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PHOTOGRAPHIC INVESTIGATION OF PROPELLANT STREAM BEHAVIOR IN A FIRING ROCKET ENGINE

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FOREWORD

This report was prepared by Bell Aerosystems Company under Contract NAS 8-11364 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory (R-P&VE-PAC) of the George C. Marshall Space Flight Center with Mr. R. J. Richmond acting as Project Manager.

The contract was started on 1 August 1964. All test work on the contract was stopped on 11 January 1966. Additional theoretical work involving geometrical and physical optics was accomplished during preparation on the final report.

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Especially acknowledged are Mr. T. F. Reinhardt's technical contributions and his readiness to discuss and to help solve major technical and scientific problems.

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1.0 SUMMARY

This program was initiated in an effort to obtain photographic records of the injection and combustion pattern of injector elements of the Rocketdyne F-1 rocket engine. This engine has a nominal thrust of 1,500,000 pounds, a chamber pressure of 1000 psia, chamber internal dimensions of 40 inches in diameter by 40 inches long, and a nozzle contraction ratio of 1.25;1. Propellants are liquid oxygen and RP-1 fuel.

A "model" windowed thrust chamber with 2-1/2 elements of F-1 injector was built, and an attempt was made to take high resolution shadowgraphs of the propellant sprays under firing conditions. The attempt was unsuccessful because the flame light from the model motor proved to be so much more intense than that of the small experimental motor on which the photographic method had been previously developed by Bell Aerosystems Company, that it completely overpowered the spark flash used from back illumination (Section 8.2.2). Completion of the F-1 development effort eliminated the requirement for this work, and this program was terminated before the photographic method could be refined to such a degree that its primary objective could be achieved. However, important secondary accomplishments relative to the high speed and high resolution photography of rocket combustion phenomena were achieved as follows.

A technique for installing and sealing windows of appreciable size, and protecting them against chemical and thermal attack by the combustion gases while keeping them sufficiently clean from deposits, was developed and proved to be very satisfactory at chamber pressures up to 850 psia (Section 6.1.2).

Correlation between shadowgraphs of water sprays taken during this program and shadowgraphs previously taken through a small firing experimental motor yielded basic information concerning the formation and internal structure of propellant sprays during firing conditions (Section 5.2).

Guidelines were established for the simulation of the injection and combustion patterns of a large thrust chamber in a model chamber small enough to permit application of high resolution shadow photography (Section 6.2).

Finally, guidelines were established for the selection and application of appropriate optical elements, light sources and photographic equipment for taking high speed and high resolution photographs of combustion phenomena occurring in a windowed motor. For this purpose, a systematic semi-theoretical analysis was conducted using geometrical and physical optics and taking into consideration the restrictions imposed by the peculiarities of the problem (Section 9.0).

2.0 BACKGROUND

An abundance of practical experience gathered during development and testing of operational engines shows that the combustion stability of a liquid propellant rocket engine (i.e., its resistance to the tendency to run into oscillating or fluctuating combustion) can be influenced by changes in the design and the operating conditions of the injector. This statement holds also with respect to "high frequency" or "acoustic" instability, i.e. loosely speaking, with respect to the occurrence of various modes of acoustic pressure oscillations or waves of high amplitudes within the gaseous content of the combustion chamber. This is of special interest because some of these modes which do the most severe damage to the chamber prove to be difficult to eliminate in practice, especially in large engines.

This experience indicates that the region adjacent to the injector face, in which the major portion of the transition from liquid propellants to hot gases takes place and which is affected directly by changes in design and operation of the injector, is a critical region with respect to the combustion stability of a liquid propellant rocket engine.

By way of example, Figure 1 provides an overall view of this region. It shows three consecutive frames of a series of shadowgraphs taken with back illumination at a rate of 2500 frames/sec through a small experimental windowed motor, operating at a chamber pressure of 300 psia. The injector contains six pairs of orifices, each pair impinging one jet of UDMH on one jet of WFNA. A photographic technique developed by Bell Aerosystems Company was used (References 1 and 2). More shadowgraphs obtained by means of this technique are shown in Figures 29, 30, 31. Figure 2 shows two frames of a series which was taken under the same conditions as Figure 1 but further downstream in the "uniform" region, where the propellants are much more finely atomized and more evenly mixed than in the poorly atomized and poorly mixed "transition" region. It shows the distribution of unburned propellant droplets approaching the nozzle end of the small experimental chamber.

The conditions in the transition region can readily be expected to influence the susceptibility of an engine to acoustic instability in two ways. First, the conditions in the transition zone (e.g., with regard to atomization, spray formation and mixing) can lead to conditions in the uniform region downstream from the transition zone (e.g., with regard to size, distribution, velocity, evaporation rates and combustion rates of propellant droplets) which render the uniform zone highly sensitive to the inevitable weak pressure fluctuations known as "random noise". Such conditions can then result in the "spontaneous" onset of sustained acoustic oscillations of high amplitudes. Secondly, depending on the type and operating conditions of the injector, the transition zone itself can be highly sensitive to disturbances in feed system or chamber, such as pulses or fluctuations of pressure and gas velocities. Such disturbances then can lead to transitory strong distortions of the injection pattern which, in turn, can change drastically the conditions in the uniform region farther downstream, and in this way can trigger sustained acoustic pressure oscillations of high amplitude. It is well known that such phenomena have been observed by Rocketdyne (Reference 3).

It is true that the last statements are of a hypothetical nature. Furthermore, the phenomena occurring in the transition region, governed by the interaction of injection, impingement, spray formation, mixing, evaporation and burning of the sprays, and their dependence on injector design and operation are of such bewildering complexity that any attempt to determine by theoretical considerations those conditions in the transition zone (let alone those criteria for injector design) which are most favorable for rendering an engine stable seems to be hopeless. A more promising approach is observing by means of shadow photography the conditions in the transition zone such as spray formation, atomization, mixing and burning of the sprays. It should be thus possible to observe directly the differences in the transition zone in a given chamber produced by various injectors; which have, in practice, resulted in various degrees of stability.

Unfortunately, information concerning the conditions in the transition region of actual engines is very slight. It is true that shadow photography has been applied to engines which seem to simulate a typical section of large engines to a satisfactory degree (References 3, 4 and 5), but resolution, scale and sharpness of the shadowgraphs have been inadequate for obtaining sufficiently detailed information. However, such detailed information can be expected if the photographic technique, which yielded shadowgraphs such as Figure 1 on a small experimental motor, is applied to larger windowed motors simulating an entire or at least a typical section of operational engines.

It is expected that such experimental investigations will provide information as to what conditions concerning the physical processes which are active in the transition region are most favorable for rendering an engine stable; i.e., insensitive to adventitious disturbances which might severely distort the injection and combustion pattern and therefore trigger acoustic instability. Additional information can be obtained if the investigations conducted during stable and undisturbed firing runs are supplemented by firing tests intended to show how the transition region is affected by controlled disturbances. These could be pressure pulses or oscillations introduced into the feed system or chamber in order to simulate events which occur, for instance, during start, shutdown, transition to main stage and thrust control. Such information should facilitate the design of a "stable" injector on a more rational basis, in contrast to the purely empirical method.

In addition, photographs, such as Figure 2, taken of regions downstream from the transition zone can provide more realistic information than presently available with regard to the characteristic properties of the uniform region such as size and spatial distribution, velocity, evaporation and burning rates of propellant droplets. Such information is necessary as a sound basis for theoretical investigations dealing with the mechanisms which drive and sustain acoustic oscillations in the combustion chamber. However, it seems it is generally recognized among rocket engineers (Reference 6, p. 45 and Reference 7) that an important way and, possibly, the most important way to prevent acoustic instability, without added "damping devices" such as baffles or absorbing liners, is: (1) to render the transition zone sufficiently insensitive to adventitious disturbances: and (2) to prevent as much as possible such disturbances during operation.

3.0 OBJECTIVE AND TECHNICAL APPROACH

Following the train of thought of the preceding section, the object of the present program was to apply the shadow photographic technique to an actual engine development. The engine selected was the Rocketdyne F-1 engine, which is a 1,500,000-lb thrust chamber operating at nominal 1000 psia chamber pressure, burning liquid oxygen and RP-1 fuel as propellants. The nominal dimensions of the F-1 combustion chamber are 40 inches I.D. by 40 inches long, with a nozzle contraction ratio of 1.25. The F-1 combustion chamber has a flat plate injector consisting of concentric alternate rings of fuel and oxidizer orifices. A radial spoke integral baffle has been added to the face to improve combustion stability. A typical injector contains about 1000 total fuel and oxidizer orifices. However, several variations in orifice size, spacing, number and impingement angle have been tried during the course of the engine development. The injector designs of particular interest to this program are listed in Table I.

The problem was to show in which way the injection and combustion pattern of the F-1 engine, i.e. the pattern of transition from liquid propellants to hot combustion gases, is influenced by changes to the geometry and operating conditions of the injector, which changes have been found in practice to influence the stability of the engine to a decisive degree.

For this purpose, a windowed motor was to be developed, intended to simulate as closely as possible the injection and combustion pattern of the F-1 engine if operated with various injector configurations, the use of which has resulted in more or less stable operation. Under actual firing conditions, short exposure shadow photographs of the pattern were to be taken, using the experimental technique developed by Bell Aerosystems Company on a small experimental rocket motor. Dimensions of liquid particles, such as blobs, sheets, ligaments and droplets, were to be determined. Also, velocities of chamber gases and liquid particles were to be measured. Special emphasis was to be given to the investigation of the 10-inch long region adjacent to the injector face.

TABLE I

F-1 ENGINE INJECTOR ELEMENTS

Injector Element No.	1 ("Buzzing")		2		3	
	Oxidizer Doublet	Fuel Doublet	Oxidizer Doublet	Fuel Doublet	Oxidizer Doublet	Fuel Doublet
Orifice diameter (in.)	0.209	0.281	0.185	0.281	0.209	0.281
Impingement distance (in.)	0.349	0.800	0.571	0.800	0.571	0.800
Impingement angle	56° 24'	30°	56°24'	30°	56°24'	30°
Injection velocity ft-sec^{-1}	163*	54*	208*	54*	163*	54*

Injector Element No.	4		7	
	Oxidizer Doublet	Fuel Doublet	Oxidizer Triplet	Fuel Doublet
Orifice diameter (in.)	0.242	0.281	0.185	0.228
Impingement distance (in.)	0.571	0.800	0.571	0.571
Impingement angle	40°	30°	40°	40°
Injection velocity ft-sec^{-1}	120*	54*	138.7*	76*

*Injection velocities calculated for flows of 5.48 lb-sec^{-1} per element LOX and 2.33 lb-sec^{-1} per element RP-1.

Specific Gravity LOX = 1.142 at -297°F
Specific Gravity RP-1 = 0.808 at 60°F

4.0 DESIGN CRITERIA FOR WINDOWED "SLAB" MOTOR

The obvious technical and economic difficulties of any attempt to apply shadow photography to a windowed motor having the actual dimensions of the F-1 engine would be prohibitive. Rather, one has to be satisfied with conducting the investigations on a small scale "model" which simulates as closely as possible those conditions existing in the actual engine which determine the peculiarities of the injection and combustion pattern. It is to be expected and will be shown in the following discussion that a perfect simulation is not possible in a model on which the investigations can reasonably be conducted. Thus, some compromises cannot be avoided.

4.1 WINDOWED CHAMBER

A tentative layout of a windowed "slab" chamber that was considered to provide the most favorable compromise is shown in Figure 3. The mechanical construction consists of a central section supporting the injector and nozzle, and two outer sections ("window frames") supporting the windows. The windows are slabs of tempered Pyrex or fused quartz. By using very heavy frame and body sections for rigidity, the danger of putting strains on the windows during assembly is virtually eliminated. The frames have a heavy center web which supports the windows so that chamber pressures up to 1200 psia can be used. In this arrangement, two 3 inch by 4 inch openings are left open on both sides for observation and photography. In order to increase the field of view to a 5 inch by 9 inch rectangle, window frames without the center web can be used; however, the chamber pressure is restricted to 500 psia in this case. By judicious use of extensions inserted between the injector and center section, the distance between the injector face the windowed section can be adequately varied.

In addition to the windowed section, non-windowed section ("extension chambers") of the same cross-section as the windowed section are provided. By adding these extensions to the windowed section, the full length of the F-1 engine (40 inches between injector face and nozzle entrance) can be achieved. A two-dimensional nozzle is to be used. Thus, the slab chamber is essentially a straight duct of constant rectangular cross-section, closed on one end by the injector and on the other end by the nozzle.

The height and width of the duct had to be chosen in such a way that a favorable compromise between the following three requirements is achieved; (1) when the chamber is fired, the conditions in at least certain regions within the duct simulate to a satisfactory degree the conditions in corresponding typical regions existing in the firing F-1 engine; (2) adequate shadow photographs of the liquid contents of these regions can be obtained; and (3) the engine can be manufactured and operated without too severe technical and economic difficulties.

To meet the first requirement, the slab chamber should be operated with the same propellant as the F-1 engine, namely LOX and RP-1 at a mixture ratio O/F = 2.35. Also, the chamber pressure at the injector face should be the same, namely 1100 psia. In order to secure this pressure and to simulate the conditions between injector and nozzle throat, such as pressure drop and gas velocities, the contraction ratio A_c/A_t should be the same as in the F-1 engine, namely 1.25, and the flow rate density within the rectangular duct should be the same, namely 4.51 lb-sec^{-1} in.$^{-2}$. It is recognized that even if these conditions are fulfilled, the conditions in the F-1 engine are perfectly simulated only in the ideal case that the difference in wall effects between both engines can be neglected.

4.2 INJECTOR

In order to meet the first requirement, the initial atomization and mixing of the propellants by means of impingement (i.e., the disintegration of the liquid streams emerging from the injector orifices into liquid particles such as blobs, sheets, ligaments and drops) should be of the same nature in both engines. It can readily be conceived that the shape and size of these particles, because they determine their surface area/ratio, are of predominant importance with regard to the processes succeeding atomization; namely, evaporation of the particles and chemical reactions between the propellants in the liquid and vapor states, as well as between the propellants and the atmosphere of hot combustion gases into which they are injected. Thus, those features which determine the shape and size of the liquid particles must be as closely as possible the same in the model and in the actual engine.

Much experimental work has been done in this field (References 8 to 13) and it has been found, as might be expected, that the shape and size of these particles depends, as far as propellants and injector are concerned, on the physical properties of the propellants such as density, viscosity and surface tension, on the shape, size, and spacing of the orifices, on the impingement angle and on the velocity at which the propellants are injected. However, it appears that the conditions under which the investigations have been conducted are restricted to very narrow areas of application so that conclusions with regard to essentially different conditions can hardly be drawn (see the critical reviews in References 14, 15, 16). Thus, the propellants and the shape, size, and spacing of the injector orifices, the impingement angles and injection velocities must be the same in the model and in the actual engine. Consequently, the pattern of injector orifices in the windowed model must be composed of elements which have the same dimensions and inject the same flow rates at the same velocities as in the actual engine so that one can arrive at a small scale windowed model only by using a smaller number of elements. However, since the behavior of the sprays is influenced by neighboring sprays produced by other elements existing in the engine, it is advisable to use, in the windowed model, as many elements as possible within the limitations imposed by the second and third requirements. This calls for a model engine as large as possible without creating severe photographic, operational, and economic difficulties. In order to arrive at a reasonable compromise, the geometrical dimensions and the flow rates of the elements to be installed in the slab chamber must be known.

The five injector elements of the F-1 engine which were finally selected for investigation and whose stability characteristics were known are shown in Table I. Each element consists of one oxidizer doublet or triplet and one fuel doublet. The spacing between alternate oxidizer doublets or triplets and fuel doublets is 0.56 inch. The flow rate for each oxidizer doublet or triplet was given as 5.48 lb-sec^{-1} LOX and the flow rate for each fuel doublet as 2.33 lb-sec^{-1} RP-1. The injector shown in Figure 3 consists of four oxidizer doublets and five fuel doublets (the fuel doublets are accidentally shown in triplets); i.e., it consists of four injector elements and one added fuel doublet ("4.5 element injector"). In this arrangement the injector pattern is balanced and both the top and bottom sections of the chamber wall are protected by the reducing effect of a layer of liquid or vaporized fuel. It is true that the overall mixture ratio of the injector is only 2.35 x 4.5 = 1.88. However, it is expected that the chemical reaction of the "unsaturate" portion of the outer fuel sprays will occur sufficiently far downstream so that the mixture ratio of the central sprays will be unaffected within a fairly long distance from the injector face, especially within the core of the propellant sprays.

4.3 INTERACTION OF CHAMBER AND INJECTOR

Dividing the total flow rate of 33.6 lb-sec^{-1} by the required flow rate density of 4.51 lb-sec^{-1} in.^{-2} one obtains the cross-sectional area of the chamber as 7.4 in.^2. Fitting the injector elements into a chamber height of five inches gives a chamber width of approximately 1.5 inches as shown in Figure 3. It was expected that this chamber will meet the three basic requirements listed before. However, some difficulties were anticipated and might require some additional compromises which are discussed as follows.

Because of wall effects, it cannot be expected, as pointed out before, that all regions within the windowed motor shown in Figure 3 simulate the pattern existing in corresponding typical regions of the F-1 engine. In order to arrive at a reasonable estimate of the regions in which this is the case, at least a rough picture of the geometrical dimensions of the injection pattern of the F-1 engine had to be obtained. Because of the lack of direct information, this picture was based on Figure 4 which is a reproduction of Figure B-1 of Reference 17. This figure, in turn, is based on experimental results obtained by Rocketdyne (Reference 18) on a two-dimensional windowed motor representing a one-inch thick slice of an engine of 120,000 pounds thrust (Reference 19, p. 215), run on LOX/RP-1 and having an inner diameter of 21.5 inches, a cylindrical length of 13 inches, and a contraction ratio of approximately 1.6.

It was recognized that using Figure 4 as a basis for the geometrical dimensions of the injection pattern in the F-1 engine can result only in a rough approximation to reality because the total flow rate of one element in the 120,000 pound engine is only 1.4 lb/sec (Reference 17, p. 631) compared with nearly 8 lb/sec for one element of the F-1 engine. Also, the injection velocities and the impingement angles differ substantially and the chamber pressure in Rocketdyne's two-dimensional motor does not seem to have been higher than 300 psia compared with the 1000 psia in the F-1 engine.

Assuming that a sufficiently good approximate picture of the geometrical dimensions of the injection pattern of the F-1 can be based on Figure 4, and taking into account the larger diameters and different spacings of the injector orifices, one arrives at the injection pattern shown in Figure 3. Which region of this pattern can be expected to simulate the conditions in the F-1 engine could be tentatively concluded from Figure 5 which shows schematically the estimated distribution of mixture ratio in three cross-sections of the propellant spray produced by an injector with the same elements as in Figure 3 but with only two oxidizer doublets and three fuel doublets ("2.5 element injector"). The estimate is based on information obtained from Reference 8, p. 49. It can be seen that only the shaded area covering three times the orifice spacing (approximately 1.7 inches) can be reasonably expected to simulate the F-1 engine because, outside this area, the mixture ratio differs greatly from the one obtained by adding injector elements; this is the case in the actual engine, indicated by the broken curves in Figure 5. It can also be seen that any number of injector elements smaller than the one shown in this figure would not simulate the effect of non-uniform distribution of propellant flow rates in the cross-section of the spray.

Accordingly, the "simulating area" in Figure 3 can be estimated to cover seven times the orifice spacing of 0.56 inch or approximately four inches. However, at least the two outermost fuel doublets will undoubtedly splash against the top and bottom of the central section and the atomization from these doublets will be nontypical. Although the streaming motion of the gas will tend to prevent the nontypical liquid particles from penetrating too deeply into the central region of the spray, the simulating area might be reduced somewhat by this phenomenon. Liquid splashing against the windows seems to be a lesser problem. If the sprays are actually as flat as estimated from Figure 4 and shown in Figure 3, splashing will occur relatively far downstream in a region where the gas velocities have reached appreciable values due to thermal expansion. It can be argued that the shaded area shown in Figure 3 does not simulate a typical region existing in the F-1 engine to a satisfactory degree because only one row of injector elements is used. In principle, this objection can be partly overcome by doubling the width of the central chamber section and installing a second row of elements along side those shown in Figure 3. However, the total flow rate would be as large as 67.2 lb-sec^{-1} and it would be more difficult to penetrate the dense sprays with the backlight illumination.

It was difficult to predict whether or not satisfactory shadowgraphs could be obtained through the windowed chamber shown in Figure 3 with the optical and electronic equipment on hand. The equipment was adequate to obtain satisfactory shadowgraphs such as Figures 1 and 2 on the small experimental motor. However, the flow rate of the latter was only 0.36 lb-sec^{-1} and the flow rate density 0.007 lb-sec^{-1} in.$^{-2}$, compared with the corresponding values for the windowed chamber shown in Figure 3 (33.6 lb-sec^{-1} and 4.51 lb-sec^{-1} in.$^{-2}$, respectively). Thus, the latter might be filled with propellant sprays to such an extent that clear shadowgraphs could not be obtained. This difficulty might be aggravated by propellant splashing against the windows; a condition which can definitely be expected to be more pronounced in Figure 3 than in the experimental motor and might obscure or distort the shadowgraphs. These difficulties would be even more serious if the injector were equipped with two rows of elements. On the other hand, the LOX used in Figure 3 would evaporate much faster than the WFNA used in the experimental motor, resulting in a rapid reduction of the liquid content of the sprays. Also, in anticipation of the splashing problem, passages were to be provided in the window frames of Figure 3 through which gaseous nitrogen would be flowed to "flush" the interior surface of the windows.

