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UNITED STATES NAVY

PROJECT SQUID

QUARTERLY PROGRESS REPORT

1 July 1949

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QUARTERLY PROGRESS REPORT

P R O J E C T S Q U I D

A Cooperative Program
Of Fundamental Research in Jet Propulsion
For The
Office of Naval Research
Of The
Navy Department



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1 July 1949



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NEW YORK UNIVERSITYPHASE 1

In connection with pulse jets; to investigate by means of optical, electronic, and mechanical methods the dependence of flame speeds and combustion rates on highly turbulent flow structure in combustible gases in tubes, ducts, and jets; and to interpret the observations in terms of aerothermodynamics and normal combustion processes in such ways as may be applicable to the analysis of phenomena in pulse jets.

Phase Leaders: I. Amron and M.W. Evans.

Combustion in Tubes Containing Grids. A Technical Report entitled, "A Study of High Velocity Flames Developed by Grids in Tubes; The Role of Turbulence in Combustion Processes" has been submitted for printing.

Construction of accessory apparatus for a small scale flame tube is progressing rapidly and will permit control of the most important variables. The design includes features of the large flame tube apparatus and also affords (1) greater flexibility, (2) more accurate measurement of the initial composition of the gas mixture, and (3) means for adjusting the humidity of the gas mixture to any desired value.

Figure 1 illustrates the schematic design of the apparatus. A gas mixture of propane and air is prepared by passing each gas through respective drying columns into a reservoir. The composition of this dry mixture is predetermined by admitting propane in the evacuated reservoir until the desired partial pressure of propane is reached and then admitting air until the total pressure attains the desired value.

After the dry gas mixture has been prepared, its humidity can be adjusted to almost any predetermined value by circulating the gas through the water saturator. By maintaining the temperature of the saturator constant with a small water bath, the aqueous pressure in the mixture may be adjusted to any value from 4.6 mm of mercury (v.p. of water at 0°C) to the vapor pressure of water at ambient temperature. After the humidity has been adjusted the saturator is disconnected from the reservoir by closing two communicating valves; this must be done to ensure that the mixture remains constant in composition as gas is withdrawn from the reservoir.

The flame tube is sealed with a cap and is evacuated prior to admitting the mixture. The gas mixture is introduced into the evacuated tube until the tube reaches atmospheric pressure. The cap at the end of the tube is

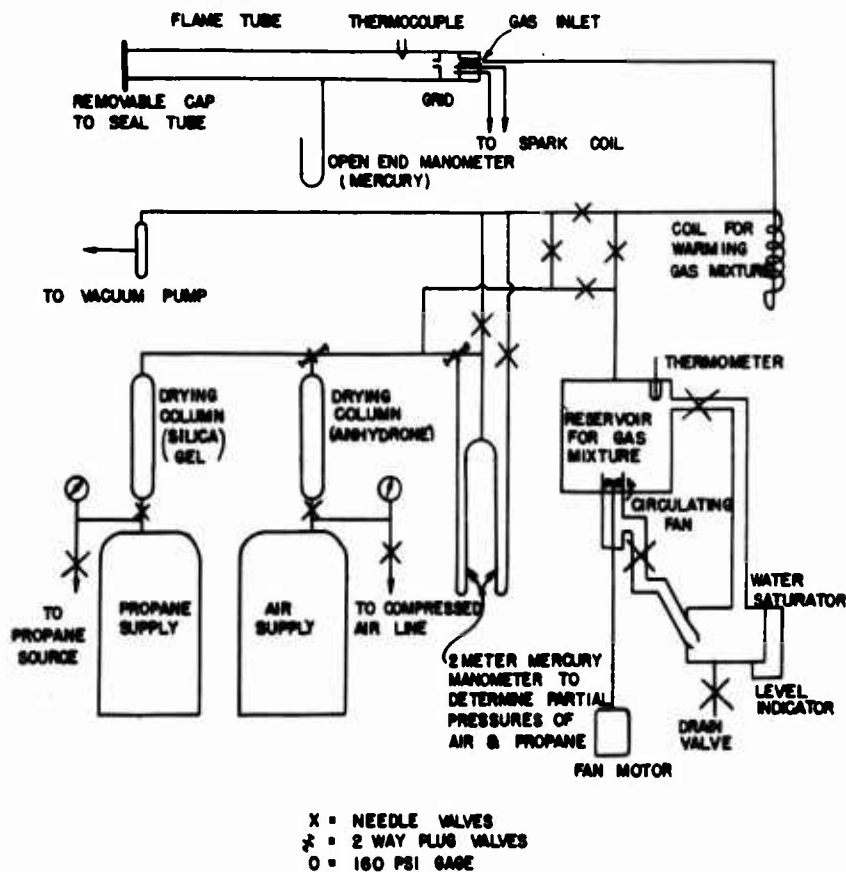


FIGURE 1. Schematic layout of the equipment to be used with the small flame tube experiments.

removed just prior to firing and therefore the tube pressure must be carefully adjusted to atmospheric so that flow does not take place during this interval

The coil in the gas line leading to the flame tube makes it possible to heat the gas mixture to some arbitrary value above room temperature so that the initial temperature of the gas may be eliminated as a variable during the first series of experiments.

Fundamental Combustion Studies. Equipment is being assembled to study the possibility of initiating combustion with methyl free radicals produced by the photolysis of azomethane. It is hoped that this investigation will yield fundamental information on the mechanism of combustion.

A spectrographic analysis of atomic flames produced in a hydrocarbon combustion is being made to study the role of free atoms and radicals in the combustion process.

PHASE 2

In connection with rockets and pulse jets; to develop theoretical methods for the calculation of transient temperature distributions and thermal stresses in solids in which heat capacities and conductivities are functions of the temperature; to measure these thermal parameters under conditions of high rates of heating which may involve absorption lag, and to study and test the theory of thermal radiation from solids and gases in relation to the measurement of temperature.

Phase Leader: J. Hett.

Analysis of a series of runs on a heated specimen is almost completed. These runs vary in length from 1.5 to 6 seconds for a temperature rise of 900°C. The only discontinuity in the specific heat is the sharp rise which occurs at the Curie point, at approximately 770°C. The results show no shift in this point as the rate of heating is increased. This is in accord with the theory that indicates that the changes which occur at the Curie point as being of electronic origin.

The work of Griffiths on the specific heats of steel under approximately static conditions shows a major peak at approximately 720°C for all specimens of low carbon content. This is the temperature at which ferrite and cementite (α iron and Fe_3C) begin to transform to austenite (γ iron plus C). As Griffiths expected, his results showed no peak at the Curie temperature since austenite is non-magnetic.

The rapid heating tests at New York University show no peak of specific heat at 720°C but do show a peak at the Curie point. This indicates that the steel does not undergo the crystalline phase change from ferrite to austenite at 723°C due to the rapid rate of rise in temperature. It is believed that the phase transformation expected at 723°C under static conditions has been displaced above 900°C. However, this upper point has not actually been observed. A paper, describing this work, is in preparation.

PHASE 3

In connection with pulse jets: To observe valve, particle, and flame motions, and to record thrusts and instantaneous pressures, temperatures, and flow speeds in and near standard or idealized components of pulse jets and related devices, and to use these observations in theoretical and electromechanical analogue treatments of pulse jets.

Phase Leader: G.E. Hudson.

Large Scale Pulse Jet Observations. The starting problems encountered with the PJ-31 were overcome by using the Merlin engine blower unit to provide ram air. With this starting technique, many runs have been made and a number of pressure and temperature records have been taken. A manometer bank is being constructed to obtain the average pressure distribution along the axis of the engine to check the average pressures computed from the instantaneous pressure records and as part of a study of the effect of variation of fuel rates on the average pressure distribution and thrust.

Small Scale Pulse Jet Observations. A two-dimension constant-area pulse jet was developed to provide an engine that would allow correlation of observations with mathematical theory. An engine with clamped glass walls and a detachable valve head has been satisfactorily developed, and a number of high speed motion pictures have been taken of the internal flame motions. These pictures indicate that each entering charge is compressed and expanded several times before it is finally expelled at the tailpipe of the jet. This unusual motion may be due to the restricted movement of the valves (to prevent side wall breakage) rather than to the uniform cross section of the engine. Further work on this engine was suspended since a considerably smaller engine would be easier to construct and observe. At present a one-half scale model of the engine is being developed.

To study the effect of inserting a grid in a standard pulse jet engine, a glass-walled model of the Dynajet engine has been built with a grid placed two inches behind the intake valves. This engine has been operated successfully a number of times, and high speed schlieren photographs have been taken of the combustion and particle motion. A comparison of these photographs with those of the same engine operating without a grid reveals no appreciable change in flow pattern except that when the grid is present, part of the cycle is characterized by jets of flame shooting through the grid into the tailpipe. These jets seem to move at higher velocities than the adjacent particles in the same region of combustion.

To determine whether the grid principle can be applied to continuously flowing combustible gases, a burner utilizing this principle has been completed and will be tested at varying ram pressures when the Merlin engine blower unit is again available at the laboratory.

Large Amplitude Vibrations. When finite amplitude oscillations occur in a gas filled tube, the differential equations involved are no longer linear and are not solved readily. For this reason, an experiment, which should be valuable in the development of a theoretical description of such motions, has been devised to indicate the important phenomena. A 1.5 inch diameter piston having a displacement of one-quarter inch was placed at one end of an aluminum tube which was open at the other end. It was found that the resonance frequency (71 cycles per second) was approximately the same as that calculated purely from acoustical considerations. Schlieren photo-

graphs of the gas motion at the tube orifice show the familiar pattern of the flow at the tail pipe of a pulse jet at resonance as illustrated in Figure.2. This experiment indicates that the theory described later under Theory of Pulse Jets may approximate some of the phenomena occurring in the pulse engine. The experimental results obtained indicate that it will be advantageous to increase the piston displacement and to use a glass-walled tube to observe the internal gas motion.

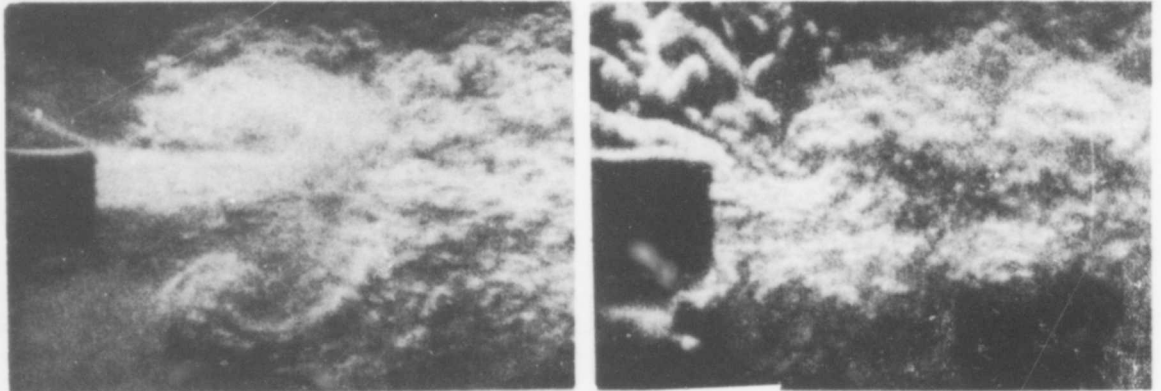


FIGURE 2. Two views showing the similarity between flow at the tail end of a small pulse jet and at the open end of a tube, resonating at its resonant frequency. The pulse jet is at the left.

Jet Formation. Study of flow over a semi-infinite plane has been delayed until improved equipment can be constructed. More data must be obtained on the specific initial and boundary conditions before the photographs can have quantitative significance. In order to study the gas flow at the head of a Dynajet, a method has been devised to produce a random density fluctuation in the air without danger of gasoline explosion. This experiment should be completed in the near future.

Theory of Jet Formation. Five idealized fluid flow problems were solved analytically. It is hoped that this series of problems will lead to the solution of problems of compressible viscous fluid flow over an edge.

The first problem considered the motion of two semi-infinite media both initially at the same pressure, density, and composition, and separated by a horizontal plane at $y = 0$. The fluid was considered incompressible, initially irrotational and laminar, and the fluid above the plane was given an initial uniform velocity u_0 parallel to the plane, while that below the plane was initially at rest. Assuming viscous stresses in the fluid when the wall was suddenly removed, the subsequent velocity distribution was determined. The

second problem treated an incompressible homogeneous fluid flowing with an initial velocity u_0 in the x direction between two infinite smooth flat plates. The fluid not contained between the planes was originally at rest. The resulting velocity distribution after both plates were suddenly removed was calculated. Third, an initially parabolic distribution of velocity was assumed to exist between two imaginary plates, and, upon removal of the plates, the resulting velocity distribution was determined.

Next, a series of problems was solved concerning flow contained initially in a tube of circular cross section immersed in a medium at rest. The first problem considered the flow in a smooth infinitely long tube of radius a . In the tube an incompressible homogeneous fluid was flowing axially, with initial velocity w_0 , with respect to the fluid outside the tube. The resulting velocity distribution in space and time was found after the tube was suddenly removed. Last, a similar problem was solved assuming an initial Poiseuille velocity distribution. These problems were soluble because the differential equations reduced to the linear heat conduction type of equation.

Theory of Pulse Jets. The effect of the periodic reversal of flow at the tailpipe of intermittent jet engines has been investigated both for the pulse jet and the Bodine resonating engine. This phenomena, known as backflow, has been observed by a number of investigators, however, it has not been possible to determine the effect of this process on net thrust. Unsuccessful attempts have been made to operate a pulse jet when a valve was placed at the exhaust port to restrict backflow. Increases in thrust; however, have been reported when the open end of the tail pipe is flared, apparently reducing the "Borda Mouthpiece" resistance to the backflow. It seems from this that the backflow process makes a positive contribution to the thrust. It is desirable, therefore, to determine this effect quantitatively and to ascertain if it is necessary to combine backflow with combustion in order to produce a thrust increase.

Observations of intermittent flow from the tailpipe of a Bodine engine, consisting of a half-open tube oscillated near resonance by a piston at the closed end, closely resembles flow from a pulse jet. This problem is treated theoretically by first neglecting the process in which the jet formed on the outflow of each cycle becomes detached. Neglecting this factor, the analysis indicates that thrust is due to the backflow. This relationship is given by:*

$$T = \rho \pi a^2 \frac{\omega^2}{8} Z^2 \quad (1)$$

*The equation given in the last Quarterly Progress Report is a zero order approximation only and leads to the value zero. The above equation (1) results from the first order approximation.

where: \bar{T} = average thrust over a cycle
 ρ = density of the atmosphere surrounding the engine
 a = radius of the tube
 ω = $2\mathcal{V}$ times the frequency of the piston drive.

Z = amplitude of motion of the fluid particle at the interface between the fluid which remains in the tube and the fluid jet which moves out on each cycle and merges with the surrounding atmosphere.

It is to be noted that this equation is valid, provided the amplitude Z is less than 0.3 times the length of the tube, in compressible flow, or for any value of Z if the medium is incompressible.

In some applications in which the flow is incompressible or nearly so, such as a Bodine engine operating under water, Z is known or can be observed; in others it must be computed theoretically. The analysis shows that, provided $\frac{Z_p}{l} < 0.3$,

$$Z = Z_p \left\{ 1 + \frac{1}{2} \frac{1 + \frac{11}{6} n \frac{a}{l}}{n \left(\frac{c^2}{l^2 \omega^2} - \frac{11}{12} \frac{a}{l} \right) - \frac{4}{\pi^2}} \right\} \quad (2)$$

in terms of: Z_p = amplitude of the piston motion
 n = ratio of the average air temperature in the tube to the ambient temperature
 l = length of tube
 c = speed of sound in the air outside the tube.

Clearly, for very small values of a/l where $n = 1$, resonance is obtained for a frequency

$$f = \frac{c}{4l}$$

according to the usual acoustic approximation. Equation (2) is no longer valid when this occurs, because of the restriction on Z/l and probably is not accurate for frequencies greater than resonance frequencies.

However, the advantages of driving a tube in resonance is immediately apparent from equations (1) and (2), since the thrust tends to become very large. In a theory that accounts for the jet detachment process, the thrust would have a maximum value (instead of becoming infinite) at resonance, this maximum being determined by the amount of energy dissipated during each cycle in the jet detachment.

From these results, it is concluded that backflow contributes to thrust, independently of combustion. Application of equation (1) to data obtained from the observations of flow in a transparent walled Dynajet, indicates that as much as 25 per cent of the thrust may be contributed by the backflow effect. This of course assumes incompressible flow exterior to the engine.

PHASE 4

In connection with rockets and pulse jets; to develop and use instruments for recording thrust and transient pressures, temperatures, densities, and radiations of hot oscillating gases, and gas and liquid velocities.

Phase Leader: J. Hett.

Temperature Instrumentation. Several successful records have been obtained giving the temperature averaged over a path through the combustion chamber of the PJ-31 pulse jet at a point approximately 6 inches downstream from the valves. A sample of such a record is given in Figure 3.

Recording was made with a 35 mm drum camera which can record as many as 16 channels simultaneously. The drums make a revolution in $\frac{1}{4}$ second. At the beginning and end of the revolution microswitches trip intensifying circuits for the two 5 inch oscilloscopes to prevent overlapping of traces on successive rotations. The traces shown in Figure 3 are made simultaneously, one for each oscilloscope. The horizontal lines are calibration marks made by the standardized strip lamp.

Reduction of the radiation curves to the temperature curve indicates peaks at approximately 2450°K . The probable error at this point is 20°K , but below 1400°K this error increases considerably because the calibration is done with a strip lamp. Work has also been completed in the laboratory for two other temperature stations which will be installed, one near the beginning and one near the end of the tailpipe. A paper describing the instrument completely is being prepared.

Pressure Gauge. Several dozen runs have been taken at various positions on the PJ-31 with both types of pressure gauges (pickups with detached and integral transmitter). A pressure gauge developed at the Royal Aircraft Establishment in Farnborough is also being tested for comparison. Publication of the results awaits correlation with the temperature measurements.

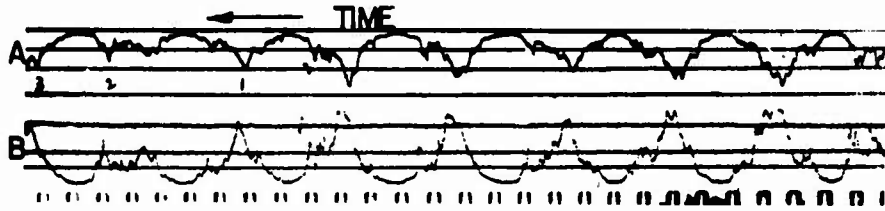


FIGURE 3. A) Radiation observed in single path.
 B) Radiation observed in double path.
 Solid lines represent calibration marks.

