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UNITED STATES NAVY

PROJECT SQUID

QUARTERLY PROGRESS REPORT

1 April, 1948

NEW YORK UNIVERSITY
POLYTECHNIC INSTITUTE OF BROOKLYN
PURDUE UNIVERSITY
CORNELL AERONAUTICAL LABORATORY
PRINCETON UNIVERSITY

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

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CONTRACT N6ORI-11, TASK ORDER II

NEW YORK UNIVERSITY

NEW YORK, NEW YORK

1 APRIL 1948

INTRODUCTION

From the experimental side, most progress during the past quarter was made with the schlieren observations of combustion details and flow through the grid of the moving-flame tube, in connection with Phase 1; with the high speed simultaneous schlieren and flame motion pictures of the small transparent walled jet, in connection with Phase 3; and with the completion of the development of pressure and temperature instrumentation, in connection with Phase 4. From the theoretical point of view, advances have been made in the linearized theory of aero-thermodynamics as applied to flame tubes (see Technical Report No. 6) and to pulse jets. Much time was spent in procuring additional equipment for fitting out the new electronics and observation trailer. This trailer is now nearing completion and is to be used in observations of the large PJ-31 engine at the Westchester County Test Site near Rye Lake.

PHASE I

In connection with pulsating jet engines: to undertake theoretical and experimental investigations of (1) flame motions with controlled initial turbulence, (2) stationary flames with controlled turbulence, (3) suitable theoretical models based on the above observation, and (4) statistical mechanics of non-uniform gases.

Summary

Since January 1948, when the Annual Report was submitted by NYU-SQUID for publication, Technical Reports Nos. 6 and 7 (on theory and experiment related to highly turbulent combustion in flame tubes) have been printed and distributed.

Our recent experimental work on flame tubes has been concerned almost entirely with a schlieren motion picture study of the flame and flow structure near the turbulence-producing grid.

Preliminary tests were made with swirl-type turbulence in a bunsen burner. These gave some indication that the flame speed is considerably increased by the swirl in the gas.

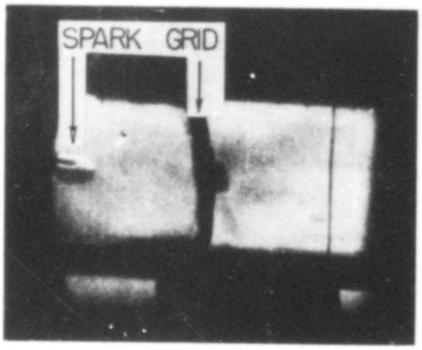
Because of the limited number of personnel available, and the pressure of other work, the high-speed Merlin engine blower, which was completed last quarter, has not yet been used to study stationary turbulent high speed flames.

A new shock tube, capable of being used with resevoir chamber pressures of 100 atmospheres, has been constructed. This will be used to study the effect of intense shock waves on combustion (taking place in the expansion chamber) and to investigate further the possibility of producing ignition by shock waves.

Moving Flame Experiments. Streak pictures and high-speed schlieren movies of the flame motion near the grid in a flame tube were obtained, and these showed that the fast flame actually appears first at the nozzles rather than several inches away as suggested in NYU-SQUID Technical Report No. 7. The reason why the flame is relatively invisible until it appears several inches from the grid is that the flame issues from a grid nozzle in the form of a *narrow* luminous jet which spreads sideways first only at the tip after the tip has passed well beyond the nozzle (see Figure 1). Figure 1 shows how the normal "thin bubble"-like flame expands from the spark igniter and produces a high-speed jet of flame after passing through the nozzle in the grid. This jet of flame then establishes the highly turbulent fast flame observed beyond the grid. Measurements of the pictures show that the expansion produced by the preliminary normal combustion between the igniter and the grid causes a flow of gas down the tube amounting to only a few feet per second (cross-sectional average velocity). Under such circumstances the effective velocity $u_0(t)$ which appears in the theory developed in Technical Report No. 6 may be neglected. Schlieren movies, showing how the flame jets penetrate the several nozzles in the grid at non-coinciding times, suggest that the combustion function $r(\lambda)$ in that Report may have a broken segment form. For purposes of simpler interpretability of the phenomenon, a multiple-spark igniter is now being constructed and is expected to yield a more nearly one-dimensional flame and flow pattern.

Preliminary studies of a schlieren "bubble" pattern issuing from the nozzles in the grid *before* the flame reaches the grid suggest that the pattern is produced by local heating of the gas by the walls of the nozzles, which are warmed by radiation from the flame. This interpretation has led to current successful attempts to make schlieren movies of the flow pattern well beyond the grid, by use of hot wires extending across the tube. Preliminary results indicate that the multiple jet model for fast flames, mentioned in Technical Report No. 7, should be modified to include circular eddies.

It is planned to make photoelectric recordings of temperatures and spectra associated with the combustion in flame tubes. Necessary equipment is now under construction and test. It is expected that the spectrum will correspond to a superposition of the spectra from all regions of a bunsen burner; otherwise essentially new reaction processes will have to be involved in the flame tube.