If it becomes necessary in order to eliminate overloading the chamber with liquids and excessive splashing of propellants against the central section and windows, the number of elements can be reduced and/or the distance between the windows (the width of the central section) can be increased. It is recognized that this results in a reduced flow rate density and increased contraction ratio. However, it will be shown later that such a compromise may be expected not to change drastically the conditions within an appreciable distance from the injector face.

4.4 PROPELLANTS

Lawhead (Reference 3) found, during photographic investigations on a windowed motor, that LOX and ethyl alcohol yielded far better photographic results than LOX and gasoline type fuels like RP-1. Hence, it was decided that RP-1 may be replaced by other fuels such as ethyl or isopropyl alcohol, UDMH, and Aerozine 50 in order to minimize deposits on the windows. However, the substitute fuel should be as similar as possible to RP-1 with respect to the physical properties affecting spray formation and atomization; namely, density, viscosity and surface tension. Also, the combustion parameters i.e., combustion temperature and c* should be as close as possible to those obtained with RP-1.

The choice of the fuel will depend also on the luminosity of the combustion flame. Shadow photography using a light source of short duration (spark) for back illumination demands that the effect of the light source on the emulsion of the photographic film be much stronger than the effect of the flame light. If the flame light was suppressed compared with the spark light by appropriate filters, and the time during which the film was exposed to the flame light was reduced to 2.5 milliseconds by means of a high-speed shutter in the camera, the optical and electronic equipment was adequate for tests with the experimental motor, operated with WFNA/UDMH at 300 psia chamber pressure.

It was to be expected that the flame light of propellant combinations such as LOX/RP-1, LOX/isopropanol of LOX/UDMH would be more intense than in the experimental motor, especially at chamber pressures of approximately 1000 psia. However, it could not be predicted whether the optical and electronic equipment used on the experimental motor was adequate under these more difficult conditions because information concerning the magnitude and spectral distribution of the radiation of high-pressure flames was extremely scarce (References 20 to 23).

Finally, there was some concern about the ability of the model thrust chamber to ignite and to operate smoothly at the high flow rate density of the F-1 engine. It is true that the F-1 engine evidently operates quite satisfactorily, and that successful tests have also been conducted with a two-dimensional research motor which simulates a "radial segment" of the F-1 engine and which has been run at the high flow rate density of this engine (References

24 and 25). However, it should be realized that even this two-dimensional motor was equipped with 17.5 injector elements in comparison with 4.5 elements which were tentatively planned for the windowed motor shown in Figure 3. Consequently, the proportion of the total propellant flow which was subject to wall effects, namely the sprays of the two outermost elements, was approximately four times as large for the windowed motor shown in Figure 3 as for the Rocketdyne two-dimensional research motor.

In view of the many uncertainties concerning the conditions which were to be expected in the windowed "slab" motor, it was decided to postpone the final design and manufacturing of the slab motor until more basic information had been obtained. For this purpose, an extensive series of water flow tests was conducted in order to obtain preliminary information with respect to the formation and geometrical dimensions of the propellant sprays produced under F-1 conditions. Furthermore, it was decided to modify an existing windowed motor of six-inch inner diameter and to operate it at a lower flow rate density. Firing tests with this motor were intended to obtain, under facilitated conditions, information concerning the formation and dimensions of the sprays under firing conditions and to check the adequacy of the existing photographic equipment. Also, tests conducted with the modified six-inch motor were expected to facilitate an estimate concerning the flow rate densities at which the slab motor shown in Figure 3 could be operated satisfactorily.

5.0 WATER FLOW TESTS

In order to obtain preliminary information on the formation and geometrical pattern of sprays produced by the injector elements given in Table I, an extensive series of open air water flow tests was conducted. During these tests, both normal (1/400 sec) and high speed (2 microsecond) exposures were taken, and both front and back lighting were used. The results provided a valuable insight into the nature of the sprays, their optical density, and their atomization, mixing, and spreading characteristics.

5.1 FLOW TESTS

Figure 6 shows the photographic setup used for the water flow tests. On the left-hand side is a 4 by 5 inch Speed-Graphic camera, using a 135 mm, f/4.7 Optar lens for closeup views. On the right-hand side is the illuminating light source (General Electric Photolight Cat. 9364688G1, xenon spark, flash duration approximately two microseconds). Between them can be seen one of the injector models which produces the spray to be photographed. Some photographs were taken with a rough screen (double layers of white fiberglass diffusion screening) inserted between light source and spray, as shown in the figure. The photographic film used was either Kodak Super Panchro-Press type "B" or Kodak Tri-X.

The flow rates were provided by a pressurized water flow test stand with a flow capacity of approximately 5 lb-sec^{-1} at a pressure of 700 psi for the fuel sprays, and by a pump-fed water flow stand with a flow capacity of approximately 5 lb-sec^{-1} at a pressure of 1200 psi for the oxidizer sprays.

By way of example, Figures 7 to 15 are typical photographs taken with this arrangement of a water spray produced by a single impinging doublet of the F-1 engine, namely the oxidizer doublet of injector element No. 4 (modified) in Table I. In this doublet, the impingement angle is 40°, the orifice diameter is 0.242 inch with a sharp edge entrance, ejection velocity is 120 ft-sec^{-1}, and total flow rate is 4.8 lb-sec^{-1}. Figures 7, 9, 12, and 14 have been taken with the "flat" side of the spray parallel to the camera film; for Figures 8, 10, 11, 13, and 15, the injector has been rotated by 90° about the longitudinal axis of the spray. The outer diameter of the fixture, which can be seen on the left-hand side of several of the photographs, is four inches. A wire of 0.04 inch diameter is stretched along the centerline of the doublet in order to provide a rough indication concerning the density of the spray at various locations along the wire.

Figures 7 and 8 were taken with front illumination and, instead of the GE-Photolight shown in Figure 6, a Strobonar No. 4 flash with a nominal duration of 2.5 milliseconds illuminated the spray from the camera side. The camera shutter, set for 1/400 second, was synchronized with the flash, resulting in an overall view of the geometrical dimensions of the spray, but with no resolution of the spray structure.

Figures 9 and 10 were taken essentially under the same conditions as Figures 7 and 8; however, the GE-Photolight with a nominal duration of two microseconds and synchronized with the camera shutter was used for front illumination. Figure 11 was taken under the same conditions as Figure 9, but farther downstream so that the center of the brightly illuminated area is approximately 14 inches from the injector face. These photographs might create the impression that the entire spray consists of droplets. However, Figures 12 and 13, taken with the GE-Photolight for back illumination in the arrangement shown in Figure 6, show that this is not the case. Rather, the shadow photographs reveal that the core of the spray which contains by far the major portion of the liquid content is poorly atomized and consists, at least within the first eight inches from the injector face, primarily of blobs and crude ligaments, while droplets are found only in the regions surrounding the core like a veil of comparatively low droplet density.

Figures 14 and 15 were taken under the same conditions as Figures 12 and 13, only farther downstream so that the center of the brightly illuminated area is approximately 14 inches from the injector face. It can be seen that here the breakup into droplets has progressed much farther.

The fact that the core of the spray has a structure completely different from its surroundings can be explained as follows (Reference 26). Within the core, the air entrained between the liquid particles travels essentially with the same velocity as the liquid so that the breakup into droplets is not primarily caused by aerodynamic forces but by the effect of surface tension. The latter has the tendency to contract relatively short stretches of a sheet or a ligament between "weak spots", first into some kind of dumbbells and then into droplets. This relatively slow process can be followed in the two series of three consecutive frames shown in Figures 16 and 17.

In contrast, in the outer regions of the spray the breakup is caused by the strong aerodynamic forces acting on the liquid sheets and ligaments, due to the large velocity difference between spray and surrounding air. This process seems to proceed at a much faster rate than the breakup due to the effect of surface tension, and results in the production of relatively small droplets in the outer regions of the spray. This explanation is supported by the fact that the effect of aerodynamic forces is much more pronounced if a liquid of lower surface tension, e.g. ether, is injected instead of water, as shown in Figure 18. Also, it can be expected that in a firing rocket chamber the effect of aerodynamic forces on the liquid content in the outer regions of the spray will be more pronounced than in the water flow tests, due to the velocity of the gases recirculating between the sprays and between sprays and chamber wall toward the injector face, while the conditions within the core of the spray will be substantially unchanged.

The statements concerning the spray formation by a single impinging pair are evidenced also by the results of several other investigators (Reference 11, Figure 3) which were obtained on impinging doublets much smaller than the very large one used from Figure 7 and 15. This indicates that the statements are justified from a rather general point of view. From Figures 19 to 26, it can be seen that they are justified even to a higher degree for multiple orifice injectors because of "secondary impingement" of sprays on sprays. The phenomenon of spray on spray impingement seems to make the above statements concerning the formation and structure of sprays applicable also to multiple orifice injectors without primary impingement ("showerhead injectors").

Figures 19 to 22 were taken on the model of a 2.5 element injector containing two oxidizer doublets and three fuel doublets of injector No. 1 in Table I. The dimensions of the orifice plate are approximately 4 inches by 4.5 inches. Figures 19 and 20 were taken with front illumination provided by the Strobonar (duration 2.5 milliseconds); Figures 21 and 22 with back illumination provided by the GE Photolight (duration 2 microseconds).

Finally, Figures 23 and 26 were taken on the injector model (shown in Figure 6) of two oxidizer doublets of injector element No. 2 in Table I. The doublets are arranged side by side in order to obtain some information as to what the spray formation produced by two rows of injector elements would look like if installed side by side in the slab chamber shown in Figure 3. Figures 23 and 24 were taken with front illumination as in Figures 19 and 20; Figures 25 and 26 were taken with back illumination as in Figures 21 and 22.

5.2 EVALUATION OF FLOW TESTS

It is recognized that all the photographs taken during water flow tests provide information concerning the spray formation in the firing engine only in a region more or less close to the injector face, before the oxidizer and fuel sprays begin to react chemically to a large extent. Even this information might be only a rough approximation because water has been used instead of RP-1 and LOX. In particular, the more or less rapid evaporation of LOX to be expected in the engine might play a major role which, of course, cannot be simulated during water flow tests. Nevertheless, some conclusions can be drawn from the photographs and used for the design of the windowed motors and for interpreting and evaluating the photographs obtained during firing tests.

5.2.1 Geometrical Dimensions of Sprays

A judicious evaluation of the numerous photographs, (i.e., such as Figures 7 to 15 which have been taken of the sprays produced by the various doublets shown in Table I) reveals that the angles and distances given for Figure 4 and Reference 17 for an engine with 120,000 lb of thrust are essentially valid also for the F-1 engine. Thus, the estimated spray pattern shown in Figure 3 can be assumed to be realistic to some extent and can be used as a basis for the design of the slab chamber. However, visual observation of volume and density of the water spray produced by the 2.5 element injector (Figures 19 to 22) made it advisable to plan at first only firing tests with this injector before proceeding to firing tests and the final design of the slab chamber with 4.5 element injectors. The reason for this decision was the desire to keep the photographic difficulties, which might result from high spray densities and splashing against walls and windows, as small as possible without rendering the intended simulation of F-1 conditions unrealistic.

5.2.2 Optical Transparency of Sprays

It can be seen from Figures 21 and 22, which cover a distance of approximately eight inches from the injector face, that no information can be obtained in this region concerning the internal structure of the spray produced by spray on spray impingement on a 2.5 element injector because of the extremely high accumulation of liquid particles. However, it can hardly be doubted that also in this case the major portion of the liquid content of the spray in this region, as in Figures 12 and 13, has the form of blobs and ligaments rather than the form of droplets. Furthermore, under firing conditions, that region where the transition from liquid propellants to hot combustion gases takes place becomes gradually optically thinner, so that shadowgrams of the internal structure of the spray can be expected to be obtained in this region, probably at distances appreciably shorter than eight inches and particularly if the brightness of the light source is increased and improved optics are used. It must be kept in mind that this region, which can be clearly seen on Figure 1, taken on a firing experimental windowed motor with a six impinging pair injector, is the main object of this program because the conditions in this region appear to depend strongly on the geometry and operating conditions of the injector. This region is also easily influenced by disturbances, and therefore is suspected of being the connecting link between such disturbances and the onset of "acoustic" high frequency instability.

5.2.3 Internal Structure of Sprays

One conclusion which can be drawn from the photographs taken during the flow tests is that we must be very cautious in basing theoretical considerations concerning the transition from liquid propellants to hot combustion gases on the general concept that the region of impingement close to the injector face acts as a "droplet factory" which produces a cloud of droplets with a more or less well defined size distribution, and delivers these droplets to a stream of hot combustion gases for further treatment. Also, the concept that the impingement process results in a thin liquid sheet which gradually breaks up into droplets does not seem to be realistic. Rather, under the injection conditions commonly used in rocket engines, the spray produced by a single impinging pair seems to have roughly the shape of a more or less flattened circular cone, and at least the core of the spray might retain this shape for an appreciable distance from the injector face because the formation of droplets from blobs and crude ligaments within the core might be a rather slow process under "cold flow" conditions. That these combustions are justified to a degree also under firing conditions is evidenced by Figure 1 and Figures 29 to 31.

Figure 27 shows the small experimental windowed motor which was used for taking these photographs. The window slit is six inches long. The injector face can be seen through the window on the left-hand side. The interior of the chamber has roughly the shape of a circular cylinder six inches long and 2.5 inches wide.

Figure 28 shows the water spray produced by a simple injector consisting of two impinging pairs, each formed by a 0.04 inch orifice impinging on a 0.06 inch orifice. Front illumination with short exposure was used in essentially the same way as for Figures 9 and 10.

Figure 29 shows three consecutive frames of a series of shadowgraphs taken through the firing experimental chamber of the spray of the same injector, each pair of orifices impinging one jet of UDMH on one jet of WFNA. The chamber pressure was 300 psia and the c* was 5000 ft/sec. Back illumination was provided by the same GE Photolight which was used for Figures 12 and 13. The repetition rate was 1250 frames/sec. The photograph covers roughly half of the chamber length. The formation of the sprays and the major portion of their gradual transition into hot combustion gases can be observed in considerable detail. The sharp shadow of a wire of 250 microns diameter which is stretched along the chamber axis proves that objects in the interior of the chamber can be observed in spite of the fact that the shadowgraph has been taken through the probably highly non-uniform density distribution of the hot combustion gases. Figure 1 was taken under the same conditions as Figure 29; however, an injection with six impinging pairs was used.

Even more details in the region close to the injector face can be seen in Figures 30 and 31. Both shadowgraphs were taken under the same conditions as Figure 29 but at a larger magnification and with a single flash of the GE Photolight. In Figure 31, the center plug and wire installed on Figures 1, 29, and 30 are replaced by a commercial spray nozzle which injects a fine mist of water into the firing chamber. The mist consists mostly of short ligaments approximately 50 microns thick or less, 50 microns being about the smallest dimension which can be resolved with the optics used.

It should be noted that the conclusions concerning the formation and structure of the propellant sprays under firing conditions which can be drawn from Figures 1 and 29 and especially from Figures 30 and 31 are about the same as the conclusions which have been drawn from the photographs which were taken during water flow tests. This indicates that these conclusions are generally realistic because the flow rate through one pair of the injector used in the experimental chamber (Figure 27) was only 0.06 lb-sec^{-1} or only 1/80 the flow rate of 4.8 lb-sec^{-1} through the doublet used for the water flow tests.

Of course, this statement holds only for that region adjacent to the injector face where the disintegration of blobs and crude ligaments into droplets and the chemical reaction has not proceeded too far. It can be seen that, in Figures 1 and 29 to 31, this region does not extend very far downstream because even the dense core of the sprays disappears in a rather short distance from the injector face. This rapid transition from liquid to gas under firing conditions seems to be difficult to reconcile with the previously mentioned fact that the core of the spray contains initially mainly liquid blobs and crude ligaments which offer only a relatively small area of attack for surface phenomena such as heat transfer, evaporation, diffusion and chemical reactions and which disintegrate only slowly to smaller particles and drops with a much larger surface to mass ratio. However, it must be realized that the recirculation and turbulence of the gaseous combustion products within the narrow confinement of the combustion chamber must be expected to be much stronger than those within the atmosphere surrounding the spray during the cold flow tests and, consequently, have a tendency to "tear apart" the core of the spray more rapidly in the chamber than during the cold flow tests. This effect might be intensified by bubble formation and growth within the bulk of the core because of the hypergolicity of the WFNA/UDMH propellant combination.

Phenomena resulting from gas evolution within the sprays of hypergolics due to liquid phase reactions have been observed also by other investigators (Reference 27, pp 73 and 74). Similar effects can be expected if cryogenic or highly volatile propellants are involved, the rapid evaporation of which will also have the tendency to form bubbles within the core of the spray.

We may conclude, therefore, that the formation and structure of the propellant sprays in the firing chamber will be very similar to those of the water flow tests for a certain distance from the injector face. At greater distances, the stream appearances will become progressively more different as the influence of chemical reaction and of combustion gas turbulence becomes more dominant.

6.0 MODIFIED SIX-INCH WINDOWED MOTOR

In order to obtain, prior to the final design of the windowed slab motor, preliminary information concerning the structure and dimensions of the propellant sprays produced by the injector elements given in Table I under firing conditions, it was decided to modify an existing windowed motor of six-inch inner diameter and to apply the previously developed shadow photographic technique to this motor.

6.1 DESCRIPTION OF THE MOTOR

6.1.1 Combustion Chamber

The essential features and the dimensions of the modified six-inch windowed motor which was used during the entire test program are shown in the schematic, Figure 32, and in the exploded view, Figure 33. The interior of the windowed section has roughly the shape of a circular cylinder approximately six inches in diameter and 10 inches long. The original chamber was designed for 500 psia chamber pressure and the modification consisted essentially in design and fabrication of heavier window frames equipped with a heavy center web. In this way the chamber became usable for pressures of at least 1100 psia at the injector end. Two 3.1 inch by 3.6 inch openings are left on both sides for observation and photography. The field of view can be increased to approximately 9 inches by 5 inches by using the original window frames; however, the chamber pressure would be restricted to approximately 500 psia.

The distance between injector face and windows can be varied by inserting three injector extensions of different lengths, as indicated in Figure 32 and shown in detail in Figure 34. Without extension, the face can just be seen through the opening nearest to the injector. With the three extensions, distances up to 17 inches from the injector face can be observed.

Chamber lengths between injector face and nozzle entrance, ranging from 24 to 34 inches depending on the injector extension used, are provided by a cylindrical chamber extension 15 inches long. It is recognized that the chamber is shorter than the F-1 engine (40 inches between injector face and nozzle entrance). However, for reasons pointed out in Section 4.0, the chamber is intended to be operated at lower flow rate densities and consequently at higher contraction ratios than the F-1 engine. Consequently, the gas velocities downstream from a cross-section where practically all liquid has been transformed into gas are lower than in the F-1 engine; i.e., events happen in the modified six-inch motor at a shorter distance from the injector face than in the F-1 engine. To be more exact, those processes such as evaporation and combustion which are essentially time controlled will proceed to a certain given degree in a shorter distance.

6.1.2 Windows

6.1.2.1 Window Materials

The windows used for viewing the interior of the combustion chamber are rectangular ground and polished slabs of tempered Pyrex or fused quartz (Figure 32). These materials were selected because of experience gathered when shadow photography was applied to a small experimental windowed motor (Figure 27). In hundreds of firings conducted with nitric acid as oxidizer and UDMH as fuel at a chamber pressure of 300 psia, the quartz windows showed no crazing and only slight deposits which could easily be removed after the run so that the same windows could be used many times. Pyrex windows showed, on each firing, a mosaic-like network of surface cracks approximately one millimeter deep ("crazing") which was obviously caused by temperature shock. This seriously impaired the quality of the shadowgraphs so that the inexpensive Pyrex windows were used only once (for preliminary tests) in order to save the expensive quartz windows for the data firings.

It was also intended to follow the same scheme under this contract. However, due to the much larger area to be observed, the quartz windows had to be much larger and consequently much more expensive. For this reason and also because it was anticipated that the windows would be exposed to more severe conditions than in the experimental motor, the windows were protected by gaseous nitrogen flushed along the inner surface. In addition, for preliminary tests, tempered Pyrex was used in order to minimize crazing. This would improve the quality of shadowgraphs taken through these windows so that they would yield more information and only a relatively small number of tests would have to be conducted with the expensive quartz windows.