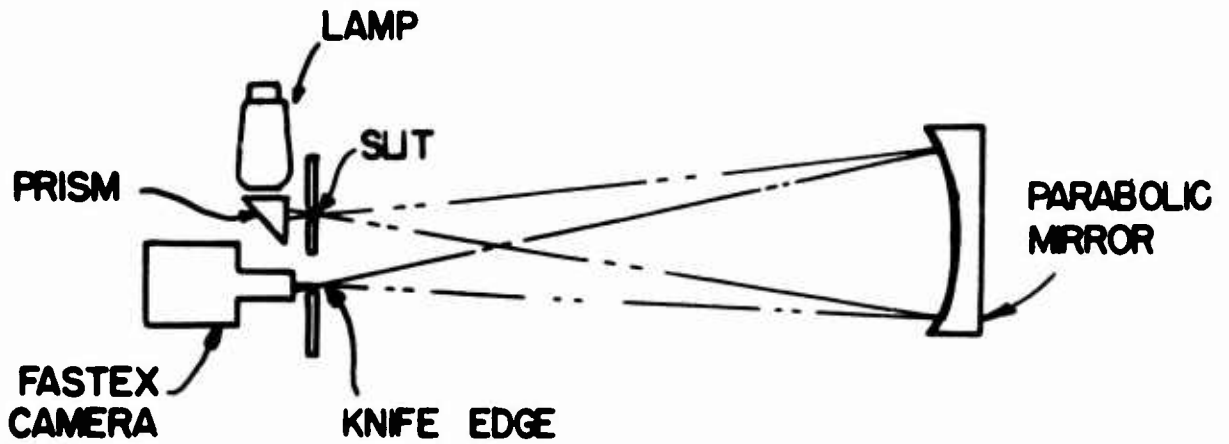


FIGURE 4. Schematic layout of single mirror schlieren system with small beam displacement.

An improved type of cooling chamber employing features of the present fire tube cooler plus actual water contact with the perimeter of the gauge is under development and appears promising.

Flowmeter. A thermistor type flowmeter was installed on the PJ-31 but burned out before adequate tests could be made. It is being replaced.

Dynamic Gas Sampling Device. Preliminary tests of a valve operating system were made to determine the overall practicability of the method of obtaining samples of a gas from the combustion chamber of a pulse jet engine during various phases in its cycle. Electronic circuits have been constructed and a design of an Invar valve system is being made.

Three Dimensional Schlieren. The instrumentation of the three dimensional schlieren is nearly completed but several small parts must still be obtained, and the equipment set up.

Single Mirror Schlieren. A schlieren system using only one parabolic mirror has been constructed for qualitative observations of gas motions. The system shown in Figure 4 has been designed for studies of large areas, for example, those involved in the flow over a semi-infinite plane, or the flow at the end of a resonating tube, or gas motion in a transparent-walled pulse jet. The beam displacement at the focus is approximately $\frac{1}{4}$ inch while the optical path is 10 feet, giving an angular displacement of approximately 10 minutes of arc. The dimensions permit the entire angular field to be viewed in the Fastax camera. Because the light beam passes through the disturbance twice, a higher sensitivity is obtained than with the double-mirror system.

P O L Y T E C H N I C I N S T I T U T E O F B R O O K L Y N

The research work at the Polytechnic Institute of Brooklyn has been confined to Phase No. 3, which is concerned with the sweat cooling of combustion chamber walls.

The work on this phase has been divided into three parts; an experimental investigation of the boundary layer along the surface of a porous flat plate with fluid injection; a theoretical investigation of the velocity and temperature fields in the boundary layer over a flat plate with uniform or distributed injection; and the development of X-ray diffraction techniques for the measurement of wall temperatures. A detailed discussion of the work done on each of these parts of Phase 3 follows:

PHASE 3

(a) To investigate the metallurgical, fabrication, and design problems involved in cooling rocket and intermittent jet motors by the diffusion of fluids through porous metal combustion chamber liners.

(b) To study analytically and experimentally (1) the diffusion of fluids through porous media under high pressures and temperatures and (2) the effects of this diffusion on the internal aerodynamics.

(c) To study problems in the field of physical-chemistry pertinent to (a) and (b) with consideration given to the clogging of pores, the use of catalysts embedded in the liner walls, and endothermic diffusion processes.

Project Leader: R.P. Harrington and S.W. Yuan.

Experimental Investigation of the Laminar Boundary Layer Along the Surface of a Porous Flat Plate with Fluid Injection. The experimental investigation of the stability of the laminar boundary layer over a porous flat plate in the wall of the turbulence channel has been continued. A rotary type industrial gas meter with a capacity of 1000 c.f.m. at a maximum pressure of 75 lbs. per square inch is used to measure the flow of injection fluid. The injection pressure is controlled by a diaphragm type pressure regulator and is measured by means of U-tube mercury manometers. Figure 1 shows a general view of a modified injection equipment described in Project Squid, Quarterly Report, 1 April 1949.

A uniform flow is established at the forward edge of the porous plate by removing the turbulent boundary layer by means of suction. Velocity profiles are then taken at various positions along the plate downstream from the suction slot; first without, and later, with injection. Figure 2 shows

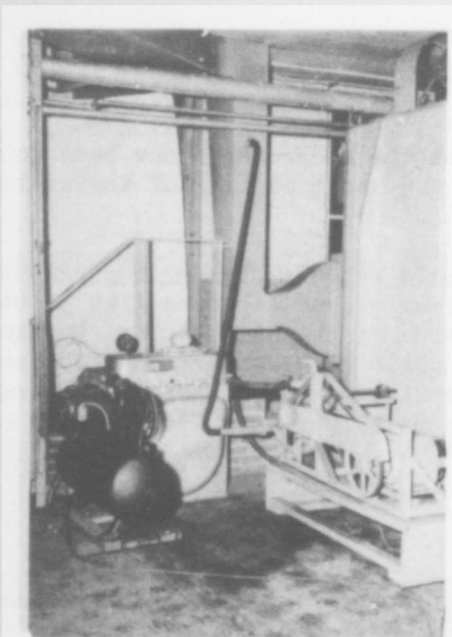


FIGURE 1. General view of turbulence channel injection apparatus.

a typical velocity profile at the $4\frac{1}{2}$ inch station at a local Reynolds number of 53,000. Figure 3 shows in logarithmic plot the velocity distribution at the 23 inch station.

The experimentally determined velocity profile at the $4\frac{1}{2}$ inch station was compared to the theoretical velocity profile given by the theory of Project SQUID Technical Memorandum PIB No. 10. The profiles differ considerably; the experimental boundary layer appears to be only one-fifth as thick as that predicted. The reason for this discrepancy may be either that the boundary layer is turbulent and therefore its thickness is difficult to determine or that the accelerating pressure gradient along the channel results in a thinner boundary layer. The reason for this discrepancy is being investigated.

Some difficulty was encountered in maintaining the calibration of a tungsten wire anemometer in use. A tungsten wire accumulates surface oxidation as the operating time is increased. In order to eliminate or decrease the accumulation of surface oxidation during an experiment the wires were stabilized by aging for approximately ten hours at maximum operating current and velocity. The wires were then calibrated. The stabilization process permitted the wire to build up an initial surface oxidation after which it was hoped the characteristics of the wire would not readily change. However, repeated calibrations seemed necessary since the oxidation process appeared to continue in operation.

The use of a non-oxidizing material for the wire seemed to be indicated and, accordingly, a change to platinum wire 0.001 inch diameter was made. Good results are obtained from units so constructed; the stabilizing process is eliminated, and the over-all time required to construct and calibrate a hot-wire unit is reduced by 60%.

Occasionally it was impossible to repeat points observed during the calibration of a hot-wire anemometer. This condition was attributed to poor sensitivity in the ammeter in the hot-wire circuit. Since the PIBAL anemometers being used were operated on the principle of constant current, a meter with poor sensitivity would permit a current variation, sufficient to cause incorrect velocity determination, to go undetected. The introduction of a precision micro-ammeter into the circuit as a replacement for the less sensitive meter has eliminated this difficulty. Calibration curves

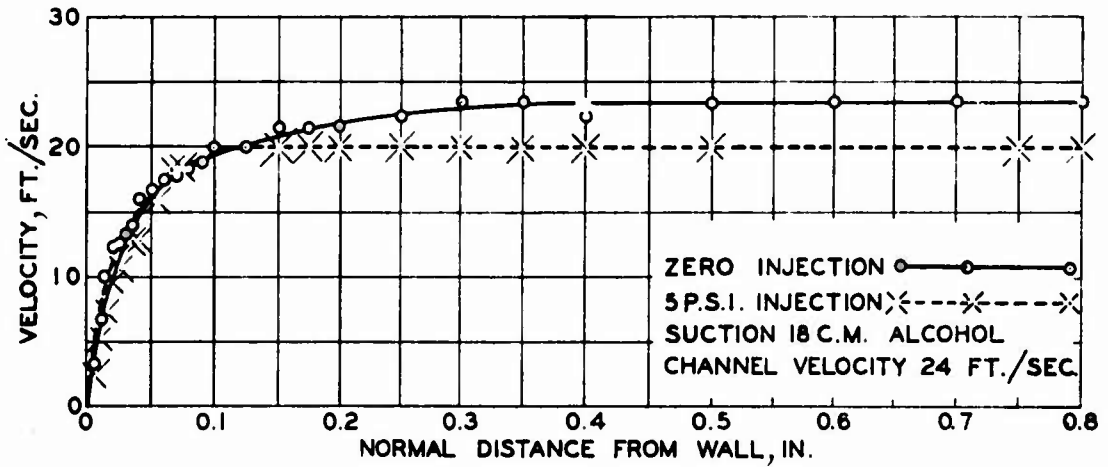


FIGURE 2. Velocity profiles at station $4\frac{1}{2}$ inches downstream from suction slot.

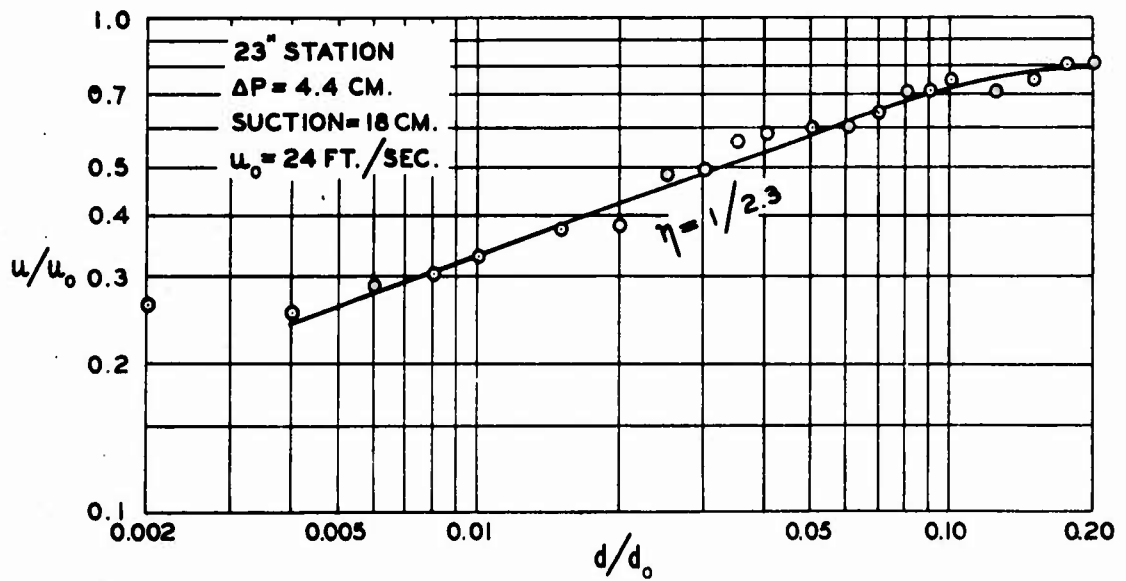


FIGURE 3. u/u_0 Normal Distance

may be readily reproduced with the present equipment.

Analytical Investigation of the Laminar Boundary Layer Along the Surface of a Porous Flat Plate with Fluid Injection. Further investigation of heat transfer in the laminar compressible boundary layer on a porous flat plate with fluid injection was described in last Quarterly SQUID Report. In this investigation better approximations to the density and viscosity variation inside the boundary layer were made. (The density ρ in this case varies inversely with a certain quartic function of distance inside the boundary layer, y , instead of varying inversely with a certain linear function of y as assumed in the previous case, Project SQUID Technical Memorandum PIB No. 10. The viscosity, μ in this case varies directly as one-half power of the quartic function of y instead of using the linear function of y as in the previous case.) The results show that about 10% less mass coolant injection is needed in the present case than was indicated in the previous case (T.M. PIB No. 10). A complete report of this investigation will be written soon.

In the investigation of heat transfer in the laminar compressible boundary layer on a porous flat plate with variable fluid injection, two types of injection fluid variation with the flow direction were considered. They are (1) the case where the injected fluid is assumed to decrease linearly as the distance from the leading edge increases, and (2) where the injected fluid is assumed to decrease bilinearly with the increase of distance in the flow direction. The results show that the initial mass fluid injection in case (2) is greater than in case (1). Both cases (1) and (2) have greater initial mass fluid injection than does the case with constant fluid injection. A report covering this investigation is in the process of being written.

A theoretical investigation of the heat transfer in the turbulent boundary layer on a sweat-cooled plate was in progress during this period. An exponential function in y and v_0/\sqrt{y} was assumed for the velocity profile in the laminar sub-layer. For an impermeable wall this velocity becomes linear with y . The outer boundary velocity of the laminar sub-layer is determined by the assumption that over the dividing line between laminar sub-layer and the turbulent layer, the viscous stress on one side must be equal to the turbulent stress in the other. The expression for the temperature ratio (temperature difference between the hot and cold sides of the wall) determining the theoretical wall temperature was then derived from the Reynold's analogy between heat transfer and skin-friction.

Experimental Determination of Hot Wall Temperatures by Means of X-ray Diffraction Techniques: General Design of the X-ray Thermometer. The general problem is to design and construct a specific scientific instrument capable of taking, under operating conditions, relatively instantaneous temperature readings of a generally inaccessible hot metal surface, such as the inner wall of a combustion chamber, -in other words, to design a workable X-ray diffraction thermometer.

The general design of the equipment, as originally conceived, consisted of a Geiger-Muller gamma ray detecting tube used in conjunction with an electronic counter (supplanting camera and film) feeding into a recorder. The detecting tube to follow automatically a diffraction line by means of a self-seeking electro-mechanical system.

X-rays, or soft gamma rays, are absorbed by the gas in a Geiger-Muller counter, which consists of a cylindrical metal cathode and a coaxial wire anode enclosed in a gas-filled chamber. The cathode may serve as part of this chamber. Since the ideal counter would allow little or no absorption of the X-rays, a very thin "window" having a minimum absorption effect is placed at one end of the tube. This window may be made of Lindemann glass, mica, or beryllium, depending upon the characteristic radiation under study. When particles or quanta of energy enter the tube, primary and/or secondary ionization of the gas in the tube is effected.

When sufficient voltage is applied to the electrodes, the electron from an ionized gas atom is attracted to the anode and in its route collides with other atoms creating further ionization. This results in an avalanche of electrons, which lowers the potential of the anode. This change in potential produces a "pulse", which can be amplified and detected by standard electronic amplifiers. The positive ions produced by the collision are attracted to the cathode and during the migration may rise to secondary emissions of electrons. These electrons, in turn, may produce spurious pulses or discharges. To prevent this action, an external quenching circuit is used which is designed to be self-quenching. In the self-quenching type of counter, a small amount of an organic gas having a high electron affinity is introduced into the tube. This gas absorbs secondary electrons, thus effectively quenching the tube.

Changing the voltage on the electrodes affects the behavior of the tube. In general, starting from zero, and increasing the potential, a point is reached where the tube acts as a counter producing pulses proportional to the energy of the impinging X-rays. With continued increase in potential, a point is reached where a wide variation of voltage does not affect the number of counts. This point is known as the plateau of the tube or the Geiger-Muller region. If the voltage is increased beyond the plateau of the tube, it will go into a state of continuous discharge. The Geiger tube is operated in the plateau region for X-ray diffraction work.

If the Geiger tube is now made to scan the area of a reflected beam of X-rays, then, all conditions remaining the same, an increase in the number of counts indicates that the tube is marking the position of a diffraction line. Since it has already been shown that the position of a given diffraction line is a function of the refracting surface temperature, then, correspondingly, the position of the counter can be calibrated in terms of temperature.

In order to determine the final equipment design, a simple X-ray spectrometer was constructed and was operated manually. Figure 4 illustrates the complete experimental arrangement. The Geiger-Muller tube is supported on a universal joint and is mounted with its comparison slit system so that its distance from the specimen is readily adjustable. This entire assembly moves on a horizontal arc whose center lies on the axis passing through the center of, and the surface of the specimen. The motion of the counter tube and slit system is manually controlled by a worm gear arrangement. The X-ray slit system, specimen, and Geiger tube slit system all lie on the circumference of a back-reflection cylindrical focusing camera.

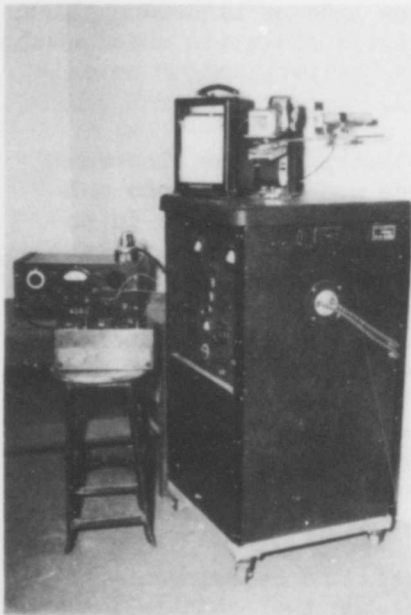


FIGURE 4. General view of X-ray set-up showing specimen furnace and horizontal control for Geiger-Muller counter.

The G-M tube was wired to the General Radio type 1500-A Counting-Rate Meter having the following selection of ranges: 0-200, 600, 2000, 6000, and 20,000 counts per minute. A continuously adjustable voltage for the G-M tube was provided with a range from 400 to 2000 volts, DC. An Esterline-Angus 5-ma pen-and-ink recorder was plugged directly in series with the panel meter, and, since the calibration was linear, the recorder deflection was proportional to the meter counts.

The first experiment was made at room temperature to determine the position of the diffraction lines and to observe the relative intensity of these lines to background count. A North American Philips diffraction unit providing manganese filtered iron radiation was used throughout these preliminary experiments. An X-ray diagram was first taken to determine the approximate position of the line. Then, with the G-M tube in position and using the photograph as an indicator, the region was scanned to locate the line. No line was apparent on the recorder since it was found that the background count was very high, on the order of 200 counts per minute, and the sporadic arrival of the counts, as heard on the monitoring speaker, did

not register as such on the Esterline recorder. It seemed that the time constant of the counting rate meter was too high, thus damping the pen movement to such an extent that the rate of traverse across the line (approximately 1° per minute) was still too rapid to observe the line. When the counting rate meter was altered by substituting a 0.125 mfd condenser for 4 mfd in the damping circuit, the diffraction line was observed. The background to line count ratio, however, was approximately 1.2 to 1. This permitted only a very weak line indication.