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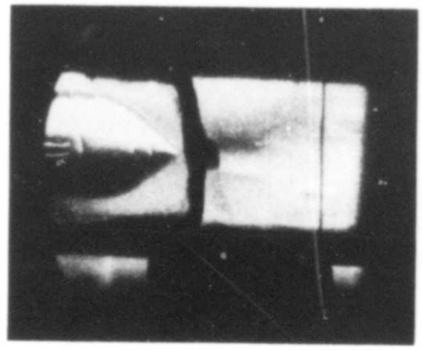

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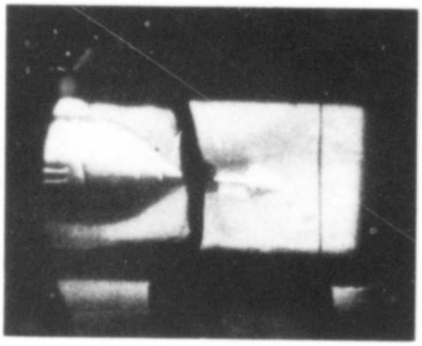

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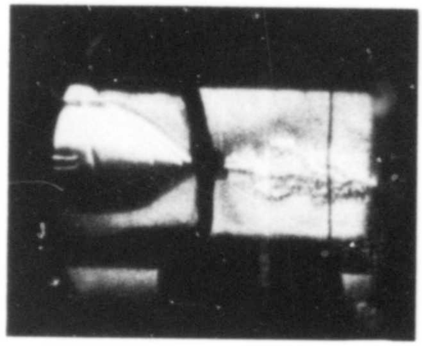

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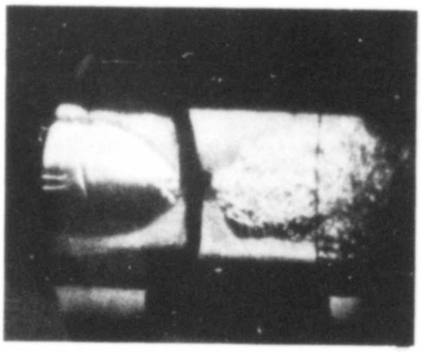

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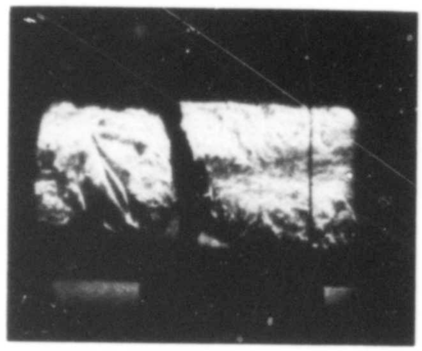

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Figure 1. Flame propagation in a flame tube 3.5" × 3.5" × 8' containing a nozzle-type grid 2.7" from spark igniter. Propane-air 7% mixture initially at ambient temperature and pressure. Times since ignition are indicated in the above typical frames taken from a schlieren movie photographed by means of a Fastex Camera at 5000 frames /sec. Note how the normal non-turbulent flame to the left of the grid developes a highly turbulent flame to the right of the grid.

PHASE II

In connection with liquid rockets and pulsating jet engines: to study (1) measurements of temperature dependence of conductivity and heat capacity of steels and other materials by means of adiabatic calorimetry and metallography, (2) characteristics of heat transfer between hot flowing gases and walls, using measurements of gas velocity and temperature by radiation and thermocouple devices, (3) calculations of temperature changes in jet and rocket walls.

Summary

The apparatus for high-speed specific heat measurements is ready for operation. The quartz wedge thermocouples are in the completion stage, nearly ready for shipment to Inyokern, where they will be used to measure the transient temperatures in rocket walls. Technical reports containing theoretical analyses of non-linear heat conduction in rocket walls and of the theory of radiation from hot gases and solids are under preparation.

Experimental

Special Heats of Steel at High Rates of Change of Temperature. After much delay due to lack of personnel, the apparatus described in previous reports has been finally rebuilt and reassembled as shown in Figure 2. Preliminary runs are under way. We expect to have definite quantitative results shortly.

Wedge Thermocouple for Measurement of Temperature in Rocket Walls. Many experiments have been performed to achieve a sharp line contact between the evaporated metal films on the knife edge of the quartz wedges. These attempts have finally been crowned with success. The problem of making electrical contact with the evaporated surface was solved by use of mechanical pressure contacts; two wedge thermocouples should be ready shortly for delivery to Inyokern.

Theoretical

Calculation of Varying Temperatures in Walls with Thermal Parameters Depending on Temperature. To obtain analytical solutions of the heat conduction equation it is necessary in general to discover transformations which lead to linear differential equations and linear boundary conditions. For the calculation of heat flow in rocket walls in which the thermal