The dimensions are 6.5 by 10.5 by 1.25 inches for the Pyrex slabs and 6.5 by 10.5 by 1.2 inches for the quartz slabs. The corners are rounded and the edges chamfered to minimize the hazard of chipping. With the original frames of the six-inch windowed motor, the windows provided a field of view of 5 inches by 9 inches and were expected to stand chamber pressures up to 500 psia. In order to use chamber pressures up to 1100 psia in the modified six-inch motor, the original frames were replaced with frames containing a heavy center web and leaving two 3.1 inch by 3.6 inch openings on both sides (Figure 32). Only Pyrex windows and the new frames were used during the firing tests covered by this report.

6.1.2.2 Window Sealing Technique

Window sealing techniques used on the six-inch chamber are basically an extension and modification of sealing techniques used successfully during the tests with the small experimental windowed motor. The window sealing technique can be seen in Figures 32 and 33. A high temperature "O" ring, seated in a groove cut into the chamber body, is used on the "hot side" of the chamber to seal the combustion gases in the chamber. On the cold side, directly opposite the "O" ring, a rectangular groove is cut into the frame around each window opening; a flat teflon washer is seated in the groove. The outer peripheral areas of the window slabs are covered with permacel tape. The windows are thus "floated" between chamber body and frames in order to prevent any metal to glass contact. This precaution previously proved to be of utmost importance during the tests with the small experimental motor.

During preliminary hydrostatic pressure tests, the following deficiencies in window sealing technique became apparent. The "O" ring could not be contained in its groove at higher pressure (> 800 psi). This was corrected by placing a tightly fitting 1/32 inch Velbestos backup ring around the outer periphery of the "O" ring, and by increasing the flange bolt torque. Furthermore, in order to distribute the window thrust load more uniformly, the original narrow washer on the cold side was replaced with a 1/32 inch thick teflon sheet which covers the entire inner surface of the window frames except for the two openings. With these modifications, the chamber was successfully tested hydrostatically to 1460 psi, and was fired at chamber pressures up to 865 psia, with no failure of any kind. It is thus expected that the sealing technique will be suitable for higher pressures than those used used during this program.

6.1.2.3 Structural Strength

A simplified stress analysis indicated that breakage of Pyrex windows could be expected in the vicinity of 1500 psi, provided the tensile strength of 4000 psi (which was the highest value quoted in Bulletin P-34 of the Corning Glass Works Company for tempered Pyrex), could be attained. Hydrostatic burst tests were conducted to check the ultimate strength of the windows. With the modified sealing technique, the chamber was pressurized with water until the first Pyrex window broke. This occurred at a pressure of 1250 psia. The broken window was replaced by a metal slab and the chamber was again pressurized until the second window broke at 1460 psia. Thus, the predictions of the structural analysis were quite accurate. In addition, the pattern of the breakage shown in Figure 35 ("cold" side) and Figure 36 ("hot" side) agreed with the stress distribution predicted by the structural analysis assuming idealized conditions of restraint. This indicates that the sealing technique used does not create strains or stresses in addition to those imposed by the chamber pressure.

The adequacy of the sealing technique, which is well known to be a major problem in the design of a windowed motor, especially at high pressures, was further evidenced by the fact that no window failure occurred during all firing runs with Pyrex windows at pressures up to 865 psia. For safety reasons, no firings at higher pressures were attempted with Pyrex windows, although the windows might have withstood higher pressures. Rather, it was expected that firings at full chamber pressure could be conducted using fused quartz windows, fabricated by the General Electric Company. This was based on the relative tensile strengths quoted for fused quartz (7000 psi) and type 7740 tempered Pyrex (2000-4000 psi). However, in preparation for run No. 16 using one aluminum and one quartz window, the quartz window burst at 400 psi during a prefire leak test. This was entirely unexpected, and no completely satisfactory explanation has been found. Inspection of the unused quartz slabs with polarized light revealed a very non-uniform stress pattern, indicating internal deficiencies such as strains or cleavage planes. This condition may have become worse with age, since the slabs had been in storage for five years. Furthermore, the fabrication of reliably homogeneous quartz slabs of this size may prove difficult. On the other hand, the experience with the tempered Pyrex windows exceeded our expectations.

6.1.2.4 Nitrogen Flushing of the Windows

The purpose of flushing the windows with nitrogen gas during a run is twofold. First, splashing of liquid propellants and carbon deposition on the windows during the run must be minimized for photographic reasons; secondly, the windows must be protected from the thermal shock resulting from temperatures ranging from -297 to 5500°F.

The efficiency of the nitrogen flush with regards to carbon deposition on the windows can be seen from Figures 37 and 38. Figure 37 is a photograph of the inner surface of the window slabs used in test No. 6 (LOX/isopropyl alcohol; P_c = 650 psia; arrangement II in Figure 34) with no nitrogen flush. Heavy carbon deposition is apparent from this photograph. The clear area on one window resulted from heavy crazing, because of the heat shock, and subsequent spalling away of the glass leaving a clear area. Obviously, measures to keep the windows clean are imperative for any kind of photography.

Figure 38 is a photograph of the window slabs after test No. 7 (LOX/ isopropyl alcohol; P_c = 770 psia; arrangement II). Approximately 0.5 lb-sec^{-1} of gaseous nitrogen was used to flush the windows from the two rows of holes drilled along the top and bottom of the chamber. The nitrogen jets hit the windows at an angle of 45° and were perpendicular to the flow of the combustion gases (Figure 32). The formerly heavy carbon deposit was reduced to a light coating and to a characteristic "sawtooth" pattern where the nitrogen jets impinge on the windows. Crazing occurred only in those regions where there was no (or very little) nitrogen flushing.

Neither deposit nor crazing would impair Fastax photography as evidenced by a film (Figures 42 to 47) taken during run No. 8 under the same conditions as No. 7 and through the upstream opening of arrangement II. The film shows also that the deposit formed immediately upon initiation of fuel flow. It is expected that spark shadow photography with high resolution would not be noticeably impaired by the deposit and only slightly by the crazing.

To further reduce the carbon formation on the windows and improve the cooling of the windows in those regions where maximum combustion is taking place, a "parallel flushing" technique was tried. Parallel flushing of the downstream windows is accomplished by two steel "inserts" (see Figure 39) fitted into the windowed section of the chamber. Each insert is essentially a steel plate which covers the upstream window in such a way that a slot 0.03 inch wide is formed between the insert and the inner surface of the window glass. Nitrogen is injected into the slot through a vertical row of holes drilled in the injector end of the windowed chamber section under an angle of 30 degrees to the window plane. Thus, a thin sheet of nitrogen is formed which flows through the slot and flushes to the inner surface of the downstream window in a direction parallel to the flow of the combustion gases. The result of using the parallel flushing technique with inserts is shown in Figure 40, which is a photograph of the inner surface of the window slabs after run No. 13 (LOX/UDMH; P_c = 830 psia, arrangement II). The upstream openings are covered by the inserts. The downstream openings show practically no crazing and approximately one-half is perfectly clear, but the downstream half is streaked with a moderately heavy deposit which is suspected to result from upstream directed turbulence caused by the slight ramp between window section and nozzle extension (Figure 39). This deposit seemed to impair the Fastax photography only slightly, as evidenced by a film taken during run No. 14 under the same conditions as run No. 13. However, the deposit would impair spark shadow photography as evidenced by a spark photograph taken through the windowed motor after run No. 13 (Figure 51).

Figure 41 is a photograph of the window slabs after test No. 15 (LOX/UDMH; P_c = 820 psia, arrangement II), which was run with parallel flushing, but with the steel inserts removed so that both openings on both sides were open. The carbon deposit is light and would impair neither Fastax photograph (as evidenced by a film taken during run No. 15) nor spark shadow photography. However, severe crazing occurred along the top and bottom edges of the upstream opening and over most of the downstream opening; evidence that the nitrogen flush was separating from the window surface except in the area immediately downstream from the points, where the nitrogen jets impinge on the windows. Thus, high resolution spark photography can be expected to succeed only on almost the entire area of the upstream opening.

In summarizing, it can be stated that by means of the various flushing methods tested, deposits and crazing can be kept on a sufficiently low level so that Fastax photography will not be impaired noticeably and spark photography only slightly. This statement is correct for distances up to 10 inches from the injector face as has been evidenced in the preceding, and might be correct also for larger distances if the effect of advancing combustion is not too hard on the windows.

Nevertheless, further improvements are feasible. This is indicated by Figure 38 where deposits and crazing occurred at the interstitial spaces between the nitrogen jets where the nitrogen sheet is not fully formed. Also, the severe crazing in the downstream opening of Figure 41 indicates that in this area the nitrogen flush separated from the window, so that the window was fully exposed during the oxidizer lead stage to the cold LOX and subsequently to the hot combustion gases. Finally, carbon deposits formed only in areas which can readily be assumed to be poorly protected by the nitrogen flush. Thus, the methods for improvement seem to consist in providing uninterrupted and undisturbed sheets of nitrogen or other gases which cover the whole inner surface of the windows. Such methods could consist for instance in increasing nitrogen flow rate and/or injection velocity, preventing turbulence by avoiding ramps or sharp edges, and finally in decreasing the angle between nitrogen jets and windows to prevent separation.

6.1.3 Nozzles

Nozzles were of the solid metal heat sink type of construction. They included a 45° convergent section blending into the throat with a 1/2 inch radius. They were cut off sharply at the throat, and had no divergent section. One nozzle, used in the initial checkout firings, was made of stainless steel, but all subsequent nozzles were of copper with a flash interior chromium plating. Throats of various diameters were to be provided in order to attain rated flow at 600, 800 and 1000 psia chamber pressure. Heat transfer calculations on the copper nozzle indicated that it was good for a four-second firing at 1000 psia if uniform heat flux distribution could be assumed.

The stainless steel nozzle, sized for 800 psia, survived the first firing, but sustained severe "nicks" in the throat at the 6-o'clock and 12-o'clock positions on the second firing. The copper nozzle (nozzle No. 2) designed for 1000 psia was used on the third firing. Although not damaged, it showed signs of severe heating at the 6-o'clock and 12-o'clock positions (in line with the impingement plane of the 2.5-element injector).

It was decided at this point that heat transfer conditions could be made less severe by rounding off the exit of the nozzle to eliminate the sharp edge. Accordingly, a design change was issued to provide a 1/2-inch exit radius on the copper nozzles, and the 1000 psia nozzle was reworked to conform to the change. On run No. 4, this nozzle burned out in the same manner as the stainless steel nozzle had done previously. A new nozzle designed for full flow at 700 psia was ordered. While waiting for the new nozzle, an attempt was made to repair the old one by puddling-in braze metal, remachining the throat, and installing it rotated 90° from its original position. The repair failed on run No. 5..

Nozzle No. 3, designed for 700 psia, lasted for seven firings. It showed the same overheating at the 6-o'clock and 12-o'clock positions, and finally was "nicked" in the throat during run No. 12.

Nozzle No. 4, which was a duplicate of nozzle No. 3, was used for the remaining three firings without incident.

It is believed that the "nicking" of the nozzles at the 6-o'clock and 12-o'clock positions is evidence of a very severe heat flux condition at the top and bottom of the injector pattern. This occurs downstream from the liquid mixing zone (approximately 10 inches from the injector face) and some evidence of this condition also appears at sharp transition sections within the combustion chamber. It is doubtful whether a forced convection liquid-cooled nozzle or a refractory nozzle would have fared better. It was considered, however, that an ablating nozzle (of graphite or one of the reinforced phenolic compositions) designed for discarding after one or two firings, might prove to be less expensive than the machined copper nozzles over an extended series of firings. This possibility was not explored further in view of the relatively few test firings actually made.

6.1.4 Injector

For reasons explained in Section 5.2.1, it was decided to conduct the first tests with a 2.5 element injector composed of two oxidizer doublets and three fuel doublets of injector element No. 1 in Table I. The spray pattern of this injector, taken from Figure 5, is indicated in Figure 32. The "simulated area" shaded in Figure 32 is 1.7 inches wide. Splashing of liquid propellants against chamber wall and windows is definitely less pronounced than in Figure 3 and occurs sufficiently downstream so that the conditions in the shaded area can hardly be disturbed by wall effects of this nature. On the other hand, it is expected that in this arrangement both top and bottom sections of the chamber wall between the windows are still sufficiently protected by the reducing effort of a layer of liquid or vaporized fuel. The windows are protected by flushing gaseous nitrogen through passages provided in the body of the windowed chamber. This precaution is expected to be effective also if the injector is rotated by 90° in order to take photographs parallel to the plane of the impingement fans. However, in this case the top and bottom sections of the chamber wall have to be protected by fuel injected through the two groups of auxiliary fuel doublets shown in Figure 32.

The total flow rate is 17.95 lb-sec^{-1} LOX/RP-1. Assuming that the value of c* is the same for the model as for the F-1 engine, the throat area for this flow rate at 1000 psia nozzle entrance pressure becomes 3.185 in.^{2}. Since the cross-sectional area in the windowed section is approximately 44 in.^{2} and in the cylindrical extension approximately 28 in.^{2}, the contraction ratios become 13.8 and 8.8, respectively, and the corresponding flow rate densities are approximately 0.41 and 0.64 lb-sec^{-1} in.$^{-2}$, respectively. This is in contrast to the F-1 engine, where the contraction ratio is 1.25 and the flow rate density is 4.51 lb-sec^{-1} in.$^{-2}$.

At these low flow rate densities, it was expected that the chamber would not be filled with propellant sprays to such an extent that clear photographs could not be obtained. Also, smooth ignition and operation could be expected.

On the other hand, the low gas velocities resulting from the high contraction ratio might be suspected to have serious consequences concerning the intended simulation of the conditions existing in the F-1 engine. Since the gas velocity in a certain cross-section where practically all liquid has been transformed into gases equals the ratio of flow rate density to gas density, it follows that the gas velocity in a given cross section of the six-inch chamber, is only approximately 11% of the gas velocity in that cross section of the F-1 engine where the gas density has the same value as in the given cross section of the six-inch chamber. However, it must be kept in mind that the tests with the modified six-inch motor at low flow rate densities are not so much intended to simulate the phenomena occurring at high gas velocities in the F-1 engine as they are intended to provide information concerning the geometrical dimensions, internal structure and optical appearance of the propellant sprays in the transition region under firing conditions.

6.2 SIMULATION OF THE TRANSITION REGION

The ultimate purpose of the test program, as stated in Section 3, was to photograph the formation and combustion of propellant sprays under conditions simulating as closely as possible those existing in the F-1 combustion chamber. It was recognized that the six-inch windowed chamber differed in some important respects from an ideal scale model of the F-1 engine. However, as pointed out in Section 4, even a specially tailored "slab" combustion chamber would have difficulty in meeting all scaling criteria while still providing a test object that could be photographed.

The question arises, of course, whether the conditions in the transition region of an engine with low contraction ratio can be simulated in an engine with high contraction ratio. It can readily be conceived that the formation and subsequent behavior of the propellant sprays are affected to some degree by the flow pattern, i.e. the magnitude and direction of the gas velocities which exist in a certain region adjacent to the injector face. Thus, essentially, the question is whether the flow pattern in this region can be realistically simulated in a small scale model chamber with higher contraction ratio in spite of the fact that farther downstream the gas velocities are certainly much lower than in the actual engine. A tentative statement that this can be accomplished to a good approximation can be arrived at by taking into account the phenomenon of recirculation of the combustion gases. Tentatively, the mechanism of this phenomenon can be envisioned as follows.

Shadowgraphs like Figures 1, 12, 26, 29, 30 and 31 suggest that large quantities of gas are carried along with the liquid contents of the spray. Thus, the sprays act like "jet pumps", transporting combustion gas from the region near the injector face toward the nozzle end. Under steady state operating conditions, the amount of gas in the region adjacent to the injector face must remain constant and the amount of gas pumped out of this region by the sprays must be replaced. This can only be accomplished by the recirculation of gases from regions farther downstream toward the injector face, through the intervals between the "flat" sides of adjacent propellant fans (Figure 4) and between the outer fuel sprays and the chamber wall (Figure 32). It can be assumed that the population of liquid particles moving toward the nozzle end is relatively thin in these intervals so that they can serve essentially as obstacle-free "suction pipes" for the "jet pumps". Now, the critical question is, where is the reservoir from which the suction pipes are fed? There does not seem to exist experimental evidence which could be the basis for a solid answer. However, it is a plausible hypothesis that gases produced by chemical reactions within the propellant fans and within the wedges of the mixed zone which extend between the propellant "fans" (Figure 4) have the strongest tendency to follow the backward pull of the "suction pipes" because combustion followed by thermal expansion has not yet substantially increased their velocity beyond essentially the injection velocity of the liquid propellants.

The objection could be raised that the recirculating gases must contain a large amount of liquid particles which should be carried away toward the injector and consequently should be observable in Figures 1 and 29 in the space close to the injector between the impinging pairs. However, it must be noted that these particles evaporate and burn on their way back toward the injector face so that only some remnants are observable on Figure 30 between the sprays produced by two impinging pairs.

Thus, the suggested hypothesis leads to the conclusion that the wedges of the mixed zone and to some extent also the propellant fans are the "reservoir" from which the propellant sprays, acting as jet pumps, are fed through the intervals between the sprays which are essentially free of liquid and act as suction pipes. Consequently, the recirculation pattern appears to be confined to a certain region extending not too far downstream from the injector face* but still comprising a certain length of the propellant fans and of the wedges of the mixing zone, i.e. a certain portion of the transition region. Furthermore, it can be concluded that in this portion the flow pattern and especially the gas velocities are controlled by the suction effect of the propellant sprays to a much higher degree than by thermal expansion. Thus, the conditions in this region can be expected to depend relatively little on the phenomena occurring farther downstream where the gas velocities are almost completely controlled by thermal expansion. Thus, it appears that the conditions existing in a certain portion of the transition region of the F-1 engine can be simulated to a reasonable degree by the conditions existing in the corresponding portion of the transition region of an engine like the modified six-inch windowed chamber (Figure 32), operating at the same chamber pressure.

However, the question remains, how far downstream the "simulated" portion of the transition region extends. A tentative answer can be obtained from test results obtained by Rocketdyne (Reference 31). Shadowgraphs taken with a Fastax camera through a firing two-dimensional windowed chamber simulating a one-inch thick radial slice of the F-1 engine showed that LOX and UDMH sprays were visible within distances of approximately four and seven inches from the injector face, respectively, This result is supported by photographs which were taken on the modified six-inch chamber during runs No. 8 and 9, using a Fastax camera exposed only to the flame light (Section 8.2.1). These photographs provide strong evidence that a large amount of liquids still exist at a distance of eight inches from the injector face.

From these results, it can be tentatively concluded that in the larger portion of the five-inch long region occupied by the propellant fans (Figure 4), combustion has not proceeded to such a degree that the velocities and the pattern of the gas flow are affected stronger by thermal expansion than by the suction effect of the sprays.

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*Some considerations leading to similar conclusions and some supporting experimental evidence can be found in References 28, 29, p 230 and Reference 30.

It is true that this statement seems to be hardly compatible with certain test results obtained by Rocketdyne (Reference 31, Figure 1). Within distances from the injector face where the suction effect of the sprays is the controlling process the downstream directed gas velocities should not be substantially higher than the injection velocity. However, streak photography applied to the two-dimensional windowed chamber simulating the F-1 engine yielded gas velocities about 3.5 times as high as the injection velocity already in a distance of 2.5 inches from the injector face, i.e. halfway between injector face and the tips of the fuel and oxidizer fans shown in Figure 32. But it must be taken into consideration that evaluation of the streaks within a short distance from the injector face where their slope is very flat is extremely difficult and apparently had to be supplemented to some degree by theoretical considerations (Reference 25, Figure 5). Taking into account also that the flow pattern must be very complex within the region where the propellant sprays mix and recirculation can be expected to be quite pronounced it seems to be a plausible conclusion that the high gas velocities which have been measured are not typical for this region, even more so because the major portion of the streaks on the photographs has been produced by droplets in the outer regions of the propellant sprays which are closest to the windows. (See also Reference 4a.)

Taking this as a plausible explanation for the discrepancies mentioned in the last paragraph, it can be concluded that in the larger portion of the five-inch long region occupied by the propellant fans the pattern of the gas flow is primarily determined by the suction effect of the propellant sprays. Since this effect is independent of the phenomena occurring farther downstream where thermal expansion is the controlling process it can be concluded that the larger portion of the transition region of the F-1 engine can be simulated in the modified six-inch chamber operated at a much higher contraction ratio.

Stringent information as to how much higher the contraction ratio of a windowed chamber with reduced flow rate density can be than in the actual engine without rendering the last conclusion unrealistic can be found only by firing tests. For this purpose, the width of the slab chamber (Figure 3) should be decreased in steps, by using central sections of decreasing width, and the correspondent changes in the transition region should be observed on the shadowgraphs.

At any rate, it was expected that the firing tests with the modified six-inch windowed chamber would supplement the water flow tests by providing realistic information concerning the formation and burning of the propellant sprays. This information could then be utilized for designing a slab chamber (Figure 3) in which the transition region and the downstream gas velocities of the F-1 engine were simulated as closely as possible. In addition, the adequacy of the existing photographic equipment for taking shadowgraphs through the slab chamber could be checked. A positive result would be very conservative, because the radiative path length would be shorter and consequently the radiation from the flame light weaker in the narrower slab chamber than in the modified six-inch chamber. Finally, the tests would facilitate an estimate concerning the flow rate densities at which the slab chamber could operate satisfactorily.

