf}	P_{inj-f}	PC-1	Oxidizer Flow lb/sec	Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks	Laser Pe	
B1156	4/29/68	1:00	Fanplane	286	270	355	328	130 tape	0.762	0.622 r = 1.225 C* = 2218	Fastax and South	H	T_o = 63 T_f = 57	0.173 orifice Fuel north	S	0.2 volt
B1157	4/29/68	1:31	Fanplane	434	432	371	363	104 tape	0.517	0.330 r = 1.566 C* = 2968	Fastax and South	H	T_o = 35 T_f = 40	0.098 orifice Fuel bottom	D (80 μsec)	First 0. Second 0
B1158	4/29/68	3:21	Fanedge	437	436	375	367	104.4 tape	0.524	0.334 r = 1.568 C* = 2939	Fastax and South	H	T_o = 45 T_f = 43	0.0986 orifice Fuel bottom	S	0.40 vol
B1159	4/30/68	10:37	Fanedge	465	462	472	457	107.4 tape	0.544	0.392 r = 1.388 C* = 2763	Fastax and South	H	T_o = 103 T_f = 98	0.0986 orifice Fuel bottom	S	0.60 vol
B1160	4/30/68	11:09	Fanedge	330	305	287	270	130 tape	0.875	0.518 r = 1.689 C* = 2050	Fastax and South	H	T_o = 103 T_f = 103	0.173 orifice Fuel bottom	D (160 μsec)	First 0. Second 0
B1161	4/30/68	1:00	Fanplane	300	281	320	298	132 tape	0.808	0.570 r = 1.417 C* = 2259	Fastax and South	H	T_o = 105 T_f = 110	0.173 orifice Fuel north	S	0.30 vol
B1162	4/30/68	1:31	Fanplane	465	462	470	459	106.8 tape	0.546	0.390 r = 1.40 C* = 2750	Fastax and South	H	T_o = 105 T_f = 111	0.0986 orifice Fuel north	D (160 μsec)	First 0. Second 0
B1163	4/30/68	3:08	Fanplane	465	462	470	456	105.2 tape	0.550	0.391 r = 1.406 C* = 2698	Fastax and South	H	T_o = 102 T_f = 108	0.0986 orifice Steel chamber, window section ≈ 3 cm from injector	S	0.35 vol
B1164	5/1/68	10:37	Fanplane	458	455	471	455	96	0.545	0.396 r = 1.376 C* = 2489	No	H	T_o = 50 T_f = 49	0.0986 orifice Steel chamber, window section ≈ 1 cm from injector	S	0.5 volt
B1165	5/1/68	11:03	Fanplane	460	458	475	460	100	0.546	0.396 r = 1.376 C* = 2578	No	H	T_o = 53 T_f = 52	0.0986 orifice Interferogram	D	exposure
B1166	5/1/68	1:41	Fanedge	297	278	322	300	126	0.782	0.580 r = 1.348 C* = 2191	Fastax and South	H	T_o = 45 T_f = 40	0.173 orifice Fuel north	D (40 μsec)	First 0. Second 0
B1167	5/2/68	10:42	Fanplane	449	443	456	442	97.6	0.536	0.386 r = 1.389 C* = 2578	No	H	T_o = 47 T_f = 44	0.0986 orifice Interferogram	D	exposure

FOLDOUT FRAME 3

Table B-II. Phase II 3-Inch-Diameter Chamber Test Summary: FNA-UDMH Propellant Combination

rformance	Emulsion Type and Development		Hologram Quality	Relative Reference Beam
	8E75		Good	1/100 with -3 cm lens in collimator and 1 diffuser (single surface)
35 volt . 05 volt	8E75		Excellent; no fringes	↑
t	8E75		Very beautiful shows erosion	
t	8E75		Good, stronger erosion	
60 volt . 03 volt	8E75		Fainter reconstruction heavier erosion	
t	8E75		Very good	
4 volt . 03 volt	8E75		Best of Phase II hologram	
t	8E75		Excellent (pyrex window)	
	8E75		Excellent. Poorer penetration due to window location	
interferogram	8E75		Failed	
50 volt . 03 volt	8E75		Good hologram Heavy erosion	↓
interferogram	8E75		Failed	1/100 with -3 cm lens in collimator and 1 diffuser (single surface)