Since a strong sharp line would be required to operate automatic electronic equipment and give reasonably accurate temperature data, the following action was planned:

(a) To increase the intensity of the X-ray beam without sacrifice to focus.

(b) To suppress the background reflection by (1) investigating the characteristic radiation of the target which may add to the background count and (2) investigating the contribution to the background by fluorescence from the specimen.

(c) To study further, the detecting system, i.e., the G-M tube and the electronic counter.

(d) To investigate possible use of other radiation such as that from a chromium target.

Improvement of Equipment. In order to make use of the $K\alpha$ radiation it is essential that the voltage remain constant at about 35000 volts. Increasing the voltage would decrease the wavelength and increase the white radiation thus only serving to increase the background count. No advantage could be gained by increasing the voltage.

Fortunately, the North American Philips X-ray tubes are designed with four windows, which produce four separate X-ray beams. Two of the beams originating from the target are narrow and two of the beams are wide, the latter yielding a greater source of X-rays. Hence, by using that window yielding the broadest beam greater intensity of X-rays is readily obtainable. Further, it is possible to use the target or source of X-rays as its own slit system, by using a limiting slit so that only a desired portion of the specimen is illuminated by this intense beam of X-rays.

When using a target as the slit system, it is essential that the G-M tube move in a vertical arc. This is necessary since the beam impinging upon the specimen is a narrow, rectangular horizontal beam. With this experimental arrangement, the back reflection cylindrical camera now contains on its circumference the following: the center of the target; the specimen; and the G-M tube slit system. This arrangement is shown in Figures 5a and 5b.

With the X-ray spectrometer rebuilt in this manner, the equipment shows an improvement of the line to background count having a ratio somewhat better than 1.5 to 1. This value was still too small.

In view of the high background count, it was suspected that there might be some impurities in the iron target. An oscillation diagram of the target taken with a single crystal, showed strong copper lines. This copper radiation was to some degree responsible for the background count. When the tube was replaced by a new Fe target tube, measurements taken give a line to background count ratio of approximately 1.7 to 1. A typical recording made with the present arrangement using the Esterline recorder

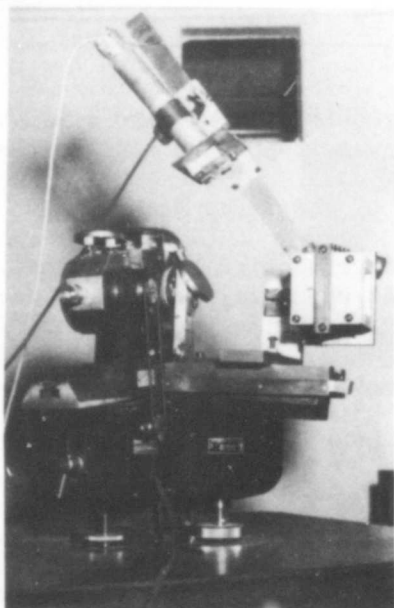


FIGURE 5a. Front view of slip and vertical arc control for G-M tube.

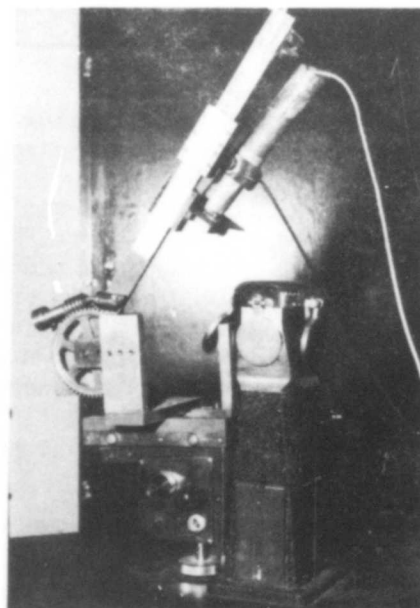


FIGURE 5b. Rear view of vertical G-M tube setup.

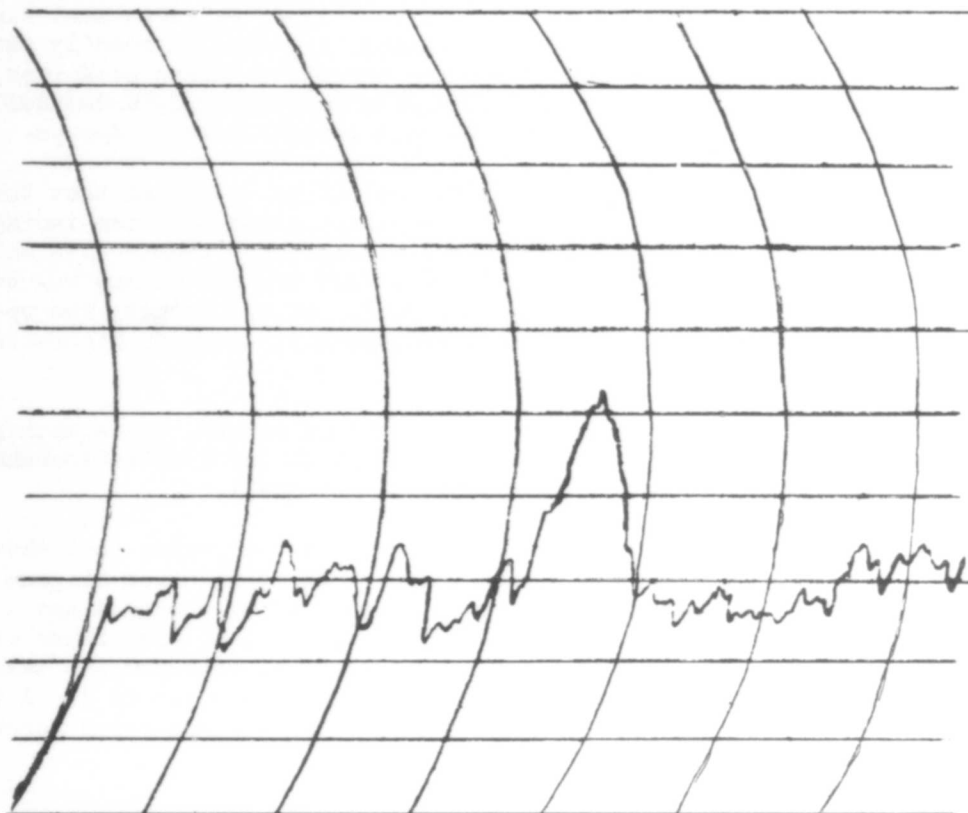


FIGURE 6. Trace showing relative line to background count obtained with general radio counter type 1500-A and Esterline recorder.

is shown in Figure 6. This diagram was taken at room temperature (72°F).

It was stated earlier that the specimen contained 18% chromium. Now, the wave length of Cr $K\alpha$ radiation is 2.2850 Å. The $K\alpha$ line of the X-ray beam, emanating from an Fe target and striking the specimen has a wave length of 1.9321 Å. Since the energy of the Fe radiation is of a higher order than that of chromium, it may be anticipated that the chromium in the specimen may re-radiate X-rays, i.e., fluoresce, and as a consequence, add its contribution to the background count. To eliminate the possible chromium fluorescence of both the $K\alpha$ and $K\beta$ lines, a substance must be used whose K absorption is greater than Cr $K\alpha$. This condition was fulfilled by titanium which has a K absorption edge of 2.4912 Å.

A thin film was prepared by spreading a paste of titanium oxide and collodion on a glass plate. (This film was tried since titanium metal having the required 3 to 4 tenths of an inch thickness was not available at this writing). This filter was then placed over the slit system in front of the G-M tube. The effect, although decreasing the intensity of the characteristic line, showed a slight improvement in the ratio of line to background count. Figure 7a shows a recording of the diffraction line without the titanium filter having a ratio of 1.4:1. Figure 7b shows a similar recording using the titanium filter and yielding a ratio of 1.5:1. These traces also indicate that there is some chromium fluorescence present.

It became apparent that the General Radio type 1500-A counting rate meter was not suitable for X-ray diffraction work. For one thing, there was no method provided to control the damping of the meter and for another, the background count with no X-rays present was too high (200 per minute). The reason for the high background count has not yet been investigated. Finally, variation in the background count was so great as to practically obscure any line.

A North American Philips Counting Unit (type No. E-58006) and a Brown recorder was made available for this experimental work. Again, it was necessary to determine the line to background ratio at room temperature before proceeding further. With this array of equipment, and maintaining all other conditions identical to those used with the General Radio counter and Esterline-Angus recorder, a test run was made.

The results are shown in Figures 7a and 7b. It is quite apparent that these traces clearly show the presence of a line above the background.

At this writing, no X-ray tubes, other than those with an Fe target as used in the above experiments were available for trial.

An examination of the final traces indicates clearly the presence of a line or lines characteristic of the specimen, and their nearly

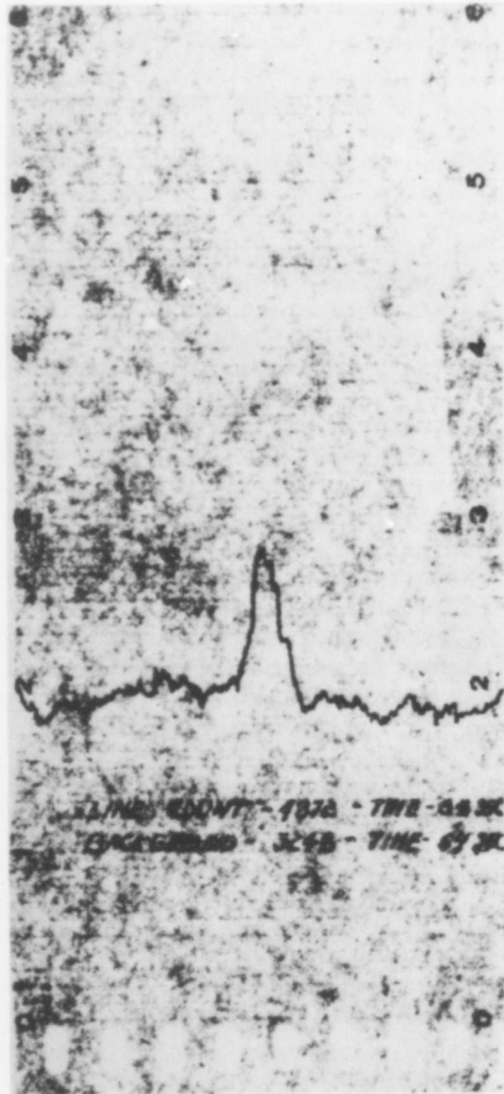
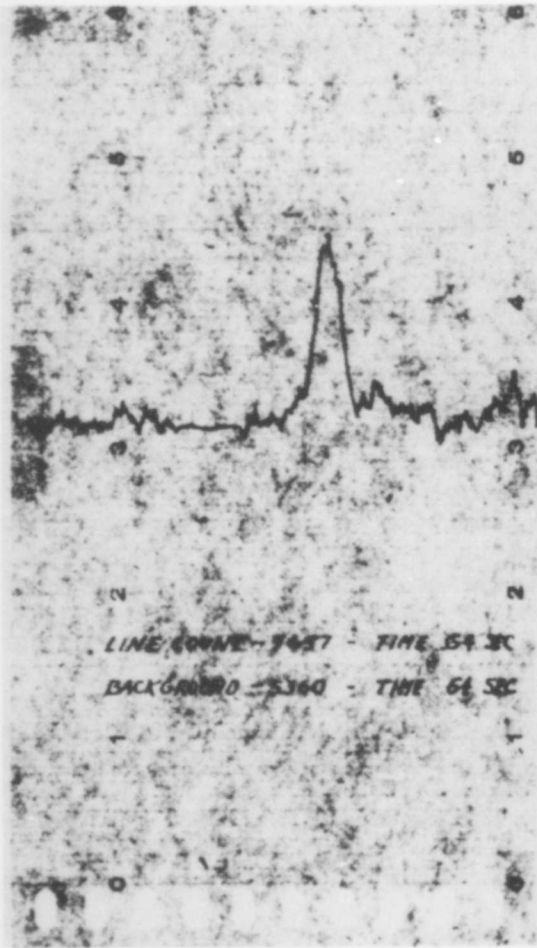


FIGURE 7a. Trace showing line to background count without titanium filter obtained with Brown recorder and North American Philips counter.

FIGURE 7b. Trace showing line to background with titanium filter obtained with the same equipment given in Figure 7a.

instantaneous detection by means of the G-M counter and allied electronic circuits. It has previously been shown "visibly" by experiments indicated in T.M. PIB-5 that these lines move with small changes in temperature. These present lines are of sufficient amplitude to operate auxiliary electronic equipment to make the Geiger-Muller tube "self-seeking."

It is recognized that some work can still be done to improve the amplitude or to increase the line to background count ratio to anticipate absorption of the X-rays not only by air, but by the combustion products of the engine in whose cylinders the wall temperatures are being measured. Proper filters or combinations of filters as well as such devices as Soller slits may overcome technical difficulties encountered in efforts to suppress the background count.

Thus, there is sufficient evidence here to indicate that an instrument may be designed and constructed to measure the surface temperatures of substances where other methods may not be feasible. Much of the work from here on is an engineering task requiring accurate design and machine work. The instrument should include a goniometer and a vernier system to obtain accurate readings of position of the G-M tube. A universal arrangement for the alignment of the slit systems and a continuous adjustment of the slit widths must also be developed before the desired instrumentation can be achieved.

PURDUE UNIVERSITYPHASE 2

To undertake, in connection with jet propulsion engines, (1) a study of the effect of turbulence on combustion rate in mixtures of hydrocarbons and air, and (2) a study of the fundamental factors involved in the flame holding processes in mixtures of hydrocarbons and air moving at high velocities.

Phase Leader: H.J. Buttner.

Heat Release Requirements for Flame Holding in a High Velocity Stream. The research during this period was devoted primarily to the construction and calibration of the test equipment to be used in conjunction with the two-dimensional nozzle-burner. Two ceramic flame holders designed for introducing a flame or heated inert gas into the main jet were fabricated. Preliminary operation of one of the flame holders indicated that the performance would be highly satisfactory.

Extensive tests were conducted to determine the effect of certain factors on the stability limits of the two-dimensional burner. These tests were made in an effort to obtain more precise quantitative data than those obtained in earlier investigations. This series of tests comprised over 340 observations of stability and flame blow-out in which the main jet flow was varied from 50 to 250 feet per second and with the main jet fuel-air ratios (gravimetric) varied from 0.05 to 0.094.

From these experiments it was found that the only requirement for stability of burning is sufficient heat release per unit of area of the main mixture stream over which the heat released from the flame holder is applied. A further interpretation may be made: as long as the flame holder is in itself stable and the heat release is sufficient, overall stability can be expected.

It was also found that the variation of the main jet fuel-air ratio had no measurable effect on the flame stability requirements.

Since one objective of combustion research is the attainment of the greatest heat release per unit of volume of combustion chamber, it was considered necessary to develop an accurate method for determining the actual volume required for combustion at some certain degree of completeness. Such a method was developed and applied to a burner. In this case, the reaction



zone was chosen as a criterion of the degree of completeness of combustion. A Gaertner L230 spectroscope with a camera attachment was used to record the region in the flame in which the CH and C₂ radiations appeared. Since these radiations are characteristic of the flame front only, and not the outer envelope in a Bunsen flame, measurement of the width of the CH and C₂ bands on the recording film permitted a determination of the limits of the flame front, or reaction zone. Spectra were taken successively along the axis of the flame in 2-inch increments, up to a total length of 23 inches from the burner port, for each fuel-air ratio. The main jet velocity was held at 100 feet per second.

It was found that the maximum width of the reaction zone increases almost linearly with an increase in the fuel-air ratio. The length of the reaction zone is a minimum at a fuel-air ratio slightly richer than stoichiometric. The volume of the reaction zone was found to be a minimum at fuel-air ratios appreciably leaner than stoichiometric.

Using theoretical values of heat release at maximum temperature of the propane-air flame and measured volumes of the reaction zone, the theoretical heat release per unit of reaction volume was determined.

Since combustion chambers are frequently cylindrical in shape, the cylindrical volumes required to enclose the reaction zones have been determined. The specific heat release values for the cylindrical volume are approximately one-half of those based on the actual volume. However, the peak values occur at about the same fuel-air ratio.

A study of combustion in the two-dimensional nozzle burner will be made with burner nozzle cross-sectional areas ranging from 2 to 24 square inches. Particular attention will be given to the determination of the application of certain parameters developed in the intermediate burner studies, such as heat release requirements for stability of burning. If this relation can be proved, basic information should then be available for design purposes that can be applied with reasonable certainty to a large variety of combustion chamber configurations, with scale effect reduced to a minor consideration.

Effect of Turbulence on Combustion. Efforts were continued to determine the correlation between the semi-theoretical turbulent velocity and turbulent intensity values and those obtained through use of the constant temperature hot-wire anemometer. Comparison of recalculated values from the data of turbulent velocity and intensity given previously¹ with the additional values obtained from this series of experiments show that agreement is very good for Reynolds' numbers in a smooth tube up to 70×10^3 . The values obtained by the hot-wire anemometer become progressively higher

¹Quarterly Progress Report, Project SQUID, Purdue University, Phase 2, 1 April 1949.

than those calculated using Nikuradse's technique², as Reynolds' numbers are further increased.

The hot-wire anemometer was checked for stability over a period of five hours and was found to be stable within the accuracy limits of the calibration instruments. The transconductance values, a direct measurement of stability, changed less than four per cent over all ranges of DC and AC wire currents in a period of two weeks duration.

Flame Temperature Patterns by Partial and Total Flame Coloration Using a Modified Sodium Line Reversal and Photographic Process. A Technical Memorandum discussing the work on this problem is being prepared. This report will include a theoretical analysis of the relations existing between partial and total coloration of a flame and a new method of application of the sodium line reversal method for flame temperature determination.

Determination of Point Temperatures in Turbulent Flames Using the Sodium Line Reversal Method Developed in the Preceding Problem. The effect of sodium chloride vapor concentration on the indicated flame temperature in a Bunsen type burner was determined. It was found that the indicated temperature, as observed in an optical path perpendicular to the axis of the burner and immediately above the inner flame cone, decreased as the concentration of the sodium chloride vapor was increased until the concentration reached a limiting value. With certain minimum concentrations, no line reversal was obtained. These results indicate a shift in the average weighting of flame temperatures toward the cooler regions and possibly to that region nearest the spectro-scope which would conform to the theoretical analysis that has been made in connection with the flame temperature studies.

An experiment was conducted to determine the possibility of introducing sodium vapor in a direction opposite to the flow of the burning gases. By utilizing a hypodermic needle and sodium vapor under pressure, it was possible to color locally the flames of a turbulent stream at any desired point without disturbing the gases upstream from that point. This method of injection of sodium chloride vapor will be applied to turbulent flames for determining equilibrium temperatures through partial flame coloration.