7.0 PHOTOGRAPHIC TECHNIQUES

Two different techniques were used during the firing tests with the modified six-inch windowed motor, namely, shadow photography using a spark light source for back illumination and Fastax photography using the flame light as the only light source.

7.1 SHADOW PHOTOGRAPHY

The purpose of this technique is to produce on a photographic film, by means of back illumination, shadows of the liquid contents of the gas-liquid mixture existing in the windowed chamber, such as blobs, ligaments and droplets. Since the liquid particles are in rapid motion, a flashing light source of sufficiently short duration has to be used for back illumination. Also, precautions have to be taken in order to minimize the effect of the flame light on the film.

From the point of view of the photographer, the problem is to find a photographic technique which embodies the most satisfactory compromise among several partially contradicting requirements, primarily among the following three: (1) large magnification from object plane to film plane, (2) large observable field of view, (3) sharp boundaries of and high contrast between the shadows and their background.

The photographic technique and equipment which previously had been developed by Bell Aerosystems for taking shadowgraphs through a small experimental windowed motor (Figure 27), operated at 300 psia chamber pressure with WFNA as oxidizer and UDMH as fuel provided a satisfactory compromise under these operating conditions, as evidenced by Figures 1, 2, 16, 17, 18, 29, 30, and 31. Whether the equipment would be adequate for investigations conducted on a much larger windowed motor simulating the more severe conditions existing in the F-1 engine (Figures 3 and 32) could be established only during firing tests. However, since during work on the experimental chamber the equipment appeared to possess considerable latitude with respect to more severe operating conditions, it was decided to utilize as much as possible of the existing equipment and to improve on it only if necessary.

7.1.1 Single-Shot Shadow Photography

The photographic setup which was finally used, after various modifications, for taking single-shot shadowgraphs through one window opening of the firing modified six-inch motor at a magnification of 0.6 between object plane and film plane is shown schematically in Figure 42 and as it appeared in the test cell in Figure 43. Only components on hand at Bell were used.

The light source is an Edgerton, Germeshausen and Grier No. 549 Microflash System (Reference 32), consisting of a Model 549-11 Flash Unit and a Model 549-21 Driver Unit. The flash unit is a guided air spark across a one-inch gap housed in a parabolic reflector and produces a nearly collimated cylindrical light beam of six-inch diameter. The nominal duration is 0.5 microsecond and the nominal beam candlepower is 50×10^6.

The flash unit was placed approximately three inches from one of the two openings in the window frame. A Taylor-Hobson lens (f/2.5, f = 234 mm) was placed as close as possible to the opposite opening in order to obtain the maximum field of view. A Speed Graphic camera equipped with an Optar lens (f/4.7, f = 135 mm) and a Synchro-Compur shutter (set for its shortest exposure time of 1/400 sec) was used. The full aperture of each lens was used.

It is recognized that, from an optical point of view, the system is afflicted with some deficiencies, mostly because of the rather poor optical properties of the reflector in the microflash unit which is designed for the illumination of a large area. Attempts to work without the reflector were not successful because the radiating area of the guided air spark (even less the area of a "point" spark light source replacing guided air spark and reflector) was not large enough to provide illumination for a sufficiently large field of view. Guidelines for correcting these deficiencies and for developing a more efficient photographic setup are discussed in Section 9.1.

By a process of trial and error, the maximum film plate illumination and a sharp shadow image of a back lighted wire located in the chamber axis were obtained with the camera objective positioned 12.4 inches from the Taylor-Hobson lens. In this position a 3.3-inch high by 2.8-inch wide area of the chamber was viewed on the film plate at a magnification of 0.6.

The operation of microflash and camera during a firing run can be described briefly as follows. At a preselected time after steady state conditions are established in the combustion chamber, the mechanical camera shutter is automatically tripped from the control panel. At the instant the shutter is fully open, the microflash is triggered through the shutter contacts. Since the shutter open time is approximately 2500 microseconds and the nominal duration of the spark flash is 0.5 microsecond, the film is exposed to the flame light approximately 5000 times as long as to the light emitted by the microflash.

In order to attenuate the flame light, two Kodak Wratten filters (Nos. 47B and 50) were placed in front of the camera objective. The spectral transmission of this filter combination has a maximum of 5% at 450 millimicrons (Reference 33).

7.1.2 Multiple Shot Shadow Photography

To obtain information concerning the physical behavior of the liquid contents of the chamber after injection (i.e., their time-wise change in shape and size) and especially to measure their velocities and evaporation rates, multiple shadowgraphs have to be taken at sufficiently short time intervals. For this purpose, Bell Aerosystems had previously (References 1 and 2) conducted an exploratory program which resulted in the development of a high speed flashing unit which replaces the microflash shown in Figure 42 and is capable of producing 10 consecutive flashes of one and the same spark flash lamp at flashing rates up to 10,000 flashes per second. To separate the shadowgraphs produced by consecutive flashes, a single sweep mirror camera had been developed which replaces the simple film holder shown in Figure 42. This equipment is shown in Figure 44. An essential component of the camera is a mirror which makes a single rapid rotationary motion and sweeps the imaging beam through an angle of 75° across a stationary sheet of film 28 inches long and 14 inches wide at speeds up to 160 m-sec^{-1}. The camera provides a magnification of 3.3 from object plane to film which can be varied only within narrow limits for final focusing.

It should be mentioned that the single sweep mirror camera is a rather crude piece of equipment intended to prove the feasibility of the shadowgraph technique in general. Only components at hand and surplus optics were used in order to keep the cost of this exploratory program as low as possible. For more advanced investigations, the camea should be replaced by a more expensive rotating drum camera.

By way of example, three consecutive frames of two series of multiple shadowgraphs obtained on another contract by this technique are shown in Figures 16 and 17. They were taken at a magnification of 3.3 and at a rate of 2500 frames/second of a stream of water and of a 50/50 water-hydrazine mixture, respectively, injected through an orifice of 500 microns diameter into the stream of combustion gases approximately 200 mm downstream from the injector face of the small experimental motor shown in Figure 27. The writing speed on the film was the highest obtainable with the mirror camera, 160 m-sec^{-1}, so that the height of the field of view was restricted to $160 \cdot 0.4 = 64$ mm on the film in order to prevent overlapping of consecutive frames. This results in a height of the field of view in the object plane of $64:3.3 = 19.4$ mm. The average diameter of the drops is 1000 microns, their average velocity is essentially the injection velocity, 12 m-sec^{-1}. It can be seen that individual droplets can readily be reidentified on consecutive frames because characteristic "constellations" of drops do not change substantially during the time interval (400 microseconds) and within the distance ($12 \cdot 0.4 = 4.8$ millimeters) traveled between consecutive frames. Thus, droplet velocities could be readily determined.

Figure 18 shows a series taken under the same conditions as Figures 16 and 17, however, ether was injected instead of water and water/hydrazine. In this case, reidentification of individual particles on consecutive frames is more difficult because, due to the low surface tension, the ether stream disintegrates into very fine droplets and ligaments the constellations of most of which change too much during the time interval between consecutive frames, 400 microseconds, to be reidentified on consecutive frames. Nevertheless, the average velocity of some particles could be measured as 18 m-sec^{-1}, resulting in a travel distance between consecutive frames of approximately 7 mm.

Even more difficult is reidentification on consecutive frames of particles within the transition region adjacent to the injector face. This can be seen on Figure 1 which was taken under the same conditions as Figures 16, 17, and 18. However, the velocity of some large liquid blobs at a distance of approximately three inches from the injector face could be measured as 30 m-sec^{-1}, resulting in a travel distance between consecutive frames of approximately 12 mm. Conceivably, in the highly turbulent transition region, liquid blobs and droplets change their shape and constellations to such a degree during the time interval between consecutive flashes (400 microseconds) and within the travel distance (12 mm) that they can be reidentified on consecutive frames only in rare cases.

It can be expected that reidentification will be substantially facilitated if the full repeating rate of the flashing unit, 10,000 frames/second, is used, resulting in a time interval of 100 microseconds and a travel distance of 30 x 100 = 3000 microns = 3 mm between consecutive flashes. However, at such high repitition rates, it is difficult to secure the same high intensity and the same short duration of each flash as at low repetition rates. Experience shows that this difficulty can be alleviated to some degree by reducing the number of flashes within one series substantially below ten, however, use of a more appropriate flash lamp might be necessary or advisable.

Another difficulty resulting from using a rate of 10,000 frames/second is that the height of the field of view on the film would be reduced to 160·0.1 = 16 mm, and in the object plane to only 16:3.3 = 4.8 mm. The last value could be raised to 16:0.5 = 32 mm if a camera objective of longer focal length is used, resulting in a magnification of 0.5 instead of 3.3. This measure might be feasible in this case because the liquid particles in the transition region are rather coarse.

Finally, Figure 2 shows two consecutive frames of a series taken of the uniform region between two and four inches from the injector face of the small experimental chamber. The diameter of the droplets varies between 50 and 350 microns, 50 microns being the diameter of the smallest droplets which can be resolved with the rather crude optics which were used for this exploratory program. Closer scrutiny of Figure 2 and similar shadowgraphs reveals that no coordination between droplet constellations on consecutive frames is possible. In part, this can be explained by the fact that the time interval between consecutive frames was 800 microseconds; i.e., twice as long as in Figures 1, 16, 17, and 18. However, it might well be conceived that the main reason is that the droplets are much smaller here than the liquid blobs in the transition region and therefore follow more readily the turbulence and higher gas velocities in the uniform region.

Again, reidentification can be facilitated by reducing the time interval between consecutive flashes from 800 to 100 microseconds; however, use of a weaker magnification than 3.3 in order to make up for the reduced light of the field of view does not seem to be feasible in this case because of the small diameter of the droplets in the uniform region. Thus, in this case the light of the field of view in the object plane can be raised above (160 x 0.1):3.3 = 4 mm only by increasing the writing speed on the film, 160 m-sec^{-1}. However, this could only be accomplished by replacing the single sweep mirror by a continuously rotating mirror, or by replacing the whole mirror camera by a rotating drum camera.

In summarizing, it can be concluded that, with some improvements, the experimental technique shown in Figure 44 is adequate for measuring velocities of liquid particles within the transition region of the small experimental chamber shown in Figure 27. Whether this is true also with respect to a chamber simulating the more severe conditions in the F-1 engine could be established only during firing tests conducted with this chamber, especially on account of the much higher flow rates and injection velocities (up to 60 m-sec^{-1} instead of 15 m-sec^{-1}). Velocities within the uniform region of the experimental chamber cannot be measured with the experimental technique shown in Figure 44 unless the flashing unit, flash lamp and camera are drastically improved. Even then it would be highly doubtful if these improvements would suffice to measure velocities within the first 10 inches from the injector face of a motor simulating the conditions of the F-1 engine because the low contraction ratio of this engine (1.25) results in gas velocities of the order of 300 m-sec^{-1} within this region. Even with a time interval between consecutive frames as short as 100 microseconds, the distance traveled by liquid particles moving with the gas would be 300 x 100 = 30,000 microns = 30 mm between consecutive frames. It cannot be expected that any constellation of particles will change so slowly that it can be reidentified on the next frame after having traveled such a long distance.

To overcome this difficulty, the frequently used "method of separate light sources" is especially appropriate (References 34 and 35). This method is based on the fact that, due to the de-ionization time of a spark discharge, the time interval between single flashes of two light sources of high intensity and short duration can be sufficiently short much easier than the one between two flashes of one and the same light source. Thus, the method consists in using two separate flash lamps instead of one for back illumination, using a half-silvered mirror as a beam splitter (Figure 45). For measuring velocities of liquid particles moving within a windowed combustion chamber, these components and the illuminating and imaging optics are arranged in such a way that the shadow of an object located in the object plane which is produced on a stationary film by one flash lamp coincides with the shadow produced by the other lamp if both light sources flash at the same instant. If one flash is delayed by a known time interval, the developed film shows two shadows of the same object produced by double exposure and the velocity of the object can be determined if the magnification from object to film plane is known.

This method can be materialized for measuring velocities in the uniform region within 10 inches from the injector face of a windowed motor simulating the conditions of the F-1 engine by using the two E.G.&G. 549 Microflash Systems available at Bell, the flash of the second unit being triggered by the flash of the first unit. The shortest time interval between the two flashes is nominally two microseconds, resulting in a distance of 300 x 0.002 = 0.6 mm traveled between the two flashes by an object moving at a velocity of 300 m-sec^{-1}. It can be hoped that within the first 10 inches from the injector face the shadows of constellations of droplets produced by the two consecutive exposures can be correlated. However, the correlation of individual droplets will scarcely be possible, because even a droplet as large as 50 microns in diameter would travel a distance of 600:50 = 12 times as long as its diameter.

Another frequently used method for measuring velocities within a windowed combustion chamber is "streak photography", the applicability of which to this program was also given serious consideration. However, the "method of separate light sources" has the important advantage that at least one can be sure about the nature of the object the velocity of which is measured while in the case of streak photography this is more or less left to surmize (Reference 4a, p. 33). Nevertheless, in view of the complexity of the problem, it might prove advisable in the course of the investigations to use both methods for comparison.

7.2 FASTAX PHOTOGRAPHY

There can be no doubt that the most valuable information concerning the combustion process in real engines has been obtained so far by taking high speed motion pictures through windowed "model" chambers simulating the conditions in real engines. Conventional high speed cameras with frame rates up to 12,000 frames/second have been used, either using the flame light alone or, with greater success, using strong back illumination in order to obtain shadowgraphs (References 3, 4b, and 36). The advantages of this method are that the experimental technique is comparatively simple and that the shadowgraphs provide a fairly detailed overall picture of the formation and combustion of the propellant sprays under stable and unstable operating conditions. Finer details within the sprays, however, such as the liquid blobs, ligaments and drops observable on Figures 1, 30, and 31 are not resolved. Another advantage of Fastax photography is that long series of frames can be taken which, when projected in motion, can provide the experienced observer with a fairly realistic general impression of the phenomena occurring in the combustion chamber even if the camera is exposed to the flame light without back illumination. For this reason, Fastax photography without back illumination has been used with advantage under this program in order to obtain some preliminary information concerning the dimensions and coarse structure of the propellant sprays within the first 10 inches from the injector face of the firing windowed motor. In this way, it could be predicted what kind of information could be obtained by taking high resolution shadowgraphs with the spark light method (Figure 42) at various distances from the injector face so that the most important regions could be investigated by the smallest number of the expensive firing runs.

It should be noted that the quality of shadowgraphs taken with high speed motion cameras can be appreciably improved by synchronizing the camera with a light source which provides intermittent back illumination by emitting flashes of short duration at high flashing rates. Complete units for this purpose which can be used for a variety of high speed cameras are commercially available (Reference 36). However, the usable frame size of cameras which can be run at 10,000 frames/second or higher is very small so that the field of view which can be covered is accordingly small, unless the photographs are taken at a large reduction in size from object to film. This restricts the usefulness of this approach to cases where the liquid particles to be observed are not too small. Also, the more complex image formation in the Fastax camera might create a problem with respect to resolution of finer details in the shadowgraphs.

8.0 FIRING TESTS

8.1 TEST CONDITIONS

All firing tests were conducted with the modified six-inch windowed motor, which has been described in Section 6.0. Figure 43 shows the motor on the test stand. Also, some components of the feed system are shown. A more detailed description of feed system, operation of the engine and instrumentation can be found in Section 11. The photographic equipment shown in Figure 43 will be described in Section 8.2.2.

A total of 15 firing runs were conducted. The data is shown in Table II. On all runs, the "2.5 element injector" (Figure 32) was used, composed of two oxidizer doublets and three fuel doublets of injector element No. 1 in Table I.

In order to minimize the photographic difficulties caused by deposits of solids, e.g. carbon, on the windows, RP-1 as a fuel was tentatively replaced by isopropyl alcohol in runs No. 1 through 10, and by UDMH in runs No. 11 through 15.

In order to simulate the impingement and mixing conditions as closely as possible, it was decided to keep the injection velocities the same as in the F-1 engine. Thus, the flow rate of 2.33 lb-sec^{-1} RP-1 per fuel doublet was corrected with respect to liquid density, resulting in a rated flow rate of 2.26 lb-sec^{-1} isopropyl alcohol or UDMH per fuel element. With 5.48 lb-sec^{-1} LOX per oxidizer doublet the rated total flow rate was 17.74 lb-sec^{-1}. The rated mixture ratio per element was 2.42 and the rated overall mixture ratio was 1.62.

Chamber pressure was varied by using various nozzles with appropriate throat areas. Ignition was accomplished by injecting, ahead of the fuel, a "slug" of triethylaluminum which ignites spontaneously with oxygen. The starting sequence was oxidizer lead (1/2 LOX flow), prestage (1/2 LOX flow + full fuel flow) and mainstage (full LOX and fuel flow). No hard start and no oscillatory combustion was noticeable.

8.2 TEST RESULTS

The first six runs were used for checking the structural strength and proper operation of motor, test stand and feed system at various chamber pressures. No damage was experienced. The remaining nine runs were used for checking the photographic equipment and for attempts to obtain shadowgraphs of the liquid contents of the windowed combustion chamber.

TAI

SIX-INCH WINDOWED CHA

Run No.	Date	$\bar{\dot{W}}_F$ (1) (lb·sec^{-1})	$\bar{\dot{W}}_o$ (1) (lb·sec^{-1})	$\bar{\dot{W}}_T$ (lb·sec^{-1})	$\bar{r}^{(2)}$	$\bar{P}_c$ (psia)	C^*_{Th} (3) (ft·sec^{-1})
1	6/2	6.97	11.36	18.33	1.63	496.4	5705
2	6/7	6.95	11.72	18.67	1.69	-	-
3	6/9	5.66	8.80	14.46	1.55	823.4	5664
4	6/14	6.13	11.36	17.49	1.85	1165.5 ?	5688
5	6/21	6.33	11.09	17.42	1.75	725.5	5672
6	7/1	6.22	-	-	-	649.6	-
7	7/30	5.77	10.87	16.64	1.88	768.5	5674
8	8/6	5.59	10.21	15.80	1.83	770	5694
9	9/3	6.43	11.53	17.96	1.79	834	5690
10	9/14	6.81	10.90	17.71	1.60	840	5660
11	9/17	6.34	10.58	16.92	1.67	865	6055
12	9/20	6.84	10.33	17.17	1.51	858	6105
13	10/20	6.68	10.69	17.37	1.60	828	6071
14	10/22	7.20	11.41	18.61	1.58	829	6082
15	10/27	6.76	11.55	18.31	1.71	819	6053

(1) Rated flow rates: 6.78 lb·sec^{-1} isopropyl alcohol, 10.96 lb·sec^{-1}

(2) Rated mixture Ratio: 1.62

(3) Shifting Equilibrium

LE II

MBER FIRINGS SUMMARY

C^*_M (4) (ft·sec^{-1})	η %	$\bar{\dot{W}}_{N_2}$ (5) (lb sec^{-1})	Type of Run	Comments
5195	0.91	-	Checkout	Stainless steel nozzle rated for 500 psia.
-	-	-	Full Duration Checkout	Stainless steel nozzle burned out
4735	0.837	0.559	Checkout	Copper nozzle rated for 1000 psia. Sharp edge. Badly discolored.
5861 ?	1.03 ?	0.605	Checkout	Copper nozzle rated for 1000 psia. Rounded edge. Nozzle burned out.
4800	0.845	0.602	Pyrex window Checkout	Copper nozzle rated for 1000 psia. Repaired. Nozzle burned out.
-	-	-	Photographic	Improved copper nozzle rated for 800 psia. Heavy carbon deposits on windows. No picture.
5396	0.952	0.556	Photographic	Same nozzle. Slight carbon deposit on windows. No picture.
5742 ?	1.01 ?	0.406	Photographic	Same nozzle. Repeat of No 7 with no spark. Slight carbon deposit.
5488	0.965	0.402	Checkout (Fastax)	New inserts for parallel window flushing and new 3.6 inch chamber extension used.
5577	0.985	0.489	Microflash double spark	No satisfactory flash picture obtained.
6017	0.995	0.450	Checkout New Fuel	First test using UDMH instead of isopropanol. Fastax (66 ft of 100 ft roll) film obtained.
5784	0.948	0.393	Repeat of Run No. 11	Fastax (50 ft of 100 ft roll) film obtained.
5729	0.944	0.525	Microflash (reflector)	Microflash units and camera acoustically insulated. Oscillogram monitored microflash unit. No flash picture.
5339	0.878	0.489	Repeat No. 13 without microflash (Fastax)	Run to determine why no picture was obtained in Run No. 13.
5376	0.890	0.330	Checkout (Fastax)	Window inserts removed. Double Fastax camera used, one with color film.