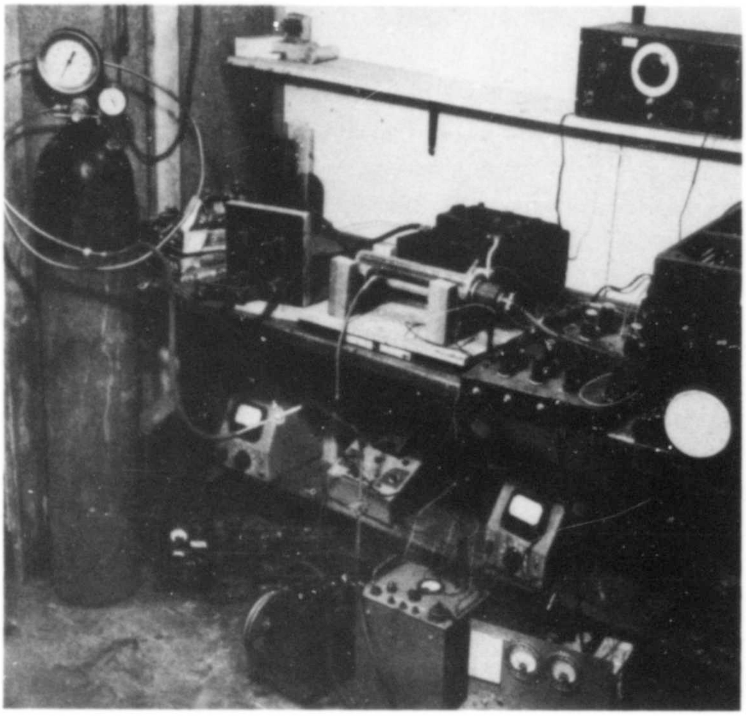

Figure 2. Aparatus for measuring specific heat of steel at high rates of change of temperature. The glass tube in the center of the picture is evacuated and contains a rod of the steel specimen, which is rapidly heated by current from storage batteries. Thermocouples and d.c. amplifiers are used to record temperatures and energy inputs.

conductivity K and heat capacity S are functions of temperature T, the introduction of a new variable $Q = \int_0^T K\,dT$ leads to a *linear* differential equation provided that S/K is regarded as known (or approximated) as a definite function of position and time. For the case of a wall initially at ambient temperature, and with an arbitrary rapid heat input thereafter, it is possible to approximate S/K very well over important ranges by means of parametized functions which permit explicit analytical solutions to be obtained. This work is well advanced and will be described in detail in a Technical Report.

Theory of Thermal Radiation. A rather extensive study of classical and quantum theoretical bases for emission and absorption of radiation by means of gases and solids has been undertaken in order to clarify the assumptions involved in the measurement of temperatures by radiation. The results of this study will by presented at a meeting held in Washington on April 28th under the sponsorship of the Instrumentation Panel of Project SQUID, and they will be included in a forthcoming Technical Report.

PHASE III

In connection with liquid rockets and pulsating jet engines: (1) to observe flame and particle motion, pressures, temperatures densities, and effects of turbulence in pulsating and rocket jet devices; (2) to study water stream analogues for gas motion in pulsating jets and rockets in order to determine characteristics of simple theoretical models, and (3) to use the above for theoretical treatments of the internal ballistics of jet devices on the basis of justified simple models.

Summary

The PJ-31 engine is now being run at the Westchester County Airpoit, Rye Lake Test Site. A large number of observations will be made on this engine soon. Simultaneous high-speed schlieren and flame motion movies have been made of the small transparent-walled jet and have given information concerning the point of ignition and relative flame and gas speeds. Technical Reports are being prepared on the water channel analogue of one-dimensional compressible gas flow and on a linearized theory of the internal aero-thermodynamics of pulse jet operation.

Experimental

Full-scale Pulse Jet Tests. The thrust stand described in the Annual Report was completed during this quarter and various modifications were made in the fuel injection system for the PJ-31 engine. These modifications include separation of the starting air system from the purge air line so that much better control may be had over starting. In addition, the automatic fuel metering unit has been cut out of the injection system completely, so that we have direct and continual control of the fuel flow. With this set-up, the engine has recently been run several times at the Rye Lake Test Site so that the operating crew could become familiar with it. Instruments and other observational devices are being mounted on it at the present time.

Tests on Small Transparent Pulse Jets. High-speed schlieren and flame movies have been made of various sections of the combustion chamber and tailpipe of the small transparent-walled pulse jet (which is modelled after the Dynajet). Selected frames of these movies are shown in Figure 3. As a result of all these observations combined with earlier streak photographic observations, the sequence of events in the engine is believed to be as follows: The valves open coincident in time with the very rapid exhaust from the tailpipe of flame and hot gases from the previous cycles. A fresh mixture flows into the combustion chamber through the valves, and the boundary of this is in contact with the hot burnt gases from the previous cycle. However, the fuel-air mixture is not "rich" enough in fuel to ignite at this boundary; but a short time later (corresponding roughly to one half the time the valves are open), at the time when the maximum compression results from the return flow into the tail pipe, ignition takes place in the interior of the fresh mixture (about 3/4 inch from the valves in the transparent-walled jet). This is probably due to a combination of circumstances. First, the proportion of fuel to air in the region of ignition is probably nearly optimum (at least in this jet motor) because the high velocity air intake at this time aspirates sufficient fuel. Second, the interface between the fresh mixture and the burnt gas probably becomes quite diffuse because of the swirling turbulence present in the chamber, so that some part of the interior of the mixture becomes sufficiently heated by diffusion to produce ignition when the pressure is raised by the return flow in the tailpipe exhaust opening (i.e. by a local superposition of compression waves travelling in the tube and combustion chamber). Following ignition, the combustion spreads in both directions and rapid burning of the mixture takes place so that the pressure rises and the valves quickly close. The forward flame "front" soon reaches the valves, while the after flame "front" catches up with the interface between the fresh and burnt mixtures, about the time this interface is being pushed into the tailpipe from the combustion chamber. Combustion then continues as the gas expands into the tailpipe. The gas is soon accelerated to a high velocity and actually overexpands out the tailpipe, so that the pressure is lowered in the combustion chamber by reflected rarefaction waves, and the valves open to admit a fresh mixture. Because the pressure in the tailpipe, too, is lowered by this over-expansion below ambient pressure, the outflow is soon decelerated by the pressure gradient, and a return flow into the "exhaust" end of the tailpipe takes place. The cycle is then repeated.