PHASE 3

To undertake the study of corrosion in connection with jet propulsion devices. The purpose of the research is to identify the corrosion products

²Nikuradse, J., Regularities of Turbulent Flow in Smooth Pipes, Forschungsheft 356 - Supplement to Forschung auf dem Gebiete des Ingenieurwesens, Edition B, Vol. 3, Sept.-Oct. 1932.

and to investigate the process of corrosion as affected by the chemical and physical properties of the materials and the conditions of exposure.

Phase Leader: H.J. Yearian.

Oxidation of Heat Resistant Alloys. Electron diffraction patterns and electron micrographs have been taken of the oxide films produced on chrome-steel alloys of 5 to 26% chromium content when heated in one atmosphere of dry oxygen at temperatures from 700 to 900° C for time intervals ranging from one-quarter hour to two hours.

These measurements supplement those made by X-ray diffraction of the heavy scale formed in 20 hours and the electron diffraction of the temper color film on the metal beneath the removed scale, which were summarized in the April Quarterly Report. In the present experiments with shorter times, a surface scale was not formed at 700 °C, and the scale formed at the higher temperatures could be removed easily before stripping the film for examination.

The alloy surfaces were prepared for oxidation by electrolytic polishing in perchloric acid-acetic anhydride, and the films were stripped electrolytically in the same solution. The results of transmission electron diffraction analysis of these films are shown in Table I, where the notation is the same as was used previously. The film is sometimes found to have a thin and a thick component. These are indicated by a) and b) respectively. Which of these lies next the metal has not been determined. The structures indicated represent the best fit with the data but it must be emphasized that the accuracy of electron diffraction measurements is not sufficient to make the structure assignments with complete certainty: e.g., X75 means that the hematite structure, α Fe_2O_3 - Cr_2O_3 , is found and it probably has a high percentage of Cr_2O_3 . It should also be pointed out that many of the stronger diffraction lines of Fe_3O_4 (symbol O) coincide with those of hematite, so that the presence of a small amount of this material can be missed.

Over the ranges of composition, temperature, and oxidation time given, no essential differences in the oxide phases are found, in contrast with the results on the scale. Both α Fe_2O_3 - Cr_2O_3 and Fe_3O_4 - FeCr_2O_4 oxide types are present in practically all cases. To the accuracy possible in electron diffraction the chromium-rich form of the oxide is indicated in most cases. Similar results were found for the films underlying the heavy scale formed in 20-hour runs (Table I) ³. It is unfortunate that the accuracy is not high enough to discover any trend correlating the percentage solid solution

³Quarterly Progress Report, Project SQUID, Purdue University, April 1949.

TABLE I

Structures Found by Transmission Electron Diffraction of Oxide Films Produced on Chromium Steels When Oxidized for Short Times in Dry Oxygen at One Atmosphere Pressure.

O = Magnetite Structure Fe_3O_4 -
 $FeCr_2O_4$

Xn = Hematite Structure
 αFe_2O_3 - Cr_2O_3

a = thin, b = thick films

% Chromium Alloy

Time & Temp. of Oxidation	5	11	13	17	26
1/2 hr 700 C	a) X-X100; O				
	b) X100; O?		X100; O	X100; O	X100; O
1 hr 700 C	X100; O		X; O	X100	X100
1/2 hr 800 C	O	X; X100; O	X; O	X50	X; O
	a) X100; O		a) X-X75; O		
1 hr 800 C	b) X100		b) X75; O?	X100; O	X100; O
2 hr 800 C	X-X100; O?		X-X100; O	X100; O	X100; O?
1/4 hr 900 C	a) X100; O				
	b) X100	X100; O	X100; O	X100; O?	X100; O
1/2 hr 900 C	a) X75				
	b) X75; O	X75; O	X75; O	X75; O	X75-X100; O
1/4 hr 1000 C	a) X-X50; O				
	b) X75; O		X-X25; O	X75-X100; O	X100; O?
1/2 hr 1000 C	a) X50				
	b) X50; O	X75-X100	X75; O	X75; O	X75; O

of Cr_2O_3 in the X-phase with percentage chromium in the alloy. It is hoped that the accuracy can be increased somewhat in the future. There is some evidence that the proportion of the higher oxide increases with time of oxidation and is larger in the thick than in the thin films. This is consistent with the earlier work done by electron diffraction in reflection from the exposed surface of the oxide film during its growth, where it was shown that the Fe_3O_4 structure first formed was soon covered with an α Fe_3O_4 structure.⁴ Conversely, the present experiments demonstrate that the whole film does not become the latter structure; thus it is probable that the Fe_3O_4 phase is most prevalent on the inside of the film and that the film grows thicker chiefly by formation of the hematite phase. This suggests that the protective mechanism lies at or near the metal-oxide interface and limits the amount of metal ion available for reaction, rather than being a limiting process located at the oxide surface, e.g., limited rate of oxygen solution or limited reaction rate.

Although there is no positive electron diffraction indication of a correlation between oxide type and composition of alloy, i.e., rate of attack, the electron micrographs of the stripped films do show a dependence of the form of the oxide on alloy composition. The low chromium alloys give an oxide showing large crystalline masses in a matrix of small crystallites, while the higher alloys grow more uniform films of small crystallites. (Additional evidence has accumulated for the existence of a very thin, nearly structureless film accompanying the latter type.) It is conceivable that the overall composition of the oxide films on the different alloys is no more variable than the diffraction measurements imply, but that the variation in their protectiveness is associated with the degree of local imperfection indicated by the electron micrographs. These imperfections might be due, for example, to segregation of the oxide phases, or to fluctuations of the amount of chromium in solid solution, either in the alloy or in the oxide.

In these short time oxidation studies some removable surface scale was formed at temperatures of 800°C and above. These scales have been analyzed by X-ray diffraction methods, Table II, to compare with the results obtained with 20-hour (and longer) oxidation periods. The general trends are the same as observed earlier;⁵ α Fe_3O_4 increases, as the percentage of chromium in the alloy diminishes or the temperature of oxidation increases. The chief differences are that the Cr_2O_3 phase extends farther in both of these respects, than was observed with the longer oxidation times, and no trace of the spinel of large parameter peculiar to the 26% alloy (O*) is observed. This greater prevalence of the high-chromium phase in the scale formed in short times is in agreement with the previous measurements at 900°C for oxidation times of 5, 20, and 100 hours. The O* phase was also not found in the five-hour oxidation.

⁴Annual Report, Project SQUID, Purdue University, Phase 3, Table V, April, 1949.

⁵Quarterly Progress Report, Project SQUID, Phase 3, Table I, April, 1949.

As has been discussed previously,⁶ these studies of oxide scale show two groups of spinels of the magnetite structure, one (O) with a lattice parameter of approximately $a = 8.38 \text{ \AA}$ and a second (O*), formed only on the 26% alloy, with $a = 8.41 \text{ \AA}$. One would expect to find spinels with a lattice parameter approaching $a = 8.34 \text{ \AA}$ if the percentage of chromium increased toward the composition FeCr_2O_4 (chromite). It is thought that the expected variation may be masked by a compensating variation of the structure. This could be due either to deviations from stoichiometric proportions, (an excess of oxygen in the structure lowers the parameter) or to a partial or complete change from the "inverted" to the "normal" metallic ion arrangement, which should increase the parameter. The O* structure might also be accounted for on this basis, having perhaps a deficiency of oxygen (formed in the presence of chromium) or having reverted to the normal arrangement.

Since no systematic investigation of these points has been found in the literature, attempts have been made to synthesize iron and iron-chromium spinels having different lattice parameters, with the idea that if this is possible, chemical analysis can be used to correlate lattice parameter measurements with composition. Several variations of two basic methods of precipitation of the hydroxide and heating of the hydroxide to obtain the oxide have been used. In most cases the material is too finely divided to give good diffraction patterns, and in any case control of the degree of oxidation is not good. When the preparation is done in air, a slightly low value of parameter, $a = 8.37 \pm .005 \text{ \AA}$ is found. On heating in air at 250°C , this material converts to the magnetic ferric oxide form, $\alpha\text{Fe}_2\text{O}_3$, which has the same structure as magnetite, but a low parameter, 8.33 \AA , associated with the deficiency of metal ion present in the lattice. When the preparation is carried out under nitrogen, a parameter of $8.38 \pm .002 \text{ \AA}$ is found. No higher values have been obtained, but it is hoped that this may be possible with better elimination of oxygen.

Measurements of the electrical properties of the oxide scale and films have been started, since these properties may be of importance in determining the rate of oxidation. The electrical resistance of the oxide, for example, may be the limiting factor, as has been shown by Wagner and Mott. Since the metal diffuses to the oxide surface in the form of positive ions, a positive space charge will be built up and stop the process if negative charge cannot be conducted through the layer to neutralize this space charge. The rough preliminary measurements of oxide and film resistance which have been made indicate that this resistance is not very high. More elaborate and systematic measurements of this kind are in progress.

Even if the resistance is low, there is another possible electrical mechanism which might limit the outward flow of negative charge (either

⁶ Annual Report, Project SQUID, Purdue University, Phase 3, January, 1949.

electrons outward or positive "holes" inward). When contact is made between a metal and a "semi-conductor," such as an oxide, a potential hill is formed which may act as a barrier to the flow of charge. Since the height and nature of this barrier is determined essentially by the difference in work functions (the energy to remove an electron) of the two materials, experiments by which this difference may be estimated have been started.

The method in use is to measure the contact potential between the specimen and a standard surface. This gives the difference in work function of the two surfaces. Comparison of such measurements before and after oxidation of the metal surface will determine the difference in work function of the metal and oxide. (There are several complicating factors in the interpretation of these data which will have to be considered in some detail).

The measurements to date have been made at room temperature only and indicate that well-aged as machined surfaces of 446, 430, and 410 commercial chromium alloys (nominal chromium content, 23-30, 14-18, 10-13% respectively) have nearly the same work function. On polishing with 3/0 paper their work functions fall by 0.20 to 0.25 volts, the decrease being progressively greater in the sequence 446-430-410. On standing in air at room temperature, the values rise by approximately 0.1 volt over a period of hours; this may be due to a slow approach to an equilibrium following the abrasion or to the formation of an oxide film. Electrolytic polishing lowers the work function of the 430 and 410 alloys by an additional 0.2 volts, and this is followed by a rapid rise, presumably due to oxidation.

When these surfaces are oxidized for 5 minutes in one atmosphere of oxygen at 670° C, the work functions of the three alloys increased 0.7 to 1.2 volts in the sequence 410-430-446. This is followed on standing in air by a rather rapid decrease of 0.2 to 0.6 volts.

Interpretation of these data, as applying in detail to the actual oxidized metal surface and the oxide in contact with it, is perhaps questionable, but the change produced on oxidation is large enough that one is probably correct in drawing the conclusion that the oxide has a higher work function than the metal. This, if true, has the consequence that the potential hill between oxide and metal would not form a barrier to the passage of electrons, but would be a barrier to the flow of positive "holes". Which type of semi-conductor the actual oxides are, electron conductor or hole conductor, is not known. This is one of their properties which should be investigated.

The electron diffraction and electron micrography of stripped films will be continued at lower temperatures and with air as the oxidant, and attempts will be made to improve the accuracy of measurement.

X-ray diffraction of heavy scales will be continued with air as oxidant, and some of the oxygen work will be repeated with a very low carbon chromium

alloy which is now available. It is hoped that personnel will be available to resume the X-ray work on oxidation of nickel-chromium steels.

The attempts to synthesize spinels with a controllable lattice parameter, and to develop methods of chemical analysis of these and the natural oxides will be continued.

The measurements of electrical resistance and work functions will be extended and attempts will be made to carry out the measurements under the conditions existing at the operating temperatures.

It is hoped that arrangements will soon be completed for neutron bombardment of chromium steels, so that radioactive tracer experiments⁷ can be started.

PHASE 5

To determine, for liquid-fuel rockets and jet engines, the radiation factor and its contribution to heat-transfer coefficients inside a pipe with gas flow at low and also at high temperatures.

Phase Leader: J.M. Smith.

Convective Heat Transfer. A disc-doughnut type mixing device was provided for rapid determination of the entrance bulk mean temperature, however, the turbulence caused by this mixer was excessive and not dependent upon a bulk Reynolds number. Furthermore, the resultant data were not reproducible. Therefore, the mixing device was removed, and another method of determining the bulk temperature was developed.

Four thermocouples were installed around the periphery at the entrance of the test section flush with the inside wall of the tube. By means of wall temperatures determined by these thermocouples, plus the limited traverse of the shielded thermocouple for gas temperature determination, an approach can be made to the bulk mean temperature, using graphical methods.

In general, such a method requires the assumption of uniform velocity distribution or the assumption of a velocity gradient similar to the temperature gradient. The errors which may possibly result by assuming one case or the other may be minimized by appropriate adjustment of heat input, so

⁷Quarterly Progress Report, Project SQUID, Purdue University, April, 1949.

that the wall and gas temperatures at the entrance are approximately equal.

Heat transfer coefficients are being determined using the methods described above. Data are being taken and analyzed for 200-degree intervals from 550 to 1950° F.

The survey of air film coefficients will be completed shortly and the data analyzed so that a technical report may be submitted.

PHASE 7

To investigate rocket motor and liquid propellant parameters at high chamber pressures.

Phase Leader: M.J. Zucrow.

Design, Construction, and Instrumentation of the Rocket Laboratory.⁸
A Navy torpedo camera has been modified to utilize 100-foot rolls of 70 mm film at the rate of one picture per second. This camera is used to photographically record test data. An electrically driven torpedo air compressor with a capacity of 20 cubic feet per hour at 3000 pounds per square inch has been received. The compressor will be employed to pressurize nitrogen at the low pressure nitrogen remaining in the supply bottles and thus reduce the waste of nitrogen.

Two firings have been conducted on 430 pound thrust uncooled motor employing red fuming nitric acid and aniline at a mixture ratio of about 1.8 to 1. The purpose of this test and similar subsequent tests is to check the firing procedures and the test stand instrumentation.

After the test station equipment and instruments are thoroughly checked by running additional tests on uncooled motors, the first test motor will be installed, and data will be obtained on high pressure operation.

Because of the difficulties encountered with direct-coupled amplifiers and their associated calibration circuits necessary with the analogue

⁸Project Engineers: W.M. Hesse
C.M. Beighley
Franklin Michaels

computer,⁹ it was decided to abandon the determination of the propellant net weight with the supply tank pressurized. Instead, the actual weight of the propellant can be determined before and after the run with the tanks vented; the actual rate of flow can be determined by differentiating an electrical signal, which is proportional to the weight of propellant in the tank, and then applying the proper correction to the resultant. Such a procedure simplifies the necessary equipment without impairing the advantages of the system.

The required amplifier-differentiator has been built and preliminary tests have been satisfactory. It was necessary to regulate the heater supply for the tubes as well as the plate voltage supply to eliminate instability due to line voltage variations. A radar power supply unit is being modified for this purpose.

The prototype units will be tested with the weighing system in operation within a few days. If these tests are satisfactory, the equipment will be assembled in final form for relay rack mounting.

Work on modifying the Brown self-balancing potentiometer into the recording potentiometer ratiometer for measuring specific thrust directly is continuing.

Investigation of Ignition Lag on Spontaneously Ignitable Propellants.¹⁰
A technical memorandum covering the design, construction, and operating principles of the electronic ignition lag timer and reaction apparatus is nearing completion. It will describe the design, construction, and operating principles of the electronic ignition lag timer and reaction apparatus and the functional relationships between the component parts of the time and reaction apparatus, as well as the various electronic principles involved in the operating theory of the timer.

Figure 1 shows the assembly of the apparatus used in the reaction box. Figure 2 shows the device used for calibrating the electronic ignition lag timer; the calibration apparatus is connected electrically to the pulse generator-cathode follower. Figure 3 shows the complete set-up of timer and reaction box. The forthcoming technical memorandum will present full details regarding the operation of the equipment illustrated in the photographs.

It is planned to complete all of the measurements of the effect of temperature upon the ignition lag of the red fuming nitric acid and aniline in

⁹Quarterly Progress Report, Project SQUID, April, 1949.

¹⁰Project Engineer: S. V. Gunn.

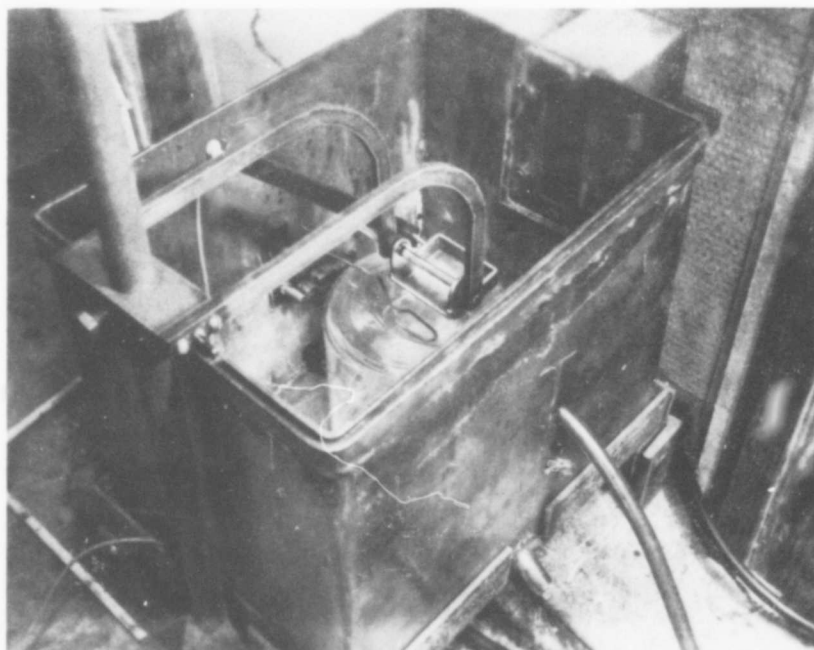


FIGURE 1. Reaction apparatus assembled in reaction box.

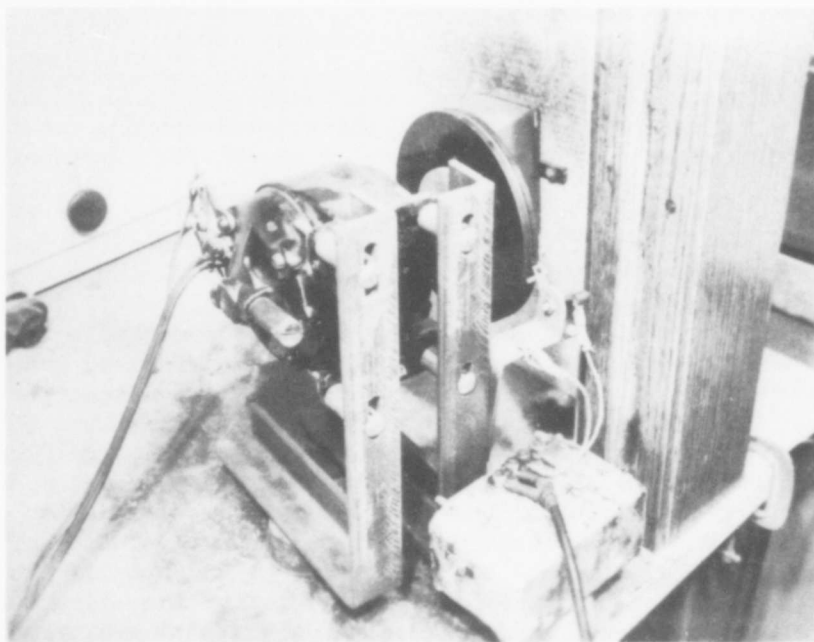


FIGURE 2. Device for calibrating electronic timer.