LOX

(4) Calculated from $C_{M^*} = \dfrac{P_c \cdot A_t \cdot g}{\dot{W}_F + \dot{W}_o + \dot{W}_{N_2}}$

(5) Total Flow Rate of N_2 - Window Flush

2

8.2.1 Fastax Photography

High speed motion picture photography was used during most of those firing tests where Pyrex windows were installed. The camera was a Wollensak "Fastax" 16 mm with an f/2, 50 mm objective. It was exposed only to the flame light without back illumination.

During the first firings, the Fastax camera was used to monitor the windows and to locate weak spots in case window slabs or seals were to fail during a test, so that corrective actions on the following runs could be taken. The primary reason for its use, however, was to obtain by means of Fastax photography some preliminary information concerning the extent and structure of the transition region in the firing chamber. It was expected that in this way one could predict what kind of information could be obtained by taking high resolution shadowgraphs with the spark light source at various distances from the injector face so that the most important regions could be investigated with the smallest number of firing runs.

The use of the Fastax camera to obtain some indication as to the location of the transition region can be illustrated by a film which was taken during run No. 8 on a region between 2.6 and 5.7 inches from the injector face (arrangement II in Figure 34). The propellant combination was LOX/isopropyl alcohol.

The film was taken with a camera running at approximately 1000 frames/second. Figures 46 through 51 are enlarged copies of six series of three consecutive frames of this film. The window opening is a rectangle with rounded curves, approximately three inches wide and 3.5 inches high. Flow direction is from left to right, time proceeds from top to bottom.

Figures 46, 47, and 48 were taken at 130,170, and 255 milliseconds, respectively, after ignition, i.e., during "prestage" where the fuel is flowing full, but the oxidizer only at approximately 1/2 full flow. It can hardly be doubted that most of the dark regions are the shadow of unburned liquid propellants, although the effect of formation of carbon in the fuel rich mixture cannot be overlooked.

Figures 49 and 50 were taken at 480 and 560 milliseconds, respectively, after ignition, i.e., during mainstage with full fuel and oxidizer flow rates. It is a plausible conjecture that the dark areas are due to the presence of large amounts of liquid propellants.

This conjecture is confirmed to a degree by Figure 51 taken 1400 milliseconds after ignition, i.e., between fuel shutdown and flame extinction. Observation of the running film showed that during this period, the combustion receded at times toward the injector so that a large amount of flame light and only small amounts of liquid propellants were visible through the window. Consequently, it can be concluded that on Figures 49 and 50 the major part of the combustion occurred downstream of the window, and the dark regions are actually due to the presence of large amounts of liquid propellants.

The conclusions reached concerning the presence of large amounts of unburned propellants in the region between 2.6 and 5.8 inches from the injector face were supported in the following test firing (run No. 9) in which a similar film was taken at a location extending from 11.16 to 14.29 inches from the injector face (arrangement III in Figure 34). The film shows patterns similar to those which can be seen on the film taken during run No. 8. However, sharp shadows of liquid propellants are not noticeable during "prestage", and the bright areas during mainstage are much larger than on run No. 8, especially in a center strip approximately two inches wide. This shows that in the region observed during run No. 9, the transition from liquid propellants to gases has proceeded farther than in the region observed during run No. 8.

In summarizing, the Fastax films taken during runs No. 8 and No. 9 provide strong evidence that, even after stabilization of mainstage, there still exists a large amount of liquid propellants in a distance from the injector face which can be estimated to be eight inches. It should be noted that this estimate is based on the assumption that the phenomena which can be seen by a camera without back illumination, are typical to a degree for the entire chamber width.

In a similar fashion, information was sought in runs No. 14 and No. 15 in which UDMH fuel was substituted for isopropyl alcohol. (The substitution was made because it was hoped that by using a less carbonaceous fuel the severe conditions imposed by the very bright flame of the LOX/alcohol combination would be alleviated.) Furthermore, during run No. 14, the Fastax camera covered a region between 7.6 and 10.7 inches from the injector face (arrangement No. II in Figure 34); i.e., a region between those covered by runs No. 8 and No. 9. During run No. 15, the camera was equipped with a wide-angle lens and covered both openings of arrangement II. In both tests, the camera aperture was set for the exposure as for the LOX/alcohol runs (No. 8 and No. 9).

Both films proved to be heavily overexposed, indicating that the flame light of the LOX/UDMH propellant combination was even brighter than that of the LOX/alcohol combination. Although impeded by overexposure, the films showed a series of randomly moving shadow patterns with no discernible streams or droplets; such as had been observed in runs No. 8 and No. 9. During run No. 15, a second Fastax camera with a wide-angle lens covered both openings of arrangement II from the opposite side. A special film (XR color negative film - Edgerton, Germeshausen and Grier, which is a triple emulsion film with a very broad exposure latitude) was used in this camera. No improvement was noticeable in comparison with the black and white films.

8.2.2 Flash Photography

Firing tests No. 6, 7, and 10 were used for checking and improving the equipment intended to provide high resolution and short exposure shadowgraphs of the liquid contents of the combustion chamber. The photographic technique, shown in Figures 42 and 43, is described in detail in Section 7.1. Essentially, the photographic setup was the same as had been successfully used for obtaining shadowgraphs like Figures 1 and 2 on a small experimental windowed motor (Figure 27) operated at 300 psia chamber pressure with WFNA as oxidizer and UDMH as fuel. Whether the equipment would be adequate for investigations conducted on a much larger windowed motor simulating the more severe conditions existing in the F-1 engine could be established only during firing tests. Firing test No. 13, 14, and 15, using the optical setup shown in Figure 42, showed that this was not the case. Run No. 13 was conducted with the LOX/UDMH combination at a chamber pressure of 830 psia. Photographs were taken through the downstream opening of arrangement II in Figure 34, covering a region between 7.6 and 10.7 inches from the injector face. The inner surface of the window in this region was flushed with nitrogen emerging from the inserts which covered the remaining window surface (Figure 39). In order to provide a photographic test object during the firing, a tungsten-tantalum rod was threaded into the injector face.

Figure 52 is a shadowgraph taken with the microflash before the run, showing the shadow of the rod. Figure 53 was taken with the microflash during the firing. The rod is visible, burning on the downstream end. There is no evidence of propellant sprays or droplets. Figure 54 was taken with the microflash after the firing. The rod is no longer visible because it was burned off at the injector face and expelled through the nozzle during the run. The dark ragged pattern on the downstream half of the opening is the shadow of carbon deposits which were mentioned before (Figure 40). Markings seen in Figure 53 correspond roughly with this pattern. Figure 55 is a photograph taken during run No. 14 which was conducted at the same conditions as No. 13. However, only the camera shutter was operated and not the microflash so that the film was exposed only to the flame light. It can be seen that this photograph is essentially identical with the photograph (Figure 53) which was taken with flame light and microflash.

It could be suspected that no shadows of droplets or other liquid particles can be seen on Figure 53 because either the camera shutter or the microflash malfunctioned. However, oscillograph recording of shutter contact and flash discharge indicated that the flash occurred while the camera shutter was open.

It could also be thought that there is no liquid left at the distance from the injector face and consequently no shadow of such could be seen on Figure 53. However, Fastax films taken during firings No. 14 and 15 under the same conditions and through the same opening through which the flash photograph of Figure 53 was taken indicated the existence of fairly large amounts of liquid, as mentioned in Section 8.2.1.

Thus, it appears that the flame light of the LOX/UDMH (and very probably also of the LOX/isopropyl alcohol) combination used in the modified six-inch chamber at approximately 850 psia chamber pressure is so much more intense than that of the WFNA/UDMH combination used in the small experimental chamber at 300 psia that its effect on the photographic film completely overpowers the effect of the back illumination provided by the photographic equipment which had been successfully used on the experimental windowed chamber.

This conclusion is corroborated by the following consideration. Figures 52 through 54 were all taken with the same optical setup and were obtained from the negatives using the same magnification, namely 3.5. In Figures 52 and 54, taken with the microflash alone, the photograph is "framed" by the window opening farthest from the camera. In Figure 53, taken through the firing engine, the photograph is framed by the window opening nearest to the camera. Consequently, the illuminated area is larger in Figure 53 than in Figures 52 and 54. If the back illumination provided by the microflash was not completely overpowered by the flame light, at least a trace of the smaller frame should be observable within the larger frame in Figure 53.

It should be noted that Figure 53 provides information concerning the optical transmittance of this chamber section. Inspite of the fact that this region contains liquid propellant blobs, ligaments and droplets moving at high velocity, combustion zones, and probably incandescent carbon particles or soot floating in the burnt gases, a shadow image of the rod was obtained. This could have been produced only by flame light, and not spark light as explained above. Since the flame light exposed the film on either side of the shadow more than within the boundary of the shadow, it follows that the flame light which originated in that region of the chamber volume farthest away from the camera than the rod was partially transmitted through the chamber volume between the rod and the camera. This is clear evidence that the optical transmittance in this chamber section is fairly high. Thus, it can be expected that the spark light used for back Illumination will not be attenuated too severely by absorption within the chamber.

The question might be raised as to why shadows of liquid filaments or droplets were not also produced by the flame light. This would not be possible since liquid droplets moving down the chamber with an axial velocity of 100 ft-sec^{-1} would traverse the field of view of the camera in the 2.5 millisecond exposure time.

8.2.3 Suppression of Test Cell Noise

During some of the firing tests up to run No. 12 the Fastax camera malfunctioned. Since the camera worked perfectly when it was operated during nonfiring checkout tests, but malfunctioned repeatedly during firing tests, it was tentatively concluded that the camera and/or its accessories were affected by the high noise level in the test cell. We were informed by the Wollensak Company that failures of this nature were a common problem. During one run (No. 14), a General Radio sound level meter was located in the cell. It indicated an average sound level of 158 decibels with several excursions over 160 db, the limit of the instrument. A sound level of 130 db is considered sufficient to cause operational difficulties on equipment containing conventional relays and/or switches. This value was obtained from the Bell Acoustics Group of the Environmental Section of the Structural Engineering Department.

Of the two units comprising the Fastax camera apparatus (camera and control unit), the control unit was considered to be the most susceptible to noise because it contained numerous relays and microswitches. The solution, therefore, to the problem was to remove the control unit from the test cell to the relative quiet of the control room. This was done before run No. 13 and no further difficulties were encountered on subsequent runs. As a further precaution against noise, all optical and electronic equipment needed for photography (camera, flash unit) which had to remain the test cell during a test firing were enclosed in acoustical noise suppressing containers. These containers, which were designed at Bell by the Acoustics Group, consist of an outer box made of Celotex board, and an inner layer of fiberglass insulation separated from the wall by a dead air space. These boxes provided sufficient sound attenuation so that no further difficulties due to sound were experienced in the remaining tests by any of the components in the test cell.

9.0 GUIDELINES FOR IMPROVED SHADOW PHOTOGRAPHIC TECHNIQUES

As discussed in Section 8.2.2, the optical and electronic equipment used during the firing tests proved to be inadequate for providing high resolution and short exposure shadowgraphs of the liquid contents of the combustion chamber under the severe conditions imposed by the requirement to simulate the conditions existing in the F-1 engine. The photographic setup (Figure 42) was essentially the same as that which had been successfully used on a small experimental motor, but under much less severe conditions. Also the equipment was selected from that presently available at Bell, and the arrangement which was thought to yield the best results obtainable with these components was arrived at by a rather crude process of trial and error. Thus, substantial improvements are possible, which can be expected to result in the development of an experimental technique which will yield satisfactory results even under conditions as severe as the requirements of this contract. Guidelines for such a development are discussed in the following subsections.

9.1 OPTICS

There is not just one "optimum" optical setup for taking shadowgraphs through a given windowed motor; as for example, the six-inch windowed motor shown in Figure 32. Rather, the problem is to find the most satisfactory compromise among several requirements, primary of which are the following three: (1) large observable field of view, (2) large magnification from object plane to film plane, and (3) sharp boundary and high contrast between the shadow of the object and its background. These requirements contradict each other to some degree, and their mutual importance depends strongly on the objects or phenomena which are of primary interest in a special case of application. For example, observation of the formation and structure of the burning propellant sprays in the transition region requires chiefly a large field of view: while investigations concerning size and shape of small liquid particles in the uniform region require large magnification and sharp shadow boundary. In addition, the compromise must consider limitations which are imposed by the requirement that all components should be obtainable at a reasonable price and in a reasonable time, preferably commercially and not requiring special development. These requirements are especially important because the major portion of the equipment has to be located in the test cell and exposed to the hazards which are inevitably involved with work on a windowed combustion chamber (window failure). Finally, the shape and dimensions of the optical train should not make its installation in a test cell of conventional dimensions too difficult.

Thus, the choice of an optical system (and test equipment and instrumentation in general) for taking shadowgraphs through a firing windowed motor in a special case of application will always be an art primarily based on skill and experience. In the following, methods are discussed which enable one to execute this art in a more rational way by means of numerical analysis.

9.1.1 Large Field of View, Small Magnification

By way of example, the schematic of Figure 56 shows an arrangement which provides a good compromise for taking shadowgraphs through one window opening of the motor shown in Figure 32, in order to provide an overall view of the liquid contents existing in the region covered by this opening. For this purpose a large "field of view" (D) is required, utilizing a portion of the opening as large as possible. In Figure 56, the areas of the window openings (C) are approximated by circular disks of w = 90 mm (3.54 inches) diameter, separated by a distance of $2 \cdot d = 360$ mm (14.2 inches). Consequently, the field of view is also a circular disk of diameter h with its center on the straight line connecting the centers of both openings. The location of the field of view is chosen to be in the middle between the windows.

The purpose of the shadowgraphic technique is to produce on a photographic film, by means of back illumination, shadows of objects located within the field of view, such as liquid or solid particles. These shadows have to have a sharp boundary, in spite of the fact that a light source of finite size has to be used in order to obtain sufficient contrast between shadow and background. This is accomplished by using a camera objective (F) which images the field of view (D) on the photographic film (H).

Back illumination is provided by a light source located behind the window farthest from the camera. The bundles of rays which would provide illumination for points on the rim of the circular field of view with a light sources of sufficiently large size are indicated by the two shaded areas in Figure 56, It can be seen that the radiating area of a light source capable of "feeding" all these bundles would have to be at least as large as the area of the window opening farthest from the camera. However, in Figure 56, the light source is assumed to be a spark gap or tube (A) which can produce a flash of sufficiently short duration (approximately 1 microsecond) and of an integrated intensity ($\text{watt} \cdot \text{cm}^{-2} \cdot \text{srad}^{-1}$) several hundred times higher than the intensity of the strongest continuous light sources, such as the sun or the carbon arc. The dimensions of such spark devices are limited. Experience shows that spark light sources with a radiating area which has the shape of or includes a circle of 4 mm diameter are feasible. In order to enable a light source with a radiating area much smaller than the area of a window opening to feed all the bundles which illuminate points on the rim of field of view, a condenser lens (B) is placed between light source and window. In the following paragraphs, it will be shown that it is advantageous to place the condenser lens as close as possible to the window as is schematically shown in Figure 56, and to arrange light source and lenses in such a way that the light source is imaged on the circle common to all bundles of rays which illuminate points on the rim of the field of view. It can be shown that this circle lies in the focal plane (G) of the camera objective (F) and its center in the focal point provided the centers of the circular disks representing window openings and field of view lie on the same straight line perpendicular to the window planes, the circular disks representing the window openings have the same diameter, and the field of view lies midway between the windows. Since these conditions are fulfilled in Figure 56, the radiating area of the light source (A) has to lie in the focal plane of the condenser lens (B).

It can be seen that in this arrangement all points on the rim of the field of view receive light from the whole radiating area of the light source. This is also true for all other points of the field of view because the rays which form the conical surface of those bundles which receive light from the light source must for all points intersect the rim of the circular image of the light source, and consequently also the rim of the light source itself. By way of example, this is shown in Figure 56 for the center point of the field of view. The area indicating the respective bundle of rays is cross hatched. Of course, the illumination in any point of the film is always weaker than in the center of the field of view because the average angle between illuminating bundle and optical axis increases with the distance between illuminated point and center of the field of view. However, it will be seen later that in practice the illumination on the film ($\text{watt}\cdot\text{cm}^{-2}$) cannot vary by more than a few percent under the conditions shown in Figure 56. Thus, the whole field on the film is almost uniformly illuminated even if the intensity of the light source is not evenly distributed over the circular radiating area of 4 mm diameter; the only limitation being that the intensity distribution in each point of the radiating area must be Lambertian, i.e., the intensity is independent of direction.

Another advantage of the arrangement shown in Figure 56 concerns discrimination against the unwanted effect of the flame light on the photographic film. Since all light rays from the light source to the film must pass through the circular image of the radiating area of the light source, nothing will be changed in this respect if a stop (G) is placed in the plane of this image with an opening that coincides with this image. Then no point of the film can receive flame light in a larger solid angle than it receives light from the light source. Without this stop, the center point on the film, for instance, would receive light from the light source in the circular cone indicated by the cross-hatched area bounded by the solid lines, while it would receive flame light in the much larger circular cone indicated by the area bounded by the broken lines.

Another opportunity to decrease the effect of the flame light on the film is offered by the fact that in the flame light stop (G). This facilitates the installation of an ultra high speed shutter close to the stop with an "open time" several times shorter than the open time of the fastest conventional high speed shutters. The latter is at least 1 millisecond, i.e., approximately still 2000 times as long as the nominal time during which the film is illuminated by the Microflash, namely 0.5 microsecond, while the open time of mechanical ultra high speed shutters with an aperture of 4.5 mm may be as short as 0.3 milliseconds (Reference 49). Suppression of flame light will be discussed in more detail in the next subsection.

Focal lengths and apertures of the lenses, location of lenses, light source, flame light stop and film plate and the diameter of the observable field of view can be determined for given dimensions of windowed chamber, light source, ultra high speed shutter and film plate by an analysis based on the equations which follow. The derivation of the equations which in part is rather involved, is omitted. It will be noted that the results of an analysis using these equations can only be approximate because (1) the lenses are assumed to be infinitely thin, (2) the window openings are approximated by circular disks, and (3) the optical effect of the window material is neglected.

Basic Equations for Tables IIIa, IIIb, and IIIc

$$2 \cdot \tan \omega = (w-h):d \tag{1}$$

$$D_s = f_c \cdot 2 \cdot \tan \omega \tag{2}$$

$$f_o : f_c = D'_s : D_s \tag{3}$$

$$D'_s = f_o \cdot 2 \cdot \tan \omega \tag{4}$$

$$D_c = w \tag{5}$$

$$D_o = h + p_o \cdot 2 \cdot \tan \omega \tag{6}$$

$$= h + f_o \cdot \frac{m+1}{m} \cdot 2 \cdot \tan \omega \tag{7}$$

$$= h + D_s' \cdot \frac{m+1}{m} \tag{8}$$

$$= w - d \cdot 2 \cdot \tan \omega + D'_s \cdot \frac{m+1}{m} \tag{9}$$

$$p_o = f_o \cdot \frac{m+1}{m} \tag{10}$$

$$p_o' = f_o \cdot (m+1) \tag{11}$$

$$a = f_o \cdot m \tag{12}$$

$$L = f_c + d + p_o + p_o' \tag{13}$$

$$p(\theta) \approx I' \cdot \frac{\pi}{4} \cdot {\frac{D_s'}{f_o}}^2 \cdot \frac{1}{m^2} \cdot \cos^4 \theta \tag{14}$$

$$\approx I' \cdot \frac{\pi}{4} \cdot {\frac{D_s}{f_c}}^2 \cdot \frac{1}{m^2} \cdot \cos^4 \theta \tag{15}$$

$$\approx I' \cdot \pi \cdot (\tan \omega)^2 \cdot \frac{1}{m^2} \cdot \cos^4 \theta \tag{16}$$

$$\tan \theta_{max} = h_{ob} : (2 \cdot f_o) \tag{17}$$

In addition, the following conditions must be fulfilled which are imposed by the practicability of lenses of suitable diameter, of spark light sources and of ultra high speed shutters:

$$f_o : D_o \geqq 2.5 \tag{18}$$

$$f_c : D_c \geqq 2.5 \tag{19}$$

$$D_s \approx 4 \text{ mm} \tag{20}$$

$$D_s' \approx 4 \text{ mm} \tag{21}$$

Finally, the following conditions must be fulfilled because the camera lens must be located outside of the chamber and because the size of the film plate is limited by practical considerations:

$$p_o \geqq d \tag{22}$$

$$h_{ob} \leqq F : m \tag{23}$$

Symbols

w = diameter of circular disk approximating area of window opening

$2 \cdot d$ = distance between "cold" window surfaces.

w and d are the only dimensions of the windowed chamber which occur in the analysis.

m = magnification from object plane to film plane

h = diameter of circular disk approximating field of view

F = length of the smallest dimensions of the film plate

Since the image of the field of view on the film has the diameter $m \cdot h$, the value of h obtained by the analysis has to be replaced by the "observable field of view" $h_{ob} = F:m < h$ if $m \cdot h$ becomes larger than F. Thus, the fact that the size of the film plate is limited by practical considerations results in a reduced observable field of view for magnifications exceeding a certain value, approximately F:w.

D_s = diameter of radiating area of spark light source.