Observations of Pulsating Jet Devices. In addition to the observations of the small transparent-walled jets, some observations were made on the effect on thrust of a Dynajet due to an extension of the length of the tailpipe or of the intake manifold ahead of the valves. These observations were made as the result of a request by the Navy in connection with a problem encountered by an industrial concern. It was found that if a tube legnth of 12 inches was added to the intake manifood, corresponding to a quarter wave length of the fundamental of the Dynajet at atmospheric conditions, the jet refused to operate. When the tube was cut in half, the jet resonated but with a considerably reduced thrust, but if a hole of sufficient size was cut in this intake tube just ahead of the valves nearly all the thrust was restored.

Wave Speeds in Water Channels: The technique for measuring the wave speeds in water channels having cross-sections of different shapes has been improved considerably by use of an electrical device for measuring the heights of the waves. With a V-shaped channel whose apex angle is 90° and a still-water depth of 1.5 inches, the measured velocities of small waves 1/8 inch high average 1.50 ft/sec. This is a deviation of 5.6% from the

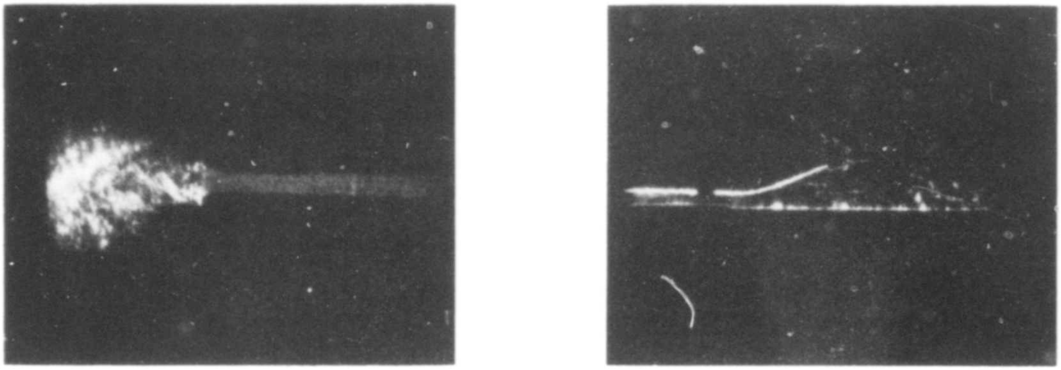

Figure 3A. Beginning of cycle. The gases have reached their maximum exhaust velocity at the tailpipe exit (left side) and the pressure is falling in the combustion chamber.

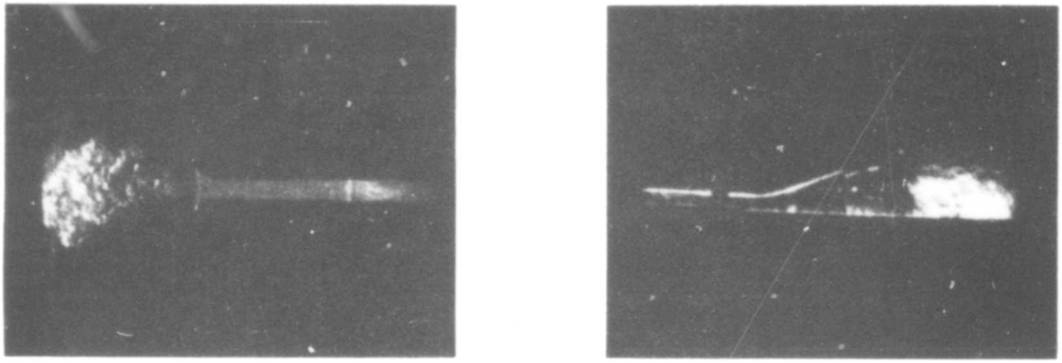

Figure 3B. One sixth of cycle. The jet has necked down and a return flow around it has taken place in the tailpipe, a fresh mixture is being introduced through the valves on the right.

Figure 3. Combined schlieren and flame pictures taken from the high-speed movies of a cycle of operation of the transparent-walled (Dyna) jet. The pictures on the left are schlierens of the gas in the tailpipe, those on the right show *schlieren* photographs of the upper half of the combustion chamber and, below the horizontal line, pictures of the *flame* when visible in the lower half of the combustion chamber.

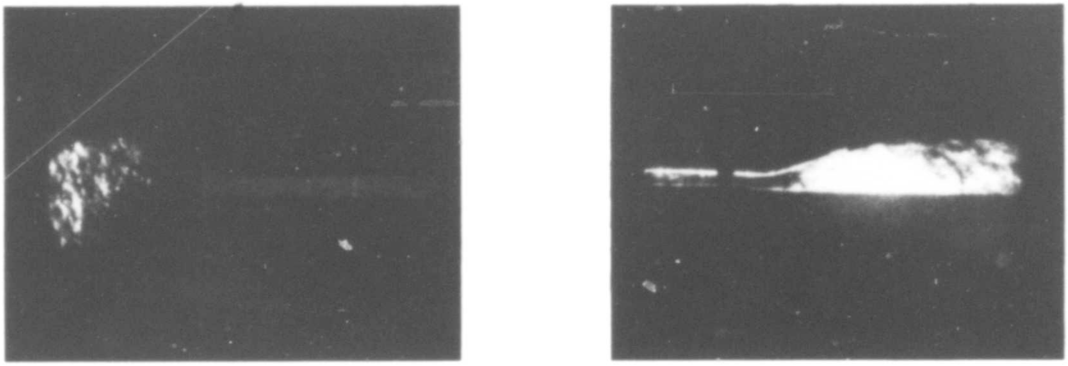

Figure 3C. One third of cycle. Coincident with the high compression on the return flow, ignition takes place, and flames spread through the fresh mixture in the combustion chamber. The lower part of the right picture shows, faintly, the region of combustion.