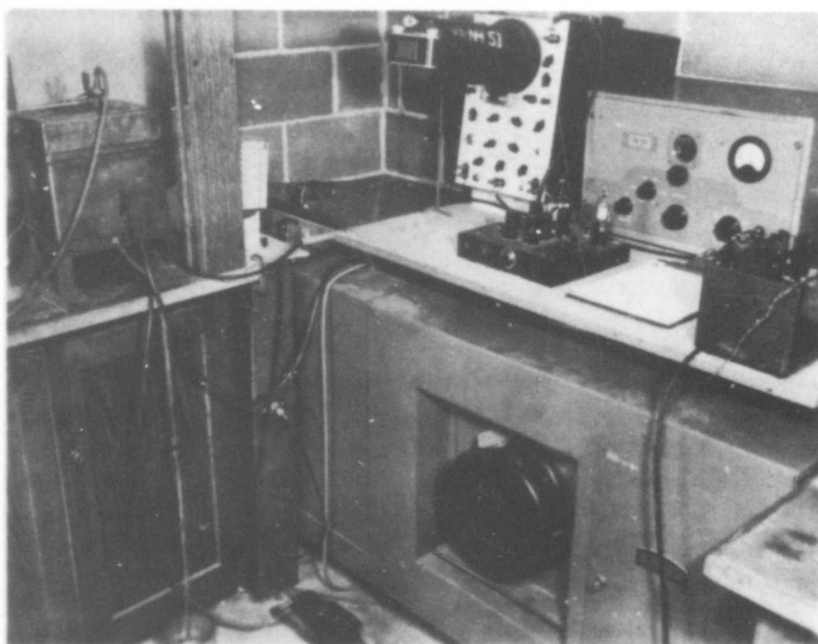


FIGURE 3. Overall laboratory setup.

the near future. After the completion of these measurements, the scope of the investigation will be widened to include other hypergolic bi-propellant systems.

Catalysis of the Reactions of Non-Hypergolic Propellants.¹¹ The investigation of the course of the liquid phase reaction between white fuming nitric acid (henceforth denoted by WFNA) and AN-F-58 jet fuel has been continued. A series of experiments was performed by adding WFNA to AN-F-58 jet fuel contained in a small Dewar flask. An iron-constantan thermocouple, sheathed by a glass tube, was placed at the interface between the WFNA and jet fuel, and the temperature at the interface was recorded by a Brown automatic temperature recorder. The increase in temperature in the region of the interface was measured for the O/F mixture ratios of 2, 3.8, 5.5, 6.3, 8, and 9 based on a constant weight of 5 grams of jet fuel. When WFNA and jet fuel are placed in contact to give a 2-phase system, there exists an induction period during which the temperature of the system rises steadily until the evolution of nitrogen dioxide begins, at which time the temperature rises very rapidly to a maximum value. The length of the induction period varies with the mixture ratio and the nature of the interface formed between the WFNA and the jet fuel. Under the experimental conditions employed in making these measurements, considerable difficulty was encountered in reproducing the interface between the two liquids at any one mixture ratio, therefore the induction times listed in Table III

¹¹ Project Engineer: C.H. Trent.

should be considered as rough, approximate values. It is noteworthy, however, that the temperature at which the evolution of nitrogen dioxide began was in no case below 160° F. Table III summarizes the results of these experiments.

Table III. Variation of Induction Time with O/F for WFNA - AN-F-58 Systems

Mixture Ratio	Grams Fuel	Grams WFNA	Induction Time-Sec.	Temp. Evolution NO ₂ °F	Initial Temp. °R.
2.0	5	10.	183.	160	55
4.8	5	24.	111.2	180	55
5.5	5	27.5	111.5	165	55
6.3	5	31.5	99.1	170	60
8.0	5	40.	134.8	168	68
9.0	5	45.	170.0	180	65

When WFNA is added to AN-F-58 in a Dewar flask provided with a mechanical stirrer to increase the interface, the oxidation proceeds immediately with a rapid rise in temperature. The maximum temperature reached is the same as that produced by the respective 2-phase system.

Another series of experiments was undertaken to determine the course of the reaction between WFNA and AN-F-58 jet fuel during the induction period preceding the evolution of nitrogen dioxide. In one experiment 27.5 g WFNA were added to 5 g of AN-F-58 contained in a Dewar flask, and the two phases were allowed to remain in contact for 91.3 seconds before the reaction was stopped. A dark red oil weighing 2 g was isolated. This oil contained nitrogen and gave reactions characteristic of a nitro-compound. When purification was attempted by distillation, the oil smoothly decomposed into a viscous black oil. Because of the complexity of the composition of AN-F-58 and the small quantities of materials used, the products of the reaction have not yet been separated into pure compounds which can be characterized; however, the facts indicate that to a certain extent there is considerable nitration of the jet fuel during the period preceding oxidation.

It is planned to rectify the AN-F-58 jet fuel into 10-degree fractions and at least determine the type of hydrocarbon present in each fraction. These 10-degree fractions in turn will be used in experiments similar to those previously described to determine the course of the reaction between WFNA and jet fuel.

The Cooling of Rocket Motor Nozzles by Transpiration Cooling Through Parallel Disks.¹² Preliminary runs have been made on Test Section No. 1 described in Quarterly Progress Report, 1 April 1949. Test Section No. 1 is composed of a rectangular-shaped flow passage with a plate glass window on one side. A fluid, liquid, or gas, is injected into the rectangular passage through a slot at the bottom. A visual study is then made of the flow pattern.

The preliminary tests, using water as the injected fluid, indicate that there is a definite velocity at which the injected fluid breaks away from the wall and is injected directly into the main gas stream. No quantitative data have been taken as yet.

A 100-point velocity traverse was made of the flow passage at a Reynolds number of 200,000. This traverse indicates a fairly uniform velocity profile across the flow passage.

Sealing the slot blocks and the coolant manifold against leaks presents a problem. A copper gasket, rubber gasket, and airplane cement have been tried, and all of these proved to be unsatisfactory. In order to eliminate this sealing problem it has been suggested that the slot be replaced by a round hole. This method will present only the problem of sealing two flat surfaces. A series of tests will be run to determine whether the fluid injected from a round hole will give the same flow characteristics as fluid injected from a slot.

In order to study visually the flow pattern produced when one gas is injected into another gas, the injected gas must be made visible in some manner. An attempt was made to mix the injected gas with smoke. It was found that the smoke particles from commercial smoke bombs clog the flow lines and slot. A new smoke generator using hydrochloric acid and ammonia fumes is under construction.

Test Section No. 1 will be run to obtain all the liquid injection data. The aforementioned smoke generator will be tested in the coolant line, and, if possible, gaseous data will be obtained. Correlation of these data in terms of the various flow parameters will follow.

The design of Test Section No. 2, the heat transfer section, has been completed. Construction and installation of this test section has been postponed until all tests on Test Section No. 1 have been completed.

¹²Project Engineer: C.M. Beighley.

C O R N E L L A E R O N A U T I C A L L A B O R A T O R Y , I N C .PHASE 1

In connection with jet propulsion engines: (1) to study the mechanism on nonsteady flow in simple ducts with particular reference to acoustic jets, inflow and outflow phenomena in jet engines, and the stability of shock waves in diffusers, and (2) to study the operation of shrouded pulse jets.

Phase Leaders: J.V. Foa and G. Rudinger.

Valveless Pulse Jet. A report on the small scale experiments which have been conducted so far has been completed.¹

Some thought was given to new designs of the inlet configuration of valveless pulse jets which would utilize the experimentally observed tendency of flows to follow a convex curvature of a wall on one side without any constraining wall on the other. (Coanda effect). If this scheme were successful, inflow could take place through a practically open inlet tube while reverse flow could be deflected by the Coanda effect and exhausted downstream. A preliminary series of experiments on the Coanda effect was undertaken with a two-dimensional model. Some carbon dioxide was added to visualize the flow. The strong deflection of a jet without any constraining wall is clearly shown in Figures 1a and 1b. The experiments were carried out both with steady (Figure 1a) and with pulsating flow (Figure 1b) and no difference was observed.

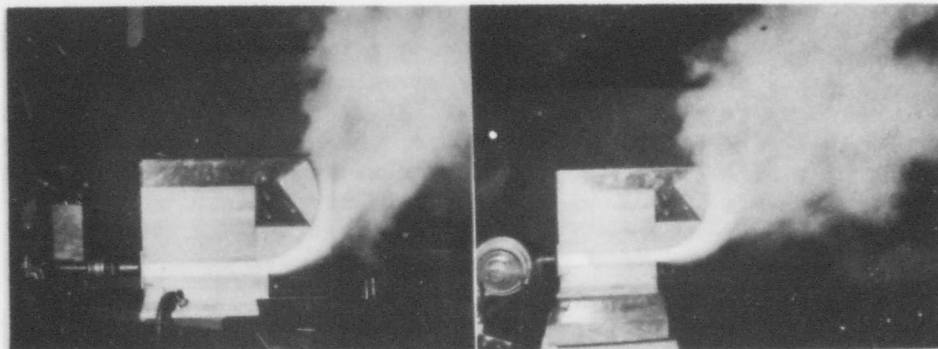


FIGURE 1a. Coanda effect in steady flow.

FIGURE 1b. Coanda effect in pulsating flow.

¹J.G. Logan, Jr., "Valveless Pulse Jet Investigations, Part I, Test of Small Scale Models," SQUID Technical Memo. No. CAL-27, May 1949.

Further work on the valveless pulse jet for helicopters has been delayed pending the availability of a test facility. Attempts will be made to develop a valveless pulse jet of short overall length for this application. Earlier, a glass-walled, two-dimensional model of a valveless pulse jet had been built to study optically the internal phenomena. Since this model did not operate smoothly, a new model was constructed of 1/16 inch steel, which allowed assembly of different combinations of round and/or square combustion chambers and tail pipes. Four combinations were tried and all operated satisfactorily although the square combination was slightly more difficult to start. It appears, therefore, that the previous difficulty with the square model was primarily due to the lower rigidity of the glass walls and not, as first believed, to the influence of the shape on the flow and combustion phenomena. The earlier model is being modified in accordance with this conclusion.

Several characteristics diagrams are being prepared to study theoretically the shape phenomena of one of the small-scale models. The combustion chamber is considered completely or partly filled with mixtures for which various values of heat release are assumed. The rate of energy release is taken as constant during a selected combustion time. The characteristics diagrams are constructed up to the time when the pressure at the closed end of the combustion chamber becomes equal to the initial pressure. This time is, at present, considered to be one-half of the total period. It is also assumed that the remaining half of the period during which scavenging and recharging take place does not contribute any thrust or drag. From a completed diagram it could be shown that at any time, the pressure is approximately uniform in the combustion chamber. Thrust is, therefore, being calculated as the product of pressure at the closed end of the combustion chamber and tail pipe area. It is then possible to calculate the operating frequency of the pulse jet and the specific impulse. The results of the first trials are promising but better assumptions for the initial conditions must be made. In the course of this investigation, it was noted that whenever an interface between hot and cold gases reaches the open end of the tail pipe, very strong pressure waves may be set up in cases where the flow velocity is sufficiently high; If, for example, the cold gas leaves the tail pipe at a Mach number one, the pressure at the exit may be considerably higher than the outside pressure. When the interface reaches the open end, the Mach number behind it may drop to less than one and the high pressure can be no longer maintained at the exit. As a result, a strong expansion wave travels into the duct.

Ducted Pulse Jet. An investigation has been started to study ducted pulse jets, where the pulse jet operates inside a surrounding duct of suitable configuration. Such a propulsion device may have a better performance than the pulse jet alone at high flight speeds and may also be better than a ram jet in certain ranges of flight Mach numbers. It is, therefore, necessary to determine whether a ducted pulse jet could produce sufficient thrust to overcome the drag and accelerate itself from rest to the design velocity.

The first analysis is based on the following assumptions: (a) the duct surrounding the pulse jet is designed to make the pulse jet operate in a flow of a fixed low Mach number (at present, $M = 0.25$ is being used); (b) the thrust of the pulse jet alone is proportional to the static pressure at some reference point of the ducted flow in which it operates; (c) the specific impulse of the pulse jet alone is constant; (d) the inlet configuration at supersonic flow is a Kantrowitz-Donaldson diffuser adjustable for any flight Mach number; (e) the average shock position is assumed to be that section of the expanding region of the diffuser where the Mach number is equal to the free stream Mach number in order to allow for flow fluctuations without spillover; and (f) the exit is a converging-diverging nozzle for complete expansion. The calculations are carried out on the basis of steady flow, assuming that all values are mean values and that the pulse jet operation is not affected by the fluctuations. From these first calculations thrust can be found for any altitude and flight Mach number. It appears that ducting not only keeps the pulse jet working at high flight Mach numbers but also has a considerable augmentation effect. A comparison of these results with the performance of a ram jet has just been started and no conclusions have been drawn.

For the purpose of verifying the validity of the steady flow assumptions made in the analysis, a preliminary experimental series was undertaken to study the rate of decay of pressure disturbances in a ducted pulse jet. A pulse jet was simulated by a mechanically controlled intermittent air jet discharging into a constant area duct. The injector nozzle was surrounded by streamlined bodies blocking various fractions of the duct. Instantaneous pressure recordings were obtained at various points along the duct and for various frequencies of the injected flow. This series has been completed but the data are still being evaluated.

Stability of Shock Waves in Supersonic Diffusers. An experimental model has been constructed to study the effect of fluctuating back pressure on the motion of a shock in a diffuser. The diffuser exit leads to a rotating valve which in turn will be connected to the Cornell Aeronautical Laboratory's altitude chamber which is to act as a low pressure reservoir. It is planned to use a stroboscopic schlieren system for observation of the shock motion. Actual experiments will start as soon as the altitude chamber becomes available.

A transient behavior of the mass flow in a duct was studied in detail in the course of a theoretical analysis of interrupted supersonic flows. If a flow in a pipe is suddenly interrupted by a valve, a high pressure is built up on the upstream side of this valve and a low pressure develops on the downstream side. The pipe is assumed to be infinitely long to eliminate any effects from waves reflected from the ends. If the original flow is supersonic, the disturbance created by a short interruption of the flow travels only a limited distance

upstream² The mean mass flow for the whole transient, from the initial interruption until reestablishment of the original flow, must, therefore, be equal to the original mass flow to m_0 . Since $m = 0$ while the valve is closed, the mass flow must reach some value greater than m_0 during the transient. At the first instant when the valve is opened, the pressure ratio across the valve is at its highest value. In spite of this, the mass flow at the first instant of the transient was found to be lower than m_0 . The complete transient was analyzed by means of the method of characteristics. Figure 2 shows the ratio m/m_0 as function of time where t_0 is the time during which the valve is closed. The steady flow Mach number in this example was 1.5.

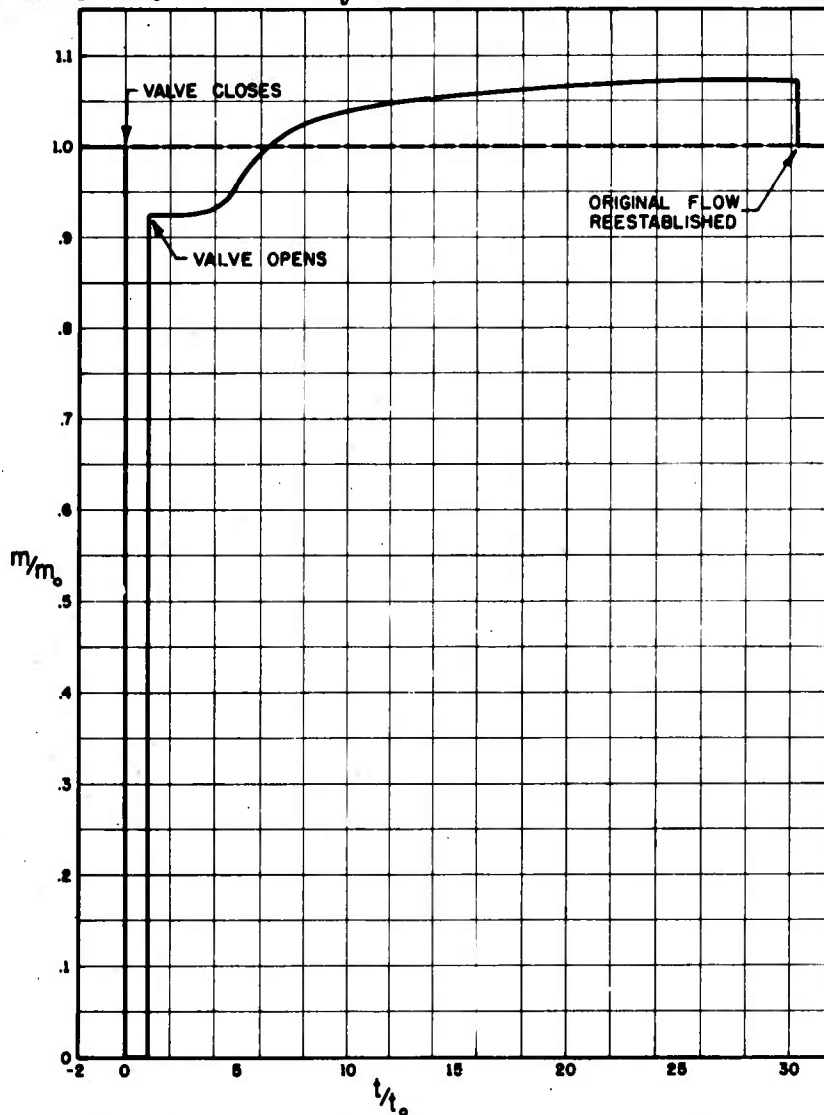


FIGURE 2. Mass flow transient at the position of a valve in an infinitely long pipe when the valve is suddenly closed and reopened after a time t_0 .

²Project SQUID, Annual Report, 1 January 1949, p. 116.

PHASE 2(a)

In connection with jet propulsion engines: to investigate ignition and flame propagation and stability as affected by physical parameters with particular reference to the interaction between flow disturbances and flame propagation.

Project Leaders: J.V. Foa and G. Markstein.

Disturbances on Burner Flames. The work on effects of disturbances on burner flames and on flame propagation in the combustion chamber was temporarily suspended during this quarter.

Combustion Tube Experiments. The study of cellular flames in tubes has been continued considering the influence of the type of fuel. Cell structure was found to occur with all fuels investigated; these included saturated and unsaturated C₂, C₃, and C₄ hydrocarbons. Previously, it was found that no cells could be observed with methane in a 4 inch tube. Photographs of the flames were taken in order to determine the average size of the cells, but have not been evaluated. From visual observation, it can be said that the cell size decreases markedly with increasing number of carbon atoms in the fuel molecule; the number of hydrogen atoms seems to have little influence.