Should be as large as compatible with other requirements concerning the light source. Usually a few millimeters or less.

D_s' = diameter of image radiating area of light source

Although a small D_s' and a small diameter of the hole in the flame stop facilitate the use of mechanical ultra high speed shutters, caution is advised in this respect on account of difficult alignment, mechanical vibrations and magnitude of spark illumination on the film. At any rate, D_s' should be slightly larger than the hole in the flame stop.

ω, θ = angles indicated in Figure 56

f_c = focal length of condenser lens

= distance between light source and nearest window

= length of optical train on left hand side of windowed chamber

D_c = aperture of condenser lens

= w in Figure 56

f_o = focal length of camera objective

= distance between camera objective and flame light stop

D_o = aperture of camera objective

p_o = distance between object plane and camera objective

p_o' = distance between camera objective and film plate

L = total length of optical train

$p_o - d$ = distance between camera lens and nearest window

$p_o + p_o' - d$ = length of optical train on right hand side of windowed chamber

a = distance between flame light stop and film plate

$p(\theta)\left[\text{watt} \cdot \text{cm}^{-2}\right]$ = area density of radiative power incident on film at angle θ from the normal.

$I'\left[\text{watt} \cdot \text{cm}^{-2} \cdot \text{srad}^{-1}\right]$ = integrated intensity of radiation emerging from the optical filter

$$= \int_{\lambda=0}^{\infty} d\lambda \cdot i(\lambda) \cdot t(\lambda)$$

where $i(\lambda)\ \left[\text{watt} \cdot \text{cm}^{-2} \cdot \text{srad}^{-1} \cdot \text{cm}^{-1}\right] = i_s(\lambda) + i_f(\lambda)$

$i_s(\lambda)$ and $i_f(\lambda)$ = spectral intensity of spark light and flame light, respectively, neglecting absorption.

$t(\lambda)$ = transmittance of optical filter

λ = wave length

9.1.1.1 Numerical Calculation for "Ideal" Lenses (Table IIIa)

From this set of equations, the following numerical analysis can be developed.

Given: $w = 90$ mm; $d = 180$ mm; $D_s = 4$ mm; $D_s' = 4$ mm; $F = 180$ mm;

Let the weakest magnification to be chosen as $m_{min} = 0.5$;

then

$$\frac{1 - 0.4 \cdot (d : w) \cdot (D_s : w)}{1 - (m_{min} + 1) : m_{min} \cdot (D_s : w)} = 1.113$$

This value is larger than the ratio $D_s' : D_s = 1$, and it can be shown that under this condition the following analysis will give the desired results.

From equations (1), (4), (7) and (18) follows:

$$d \cdot (2 \cdot \tan\omega)^2 - R \cdot 2 \cdot \tan\omega + 0.4 \cdot D_s' \leqq 0$$

where $R = w + D_s' \cdot (m_{min} + 1) : m_{min} = 102$ mm

$$2 \cdot \tan\omega \leqq \left(R - \sqrt{R^2 - 1.6 \cdot d \cdot D_s'}\right) : (2 \cdot d) = 0.01615$$

chosen: $2 \cdot \tan\omega = 0.01615$

from equation (1): $h = w - d \cdot 2 \cdot \tan\omega = 90 - 180 \cdot 0.01615 = 87.09$ mm

from equation (4): $f_o = D_s' : (2 \cdot \tan\omega) = 4 : 0.01615 = 247.74$ mm

from equation (18): $D_o \leqq 0.4 \cdot f_o$ Chosen: $D_o = 0.4 \cdot f_o = 99.09$ mm

from equation (3): $f_c = f_o \cdot (D_s : D_s') = f_o \cdot (4:4) = 247.74$ mm

from equation (5): $f_c : D_c = f_c : w = 247.74 : 90 = 2.75 > 2.5$ (equation 19)

Distance, diameter h_{ob} of observable field of view and the quantity $p(\theta) : (I' \cdot \cos^4\theta)$ can then be easily determined for various magnifications from object plane to film plate by using equations (10), (11), (12), (13), (15) and (23), as shown in Table IIIa (all lengths in millimeters). The second column shows that for magnifications larger than approximately 2 the observable field of view is smaller than the calculated value h and decreases with increasing magnification because of the limited size of the film plate, the smallest dimension of which is assumed to be 180 mm. The seventh column shows the decrease of illumination on the film with increasing magnification.

9.1.1.2 Numerical Calculations for Commercially Available Lenses (Table IIIb)

After the "ideal" focal lengths and apertures of the two lenses have been determined by this analysis the next step is to find commercially available lenses with characteristics as close as possible to the ideal ones. By way of example, a Dallmeyer Pentac objective with a focal length of 12 inches (304.8 mm) and an f/D = 2.9 was tentatively selected for condenser lens and camera objective. For the same given values $w = 90$ mm, $d = 180$ mm, $D_s = 4$ mm, $D_s' = 4$ mm, $F = 180$ mm follows from equation (5): $D_c : f_c = w : f_c = 90 : 304.8 = 0.295 < 1:2.9 = 0.345$. The quantities shown in Table IIIa for the ideal lenses are shown in Table IIIb if the two Pentac lenses are used. The values for the second column follow from

equation (4): $2 \cdot \tan \omega = D_s' : f_o = 4 : 304.8 = 0.1312$ and

equation (1): $h = w - d \cdot 2 \cdot \tan \omega = 90 - 180 : 0.01312 = 87.64$ mm and

equation (23): $h_{ob} \leqq F : m = 180 : m$

equation (7): yields $D_o = h + f_o \cdot (m_{min} + 1) : (m_{min}) \cdot 2 \cdot \tan \omega$

$$= 87.64 + 304.8 \cdot (0.5 + 1) : (0.5) \cdot 0.0132 = 95.64 \text{ mm}$$

$$D_o : f_o = 95.64 : 304.8 = 0.314 < \frac{1}{2.9} = 0.345$$

The remaining values in Table IIIb as a function of magnification are obtained by the procedure used for Table IIIa.

9.1.1.3 Numerical Calculation for Small Light Source (Table IIIc)

If a spark light source with a radiating area of only 2 mm instead of 4 mm is available, the following analysis has to be used:

Given: $w = 90$ mm, $d = 180$ mm, $D_s = 2$ mm, $D_s' = 4$ mm, $F = 180$ mm

Let the weakest magnification to be used be chosen as $m_{min} = 0.5$,

then
$$\frac{1 - 0.4 \cdot (d:w) \cdot (D_s : w)}{1 - (m_{min} + 1) : m_{min} \cdot (D_s : w)} = 1.052$$

This value is smaller than the ratio $D_S':D_S = 4:2 = 2$, and it can be shown that under this condition the following analysis will give the desired results.

From equations (2), (5) and (19) follows:

$$2 \cdot \tan \omega \leqq D_s : (2.5 \cdot w) = 2 : (2.5 \cdot 90) = 0.0089$$

Chosen: $2 \cdot \tan \omega = 0.0089$

from equation (2): $f_c = D_s : (2 \cdot \tan \omega) = 2 : (0.0089) = 225$ mm

from equation (5): $D_c = w = 90$ mm $\quad f_c : D_c = 2.5$ (equation 19)

from equation (3): $f_o = f_c \cdot (D_s' : D_s) = 225 \cdot (4:2) = 450 \text{ mm} > d = 180$ mm

from equation (1): $h = w - d \cdot 2 \cdot \tan \omega = 90 - 180 \cdot 0.0089 = 88.4$ mm

from equation (8): $D_o = h + D_s' \cdot (m_{min} + 1) : m_{min}$

$$= 88.4 + 4 \cdot (0.5 + 1) : 0.5 = 100.4$$

$$f_o : D_o = 450 : 100.4 = 4.5 > 2.5 \quad \text{(equation 18)}$$

For this case, the quantities shown in Tables IIIa and IIIb are shown in Table IIIc.

9.1.1.4 Discussion of Tables IIIa, IIIb, IIIc

Comparison between Tables IIIa, IIIb and IIIc reveals that the deviation from the "ideal" focal lengths and apertures of the lenses and the reduction of the diameter of the radiating area of the light source result in weaker illumination $p(\theta)$ on the film and in increased lengths of the optical train, columns (3), (4) and (5). Furthermore, in all three cases, $p(\theta)$ becomes very weak and the dimensions of the optical train become very long for larger magnifications (5 and 10).

Weak illumination is a definite deficiency in the system because, for a given exposure time, the illumination must be greater than a certain threshold value determined by the film emulsion in order to expose the film at all, and must be sufficiently larger than this value in order to provide a good contrast between the shadow images and the background.

The long optical train required at large magnifications is also a definite deficiency of the system because of the difficulty of installation in a rocket test cell of conventional dimensions. Especially disturbing is the fact that a comparison between columns (4) and (5) shows that the length of the optical train on the right hand side of the chamber is several times as long as on the left hand side. This difficulty would be overcome either by "folding" the train on the right by means of a plane mirror or by placing the windowed chamber "off center" in the test cell. In any event, the long optical train would be highly susceptible to the noise and mechanical vibrations inherent to a rocket test cell.

It is true that one has to be satisfied with a smaller field of view in the case of larger magnification (column 2). However, this cannot be considered to be a deficiency of the system shown in Figure 56, because for any system the diameter of the field of view cannot be larger than the ratio F:m, where F is the dimension of the film plate which is restricted by practical considerations.

9.1.2 Large Magnification, Small Field of View (Table IIId)

The system shown in the schematic (Figure 57) shows an arrangement for taking shadowgraphs with large magnification and, consequently, a small field of view, which however improves upon the deficiencies of the system shown in Figure 56 with respect to weak illumination and long dimensions of the optical train. It will be shown later that for large magnifications and a small field of view the diameter of the window openings is irrelevant. Therefore, the following analysis for the arrangement shown in Figure 57 will at first be developed without regard to any limitation imposed by the dimensions of the window openings*, as indicated by the dashed lines in Figure 57.

It can be shown that in this system it is advantageous to place the camera and condenser lenses as close as possible to the chamber windows and to image the spark on the camera objective as is shown in Figure 57.

The shape and quality of the spark and the shape and location of the field of view is the same as in the optical system shown in Figure 56. Also, it can be seen that focusing the spark on the camera lens provides a nearly uniform illumination of the whole field of view and that no point of the film can receive flame light in a larger solid angle than it receives light from the light source, just as this is the case in the system shown in Figure 56. Finally, it can be shown that this arrangement provides maximum illumination on the film for a given light source and film plate as long as the only limitation imposed by the chamber on the optical system is the "working distance", 2·d.

Basic Equations for Table IIId

An analysis for this system is based on the following set of equations which are also given without derivation.

$$f_o = \frac{m}{m+1} \cdot d \qquad (24)$$

---

*Thus, the optical system described by this analysis is applicable to any investigation requiring shadow photography at high magnification where the only geometrical constraint imposed on the optical system is a minimum distance between the optical components and the test object which is determined by the test conditions (e.g., investigations of "cold" sprays!).

$$p_o' = m \cdot d \tag{25}$$

$$D_o = D_s' \tag{26}$$

$$D_c = D_o + 2 \cdot h_{ob} \tag{27}$$

$$h_{ob} = F:m \tag{28}$$

$$f_c = \frac{2 \cdot d}{1 + (D_o : D_s)} \tag{29}$$

$$p_c = \frac{2 \cdot d}{D_o : D_s} \tag{30}$$

$$\tan(2 \cdot \omega) = \frac{D_o}{d} \cdot \frac{1}{1 - (D_o^2 - h_{ob}^2) : (4 \cdot d^2)} \tag{31}$$

$$L = p_c + 2 \cdot d + p_o' \tag{32}$$

$$\begin{aligned} p(\theta) &\approx I' \cdot (\pi : 4) \cdot (D_o : (m \cdot d))^2 \cdot \cos^4(\theta) \\ &\approx I' \cdot (\pi : 4) \cdot \frac{\tan^2(2 \cdot \omega)}{m^2} \cdot \cos^4(\theta) \end{aligned} \tag{33}$$

$$\tan(\theta_{max}) = h_{ob} : (2 \cdot d) \tag{34}$$

Again, the following constraints are imposed by practical considerations:

$$\frac{f_c}{D_c} \geq 2.5 \tag{35}$$

$$\frac{f_o}{D_o} \geq 2.5 \tag{36}$$

$$D_s \approx 4 \text{ mm} \tag{37}$$

From equations (27), (28), (29) and (35) follows:

$$D_o^2 + \left(D_s + \frac{2 \cdot F}{m}\right) \cdot D_o \leq 2 \cdot D_s \cdot \left(\frac{d}{2.5} - \frac{F}{m}\right) \tag{38}$$

Since the left-hand side of equation (38) is larger than zero, it follows that

$$\frac{d}{2.5} - \frac{F}{m} > 0 \tag{39}$$

or $$m > 2.5 \frac{F}{d} \tag{40}$$

For a chosen magnification consistent with equation (40), the illumination p (θ) in any given point of the film increases with increasing D_o according to equation (33) and attains its maximum value when D_o attains its maximum value. The latter can be calculated by choosing the equal sign in equation (38). However, it should be noted that these maximum values are lower the closer the chosen magnification approaches the right-hand side of equation (40). It can be seen that for an equal sign in equation (40), $D_o = 0$ from equation (38) and consequently p(θ) = 0 from equation (33).

Equation (38) solved for D_o yields:

$$D_o = -X + (X^2 + Y)^{1/2} \tag{41}$$

where $$X = \frac{D_s}{2} + \frac{F}{m} \tag{41a}$$

and $$Y = 2 \cdot D_s \cdot \left(\frac{d}{2.5} - \frac{F}{m} \right) \tag{41b}$$

For a given F, D_s, d and a value of m compatible with equation (40), the entire optical system is determined (equations 24 through 37). Since the limitation imposed on the f-number of the condenser lens in turn limits the minimum magnification, the following upper and lower limits are placed on the optical system for an $f_c : D_c = 2.5$:

from equation (40) $$2.5 \cdot \frac{F}{m} < m < \infty \tag{42}$$

from equations (41) and (42) $$0 < D_o < -\frac{D_s}{2} + \sqrt{\left(\frac{D_s}{2}\right)^2 + \frac{2 \cdot D_s \cdot d}{2.5}} \tag{43}$$

from equations (24) and (42) $$\frac{2.5 \cdot F \cdot d}{1 + 2.5 \cdot (F : d)} < f_o < d \tag{44}$$

from equations (25) and (42) $$2.5 \cdot F < p_o' < \infty \tag{45}$$

from equations (27), (28)
(41), (42) $$D_{o\infty} < D_c < \frac{2 \cdot d}{2.5} \tag{46}$$

where $D_{o\infty}$ is that value which follows from equation (41) if m approaches infinity. This value is the right-hand side of equation (43).

from equations (29), (41) and (42)

$$\frac{2\cdot d}{1 + D_{o\infty} : D_s} < f_c < 2\cdot d \tag{47}$$

from equations (30), (41) and (42)

$$\frac{2\cdot d\cdot D_s}{D_{o\infty}} < P_c < \infty \tag{48}$$

from equations (28)and (42)

$$0 < h_{ob} < \frac{d}{2.5} \tag{49}$$

Numerical Analysis for Table IIId

From these equations, the following numerical analysis can be developed.

Given: $d = 180$ mm, $D_s = 4$ mm, $F = 180$ mm

from equation (40) $m > (2.5)\,\frac{(180)}{180} = 2.5$

Therefore, this system can be used only for magnifications greater than 2.5. However, the film illumination is very weak for magnifications near this lower limit (see discussion following equation 40). Therefore, only magnifications appreciably larger than 2.5 should be considered. For m = 5 and 10, the diameter and focal lengths of the of the lens are determined as follows:

m = 5	m = 10
From equation (41a)	
$X = \frac{4}{2} + \frac{180}{5} = 38$	$X = \frac{4}{2} + \frac{180}{10} = 20$
From equation (41b)	
$Y = (2)(4)\left(\frac{180}{2.5} - \frac{180}{5}\right) = 288$	$Y = (2)(4)\left(\frac{180}{2.5} - \frac{180}{10}\right) = 432$
From equation (41)	
$D_o = -38 + \left[(38)^2 + 288\right]^{1/2} = 3.62$	$D_o = -20 + \left[(20)^2 + 432\right]^{1/2} = 8.84$

m = 5	m = 10
From equation (24)	
$f_o = \frac{5}{1+5}\ (180) = 150$	$f_o = \frac{10}{1+10}\ (180) = 163.6$
$\frac{f_o}{D_o} = 41.5 > 2.5$ (equation 36)	$\frac{f_o}{D_o} = 18.5 > 2.5$ (equation 36)
From equation (28)	
$h_{ob} = \frac{180}{5} = 36$	$h_{ob} = \frac{180}{10} = 18$
From equation (27)	
$D_c = 3.62 + 2(36) = 75.6$	$D_c = 8.844 + 2(18) = 44.8$
From equation (29)	
$f_c = \frac{(2)\ (180)}{1 + \frac{3.62}{4}} = 189.0$	$f_c = \frac{(2)\ (180)}{1 + \frac{8.84}{4}} = 112.1$
$\frac{f_c}{D_c} = 2.5$ (equation 35)	$\frac{f_c}{D_c} = 2.5$ (equation 35)

p_o', p_c, ω, L, $p(\theta)$:$(I' \cdot \cos^4(\theta))$ and θ_{max} can be calculated from equations (25), (30), (31), (32), (33) and (34) respectively. The calculated values for magnification of 5 and 10 are shown in Table IIId. The total length of the optical system (column 3) and especially the length of the optical train on the camera side of the chamber (column 5) are considerably less than that of the optical system shown in Figure 56 with ideal lenses (Table IIIa). Also, as might be expected, the film plate illumination (column 7) is greatly increased, namely, by a factor of 1.62 at m = 5 and by a factor of 9.5 at m = 10.

This system does not require a flame light stop because the spark light is focused on the camera objective and completely fills it when the lens is stopped down to the required aperture. Either a high speed mechanical shutter or a Kerr cell can be located behind the objective. However, at magnifications higher than 5 the Kerr cell would be required because the aperture is too large for an ultra-fast mechanical shutter.

As mentioned before, the analysis for the optical system shown in Figure 57 has been made so far under the assumption that the dimensions of the window openings are irrelevant. However, the question arises under what conditions this assumption is justified if the dimensions of the openings are given. If can be shown that the only condition is that

$$\frac{2 \cdot F}{w + D_s \cdot \left[1 - \frac{2 \cdot d}{2.5 \cdot w}\right]} \leq 2.5 \frac{F}{d} \tag{50}$$

In other words, should the window size w be so large that equation (50) is fulfilled then the dimensions of the window openings are irrelevant and the analysis will give the desired results for all magnifications consistent with equation (40), keeping in ming the discussion following equation (40). On the other hand should the left hand side of equation (50) be greater than the right hand side, then the window size is relevant. It is true that also in this case the analysis is still valid, however, only for magnifications larger than the left hand side of equation (50).

For the given values of F, d and D_s used in the numerical analysis and a given value of w = 90 mm, the left hand side of equation (50) is

$$\frac{(2)(180)}{90 + 4 \cdot \left[1 - \frac{(2)(180)}{(2.5)\,(180)}\right]} = 4.11,$$

and the right-hand side is

$$(2.5)\frac{(180)}{180} = 2.5$$

Since equation (50) is not fulfilled, the optical system can be designed for use with the windowed motor only for magnifications greater than 4.11, as was done in the numerical analysis.

9.1.3 Very Large Magnification, Small Field of View

A third lens can be used as shown in Figure 58 to further shorten the optical train at high magnification by achieving the total magnification in two steps. For a given m the only change required in the two lens system shown in Figure 57 is the focal length of the camera objective which must be shortened.

A second image of the spark (I), smaller than the first image located on the first camera lens (E), is formed behind the second camera lens (H). This facilitates the use of an ultra-fast mechanical shutter or Kerr cell.

Basic Equations for Table IIIe

The basic equations used to determine the optical system between the first camera lens and the spark are the same as for the two lens system with the following exceptions.

Equation (24) becomes $$f_{o_1} = \frac{m_{o_1}}{1 + m_{o_1}} \cdot d \qquad (51)$$

where the subscript "1" is added to designate the first camera objective and m_{o_1} is the chosen magnification of this lens

Equation (25) becomes $$p_{o_1}' = m_{o_1} \cdot d \qquad (52)$$

In equations (26),(27) and (29) through (31) and equations (36), (38) and (41), D_o is replaced by D_{o_1}. In equation (36) f_o becomes f_{o_1}. The sumbol D_s' used in equation (26) is used below to designate the diameter of the second spark image (I).