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

Table B-II. Phase II 3-Inch-Diameter Chamber Test Summary: FNA-UDMH Propellant Combination (Continued)

Run No.	Date	Time	Viewing Angle	P_{to}	P_{inj-o}	P_{tf}	P_{inj-f}	PC-1	Oxidizer Flow lb/sec	Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks	Laser Performance		Emulsion Type and Development		Hologram Quality	Relative Reference Beam
B1168	5/2/68	12:49	Fanplane	450	445	455	442	96	0.538 r = 1.393 C* = 2535	0.386	No	Laser photo	T_o = 33 T_f = 33	0.0986 orifice Fuel north	S	0.45 volt	Eastman S0243	5 minutes in D-19 Std	NA overdeveloped	
B1169	5/2/68	1:13	Fanplane	448	445	457	445	99	0.533 r = 1.377 C* = 2615	0.389	No	Laser photo	T_o = 37 T_f = 41		S	0.45 volt	Eastman S0243	4 minutes in D-19 Std	NA overdeveloped	
B1170	5/2/68	3:05	Fanplane	451	448	458	445	98.4	0.540 r = 1.391 C* = 2580	0.388	Fastax high speed	No	T_o = 38 T_f = 39							
B1171	5/2/68	3:25	Fanplane	350	341	354	340		0.531 r = 1.383 C* =	0.384	No	H	T_o = 50 T_f = 50	0.0986 orifice Open flame	S	0.45 volt	Agba 8E75	Fogged ~2 minutes	Weak due to fogging	
B1172	5/2/68	3:41	Fanplane	355	346	360	345		0.535 r = 1.387 C* =	0.387	No	Laser photo	T_o = 63 T_f = 63	0.0986 orifice Open flame	S	0.45 volt	Eastman S0243	4 minutes in D-19 Std	NA	

APPENDIX C

SUMMARY OF PHASE III TEST RESULTS

FOLDOUT FRAME 1

Table C-I. Phase III 18-Inch Diameter Chamber Test Summary: N_2O_4 and 50/50 N_2H_4-UDMH Propellant Combination