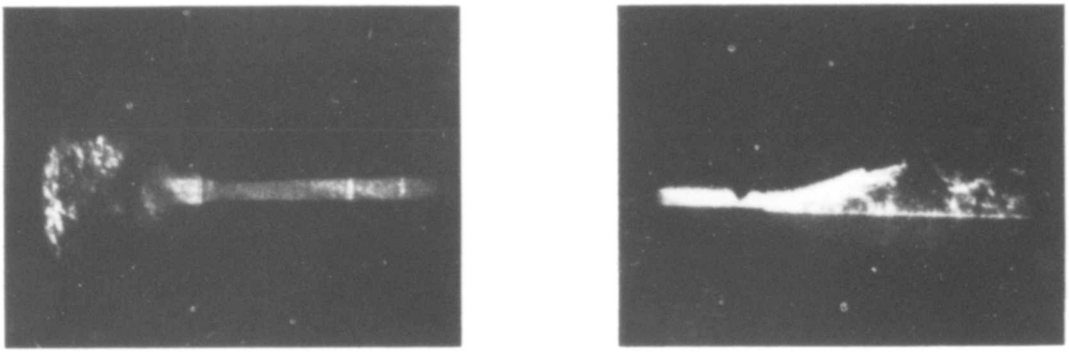

Figure 3D. Two thirds of cycle. The combustion has spread into the tailpipe from the combustion chamber which is still filled with hot turbulent gas. A jet is being formed on the left as the gases expand out the tailpipe.

theoretically calculated value of 1.42 ft/sec. A technical report on this subject is being prepared and will be issued as soon as sufficient experimental data is collected.

Theoretical

Theory of Pulse Jets. During the past two months new methods for the mathematical solution of aero-thermodynamics equations for pulse jets have been developed. The methods depend on linearizations of the equations in ways related to those described in Technical Report No. 6 for flame tubes, but with different types of linearization for the intake and the exhaust phases. As in the flame tube theory, explicit analytical solutions in terms of combustion functions and boundary functions are obtained. Details will be described in a forthcoming Technical Report.

PHASE IV

In connection with liquid rockets and pulsating jet engines: to develop instruments for recording transient thrust and pressures, temperatures, and densities of hot oscillating gases, and gas velocities.

Summary

The pressure gauge instruments have been perfected to the point where they are ready to be used to explore the transient pressure distribution inside th PJ-31 engine. This is also true of the temperature instrumentation. The fuel flow gauge using a thermistor type pickup is nearly in this stage. There remains only the calibration of this instrument in a simulated gasoline flow pipe.

Pressure Gauges. During this quarter we have improved the FM receiver circuit for use with the condenser-type gauges. In preparation for the field tests of the PJ-31 engine, five complete condenser gauge units have been constructed together with fittings for adaptation to the engine. In addition, several invar limit gauges have been designed and tested and will be used with the large pulse jet as a check on the peak readings of the condenser gauges and to help determine their zero level.

The effect of the 9-hole cooling chambers at the response of the condenser gauges has been tested, and other special apparatus has been constructed for testing the electronic circuits.

Temperature Measurements. During the last quarter of 1947 studies of semi-transparent flames led us to improve the design reported in the Annual Report for 1947.

The new optical design is given in Figure 4. Photos of the actual apparatus are shown in Figure 5. Note that the photo-cells observe cones of light which are practically coincident except that the vertex of one is a front-surfaced mirror and the other a cool black body. Separation of the beams at the receiver is achieved by the use of a prism. The output of each photomultiplier is fed to a d.c. amplifier of a Dumont 208B oscilloscope.

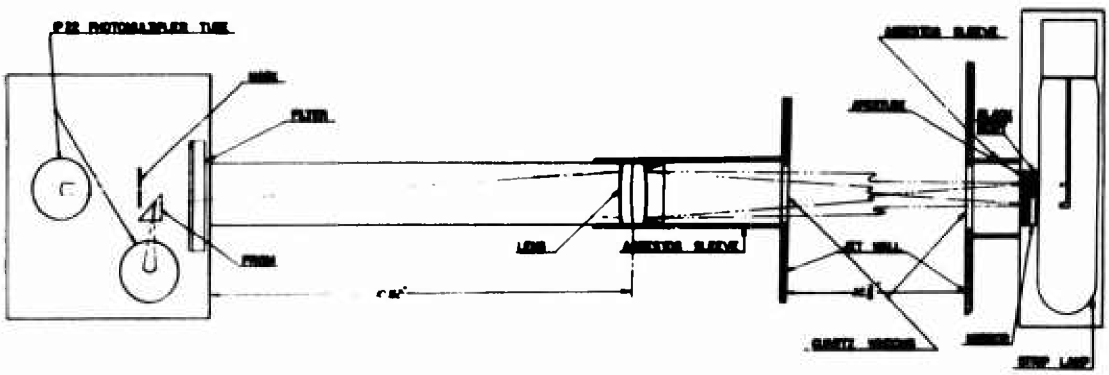

Figure 4. Optical system for temperature measurements in pulse jets.