The limit compositions at which the cell structure disappears has been determined for all these gases. It was found that in every case the limit lies very close to stoichiometric composition, the cells appearing always to the rich side of the limit. Table I gives the limit compositions in volume percent of fuel in the fuel-air mixture, and the deviations from stoichiometric composition. Since these deviations are within the errors of measurement, it would seem plausible that the limit may be exactly at stoichiometric composition. In all cases a certain amount of nitrogen was added to the mixture to reduce the flame propagation velocity to prevent flash back. It had been established previously that the nitrogen concentration did not affect the limit air-fuel ratio.

Substitution of carbon dioxide instead of nitrogen as diluent gas was tried in combination with butane air mixtures. Apart from a decided change of color of the rich flame from greenish to blue, the phenomena are substantially the same as with nitrogen; the size of the cells has not yet been determined, but appears to be slightly smaller than with nitrogen.

The irregular motion of the cells was generally too fast to be analyzed by visual observation or by motion pictures taken in the direct light of the flame. Therefore, high speed shadowgraph motion pictures

TABLE I

Limit Compositions for Cellular Flame Structure

Fuel	Volume percent of fuel in fuel-air mixture	Percent deviation from stoichiometric composition
Acetylene	7.86	+1.5
Ethylene	6.42	-1.7
Ethane	5.83	+3.0
Propylene	4.33	-3.0
Propane	4.08	+1.2
Butadiene-1,3	3.75	+1.9
Butene-2	3.53	+4.2
iso-Butylene	3.45	+2.0
n-Butane	3.14	+0.2
iso-Butane	3.12	-0.3
Average	----	+ 0.9

of cellular flames were taken by using a parallel beam of light traversing the flame tube axially. They revealed that the larger cells have a tendency to grow at the expense of their smaller neighbors, and split up into two or more cells when their size substantially exceeds the average size.

The determination of cell size as a function of pressure has not been carried out because the altitude chamber has not been available. These tests are now scheduled to take place in the near future.

High-speed movie shadowgraph studies of the modifications of flame structure which occur when the flame causes oscillations of the gas column have been continued. The optical system used for taking these shadowgraphs was the same as in the study of the undisturbed cell structure. The flame propagated from the upper open end to the lower closed end of the tube. Under these conditions, three distinct stages can be observed, as mentioned in previous reports: an initial "uniform movement" without oscillations, an intermediate stage with small amplitude oscillations and little change of propagation velocity and a final stage of large amplitude oscillations accompanied by a substantial increase of propagation velocity.

The results of these studies obtained so far are of a preliminary nature, but have already revealed some interesting information. In the rich mixtures studied until now, the state of uniform movement is characterized by cell structures very similar to the ones observed with stationary or almost stationary flames. Figure 3 shows what happens during the period of small amplitude

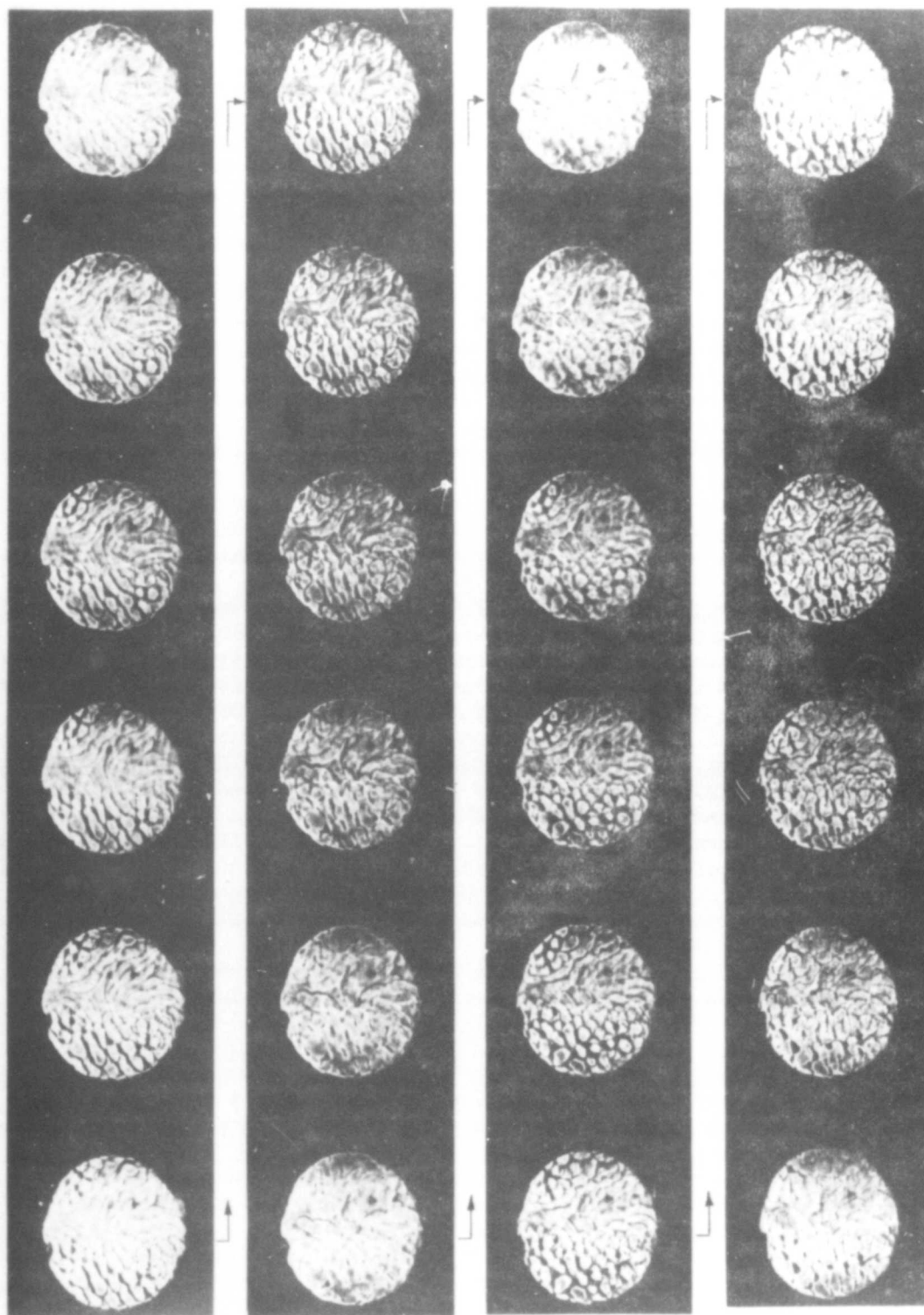


FIGURE 3. Shadowgraph high-speed movie of vibratory flame motion. Oscillation of small amplitude, $f = 100$ c.p.s. approximately 1500 frames p.s.

oscillations; cells are seen to appear and disappear periodically in the rhythm of the oscillation. If it is admitted that the undisturbed cell structure is caused by an instability of the flame front, then the oscillations of the gas column must cause periodic increases and decreases of the instability. This may be due to the effect of acceleration on the stability of the flame front, regarded as an interface of two gases of different density, as postulated by G.I. Taylor. Acceleration towards the unburned gas should cause instability and towards the burned gas result in stability.

In order to obtain a correlation of the pressure variation at the closed end of the tube and the observed flame structure, the light spot of an oscilloscope connected with a pressure pickup in the flame tube was photographed simultaneously with the flame shadowgraphs on the high-speed movie. This technique appears very promising for studies of this type. Qualitative evaluation of the records obtained in the case of weak oscillations showed that the instant of most pronounced cell structure corresponds to a minimum of pressure at the closed end. Since this corresponds also to maximum acceleration towards the closed end (i.e., towards the unburned gas), the result is in agreement with the explanation given above.

During the stage of strong oscillations, the shadowgraphs showed a different flame structure, characterized by a coarser pattern which shows very pronounced changes during each cycle of the oscillation. This structure seems to have a tendency to assume regular geometrical patterns; in a tube of 2 3/4 inch ID, a pattern with a threefold axis of symmetry in the center was repeatedly observed as shown in Figure 4. Due to the high frame rate, only about half a cycle is shown. On this particular reel, recurrence of this type of pattern during twelve cycles was observed. Close inspection of the reel revealed, however, that the patterns in alternate cycles are similar but turned through an angle of 60 degrees with respect to each other; the period of the pattern is thus twice the period of the oscillation. An interpretation of this phenomenon has not been attempted. High-speed motion picture studies of vibratory flame motion are continuing.

The theoretical studies of flame front stability and of vibratory flame motion have been continued. Memoranda on these studies are being prepared.

A study of the effect of the rate of combustion on the impulse of a straight tube closed at one end has been undertaken. An example was computed by the method of characteristics to serve as a check.

First a thermodynamic approach was attempted neglecting the effect of waves. Attempts to assume a pressure-time curve and to calculate the corresponding rate of heat release were unsuccessful because no simple analytical expression for the pressure curve could be found that did not give excessive heat absorption during blowdown.

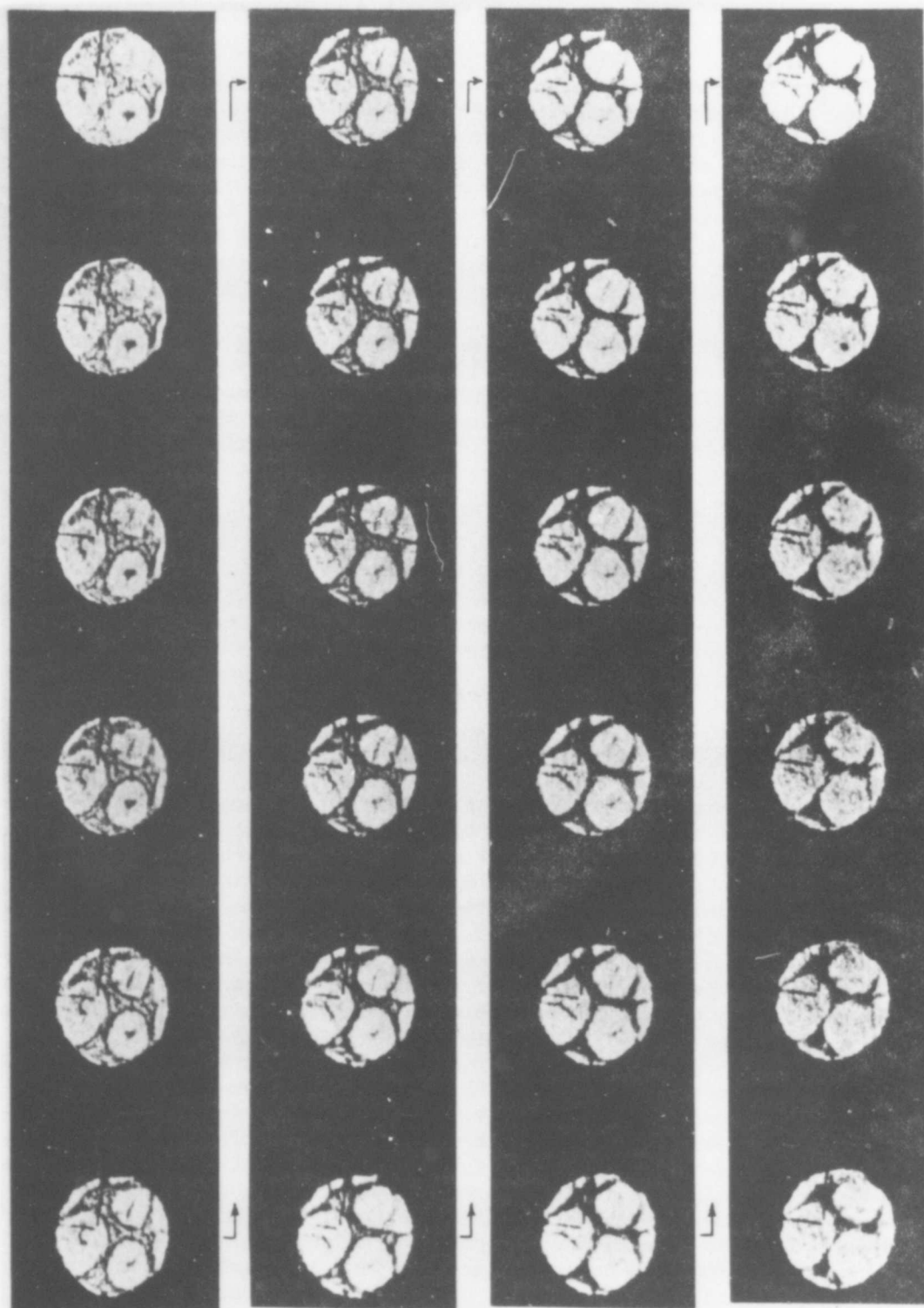


FIGURE 4. Shadowgraph high-speed movie of vibratory flame motion. Oscillation of large amplitude, $f =$ c.p.s. approximately 4500 frames per second.

Attempts to treat the problem as a variational problem led to trivial solutions. Examination of the characteristics diagram showed that practically the entire pressure rise (at the closed end) took place before a wave from the interface reached the closed end. During the time preceding the passing of this wave, combustion took place at constant volume and the pressure could be calculated easily. The time for the wave to reach the closed end could also be calculated, thus a reasonable estimate for the peak pressure could be obtained. However, it did not seem possible to calculate the rest of the cycle without considering wave phenomena.

Another attempt at the solution was made by writing the equations of motion in Lagrangian coordinates and linearizing them by expanding the unknown in a series with the rate of heat release as parameter. This approach is similar to that used previously³ differing in that energy release takes place simultaneously throughout the entire combustible mixture and not in a travelling zone of limited width.

PHASE 2 (b)

To study the mechanism of combustion and attendant reactions by the application of spectrographic and other techniques.

Phase Leaders: P.K. Porter and J.T. Grey.

Combustion Spectra. The study of combustion phenomena at low pressure has been continued through the spectrographic examination in the ultraviolet region of stable flames, burning over a range of pressures and oxygen-fuel ratios. The variation in the intensity of the OH, CH, and C₂ bands as a function of pressure, mass flow, partial pressure of the hydrocarbon, and oxygen-fuel ratio has been evaluated. Within the limits of the variables examined, the intensity of the OH bands is found to be independent of the mass flow and the partial pressure of methane and to increase linearly with burner pressure up to about 25 mm, at which point a gradual progressive increase in the slope of the curve begins. The CH bands were also found to be independent of the mass flow, to increase linearly with increasing partial pressure of methane and also with decreasing oxygen-fuel ratio, and to increase with burner pressure up to about 25 mm, at which point a gradual progressive decrease in the slope of the curve was found. The fact that linear increases were observed for both the partial pressure of methane and the oxygen-fuel ratio (which represents the reciprocal of the partial pressure of methane) indicates that the spread of experimental parameters was insufficient to establish the dependence uniquely. The intensity of the C₂ bands was found to increase linearly with increasing partial pressure of methane and to increase with pressure up to a burner pressure of

³S.A. Schaaf, Zonal Combustion in Tubes, Quarterly of Applied Mathematics, Vol. 6, 257-266, 1948.

about 25 mm, at which point a gradual progressive decrease in the slope of the curve was observed. These data have been compiled in Technical Memorandum CAL-24.

It is proposed to continue this investigation in accord with the program outlined in Technical Memorandum CAL-22 and the Annual Squid Report on this project for 1948.

PHASE 3

To study the physical properties and mechanism of failure of materials for high temperature application in connection with jet engines.

Phase Leaders: P.K. Porter and L.W. Smith.

Sigma Phase Strengthening. One part of the investigation of the effect of sigma phase on the high temperature properties of stainless steels was concluded and reported in detail as CAL Technical Memo No. 26, 1 May 1949. This study was concerned with the 25Cr-20Ni type steel and particularly the 2 percent silicon variety. The following conclusions were made:

1. The sigma phase, in general, increases appreciably the tensile and yield strengths of the 25Cr-20Ni type of alloy at temperatures up to 1400° F.
2. The creep strength may be increased for relatively short life applications involving deformation in the order of one percent per hour for temperatures up to approximately 1400° F.
3. Where slow strain rate conditions are involved, as in long service life applications, the sigma phase lowers creep resistance.
4. The pattern of distribution of the sigma constituent in the austenite matrix is quite significant in effecting the magnitude of these effects. The finer the sigma particle size the greater is the decrease in long time creep strength relative to the fully austenitic-structure. This is quite likely due to the large number of grain boundary discontinuities introduced into the micro-structure which provide additional dislocations leading to plastic flow under slow strain rate and high temperature conditions.
5. Sigma phase materially decreases the room temperature ductility of the parent alloy although increasing ductility is restored at room temperatures above 1000 to 1200° F. This property is quite dependent upon the sigma distribution, the better ductility characteristics being obtained with the finer and more random occurrence of the sigma.
6. Room temperature bend properties of the sheet alloy are decreased as the result of sigma formation with time at temperatures in the

range of 1200°F to 1800°F. This condition may be improved, where practical, by controlling the pattern of sigma formation.

7. Cold working in conjunction with the selection of exposure temperature provides a convenient and flexible means for controlling the mode of distribution of the resultant sigma constituent.

8. While the sigma phase can be readily formed and manipulated in the two percent silicon analysis, type 314, greater difficulty is encountered in promoting this constituent in the low silicon grade, type 310. Smaller quantities of this phase and more sluggish reactions are the case for the 310 analysis.

9. The possibility of deliberately utilizing the sigma phase in the 25 Cr-20Ni-2Si stainless steel for improvement of the high temperature strength properties of this alloy would seem to have some merit for the shorter time service applications. It is unlikely that similar long time high temperature gains can be made in this manner.

While this phase of the work is momentarily inactive, it is planned to investigate further the possibility of utilizing the sigma constituent as a high temperature strengthener for the austenitic stainless steels. In view of the results obtained and the conclusions made for the types 310 and 314 steels, it is likely that improvement of the austenitic chromium-nickel steels, through manipulation of the sigma phase, can be made only for the shorter time service applications. These conclusions will be checked using types 309 and 317 stainless steels.

Dynamic Creep. The creep of metals at high temperatures under fluctuating load conditions is being studied with the objective of evaluating the effect of the following variables: frequency of sine wave stress variation; amplitude of fluctuating load; magnitude of static load; and temperature (cold working and annealing range).

Initial tests have been made with an Armco iron sheet and have served the purpose of establishing a satisfactory testing technique with the fluctuating load apparatus. It is expected that the correlated data to be obtained with a material such as Armco iron should evaluate the effect of the above listed variables without introducing such factors as microstructural changes occurring during the course of testing.

A test schedule for the Armco iron has been set up involving tests at 800° F, 1000° F, and 1200° F with at least two static stresses at each temperature. For each static stress two fluctuating loads of amplitude equal to 25 and 50 percent of the static value will be superimposed and each stress combination will be tested at four frequencies of approximately 1, 10, 100, and 1000 cycles per minute. Such a series of tests should be capable of evaluating the material's creep characteristics under fluctuating load conditions. Results of a similar nature will be obtained later on commercial heat-resistant alloys.