FOLDOUT FRAME 2

Run No.	Date	Time	Thrust F	P_{t_o}	P_{inj-o}	P_{t_f}	P_{inj-f}	PC-1D psig	Oxidizer Flow lb/sec / Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Remarks	Laser Performance	Emulsion Type and Development Time	Remarks
B1173	5/16/68	11:16	—	340	141	327	141.5	63	32.7 24.3 r = 1.345	North and South	H	T_o = 66 T_f = 68	Instability Trip 0.173			
B1174	5/20/68	2:24	16,868	564	255	616	381.5	110	46.06 — r = —		H	T_o = 82 T_f = 85	Fair but dim	M 0.24 volt (100 μsec duration)	8E75 (1.5 min)	Very faint low contrast
B1175	5/22/68	1:23	14,930	498	222	458	295	95	42.306 40.118 r = 1.055 C* = 5270		H	T_o = 68 T_f = 70	Laser failed due to vibration		8E75	
B1176	5/23/68	1:50	11,203	504	161	341	154	68.8	32.66 25.05 r = 1.304 C* = 5560		H	T_o = 73 T_f = 73	Instability Trip 0.161		8E75	
B1177	5/24/68	10:25	9,176	497	125.8	345	107.5	45.3	29.08 19.53 r = 1.489 C* = 9696	North and South	H	T_o = 65 T_f = 65	Instability Trip 0.108		8E75	
B1178	5/24/68	12:48	10,477	550	151.6	344	131.7	63.6	32.83 22.84 r = 1.437 C* = 5412	North	H	T_o = 69 T_f = 68	Instability Trip 0.202 Hologram taken 0.45 sec after cutoff - no purge - hologram very interesting	M 0.12 volt (40 μsec duration)	8E75	Water droplets contrast low - otherwise good
B1179	5/24/68	1:25	13,584	440	200	370	245	86.7	40.574 36.66 r = 1.107 C* = 5062	None	H	T_o = 68 T_f = 69	Fair but dim	S 0.28 volt	8E75	Only left half shows reconstruction - clouds and turbulence
B1180	5/24/68	1:48	13,518	442	201.5	370	248	87.8	40.803 36.68 r = 1.112 C* = 5099	North and South	H	T_o = 70 T_f = 70	N.G. obscured - 2nd run on window	S 0.78 volt	8E75	Heavy eroded plexiglas reconstructs in small spot only
B1181	5/27/68	11:12	13,509	435	197	365	242	86.2	40.243 36.569 r = 1.100 C* = 5074		H	T_o = 74 T_f = 76	Poor, dim and diffused	M 0.1 volt (80 μsec duration)	8E75	Very fast reconstruction
B1182	5/27/68	1:11	13,342	440	198	368	245	86.7	40.319 36.570 r = 1.103 C* = 5133		H	T_o = 78 T_f = 80	N.G. dark and obscure - 2nd run on window		8E75	Heavily modulated could be fringes
B1183	5/28/68	3:22	13,600	439	208	366	299	89.2	41.449 36.596 r = 1.132 C* = 5185		H	T_o = 95 T_f = 97			8E75	No exposure
B1184	5/29/68	9:19	—	441	203	370	245	87	40.699 35.670 r = 1.140 C* = 5184		H	T_o = 78 T_f = 79	Brighter - fair - may be best	S 0.2 volt	8E75 (30 sec)	Excellent
B1185	5/29/68	10:06	13,703	442	202.4	370	245	87.9	40.587 36.130 r = 1.123 C* = 5144		H	T_o = 78 T_f = 80	Poor - interesting fringes	S 0.72 volt	8E75 (30 sec)	Fringes (?)
B1186	5/29/68	10:39	13,793	441	204	369	245	88.2	40.732 36.260 r = 1.128 C* = 5148	North and South	H	T_o = 80 T_f = 80	Bare plastic N.G. dark	D (260 μsec) 0.19 volt 0.02 volt	8E75 (60 sec)	Hologram of eroded plexiglas

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Run No.	Date	Time	Thrust F	P_{t_o}	P_{inj-o}	P_{t_f}	P_{inj-f}	PC-1D psig	Oxidizer Flow lb/sec / Fuel Flow lb/sec	ETS Camera	Hologram Photograph	Propellant Temperature (°F)	Rema[rks]
B1187	6/4/68	3:19	14,284	505	283	350	240	91.28	52.176 37.493 r = 1.392 C* = 4567	North and South		T_o = 90 T_f = 87	
B1188	6/5/68	10:54	14,170	505	277	352	238	89.13	50.64 37.78 r = 1.340 C* = 4548		H	T_o = 68 T_f = 69	1/2 glass v[...] north
B1189	6/5/68	1:23	13,382	430	251	340	230	85.2	48.25 33.20 r = 1.453 C* = 4712		H	T_o = 70 T_f = 68	Vicor wind[...]
B1190	6/5/68	3:22	13,316	429	252	340	230	84.5	48.22 33.11 r = 1.456 C* = 4720		H	T_o = 71 T_f = 69	
B1191	6/6/68	10:29	13,346	440	249	345	229	84	47.87 32.81 r = 1.459 C* = 4743		H	T_o = 69 T_f = 64	
B1192	6/6/68	11:22	13,260	438	249	339	227	84.2	48.03 32.88 r = 1.460 C* = 4730	North and South		T_o = 64 T_f = 65	Polished pl[...] dows both [...]

Table C-II. Phase III 18-Inch Diameter Chamber Test Summary: FNA-UDMH Propellant Combination

FOLDOUT FRAME 3

ırks	Laser Performance	Emulsion Type and Development Time	Remarks
	S 0.44 volt	8E75	Dim reconstruction
ɿindow -	S 0.66 volt	8E75 (80 sec)	Dim to point of being unreadable
ɔw - north	S 0.88 volt	8E75	Weak left side only barely reconstructs
	S 0.48 volt	8E75	Weak low contrast
	M 0.54 volt for 80 μsec	8E75	Low contrast
astic win- sides	S 0.38 volt	8E75	Very faint

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