The remaining equations are:

$$f_{o_2} = m_{o_1} \cdot h \cdot \left[\frac{1}{2.5} - \frac{D_{o_1} + m_{o_1} \cdot h}{d} \cdot \left(\frac{1}{m_{o_1}} + \frac{1}{m} \right) \right]^{-1} \qquad (53)$$

$$D_{o_2} = f_{o_2} : 2.5 \qquad (54)$$

$$p_{o_2} = \left[1 + (m_{o_1} : m) \right] \cdot f_{o_2} \qquad (55)$$

$$p_{o_2}' = \left[1 + (m : m_{o_1}) \right] \cdot f_{o_2} \qquad (56)$$

$$D_s' = (D_{o_1} : m_{o_1}) \cdot f_{o_2} \cdot \left[d + (f_{o_2} : m) \right]^{-1} \qquad (57)$$

$$a = (D_s' : D_{o_1}) \cdot m \cdot d \qquad (58)$$

$$L = 2 \cdot d \cdot \left[1 + (D_s : D_{o_1}) + (m_{o_1} : 2) \right] + f_{o_2} \cdot \left[2 + (m_{o_1} : m) + (m : m_{o_1}) \right] \qquad (59)$$

$$p(\theta) \approx I' \cdot (\pi : 4) \cdot (D_s' : a)^2 \cdot \cos^4(\theta) \qquad (60)$$

$$\approx I' \cdot (\pi : 4) \cdot \left[D_{o_1} : (m \cdot d) \right]^2 \cdot \cos^4(\theta)$$

$$\approx I' \cdot (\pi : 4) \cdot \frac{\tan^2(2\omega)}{m^2} \cdot \cos^4(\theta)$$

$$\tan\theta_{max} = \frac{m \cdot h_{ob}}{2 \cdot a} = \frac{h_{ob}}{2D_s'} \cdot \frac{D_{o_1}}{d} \approx \frac{h_{ob}}{2 \cdot D_s'} \cdot \tan(2\omega) \tag{61}$$

$$m_{o_2} = m : m_{o_1} \tag{62}$$

An f/D of 2.5 has been chosen for the second camera lens since the smaller this ratio, the shorter is the optical path associated with the lens.

Numerical Calculation for Table IIIe

The results of a numerical analysis for this three lens system is shown in Table IIIe for a magnification of 10. The illumination per unit intensity at the center of the film plate (column 7) is the same as for the two lens systems but the total optical train is 17% shorter. A spark image of 3.3 mm diameter (column 10) lies 665 mm (column 12) from the film plate. This is small enough to permit the use of an ultra-fast mechanical shutter.

The discussion following equation (50) concerning the condition for which the dimensions of the window openings are or are not relevant for the optical system shown in Figure 57 applies also to this optical system (Figure 58).

9.1.4 Summary of Section 9.1 (Optics)

In summary, three optical systems have been described for the purpose of taking high speed shadow photographs of the combustion phenomena in a windowed chamber. The basic equations for an analysis of each of the three systems have been given and, by way of example, a numerical analysis has been conducted for each system.

Each optical system provides the most satisfactory compromise for a different range of magnifications between object and film.

If a large field of view is desired, then one must be satisfied with low or moderate magnifications and the system shown in Figure 56 should be used. The system is discussed in Section 9.1.1 and the results of a numerical analysis are shown in Tables IIIa, IIIb, IIIc.

If a high magnification is desired, then one must be satisfied with a small field of view and the system shown in Figure 57 must be used. The system is discussed in Section 9.1.2 and the results of a numerical analysis are shown in Table IIId.

TABL

RESULTS OF NUMERICAL CAL

	①	②	③	④	⑤	⑥
Constants	m	h_{ob}	L	f_c	$p_o + p'_o - d$	p'_o
IIIa						
w = 90 mm	0.5	87<*	1543	248	935	372
-d = 180 mm	1	87<*	1418	248	810	495
	2	87<*	1543	248	935	743
D_s = 4 mm	5	36=*	2211	248	1603	1486
	10	18=*	3425	248	2817	2725
D'_s = 4 mm						
F = 180 mm						
IIIb						
w = 90 mm	0.5	88<*	1858	305	1193	458
d = 180 mm	1	88<*	1705	305	1040	610
	2	88<*	1858	305	1193	915
D_s = 4 mm	5	36=*	2681	305	2016	1830
	10	18=*	4176	305	3511	3355
D'_s = 4 mm						
F = 180 mm						
$f_c = f_o$ = 305 mm						
$(F/D)_{min} = 2.9$						
IIIc						
w = 90 mm	0.5	88<*	2430	225	1845	675
d = 180 mm	1	88<*	2205	225	1620	900
	2	88<*	2430	225	1845	1350
D_s = 2 mm	5	36=*	3645	225	3060	2700
	10	18=*	5850	225	5265	4950
D'_s = 4 mm						
F = 180 mm						
IIId						
	m	h_{ob}	L	P_c		p'_o
d = 180 mm	5	36=*	1658	398	900	900
	10	18=*	2323	163	1800	1800
D_s = 4 mm						
F = 180 mm						
IIIe						
d = 180 mm	m	h_{ob}	L	P_c	$p'_{o_1} + p'_{o_2} + p'_{o_2}$	
D_s = 4 mm	10	18=*	1917	163	1394	1394
F = 180 mm						

E III

ULATIONS FOR SECTION 9.1

⑦	⑧	⑨	⑩	⑪	⑫
$p(\theta):(I'\cdot\cos^4(\theta))$	θ_{max}	$\cos^4(\theta_{max})$	D'_s	p_o-d	a
819×10^{-6}	9°58'	0.941	4	563	124
205×10^{-6}	9°58'	0.941	4	315	247
51×10^{-6}	9°58'	0.941	4	192	495
8×10^{-6}	4° 9'	0.990	4	117	1238
2×10^{-6}	2° 5'	0.997	4	92	2477
541×10^{-6}	8°11'	0.960	4	735	153
135×10^{-6}	8°11'	0.960	4	430	305
34×10^{-6}	8°11'	0.960	4	278	610
5×10^{-6}	3°23'	0.993	4	186	1525
1×10^{-6}	1°41'	0.998	4	156	3050
260×10^{-6}	5°37'	0.981	4	1170	225
65×10^{-6}	5°37'	0.981	4	720	450
16×10^{-6}	5°37'	0.981	4	495	900
3×10^{-6}	2°17'	0.997	4	360	2250
0.6×10^{-6}	1° 9'	0.999	4	315	4500
$p(\theta):(I'\cdot\cos^4(\theta))$	θ_{max}	$\cos^4(\theta_{max})$	D_o	p_o-d	p'_o
13×10^{-6}	5°43'	0.980	3.6	0	900
19×10^{-6}	2°52'	0.995	8.8	0	1800
$p(\theta):(I'\cdot\cos^4(\theta))$	θ_{max}	$\cos^4(\theta_{max})$	D'_s	p_o-d	a
19×10^{-6}	7°41'	0.964	3.3	0	665

2

Very high magnifications restrict the observable field of view to still smaller dimensions and the system shown in Figure 58 should be used. The system is discussed in Section 9.1.3 and the results of a numerical analysis are given in Table IIIe.

As mentioned before, it should be kept in mind that in the above analysis (1) the lenses are assumed to be infinitely thin, (2) the window openings are approximated by circular disks, and (3) the optical effect of the window material is neglected. If in a practical case of application these assumptions are not justified to a sufficient degree, then the results of the analysis can provide only a rational basis for final adjustments.

9.2 SHADOW FORMATION

The analysis conducted in Section 9.1 led to optical systems which can be expected to provide a satisfactory compromise concerning the purpose which it is intended to serve. The question remains, whether shadows with sharp boundary and high contrast between shadow and background can be obtained of objects located within the field of view. Obviously, a general answer is impossible since the objects might have any shape and size and their images on the film might overlap. It is true, that sharp shadowgraphs can be obtained of objects with a large variety in shape and sizes (e.g., Figures 1, 2, 12, 30, and 31). Nevertheless, the following discussion can shed some light on the optical phenomena involved in the formation of a shadow.

As long as the objects are not so small that diffraction is the dominating phenomena (References 37 and 38), the shadow of a highly transparent body embedded in a highly transparent medium is the result of refraction due to the difference in index of refraction between body and medium. Thus, a simple lens might serve in very rough approximation as a model for the object. A straightforward application of geometrical optics leads then to the following statement. Assume that a "thin" symmetrical convex-convex lens is placed in the center of the field of view in Figure 56. Let the diameter of the lens be d and its "thickness" (the distance between the two points where the surface of the lens intersects its axis) be h. Let the "relative thickness", (the ratio h:d) be larger than $\left(1-\sqrt{1-\tan^2\left(\frac{w}{2}\right)}\right) : \tan\frac{w}{2}$, where w is the angle shown in Figure 56 which is determined by the optical setup and does not depend on size and shape of the model lens. Then the shadow of the model lens produced on the film by the light source will be bounded by a circle of diameter d. The field of view outside of this circle will be illuminated by the spark light as if the model lens did not exist, and within the circle a ring adjacent to the circle will not receive any light from the light source. The width of this dark ring increases with increasing relative thickness h:d. In other words, any model lens of any size but of sufficiently large relative thickness will produce a well defined shadow on the film. It can be shown that this is also true if the lens is not located in the center but anywhere within the field of view. Under the conditions of Figure 56, the limiting value of h:d is 3.28×10^{-3};

i.e., even an extremely "flat" model lens will produce a well defined shadow. Of course, these considerations based on the optical properties of a model lens can be expected to be applicable to liquid particles only to a very rough approximation. In short, they indicate that it is easier to obtain a sharp shadow of a "plump" object than of a flat object.

9.3 SUPPRESSION OF ILLUMINATION ON THE FILM BY FLAME LIGHT

In Section 8.2.2, the failure of the microflash spark light source to produce shadowgraphs of the liquid contents of the firing windowed motor was traced to the fact that, in the arrangement shown in Figure 42, the effect of the flame light on the photographic film completely overpowers the effect of the back illumination provided by the microflash.

The visible light radiated from the combustion chamber originates from zones of chemical reaction and from incandescent carbon particles or soot floating in the burned gases. The burned gases themselves are colorless, that is, they do not emit visible radiation.

The intensity of the flame light emitted from a given section of a rocket chamber and the optical transmittance of this section depends on the propellants, the mixture ratio, chamber diameter and pressure, and the distribution of the reaction zones and carbon particles within the chamber volume. Unfortunately, there is only meager information available concerning the intensity of flame radiation at the combustion pressures and radiating path lengths (chamber diameter) typical of rocket combustors. The extensive spectroscopic examination of flame radiation at atmospheric and lower pressures (References 20 and 21) and the few investigations at high pressures (Reference 22) have been mostly concerned with the quality of the radiation, that is, the spectral distribution rather than with the intensity. In addition, these investigations are invariably conducted on thin flames, so that extrapolation to rocket chamber diameters is not feasible.

The investigation by Diederichsen and Wolfhard (Reference 22) on oxygen fed flames shows that the combustion pressure greatly affects the quality and intensity of flame light. Whereas at one atmosphere flame light occurs in intense banded spectra, at 40 atmospheres the radiation from the reaction zone becomes continuous throughout the visible spectrum and far into the ultraviolet and is pressure sensitive. The continuum may be partly caused by radiating carbon particles if they are present but the greater part of the continuous light is produced by molecular recombinations in the reaction zone. The intensity of this gas continuum increases proportionally to p^n where p is the combustion pressure and n is between 1 and 2.

Since the intensity and spectral distribution of the flame light and the optical transmittance of the chamber contents are necessarily fixed by the test conditions, nothing can be done to diminish the flame light itself. Several ways are possible to decrease the effect of the flame light on the photographic film:

(1) The first way is based on the fact that, in the arrangement shown in Figure 42, the optical properties of the reflector and the location of the spark gap in the microflash were not adequate for producing a well-defined image of the spark which just covered the Optar lens of the camera. This is understandable because the Microflash was developed for illuminating a large area. As discussed in Section 9.1, this serious deficiency can be improved by using the more sophisticated arrangements shown in Figures 56 to 58 so that all points on the film within the image of the field of view receive light from the whole radiating area of the light source. In addition, the flame light stop G insures that no point on the film can receive flame light in a larger solid angle than it receives from the light source.

(2) Diederichsen and Wolfhard provide some information concerning the magnitude of the continuous flame light by comparing it to the radiation emitted by a tungsten strip lamp of 2263°C (4100°F) brightness temperature. They show that at 450 millimicron wavelength the lamp intensity is approximately 10^3 times that of a gaseous CH_4/O_2 diffusion flame with a 10 mm radiating path length burning at 40 atmospheres. It is known that an air or mercury spark has an intensity at 450 millimicrons many times that of a tungsten lamp. This strongly indicates, that even with liberal allowances for the effect of the larger diameter, combustion pressure and different propellant combinations on the flame intensity, that the intensity of the visible light radiated from a combustion chamber is probably much less than the spark intensity. Therefore the failure to obtain shadow photographs was due to the long exposure time to flame light. In the arrangement shown in Figure 42, which was used during the test program, the nominal duration of the microflash is 0.5 microsecond while the nominal "open time" of the camera shutter was 2.5 milliseconds. Thus, the time during which the film was exposed to the flame light was 5000 times as long as the time during which the film was exposed to the flame light. This malproportion can be corrected by using a mechanical or electro-optical ultra-high speed shutter in front of the film. As is discussed in Section 9.1.1, this measure is facilitated by the small size of the opening in the flame light stop G in Figure 56.

(3) The third way consists in increasing the intensity of the spark light source used for back illumination. This possibility will be discussed in Section 9.4.

(4) Finally, the effect of the flame light on the film can be attenuated by using a spark light source with a "selective radiation"; i.e., one the radiation of which is concentrated predominantly in a sufficiently narrow spectral region. Absorption or interference filters can then be used, as indicated on Figures 56 to 58, which pass the major portion of the spark light but cut off most of the flame light. Such selection spark light sources are discussed in Section 9.4.

It should be emphasized that there is no proof that the available light sources are not appropriate for taking high resolution shadowgraphs through the modified six-inch motor provided that the exposure time to flame light is sufficiently shortened. Thus, the use of a ultra-high speed mechanical, or electro-optical shutter in conjunction with improved optics should be the first modifications to be tried. However, in view of the complexity and difficulty of the problem, the possibilities pointed out in items (3) and (4) should not be neglected.

9.4 SPARK LIGHT SOURCE

According to the considerations of Section 9.2, the requirements for a spark light source suitable for taking shadowgraphs through a firing windowed motor under conditions as severe as the ones imposed by the specifications of this contract can be summarized as follows:

(1) The duration of the spark should be as short as possible but not longer than one microsecond.

(2) The radiating area of the light source should comprise a circular disk of at least 4 mm diameter.

(3) The position of the radiating area with respect to the optical train should be the same for each discharge. Experience shows that this can be accomplished best by discharging the spark through a capillary in such a way that the capillary is completely filled with the emitting plasma during the effective duration of the discharge.

(4) The intensity of the radiation (watt-cm^{-2}-srad^{-1}) should be as high as possible without rendering power supply and operation too difficult.

(5) The radiation should be selective; i.e., the major portion of the radiation should be concentrated in one or in a few spectral regions.

A literature survey and correspondence with manufacturers specializing in spark light sources revealed that no light source seems to be on the market in the United States at the present time which can be expected to meet all requirements to a sufficient degree. However, it appears that commercially available light sources can be improved to meet this goal.

As an approach to accomplish this without a major effort, it was suggested to increase initial pressure and power input of a light source using a quenched high pressure xenon spark. In essence, a spark light source based on this principle works like this. To both ends of a short glass or quartz capillary is attached a bulb of much larger volume than the capillary. An electrode is located in each bulb aligned with the capillary. This "spark lamp" is filled with a rare gas (e.g., xenon or argon). If a capacitor charged to a sufficiently high voltage is discharged through the lamp, a spark develops between the electrodes. The spark produces very high pressures and temperatures within the capillary which, however, decrease rapidly due to the thermal expansion of the plasma out of the capillary into the two bulbs ("quenched" spark). Thus, the radiating area which can be used in the arrangements shown in Figure 56 and 58 is a circular disk with a diameter which equals approximately the inner diameter of the capillary. The area radiates for a very short time (shorter than one microsecond under appropriate conditions) with the intensity emitted by a plasma at high pressures and extremely high temperatures.

It is true that the extremely high electron and ion density which is produced in the spark plasma at high pressures and power inputs will result in a spark of high intensity, short duration and fairly large radiating area. Therefore, this approach should be the first step to be tried. However, it is well known that the radiation of a rare gas plasma loses the characteristics of a line spectrum with increasing electron and ion density and assumes more and more the characteristics of a continuous spectrum (References 40 and 42). Obviously, this will make the use of filters for discriminating against the flame light less efficient..

It appears that this deficiency could be substantially corrected by adding mercury vapor to the rare gas filling of the spark lamp, because extensive investigations have shown that even at elevated pressures and power inputs the spectrum of such a spark retains the characteristics of a line spectrum to a larger extent than that of a pure rare gas spark, although the continuum is stronger than in the spectrum of a mercury arc (References 40 to 45).

The quenched high pressure mercury spark lamp can be materialized by adding a drop of mercury to the rare gas filling of the quenched spark lamp described above. Before operation, the lamp is heated until evaporation of the mercury creates a pressure compatible with the structural strength of the lamp. The manufacturers contacted agreed that such a development, while involving considerable effort, could be accomplished by a competent group of specialists.

Thus, there is evidence that a judicious choice of initial pressure and power supply for a quenched mercury spark lamp will result in a good compromise between short duration, high intensity and large radiating area on the one hand and sufficient spectral selectivity on the other hand. The concentration of the predominant radiation in a sufficiently narrow spectral region or regions which in this way is accomplished will then render it possible to use absorption or interference filters which pass the major portion of the spark light but cut off most of the flame light.

It can be argued that it would be difficult to sufficiently cut down the duration of the effective radiation of a mercury spark because of the slow de-ionization rate of the mercury vapor. However, this problem does not seem to be critical as can be concluded from Figures 59 and 60. Both shadowgraphs were taken through the small experimental motor mentioned before (Figure 27). The first was taken with a General Electric Photolight, Model GET-27364 (Reference 46), which uses a spark discharge in a xenon atmosphere, while the second was taken with a General Electric Microsecond Photolight (Reference 47) which uses a BH6 high pressure mercury vapor lamp. It can be seen that the contours are not much more blurred in Figure 60 than in Figure 59 in spite of the fact that the spark in the BH6 lamp is not quenched and that the mercury vapor is not produced by preheating the lamp but by the spark discharge itself. In fact, the GE Photolight using the BH6 lamp proved to be very useful for investigations on the experimental motor; however, for investigations on the six-inch windowed motor (Figure 32), the size of its radiating area and its intensity might not be sufficient.

In conclusion, it should be mentioned that recently a pulsed laser has been used as a light source for shadow and Schlieren photography with short exposure time (References 48, 49, 50 and 51). Some of the results seem to be promising. However, more development will be needed to render the method usable for taking shadowgraphs through a firing windowed rocket motor.

10.0 RECOMMENDATIONS

As pointed out before, the objective of the program was primarily to apply high speed and high resolution shadow photography to the investigation of the formation and combustion of propellant sprays, within a region adjacent to the injector face of actual engines where the major part of the transition from liquid propellants to hot combustion gases takes place. An attempt was made to obtain shadowgraphs of propellant sprays in a six-inch windowed combustion chamber simulating the conditions existing in a region of the Rocketdyne F-1 engine. The objective could not be achieved because the intense flame light resulted in photographic difficulties which could not be overcome without substantial improvement of the photographic technique. In the following, a stepwise approach to accomplish such improvements is recommended in order to render possible a successful completion of the investigations which were begun under this contract, or successful investigations to be conducted under a future project of a similar nature. However, at least some of the steps should be made concurrently.

The first step should consist of selecting, procuring and testing appropriate and commercially available optical components in order to secure a sufficiently large and evenly illuminated field of view, and to facilitate discrimination against the unwanted effect of flame light. Detailed guidelines for this step are given in Section 9.1.

The second step should consist of selecting, procuring and testing of a ultra-high speed mechanical or electro-optical (Kerr cell) shutter in order to shorten the time during which the film is exposed to the flame light alone. Guidelines in this respect are given in Section 9.1.1 and 9.3.

The third step should consist of selecting, procuring and testing a spark light source of a duration not longer than one microsecond with a radiating area not smaller than a circle of 4 mm diameter, with a selective spectral intensity distribution, and with an intensity as high as compatible with the other three requirements. A commercially available quenched capillary spark in a xenon atmosphere seems to be most promising. Improvement seems to be possible by raising the initial pressure of the spark atmosphere. This step is discussed in detail in Section 9.4.

The fourth step should consist of selecting, procuring and testing appropriate absorption or interference filters in order to discriminate further against the effect of flame light by taking advantage of the before mentioned spectral selectivity of the spark light source. This step should include spectroscopic investigations concerning the intensity and spectral distribution of the radiation emitted by the combustion flame and by the spark light source.

The fifth step should consist of replacing the xenon atmosphere in the capillary spark by a mercury vapor atmosphere in order to increase the spectral selectivity.

However, since the development of a light source of this kind might involve considerable effort, this step should be taken only if found necessary. The physical background of this step is discussed in Section 9.4.

It can be expected that after these improvements, single-shot shadowgraphs of the quality evidenced by Figures 1, 2, 29, 30 and 31 can be obtained, which provide detailed information concerning the formation and combustion of the propellant sprays and the size, shape and distribution of liquid particles at various distances from the injector face. Measurement of particle and gas velocities by means of one or more of the multiple shot photographic techniques which are discussed in Section 7.1.2 should be attempted only after this information has been obtained, because the judicious selection of the most appropriate technique depends strongly on this information.