High Temperature Deformation. In order to extend the strain rate range of the high temperature deformation data previously obtained through true stress-true strain tensile testing of high purity copper, aluminum, and Armco iron, these same materials are to be tested in creep apparatus under constant true stress conditions. By using lower stress values it should be possible to extrapolate the activation energy of deformation versus stress relationship to zero stress more accurately and thereby obtain a more precise comparison with the activation energy values of self-diffusion for these same metals.

A series of creep tests is planned for the Armco iron in which the carbon content will be varied over the range of approximately 0.001 to 0.1 percent by wet hydrogen and carburizing treatments. Such tests should be helpful in clarifying the role taken by an interstitial solute element in hindering creep deformation according to a diffusion type mechanism.

High Temperature Bending Fatigue. Activity is being resumed in evaluating the bending fatigue properties of a number of heat-resistant sheet materials such as 314 stainless steel, inconel, and S-816 in the 1200° F to 1800° F temperature range.

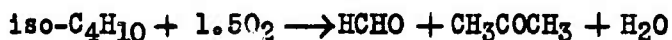
P R I N C E T O N U N I V E R S I T YPHASE 2¹

To study: (1) the characteristics of combustion in high velocity fuel-oxidant streams, ignitibility, efficiency, after-burning, thrust, etc.; (2) effects of sub-atmospheric pressures; (3) interactions between ionization and flame; (4) observation of optical and mass spectra; and (5) theory of adiabatic exothermic reaction.

Phase Leader: R.N. Pease.

The following topics are currently under investigation: (1) use of hydrogen atoms to sensitise hydrocarbon-oxygen mixtures; (2) slow combustion of the butanes; (3) slow combustion of ammonia; (4) kinetics of the decomposition of diborane, and of aluminum borohydride; (5) photo-chemical explosion of hydrogen-chlorine mixtures; and (6) hydrogen-atom diffusion theory of flame speeds.

As a means of elucidating the mechanism of hydrocarbon combustion, the interaction of hydrogen atoms from a Wood's discharge tube with hydrocarbon-oxygen mixtures at room temperature, and pressures of about 0.5 mm, has been studied (Technical Memorandum Pr-13). Under like conditions it is found that olefines react more rapidly than paraffins and that for methane through butane there is about a 10-fold increase in reactivity. The products for the most part are aldehydes. However, with isobutane, acetone is obtained along with roughly equal quantities of formaldehyde, as though the overall reaction were:-



A somewhat similar result is obtained when iso-butane reacts with a small amount of oxygen (5%) at 300-450°C and 1 atm. Substantial quantities of formaldehyde (and water) are again obtained but it is not certain as yet how much acetone is formed. (There is always a considerable amount of carbon monoxide.) With n-butane the products tend to be formaldehyde and acetaldehyde, along with water and carbon monoxide.

In the slow non-catalytic oxidation of ammonia (Technical Memorandum Pr-10), it is found that the per cent ammonia reacting decreases rapidly as the per cent ammonia in the reaction mixture (with oxygen) is increased.

¹This phase is jointly sponsored with the U.S. Bureau of Ordnance APL-JHU associated contract number NOrd-7920, Task PRN-3.



This effect is so marked that equal percentages react at about 450°C for 1% ammonia in oxygen, and at 675°C for a 50% ammonia mixture. Thus, ammonia is an inhibitor of its own oxidation. Since there is little difference in rates for an empty silica reaction tube and a similar tube packed with silica tubing, the reaction is not surface-catalysed in the ordinary sense. However, if either tube is first washed out with a potassium chloride solution, rates are decreased. This would point to a chain reaction, with chains initiated and terminated at the walls.

Studies of the kinetics of decomposition of diborane (B_2H_6) and of aluminum borohydride ($Al(BH_4)_3$) as vapors at sub-atmospheric pressure reveal that both react at conventional rates in the range 100°- 200°C. With diborane (Technical Memorandum Pr-14) the reaction seems to be fundamentally of 3/2 order, indicating a dissociative equilibrium as the primary process. There is little effect of surface, but added hydrogen is definitely a depressant. This is consistent with the progressive fall in calculated 3/2 order rate constants.

The decomposition of aluminum borohydride (Technical Memorandum Pr-12) is likewise little affected by surface. However, in this case the fundamental order seems to be nearer the first.

Further work will be done on the systems discussed. In addition it is planned to study spark and pilot-flame ignition of analogous systems.

The following Technical Memoranda have been submitted:-

Technical Memorandum Pr-10, "The Thermal Oxidation of Ammonia with Oxygen," by E.R. Stephens, 15 April 1949.

Technical Memorandum Pr-12, "A Further Study of the Kinetics of Thermal Decomposition of Aluminum Borohydride," by R.S. Brokaw, 31 March 1949.

Technical Memorandum Pr-13, "Hydrocarbon Oxidation Initiated by Atomic Hydrogen," by E.J. Badin, 15 June 1949.

Technical Memorandum Pr-14, "Preliminary Report on the Kinetics of the Thermal Decomposition of Diborane," by R.P. Clarke, 15 June 1949.

PHASE 3

To investigate theoretically and experimentally several of the basic problems associated with the development of propulsive devices of the ducted type. Specifically these problems are: (1) mixing of primary and secondary streams; (2) study of schemes such as "Coanda effect" to improve mixing; (3) combustion chamber problems of ducted rockets.

Phase Leader: J.V. Charyk.

Air Ejector. The present axially symmetric air ejector is illustrated in Figure 1. It consists of a standard rocket body adapted to the air supply formerly used for the two dimensional mixing channel. The supersonic jet is directed into a 6 inch OD plexiglass duct that can be adjusted to any fixed length and is mounted so as to move freely along its center line so that net thrust can be measured by the platform scale through the linkage shown. Figure 2 shows the device fitted with an inlet diffuser. The downstream end of the duct (not shown) can be similarly fitted with an exit nozzle.

For performance studies the present arrangement is somewhat superior to the two dimensional channel previously employed. The latter is, of course, better suited for fundamental studies of the basic mechanism of mixing. It is planned to continue the two dimensional studies with a modified channel at a later date.

The axially symmetric configuration has eliminated the dominance of friction effects that result from width limitations experienced in the ejector studies with the two dimensional channel. The air supply was not sufficient to increase the channel width to a more satisfactory dimension. Therefore, it is hoped that with the axially symmetric arrangement which is similar to the rocket ejector configuration it will be possible to correlate the results. The new arrangement also enables thrust readings to be taken and direct comparisons to be made of the efficiencies of various inlet and exit sections.

A series of tests have been run where velocity at the end of the duct and thrust less friction of the duct (net thrust) have been measured as a function of primary jet stagnation pressure. Figure 3 shows the measured

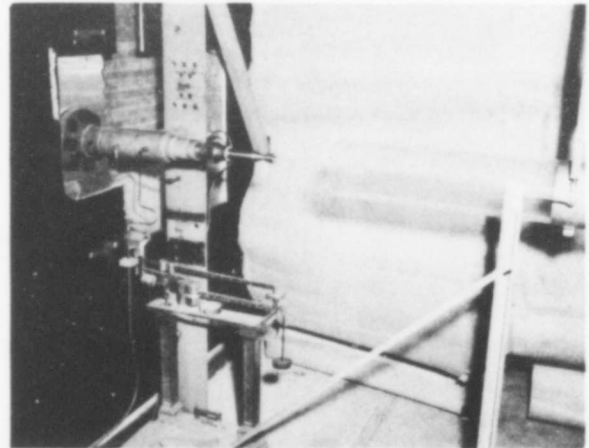


FIGURE 1.

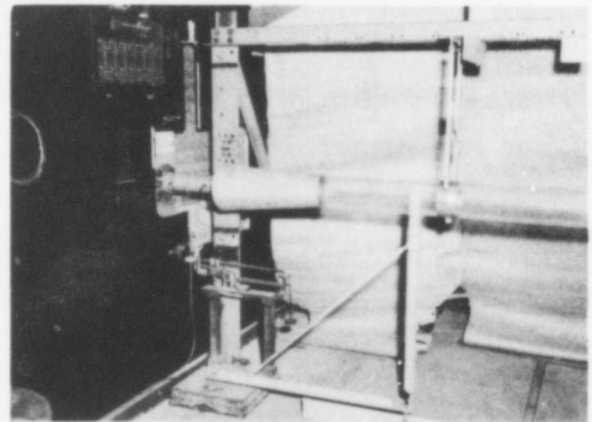


FIGURE 2.

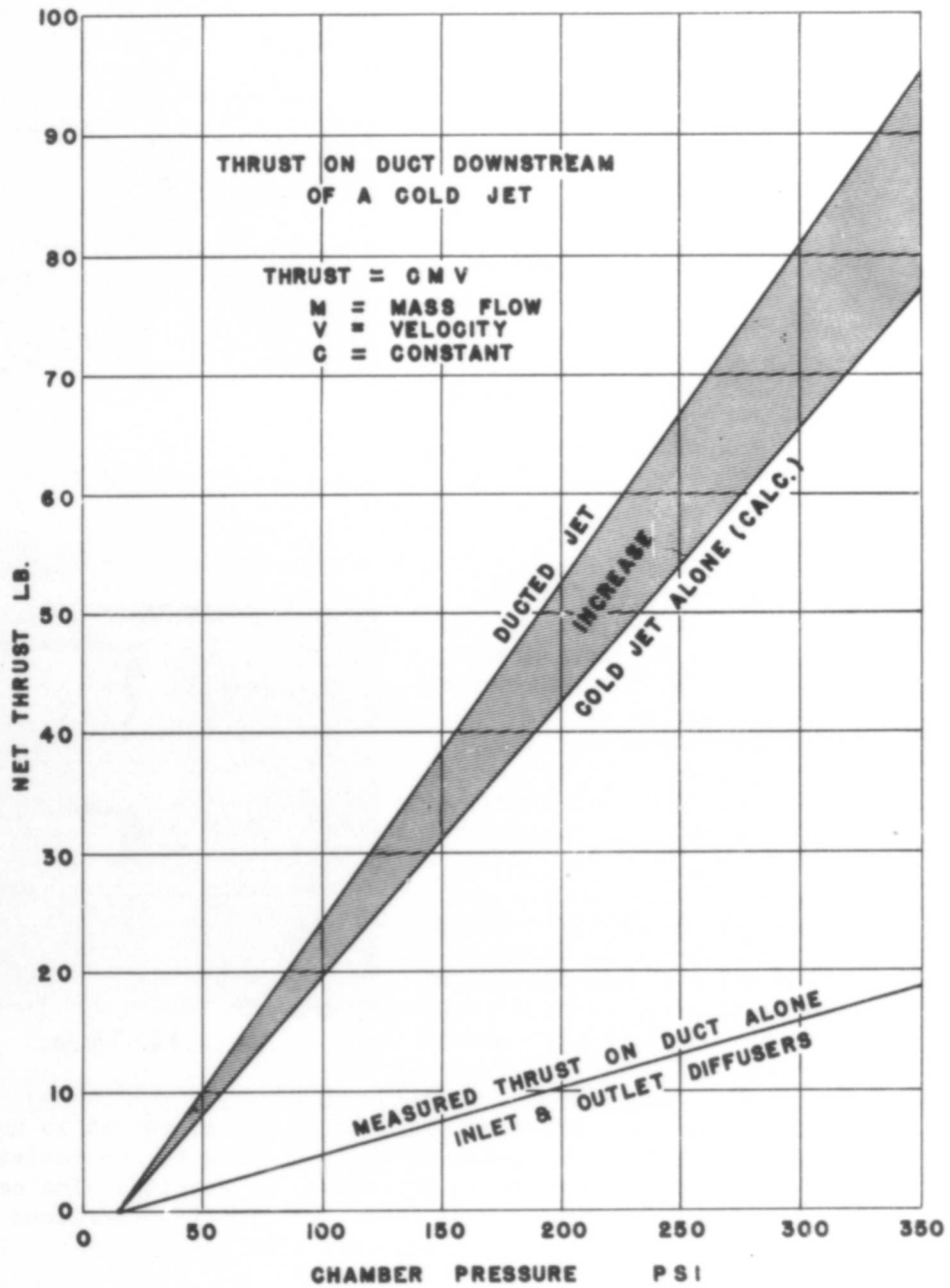


FIGURE 3

net thrust of the duct compared to the calculated thrust of the cold jet alone. It is to be noted that the relationship is linear. The inlet and outlet sections in this case were simple tapered sections of rolled sheet metal. With improved designs it is expected that better augmentation can be achieved. Tests will be run to investigate various entrance and exit configurations as well as the effect of duct length. From the measurements of velocity, temperature, and so forth, the total mass flow in the duct can be determined. By subtracting the known mass flow of the primary jet the induced mass flow is found.

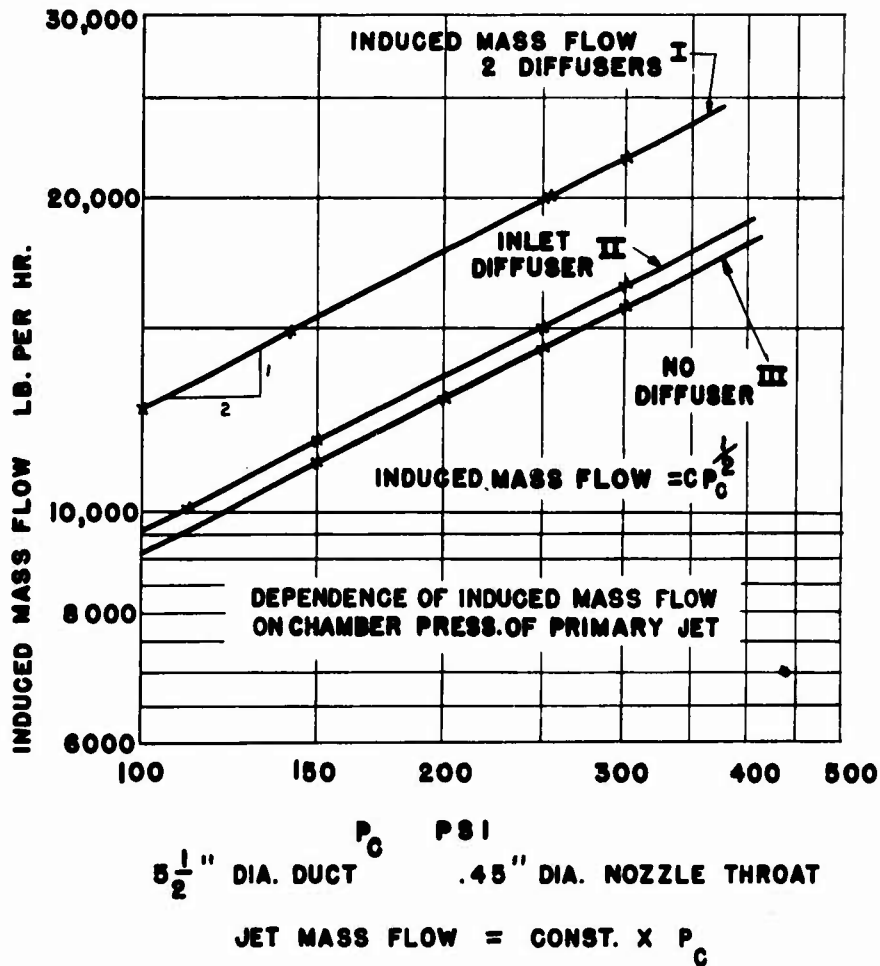


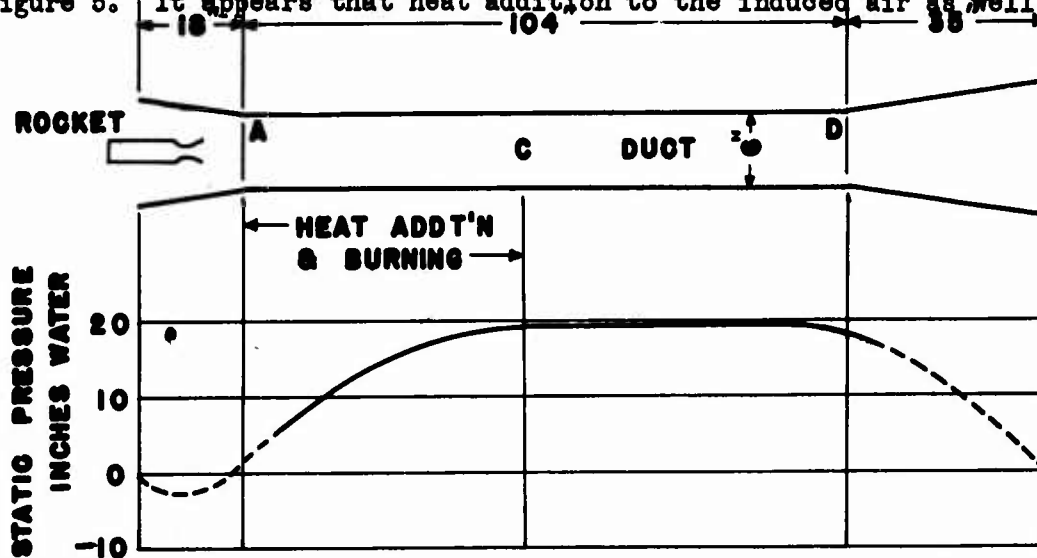
FIGURE 4

The data appear to indicate a simple relationship of the induced mass flow with the stagnation pressure of the primary air. This is indicated in Figure 4 which shows that the induced mass flow varies as the square root of the stagnation pressure or as the square root of the mass flow of the primary or inducing air. The ratio of duct to primary jet area was about 20/1 in these tests.

The following test program is planned for the axially symmetric air ejector:-

1. Various inlet diffusers will be tested in order to obtain improved performance. Information from these tests will be utilized in the ducted rocket program.
2. A smooth approach duct with gradual expansion from an inlet throat 2 3/4 inches diameter to a 6 inch diameter main body will be tested to investigate the area ratio parameter to determine its quantitative effect of the induced mass to primary mass relationship.
3. A primary jet nozzle with a throat area approximately 70% of that now in use will be tested to further check the effect on performance of the ratio of duct to primary jet area and to serve as a basis for comparison with the hot jet tests involving a rocket of the identical size and shape.
4. The plexiglass duct will be instrumented for static and total head pressure distributions throughout its length.
5. The effect of duct length will be studied.

Rocket Ejector. An investigation of static pressure distribution along the duct length for a typical case has been made and is shown diagrammatically in Figure 5. It appears that heat addition to the induced air as well as



STATIC PRESSURE DISTRIBUTION
FIGURE 5.

the additional chemical reaction of the unburned rocket exhaust products with induced air occur primarily between A and C (where the slope of the pressure curve approaches zero). This indicates that the duct length may be shortened appreciably without effecting performance.

Instrumentation for the accurate determination of temperatures in the duct is being studied. Present techniques have been found to give unreliable data.

The effect of varying the mixture ratio of the rocket propellants has been studied. A rich mixture provides more chemical energy in the exhaust, as expected, and has the effect of decreasing the induced mass flow. It has not been possible to obtain conclusive quantitative results of the interrelation of these effects.