Direct calibration is done by removing the quartz windows from the jet tube and moving the standard lamp back of both apertures. Upon replacing the windows, the losses due to these are easily determined. It is hoped to test this device shortly on the full-scale pulse jet.

In connection with temperature measurements we are investigating the infrared emission of the pulse jet. We have a lead sulphide cell which, when used with a Dynajet, confirms our earlier impressions that there is little energy in this jet in the infrared. For a more extended range in the infrared we are investigating special thermistors which we hope to obtain from the Bell Laboratories, through the courtesy of the Bureau of Ships.

Liquid Velocity Flow Meters. A new set of thermistors, the air anemometer type, were received from Western Electric. These were adapted by us for liquid flow by imbedding them in a streamlined plastic form. This entire measuring element is now far more sensitive than a comparable platinum or tungsten hot-wire anemometer. It will be enclosed in a Plexiglass mounting which is to be inserted into the fuel line of the large jet. The mounting has successfully withstood internal pressures up to 200 psi.

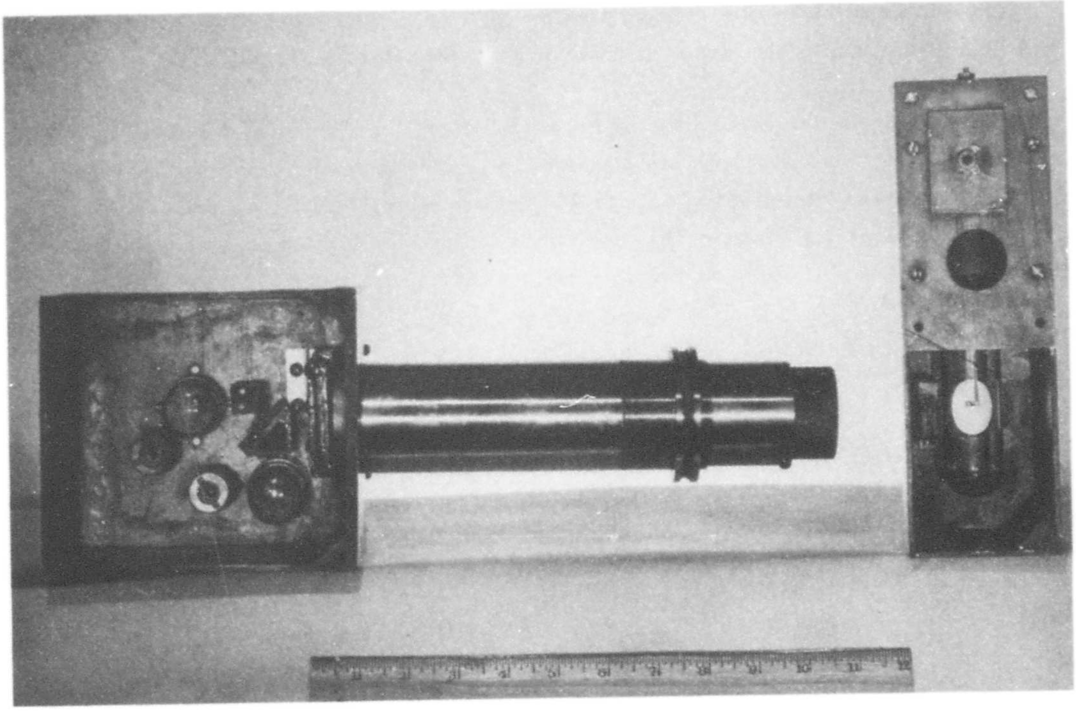

Figure 5. Temperature-measuring equipment. On the right is the mirror and calibrating lamp, which is mounted on one side of the jet. On the left is the receiver which is mounted on the opposite side of the jet. The box contains two photomultiplier tubes, one for the simple beam, the other for the mirror beam.

A compensator circuit to balance the falling off of response with increased frequency has been built and tested. The circuit used was adapted from an NACA compensator designed for a hot-wire anemometer. We have determined by experiment the optimum current flow to be five milliamperes for this type of thermistor. The graph of Figure 6 indicates the response characteristics of the instrument with and without compensator.

PHASE V

In connection with liquid rockets and pulsating jet engines: to study drag characteristics of pulsating jet and other devices under conditions of non-steady or of supersonic flow, using firing range photography, wind tunnel measurements, and theoretical investigation.