In general, it is advisable to start a future test program at less severe operating conditions than were encountered under this contract, and to proceed gradually to more severe conditions. For instance, elimination of the difficulties created by the extremely strong flame light at higher chamber pressures could be facilitated by starting with tests at lower pressures, such as 300 to 500 psia.

11.0 TEST EQUIPMENT AND INSTRUMENTATION

11.1 TEST STAND

All firing tests of the six-inch windowed chamber were conducted in Test Cell K-2 of Bell's Wheatfield Rocket Test facility. A test cell schematic is shown in Figure 61. The test stand is equipped with a 15 gallon fuel tank and a 20-gallon oxidizer tank, both of which are rated at 3000 psia working pressure.

To minimize oxidizer boil-off and to assure liquid oxidizer at the injector during a test firing, the liquid oxygen tank and main feed line are vacuum jacketed. A vacuum pump is used to maintain pressure in the jackets at 20 microns. Tank pressurant gases used were helium and nitrogen to the liquid oxygen and fuel propellant tanks, respectively. Mechanical boosters were used with the nitrogen and helium to boost trailer pressure (2200 psi) to the required cascade pressure (5000 psi). This resulted in much more efficient utilization of the pressurizing gas.

High pressure helium was used for the LOX feed system to minimize "collapse" of the pressurant gas when in contact with the cold LOX.

11.2 AUTOMATIC FIRE SEQUENCE PANEL

To provide for automatic operation of valves during a firing run, a fire sequence panel was designed and fabricated. Timed intervals were provided by Agastat time delay relays. The panel was set to provide the following firing sequence and subsequently provided smooth ignition and steady state fire during all tests conducted. To reduce degradation of the uncooled chamber hardware, particularly nozzles, the run duration was decreased by 0.3 second after Test No. 6.

AUTOMATIC FIRE SEQUENCE

Operation	Time (sec)
Arm Panel	0
Fire Switch On	0
Fuel Prefire Purge	0.1
Oxidizer Prefire Valve Opens	0.3
Signal to Fuel Fire Valve	2.0
Signal to Oxidizer Main Valve	2.1
Fuel Fire Valve Opens	2.5
Oxidizer Main Valve Opens	2.6
Steady State Fire	2.7
Camera Signal	3.6
Shutdown (All Valves)	4.1

11.3 INSTRUMENTATION

Instrumentation requirements for use on the six-inch windowed chamber were similar to those found in a standard rocket test cell. To provide accurate oxidizer feed temperatures (flowmeter and injector inlet positions), two transonic platinum resistance probes were used instead of the standard chromel-alumel thermocouple probes ordinarily used in the propellant feed lines.

With the exception of chamber pressure determinations, all other pressures (propellant feed and tank pressures) were measured with standard Taber transducers. High frequency response (3000 cps) Alinco transducers were used initially for chamber pressure determinations, but were later replaced by Taber transducers when it was discovered that the Alincos were temperature sensitive to the prefire LOX flow. In addition, tank, valve actuation, and nitrogen purge pressures were gauge monitored. Propellant flow rates were measured with standard turbine flowmeters with two in each feed line.

All transducer outputs were recorded on Speedomax or oscillograph recorders for immediate examination, and simultaneously on tape for subsequent detailed study and analyses.

11.4 IGNITION AND START SEQUENCE

Since the propellant combinations of LOX/isopropyl alcohol and LOX/UDMH are not hypergolic, it was necessary to provide an ignition system. A hypergolic slug starting technique was chosen to accomplish ignition of the thrust chamber. In this technique, a "slug" of fuel that is spontaneously reactive with liquid oxygen (triethyl aluminum, or "TEA"), is located in the fuel line ahead of the main fuel between two burst discs. When the fuel valve is actuated, the main fuel pressure breaks the burst discs and the hypergolic fuel is forced into the chamber ahead of the main fuel, where it ignites spontaneously with the oxygen. The combustion thus started is sustained by the main fuel.

In the six-inch windowed chamber firings, a prestage LOX flow of approximately half that of mainstage flow was provided for approximately 2.2 seconds before fuel flow began. This allowed the injector and feed system to chill before mainstage flow began, and increased chamber pressure by a few psi so that smooth ignition with the triethyl aluminum was assured. In all tests made, ignition and transition to mainstage combustion was very smooth.

11.5 SIX-INCH WINDOWED CHAMBER FIRINGS

The initial firing of the six-inch windowed motor occurred on 2 June 1965 and was followed by 14 more firings from the period 7 June to 27 October 1965. These tests included two firings at the 500 chamber pressure level, 12 firings at the 750 to 800 psia chamber pressure level and one firing at the 1000 psia chamber pressure level. Test data on all 15 runs are shown in Table II.

For the first four runs, aluminum slabs were used instead of transparent windows. The temperature rise within the slabs in a distance of approximately one millimeter from the inner surface was measured by means of thermocouples. It never exceeded 250°F.

With the completion of run No. 5, the first series of checkout runs was completed. These tests were required to evaluate test stand and chamber hardware functioning. With the exception of the nozzles, chamber hardware functioned satisfactorily in this series of tests. In particular, window sealing and mounting techniques developed earlier in the program performed very well. A small amount of surface crazing of the pyrex windows was the only damage sustained by them during run No. 5.

During the first four runs, some difficulty was encountered in obtaining reliable measurements of chamber pressure. Originally it had been decided to use Alinco (Allegany Instrument Company) pressure transducers for chamber pressure measurements because of their high frequency response (3000 cps) in order to get some information concerning the level of "random noise" in the chamber. Furthermore, their small size made them particularly suitable for close coupled mounting. Alinco transducers had been used extensively previously at Bell with good results for similar pressure measurements on rocket engines using non-cryogenic propellants.

During the course of the first several test runs, it was discovered that the Alinco transducers were highly temperature sensitive with respect to the cold liquid oxygen. It is suspected that this fact is the reason why in run No. 2 no pressure measurements were obtained in all, and in run No. 4 measurements were obtained which probably were too high. Thus, starting with run No. 5, the Alincos were replaced by standard Taber transducers and reliable values for steady-state chamber pressures were obtained for the remaining tests. During test No. 10, a Kistler high frequency transducer was mounted on the chamber section of the windowed motor to obtain some information concerning the level of "random noise" during the firing. The maximum peak to peak chamber pressure fluctuations were determined to be about 4% of the steady state chamber pressure.

In run No. 6, no values for the LOX flow rate were obtained because the rotors of the Potter turbine meters did not turn during the run. This was believed to have occurred because of moisture accumulation in the bearings, which froze upon contact with LOX. The turbine meters were flushed and dried and interior rotation checked immediately before each subsequent run. No further difficulties with this problem were experienced.

At the end of the fifth test run, most of the operational difficulties (chamber pressure determinations) had been resolved and confidence in the operational characteristics of the cell hardware, and satisfactory functioning of the windows and seals had been established. Therefore, in test No. 6, the first high speed shadowgraph was attempted. No picture was obtained in this test because the windows became coated with a heavy carbon deposit before the picture was attempted. In this test, the nitrogen window flush was not used, because a Fastax film obtained from the previous test indicated that high turbulence from the impinging nitrogen jets (top and bottom) might cause an undesirable disturbance in the propellant mixing and atomization zone. Also, the effect of removing the nitrogen flush with regards to sooting of the windows was not known at this time.

In run No. 7, an attempt to obtain a high speed shadowgraph was again made. The nitrogen flush was again used in this test and although carbon deposition on the windows was reduced to a light coating no satisfactory picture was obtained.

Test run No. 8 was run under the same test conditions as run No. 7 except no spark was used, the film being exposed to the flame light alone. The purpose of this test was to determine why no picture was obtained in run No. 7 by comparing the photographs obtained in each test under different illumination conditions, that is, with and without the spark flash. Since the photographs were nearly identical, it was concluded that the film was being exposed from the flame light alone.

Two final runs using the LOX/isopropyl alcohol propellant combination (9 and 10) were made using the improved "parallel-flushing" technique and a new nozzle extension (36") moving the region observed from 2.56 and 5.69 to 11.16" and 14.29 downstream from the injector face.

During run No. 9, photographs were taken with a Fastax camera operated at approximately 2000 frames per second. This was done to determine the efficiency of the "parallel flush" technique and to gain some indication of the degree of combustion occurring at the new window location.

The film showed patterns similar to those which could be seen on the film taken during run No. 8 in a region between 2.56 and 5.69 inches. However, sharp shadows of liquid propellants were not noticeable during "prestage" and the bright areas during mainstage were much larger than in run No. 8, especially in a center strip approximately two inches wide. This corroborated the expectation that in the region observed during run No. 9, the transition from liquid propellants to gases had proceeded farther than in the region observed during run No. 8.

Run No. 10 was made under the same conditions as run No. 9; however, a single photograph was taken with the Speed Graphic camera. Background illumination was provided by the E.G.G. Microflash, and two Kodak Wratten filters (No. 47B and No. 50) in series were installed in front of the camera to reduce the flame light. Although the photograph showed more contrast than the one taken during run No. 7, the dark areas were of a cloudy appearance, similar to those observable in the Fastax film taken during run No. 9, and sharp shadowgraphs of liquid particles could not be seen.

At this stage of the test program, it was decided to make a fuel change from isopropyl alcohol to UDMH in an attempt to alleviate, by using a less carbonaceous fuel, the severe conditions which might be imposed by the very bright flame light of the LOX/isopropanol propellant combination.

It was planned to observe the effect of the flame light by taking a photograph with the Fastax under the same conditions as on run No. 9. However, on both runs the camera malfunctioned so that only approximately half the film ran off, and was overexposed to such a degree that no reliable conclusions could be drawn.

In view of the experiences gained during firing runs 9 to 12, it was decided to postpone additional firing tests until the possible effect of the high noise level on the Fastax camera and E.G. and G. microflash unit had been investigated and corrected. During this period, the E.G. and G. microflash unit was modified so that the discharge of the spark condenser could be monitored on the oscillograph. This allowed the possibility of determining if the unit had fired and, if so, at the proper time; e.g., during the instant the shutter was wide open.

Upon resumption of the test firings, three additional test firings were made with the six-inch windowed chamber. In all of these thests, the three-inch extension was used in arrangement II (Figure 34). The steel inserts, for directing nitrogen flush over the window surface parallel to the chamber axis, werc used in Tests 13 and 14, but were removed for Test 15.

Test No. 13 was set up to take a single spark photograph through the downstream pair of windows approximately nine inches from the injector face. The E.G. and G. microflash unit provided the background illumination. Two Kodak Wratten filters (No. 47B and No. 50) in series were placed in front of the objective of the Speed Graphic camera. In order to provide a photographic object in the field of view during the test, a tungsten-tantalum rod was threaded into the injector face at a position 1/4 inch below the center line and one inch toward the camera. Three flash photographs were taken with this set-up; before, during, and after the test firing. Results of this test were similar to those obtained in earlier runs. The film exposure was apparently due entirely to the flame light. (In this test, oscillograph records showed that the spark and camera had functioned correctly.) This was confirmed in test No. 14 in which an exposure was made without the spark during the firing. It was similar to the one obtained in run No. 13.

In the final test firing, the steel inserts were removed, and the entire window surface was flushed by a set of nitrogen jets directed parallel to the motor axis. Photographic coverage of this test was provided by two Fastax cameras having wide-angle lenses; one camera using color film, the other using black and white. During the test, severe crazing of approximately half of the window surface occurred; evidence that the nitrogen flush was separating from the window surface except in the area immediately downstream from the impingment points.

12.0 REFERENCES

1. "A High-Speed and High-Resolution Photographic Technique for the Observation of Propellants Injected into a Firing Combustion Chamber", Technical Note, Bell Aerosystems Report No. 8007-981-008, 18 May 1959 (AFOSR Doc. No. TN59-8).

2. "Observation of Propellants Injected Into a Firing Rocket Chamber", Technical Report, Bell Aerosystems Report No. 8007-981-011, July 1960 (AFOSR TR No. 60-98).

3. Lawhead, R. B., (Rocketdyne), " Photographic Studies of Combustion Processes in Liquid Propellant Rockets", Eighth Symposium on Combustion, Pasadena, August 1960, The Williams and Wilkins Co., Baltimore 1962, p. 1140.

4a. Combs, L. P., and Hoehn, F. W., "Steady-State Rocket Combustion of Gaseous Hydrogen and Liquid Oxygen. Part I: Experimental Investigation", Rocketdyne Research Report No. 64-24, June 1964.

4b. Combs, L. P., "Calculated Propellant Heating Under F-1 Combustion Chamber Conditions", Rocketdyne Research Report No. 64-25, June 1964.

5. Lambiris, S., "Summary Report on an Investigation of Combustion Instability for Liquid Oxygen and Liquid and Cold Gas Hydrogen Propellants", Pratt & Whitney Aircraft Report No. FR-1005, 19 June 1964.

6. Levine, R. S., " Some Considerations of Liquid-Propellant Combustion Instability", Chemical Engineering Progress Symposium Series No. 33, Vol. 57, 1961.

7. Levine, R. S., A Photographic Description of the Mechanism of a "POP". Paper Presented at the Apollo Engine Contractors Combustion Instability Symposium, NASA MSC, Houston, 3-5 August 1965, (CONFIDENTIAL).

8. Rupe, J. H., " The Liquid-Phase Mixing of a Pair of Impinging Streams", JPL Progress Report No. 20-195, August 1963.

9. Heidmann, M. F., and Auble, C. M., "Injection Principles From Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane", NACA RM E55C22, June 1955.

10. Tanasawa, Y., "The Atomization of Liquid by Means of Flat Impingement", paper presented at the American Rocket Society 11th Annual Meeting, New York, Rev. 1956, preprint No. 356-56.

11. Ingebo, R. D., "Drop-Size Distributions for Impinging Jet Breakup in Airstreams Simulating the Velocity Conditions in Rocket Combustors", NACA Technical Rate TN-4222, March 1958.

12. Foster, H. H., and Heidmann, M. F., "Spatial Characteristics of Water Spray Formed by Two Impinging Jets at Several Jet Velocities in Quiescent Air", NASA TN-D-301, July 1960.

13. Heidmann, M. F., and Foster, H. H., "Effect of Impingement Angle on Drop-Size Distribution and Spray Pattern of Two Impinging Water Jets", NASA TN-D-872, July 1961.

14. Fuhs, A. E., "Spray Formation and Breakup, and Spray Combustion", Sundstrand Turbo, Technical Note No. 4 AFOSR TN-58-414, ASTIA No. AD158217, AMF/TD No. 11999 Feb. 1958.

15. Bixson, L. L., and Deboi, H. H., "Investigation of Rational Scaling Procedure for Liquid Fuel Rocket Engines", Sundstrand Avaition, Engineering and Testing Laboratories, Pacoima Calif., Technical Documentary Report SSD-TDR-62-78, June 1962.

16. Lewis J. D., (Ministry of Aviation, Rocket Propulsion Establishment, Westcott, England), "Studies of Atomization and Injection Processes in the Liquid Propellant Rocket Engine", Fifth AGARD Colloquium on Combustion and Propulsion, Braunschweig, April 1962, The Macmillan Company, New York, 1963, p. 141.

17. Lambiris, S., Combs, L. P., and Levine, R. S., (Rocketdyne), "Stable Combustion Processes in Liquid Propellant Rocket Engines", Fifth AGARD Colloquium on Combustion and Propulsion, Braunschweig, April 1962, The Macmillan Company, New York 1963, p. 569.

18. Lawhead, R. B., et al. (Rocketdyne), "Some Aspects of Combustion Instability Research at the North American Aviation Propulsion Field Laboratory", Proceedings of the Third Conference on Combustion Instability, Princeton University, October 1955, (CONFIDENTIAL), p. 212.

19. Lawhead, R. B., (Rocketdyne), "Photographic Studies of Combustion Processes in Liquid Propellant Rockets", Eighth Symposium on Combustion, Pasadena, August 1960, The Williams and Wilkins Co., Baltimore 1962, p. 1140.

20. Gaydon, A. G., "The Spectroscopy of Flames", Chapman & Hall Ltd., London, 1957.

21. Gaydon, A. G., and Wolfhard, H. G., "Flames, Their Structure, Radiation, and Temperature", Chapman & Hall, Ltd., London, 1960.

22. Diederichsen, J., and Wolfhard, H.G., "Spectrographic Examination of Gaseous Flames at High Pressure" Paper, Proceedings of the Royal Society of London, Vol. 235-236, 1956.

23. Ziebland, H., "An Investigation of the Heat Transfer by Radiation in Rocket Combustion Chambers at 10 atm Pressure, and Some Provisional Results at 30 atm and 60 atm", Ministry of Aviation, Explosives Research and Development Establishment (British), Report No. 25/R/64, 29 January 1965.

24. Arbit, H. A., "Design, Assembly, and Operation of a High-Pressure Two-Dimensional Research Motor", Rocketdyne Research Report No. 64-16, May 1964.

25. Sherwood, C.M., "Steady-State Streak Film Analysis in the High-Pressure Two-Dimensional Research Motor", Rocketdyne Research Report No. 64-34, October 1964 (CONFIDENTIAL).

26. Rossmann, T. G., "Experimental Techniques for Investigating Instability in Liquid Propellant Rocket Engines", Proceedings of the First ICRPG Combustion Instability Conference, Orlando AFB, November 1964, CPIA Publication No. 68, January 1965.

27. Rupe, J. H., and Evans, D. C., "Designing for Compatibility in High-Performance Liquid Propellant Engines", Astronautics and Aeronautics, June 1965.

28. Martin, F. J., Miller, E., Miller, K. D. (Kellog), "Some Factors Affecting Rocket Combustion Stability", Kellog Report No. SPD 304 (CONFIDENTIAL), 1950.

29. Lawhead, R. B., et al. (Rocketdyne), "Some Aspects of Combustion Instability Research at the North American Aviation Propulsion Field Laboratory", Proceedings of the Third Conference on Combustion Instability, Princeton University, October 1955,(CONFIDENTIAL),p. 212.

30. Hern, R. G., Siddall, R. G., Thring, W. W. (Univ. of Sheffield, England), "Flow Patterns in a Phase Change Rocket Combustion Model", Ninth Symposium on Combustion, Ithaca, August 1962, p. 965.

31. Combs, L. P., "Calculated Propellant Heating Under F-1 Combustion Chamber Conditions", Rocketdyne Research Report No. 64-25, June 1964.

32. E. G. & G. 549 Microflash System Operation Manual No. B-3114, 15 July 1965.

33. Kodak Wratten Filters, Eastman Kodak Co., Scientific and Technical Data Book No. B-3.

34. Kinematographie Auf Ruhendem Film Und Mit Extrem Hoher Bildfrequenz (Mit H. Schardin) Zeitschrift Fur Physik 56 (1929), 375

35. York, J. L. and Stubbs, H. E., Ann Arbor, Mich., "Photographic Analysis of Sprays", Transactions of the ASME, October 1952.

36. Barrere and Moutet, "Study of Ignition Lag of Liquid Propellants", Fifth Symposium on Combustion, Pittsburg, Aug. 1954, p. 170.

37. Bredfeldt, H. R., "Evaluation of a Light Scattering Technique for Determining the Spray Characteristics of Impinging Liquid Jets", Technical Report No. 648, Princeton University, Department of Aerospace and Mechanical Sciences March 1964.

38. Nicholls, J. A., Dabora, E. K., and Ragland, K. W., "A Study of Two Phase Detonation as it Relates to Rocket Motor Combustion Instability", NASA Report No. CR-272, August 1965.

39. "Type 501 High Speed Stroboscope", Edgerton, Germeshausen & Grier Data Sheet No. 501.

40. Rompe, R., and Schultz, P., "Messungen Und Quecksilberstossentladungen Bei Höheren Drucken", Physikalische Zeitschrift, XLII 1941.

41. Schmidt, S. F., Briggs, R. O., and Looschen, F. W., "Use of High Pressure Mercury-Arc Lamps for Pulsed Light Applications", A Paper Recommended by the AIEE Committee on Instruments and Measurements and Approved by the AIEE Technical Program Committee for Presentation at the AIEE Summer and Pacific General Meeting, Pasadena, Calif., June 12-16, 1950.

42. Glaser, G., "Zur Lichtemission Stromstarker Funkentladungen", Paper from Optik 7 Heft 1, 1950.

43. Schardin, H., and Fünfer, E., "Grundlagen Der Funken Kinematographie", Zeitschrift Fur Angewandte Physik. January 1952.

44. Fayolle, P., and Naslin, P., "Simple Electronic Devices for High-Speed Photography and Cinematography", Journal of the Society of Motion Picture and Television Engineers, Vol. 60, May 1953.

45. Früngel, F., "High Speed Slow Motion Pictures by Means of Spark Flashes", Explosivstoffe, Zeitschrift Des Spreng-, Schiess-, Zünd-, Brand- Und Gasschutzwesens. Erwin Barth Verlag, Mannheim 1958 Heft 10.

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