In the rocket ejector, provision was made for separate measurement of rocket thrust and duct thrust. As a result it is possible to study the effect of the presence of the duct on the performance of the rocket motor. Tests have shown a consistent improvement in rocket thrust with the duct in place. This increase is approximately 15 to 25 per cent. A partial explanation for this improvement may be due to the fact that the rocket exhausts into a low pressure region thus obtaining higher value for C_F , the rocket thrust coefficient. However, this does not explain the total effect noted. A further study of the effect is planned.

In order to improve the value of c^* for the rocket, a new four-hole injector will be tested shortly. As far as the overall rocket and ducting system is concerned, a slight improvement in c^* for the rocket is unlikely to affect performance appreciably. However, it was thought worthwhile to investigate this point. In addition, the effect of rocket nozzle design is being studied. It is not possible to predict the exit area for correct expansion for the case of the rocket in the duct and the effect of deviations from proper expansion on duct and rocket performance is being determined.

The following rocket studies are planned for the near future:-

1. The investigation of the relationship between c^* and L^* for two types of injectors.
2. Effect of nozzle design on rocket performance in duct.
3. Refinement of duct instrumentation.
4. Study of mixture ratio on ducted rocket performance.
5. Effect of duct length.

PHASE 4

To investigate theoretically and experimentally the feasibility of a valveless intermittent jet engine.

Phase Leader: A. Kahane.

Experimental Program on the Intermittent Ram Jet. The thrust balance, which measures the force on the engine, has been completed. The reaction

plate balance has been abandoned because of the difficulty of making an adequate correction for the air which flows on the exterior of the engine. The value of thrust quoted in the Annual Report, 1 January 1949, was incorrect, since an erroneous correction factor was used.

Tests were started in the 4 inch square constant area tube to determine some of the peak pressure rise characteristics of intermittent combustion in a flowing gas. These tests were discontinued when it was found difficult to reproduce the resulting pressure rises. The trouble appeared to be in the diesel type fuel flow valve, which was not originally designed for the present operating condition of high frequency and large fuel flows. The lapped surface of the valve would tend to score and stick under these adverse operating conditions. In addition, since there were oscillations between the fuel flow valve and the nozzle after cutoff, a complete cutoff of injection was never obtained. Nevertheless, some trends were observed, the most significant of which was the variation of peak pressure with jet speed. The peak pressure was found to increase with increasing jet speed (see Figure 6). The reason for this type of variation is not known. One possibility is that the scale of vortices shed from the injection nozzle (which is located just ahead of the ignition torch) increases with increasing airspeed, causing an increase of the flame burning velocity.

The thrust and fuel consumption tests of an engine with change of cross sectional area were originally to be conducted on a 4 inch diameter circular cross section engine. These tests were stopped when it became evident that the fuel injection had not been satisfactorily developed, and it was decided to return to the 4 inch square tube with large glass windows, where the spray could be observed periodically. Insert blocks have been built providing two dimensional diffuser sections. Thrust tests have been started with an inlet to combustion chamber area-ratio of 0.5 diffuser. Values of positive thrust (thrust greater than drag) have been obtained at $M = .5$. The thrust and fuel consumption characteristics will soon be reported in a Technical Memorandum.

The Fiedler-Sellers Corp. is under subcontract to develop a fuel-injection nozzle which will eliminate the difficulties encountered in the operation of the present nozzles. The nozzle has been designed to operate without an additional flow valve. Sixteen individual and adjustable spring loaded injection valves used will face the fuel entry side of the orifice to obtain a greater penetration of spray jet than obtained with a previous nozzle (No. 4). The orifices will be fitted with interchangeable inserts; length of the spray is dependent on the length to diameter ratio of the orifice.

A phase sensitive amplifier system with a ring demodulator has been built for use with the Statham pressure pickups, using a single ended output rather than push-pull. A 2000 cycles per second galvanometer is being used rather than the 8000 cycles per second used previously to obtain greater sensitivity.

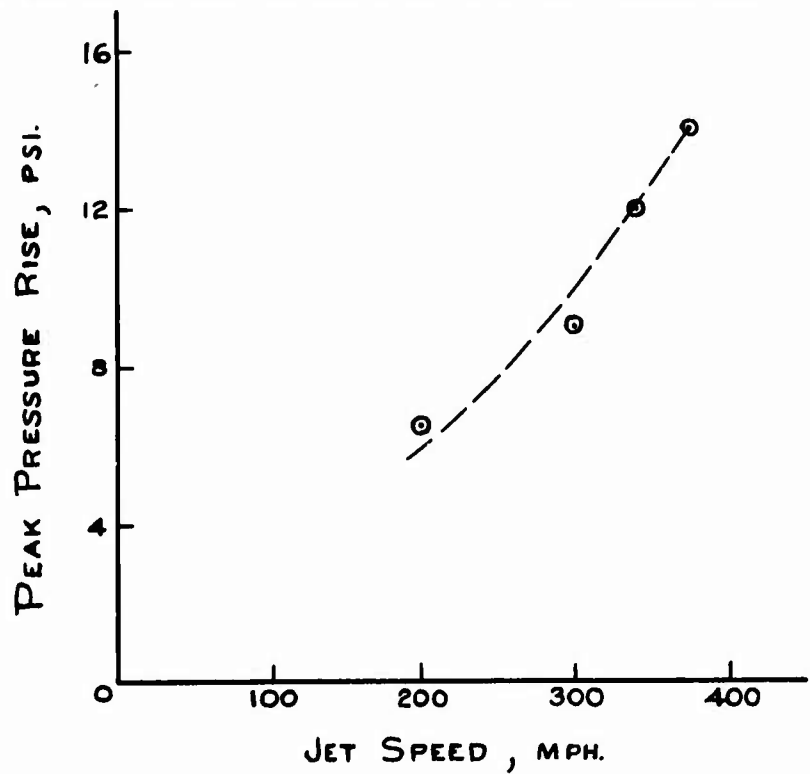


FIGURE 6. Variation of peak pressure rise during intermittent combustion with jet speed; injection frequency 25 cycles per second.

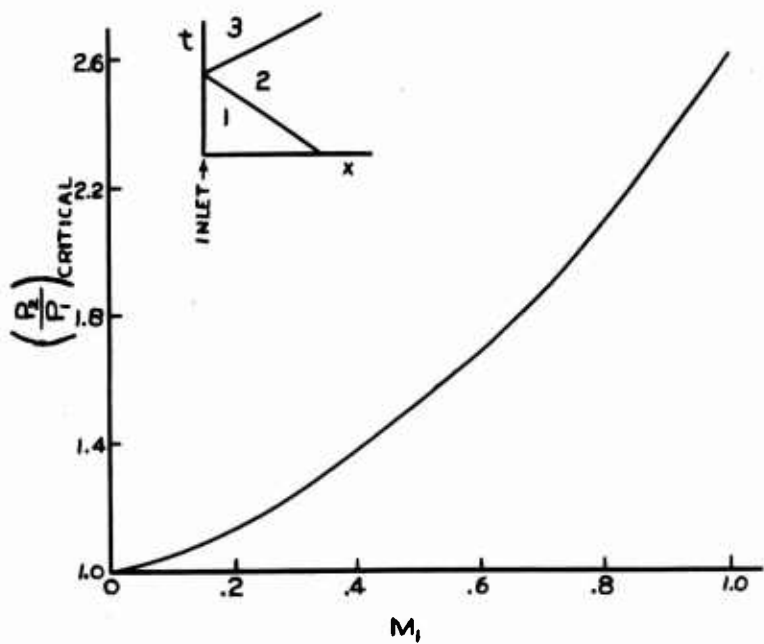


FIGURE 7. Critical pressure ratio for spillage of upstream moving shock.

Phase sensitive amplifiers have been built for use with a cathode ray oscilloscope to provide visual observation of the pressure records simultaneously with their recording on the electro-magnetic oscillograph.

Theoretical Calculations. Computation of the gas dynamics of flame tubes and intermittent combustion in a flowing gas has been extended to values of γ of the flame of 1.30.

Characteristic diagram calculation of an engine with an inlet diffuser (inlet-combustion chamber area-ratio of 0.65) has been carried out for the flight Mach number 0.4. The diffuser was simulated by a single discontinuous step of cross section area.

A simple formula has been derived which gives some insight into the inlet spillage problem. The formula is:-

$$\left(\frac{P_2}{P_1}\right)_{\text{critical}} = \left[\frac{\gamma-1}{4} M_1 + \frac{1}{2} \left(1 + \sqrt{1 + \frac{\gamma-1}{2} M_1^2} \right) \right]^{\frac{2}{\gamma-1}}$$

where:

$\left(\frac{P_2}{P_1}\right)_{\text{critical}}$ is the highest pressure ratio shock wave approaching the inlet for which no spillage occurs after reflection.
 M_1 the local Mach number at the inlet just before the shock wave reaches the inlet.

The formula, which was derived assumes one-dimensional flow and isentropicity of the shock wave, is plotted in Figure 7. It is interesting to note that the critical pressure ratio is a function only of inlet Mach number.

Calculations of waves interacting with diffuser inlets (simulated by a tube with a single sudden change of cross section area) for the subsonic engine indicate that a compression wave incident upon a decreasing area section (a subsonic diffuser-like duct) increases in strength, whereas the reverse is true for a compression wave passing through an increasing area duct. (The statement made in the Annual Report, 1 January 1949, with reference to this was in error).

ADMINISTRATION AND TECHNICAL DIRECTION

During the quarter, the following Technical Memoranda were given limited distribution:

- Technical Memo PUR-5 "Some Thermodynamic Properties of the Nitroparaffins,"
C.L. Dorsey, L.H. Going, D.E. Holcomb.
Technical Memo PUR-6 "The Calculated Performance of Hydrocarbon White Fuming
Nitric Acid Propellants at High Chamber Pressures,"
C.H. Trent and M.J. Zucrow.

During the quarter, the following Reports were given general distribution:-

- Annual Program Report dated 1 January 1949.
Quarterly Progress Report dated 1 April 1949.
Technical Report No. 16 "Flame and Particle Motions in a Small Pulse Jet
Engine," Paul Elias.
Technical Report No. 9 "Compressible Flow Through Reed Valves for Pulse
Jet Engines, I. Hinged Reed Valves," Paul Torda,
I.P. Villalba, and J.H. Brick.
Technical Report No. 15 "A Water Analogue of the Isentropic Flow of Com-
pressible Gases Which Have Arbitrary Ratios of
Specific Heats," Ronald F. Probststein and George
Hudson.

The classified mailings (Pr-11 and CAL-25) were completed and three issues of Library Abstracts were distributed during the period.

The Policy Committee met on 12 May 1949, in New York City.

U N I V E R S I T Y O F D E L A W A R EPHASE 1

Heat Transfer in Passages with Free Convection and Counter Flow.

1. The visual study is to be carried out using a vertical rectangular duct having two opposed glass walls with provision to heat the middle portion. Free convection will be upward but arrangement will be made to force air downward at a controllable velocity. By means of spark photography, the resulting gas flow can be studied.

2. The quantitative study is to be carried out with emphasis on the cooling effect of liquid under conditions of free convection with forced counterflow. Various liquids will be chosen so as to give a wide variation in the Grashof number.

Phase Leader: S.A. Guerrieri.

Substantially all of the principal parts of the two types of apparatus to be used for the project have been received and assembled. A travelling thermocouple technique and assembly has been developed for obtaining temperature profiles of the fluid in the tube. Some preliminary schlieren photographs have been taken with a temporary apparatus to check the possibilities of the visual unit.

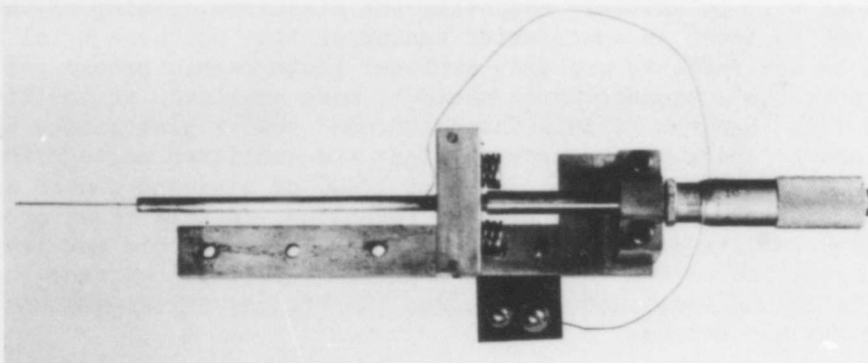


FIGURE 1. Travelling thermocouple assembly.

Quantitative Study. The travelling thermocouple assembly for the determination of horizontal temperature profiles across the vertical tube is shown in Figure 1. The thermocouple assembly comprises a constantan wire inside of, and electrically insulated from, a copper tube 0.016" I.D. by 0.022" O.D. This combination is commercially available in lengths up to

several feet. A thermocouple is made by cutting a piece of the proper length and applying a small drop of solder to the exposed tip. The fine tube at the left of Figure 1 is the thermocouple element which extends into the fluid stream from a hollow steel rod. The rod protects the thermocouple and prevents it from being damaged by the friction of the packing gland. The manner in which the thermocouple leads are brought out of the protecting tube and connected to binding posts is evident in the illustration. The hollow steel rod is connected to a micrometer spindle through a ball joint kept tight and free of back-lash by means of the two springs which can be seen at about the middle of the assembly. The micrometer enables an accurate location of the thermocouple junction to be determined. It is expected that this arrangement provides a complete thermocouple assembly which will cause a minimum of disturbance to the pattern of the flowing fluid but which is nevertheless rigid enough to hold a definite position in the fluid without appreciable sag or vibration.

Preliminary Test of Visual Procedure. In view of the importance placed on the proposed visual procedure as a means for studying the heat transfer mechanism it was decided to test in a rough way the possibilities of the visual experimental unit by means of a simple unit resembling the heating section of the principal unit. This was constructed with two electrically heated aluminum plates approximately 10 inches by 14 inches high placed parallel to each other about 1 inch apart. The two vertical ends were closed by means of plate glass. The top side of the enclosure so formed was left open to the atmosphere while the bottom end was connected to the suction side of a blower in order to pass air in the heated section in a direction counter to natural convection. No means were provided for measuring temperatures or rates of air flow, although the air flow rate could be varied at will by suitably adjusting the discharge opening of the blower. In order not to spend an unwarranted amount of time on these trial tests it seemed to be desirable to use only whatever photographic procedures were possible with the equipment which could be made available at the time by the combustion research group. These included shadow photography employing an electric spark as a source of light and schlieren photography employing a camera with a shutter speed of $1/400$ of a second and an arc lamp as a light source. The shadow picture technique, in this case, produced inconclusive results due to the fact that the apparatus did not include collimating devices. The result was that light reflections from the aluminum walls of the test section obscured the effects of temperature gradients in the air stream.

On the other hand, the tests with the schlieren apparatus appear to substantiate the possibilities of the visual experimental apparatus. Three of the pictures taken with the schlieren apparatus are included in this report. In all of the tests the heated plates were at approximately 200° F while room air was at about 95° F. Figure 2 presents a schlieren pattern obtained with a very low air rate, probably under 0.5 feet per second, estimated by visual observation of the flow pattern projected on a screen.

The trace of the edge of one of the aluminum plates is clearly evident on the light side of the figure. The edge of the other plate appears as a fine white line in the dark field. Focusing attention on the right hand half of the picture, the hot layer nearest the wall appears as a bright band about $3/16$ " wide. This shades off into the darker central region comprising the downward flowing cooler air. On crossing the center line the light and dark regions are reversed for corresponding conditions in the apparatus.

Figure 3 is a similar photograph taken with higher air velocity. Comparing this figure with Figure 2 one notes two important differences. In the first place, the downward flow of the central core is apparently more turbulent, evidenced by the wave-like appearance of this region in the photograph. Secondly, the boundary layer appears to be somewhat thinner and there appears to be a certain amount of shearing of the outer skin of the boundary layer by the downward flowing central core. It is of interest to note that the hot air layer near the wall appears to become thicker toward the bottom of the cell.

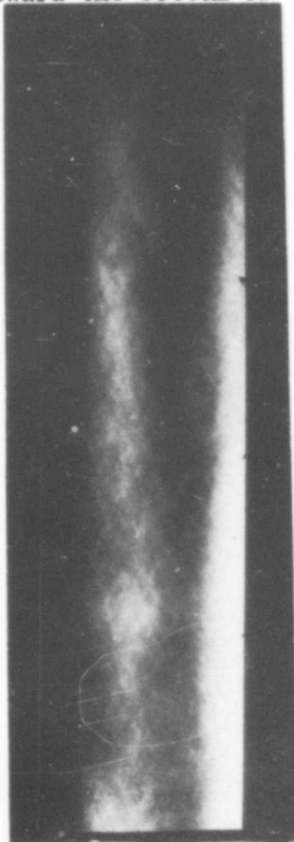


FIGURE 2

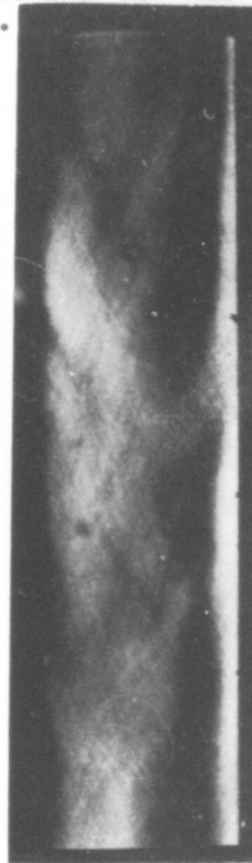


FIGURE 3

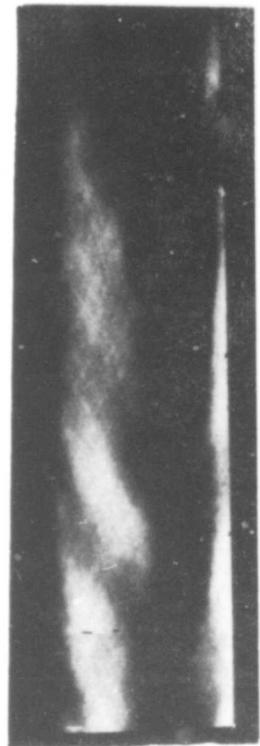


FIGURE 4

Schlieren photographs of flow patterns at various flow rates.

Figure 4 presents a similar photograph taken with a still higher air velocity and shows even more strongly the effect of air velocity, in that the wave-like character of the central core is more pronounced and the warm layer adjacent to the walls is noticeably thinner. It is not possible at this time to explain what appears to be non-uniform shearing of the warm layer by the downward flowing central core. Unfortunately, these still pictures do not show the direction of flow or relative velocity of the warm layer near the walls. It is expected that later pictures, especially moving pictures, taken with the principal experimental apparatus will answer these questions, and possibly modify our present concept of the action. However, on the basis of these preliminary pictures, we are probably safe in concluding that the basic concepts of the design of the principal apparatus are sound.

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