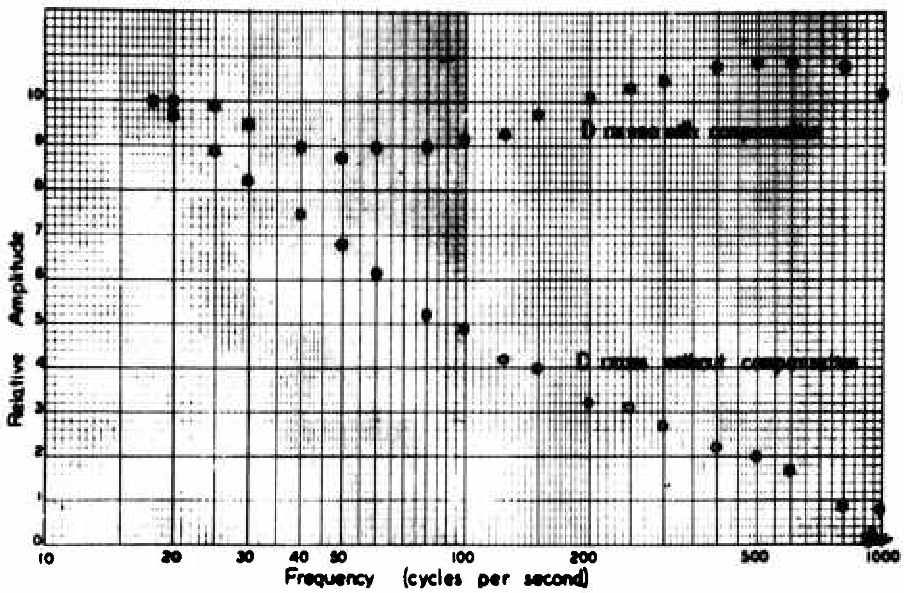

Figure 6. Frequency response characteristics of a thermistor element.

Summary

The theoretical study of two- and three-dimensional non-steady jets was pursued intensively during this period.

Theoretical

Analytic Description of the Flow Pattern at the Exhaust End of the Tail Pipe. Theoretical analysis of non-steady three-dimensional jets was started during this period. The corresponding two-dimensional case has been studied more particularly, with a view toward development of a technique which could be extended to the general problem. Results obtained have been tested for the particular case of the classical steady-jet problems in which solutions are available, based on the mapping of rigid boundaries and "free" jets onto the complex plane.

In the problem studied during this quarter, the velocity fields inside and outside the jet are respectively assumed to be of the form $A(t)\ f(x,y) + G(t)\ g(x,y)$ and $B(t)\ f(x,y) + G(t)\ g(x,y)$. These velocities are assumed to be irrotational within each region, while the jet boundary is a line of discontinuity extended to include the outline of a portion of the tube proper. The jet boundary varies with time; its instantaneous position and shape are governed by the requirements that *(a)* fluid particles on the boundary remain on the boundary, *(b)* normal component of velocity is continuous across the boundary, and *(c)* pressure is continuous across the boundary. Additional boundary conditions are involved in its determination, such as space and time variation of axial velocities at the exhaust end of the tube, and zero normal velocities along the outline of the tube. A surface of vorticity coinciding with the outer surface of the tube contributes the term $G(t)\, g(x,y)$ in the expression given above for the velocity distribution.

The situation thus corresponds to a boundary value problem of unusual and difficult type. It consists of the solution of two potential problems satisfying given boundary conditions along the rigid boundaries and non-linear partial differential equations along the moving discontinuity line $F(x,y,t) = 0$.

An attempt is in process to disconnect the problem of jet boundary determination from that of the potential equations. Certain approximations have been made mathematically toward this end, but results are still to be evaluated. It appears at this stage that exact mathematical procedure would be extremely involved, and that some form of approximate technique must be evolved for making any kind of progress with this problem.

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FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-98, TASK ORDER II

POLYTECHNIC INSTITUTE OF BROOKLYN
BROOKLYN, NEW YORK

1 APRIL 1948

INTRODUCTION

Research work on Project SQUID at the Polytechnic Institute of Brooklyn during the first quarter of 1948 has dealt mainly with the writing of Technical Reports and with the final preparation of test models and instrumentation for the experimental program. It is expected that in the subsequent quarter some phases of the experimental work will be completed, while others will have progressed considerably.

Test facilities at the Susquehanna Ordnance Depot, Williamsport, Pennsylvania, have been acquired on contract from the U.S. Navy Bureau of Aeronautics. A crew of two men has been in residence since January for preparing the equipment and instrumentation and obtaining certain necessary apparatus which had been removed from the facility.

A 40' × 90' Quonset hut adjacent to the present Aeronautical Laboratory has been completed. Work is going ahead on the installation of the equipment.

A Technical Report entitled: "On the Structure of Shock Waves in a Viscous Heat-Conducting Compressible Fluid. Part I: Shock Waves in a One-Dimensional Flow with Constant Coefficients of Viscosity and Conductivity," by Prof. Hans J. Reissner and Mr. Leonard Meyerhoff, has been submitted to the Project SQUID administrative headquarters for publication. Another Technical Report, dealing with Phase I, is being completed and will be submitted for publication very shortly. Several technical memoranda are in the process of being written. The instrumentation program has in general progressed satisfactorily. A short discussion of this work follows:

Preliminary checks on the completed carrier-type amplifiers and phase detectors developed for use with the pressure and thrust measuring strain gauge instrument showed that the present design must be modified to provide increased sensitivity and linearity of response. This is being done at present, and the modified amplifiers and detectors are under construction.

As soon as they are completed and checked, calibration of the pressure transducers will be possible. The necessary pressure calibration equipment has been built and set up for use.

The construction of magnetostriction transducers for measurement of gas temperatures is continuing slowly, largely because of difficulties encountered in measuring the dynamic characteristics of the transducers. A 15,000-cycle unit has been constructed, and materials are now being ordered for the construction of a 100,000-cycle transducer.

The x-ray method of surface temperature determination has been held back by the lack of a Geiger counter. One was ordered, but at the last minute the Navy was given priority, and its use in this work will be delayed since delivery is not expected until late April. In the meantime experiments will be carried out by means of sensitized films. Photographic methods for the gas density measurements are not fully satisfactory, and therefore this phase of the instrumentation program must await delivery of a Geiger counter.

Several of the new type hot wires have been built, but existing equipment must be modified before they can be used for flow velocity, direction, and turbulence measurements.

Dr. S. W. Yuan and Prof. Hans J. Reissner attended the National Flight Propulsion meetings at Cleveland. At the request of Dr. Pol Duqez the former gave a discussion on the theoretical phase of the study of cooling by injection of a fluid through a porous material. Messrs. Weiss and Lefeber met with the Submarine Signal Company in Boston for a discussion of transducers. Mr. Weiss also visited General Electric Company at Schenectady regarding some problems on temperature measurements; and later, with Mr. Paul Libby, he inspected the pilot model of the supersonic wind tunnel at Princeton University, with a view toward possible duplication for instrument calibration purposes.

PHASE I

In connection with pulse jet engines: To study the intermittent air intake process and the overall aero-thermodynamical mechanism of the pulse jet at subsonic and supersonic speeds. The study will cover theoretical and experimental investigations of (1) reciprocating and rotating valve mechanisms, (2) internally coupled pulse jets and related devices, and (3) such processes as may be necessary for the formulation of a unified pulse jet theory.

Summary

The technical report on air-inflow between hinged reed valves has been finished. At the Williamsport test stand the existing instruments have been calibrated and some new instruments purchased. Preliminary runs have been made with the McDonnell engine. The "cold" (l.c.) test model for the rotating sleeve valve tests is nearing completion at P.I.B.A.L.

Progress

Air Inflow Analysis. The method of analysis of air inflow between hinged and clamped reed valves has been described previously. A technical report on the inflow analysis between hinged reed valves is in the last stages of preparation. It includes some numerical examples illustrating the type of flow attainable. All calculations have been completed and the report will be submitted shortly to SQUID Administration. In this report it is shown that the transverse acceleration in the flow is to a great extent dependent upon the area ratio of entrance and exit cross-sections at the start of the inflow period. A suitable chosen mass distribution enables the reeds to follow the shapes of the instantaneous stream-lines; thus, for the selected area ratio, a smooth nozzle flow results. In the typical examples included, the following functions, checked in Figure 1, have been evaluated for the basic parameter $\frac{A_{o,t}}{A_{h,t}}$.

$\frac{A_{o,t}}{A_{h,t}}$	ρ	A	U	P_i	M	P_{cc}
3:1	x	x	x	x	x	x
3:33:1	x	x	x	x		
5:1	x	x	x	x	x	x

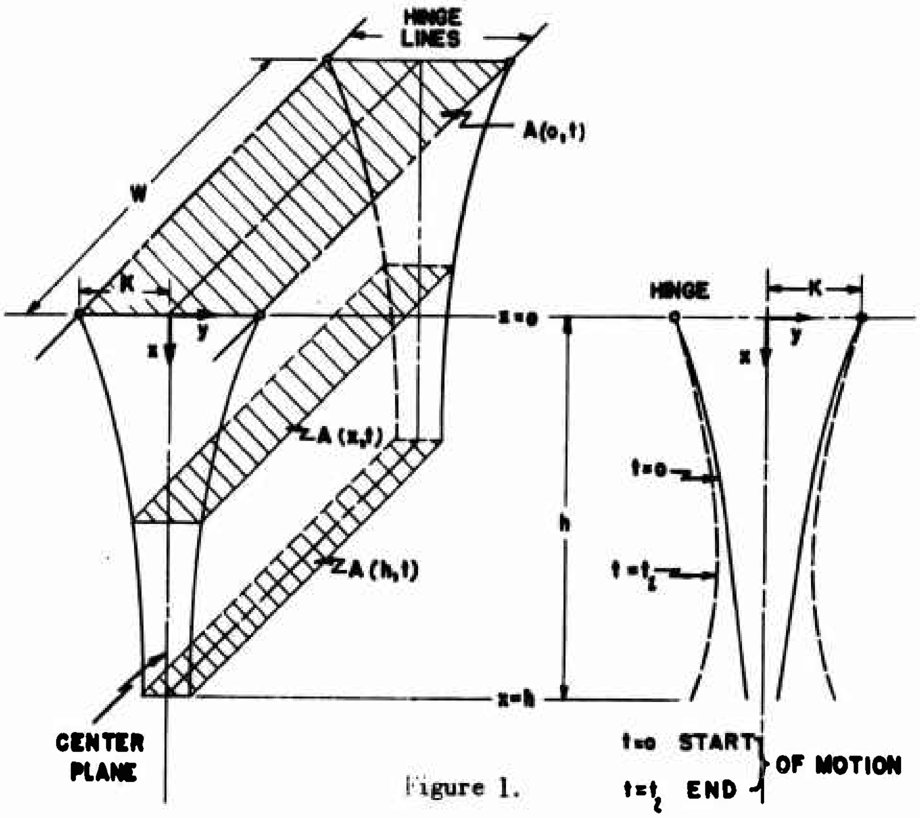


Figure 1.

where : ρ = density distribution

A = cross sectional distribution

U = inflow velocity distribution

P_i = inflow pressure distribution

M = mass distribution of reed

P_{CC} = pressure distribution on combustion chamber side of reed.

Work at the Williamsport Test Stand. The existing equipment has been checked, and it was found that part of the equipment necessary for hot tests of pulse jet engines has been removed or dismantled by the previous users of the test stand. Part of this equipment has already been recovered and reassembled and the instruments calibrated. One bourdon pressure meter and one electric flow meter needed thorough overhauling due to damage from rodents. The mechanical fuel flow meters of sufficient capacity were not at hand and were not recoverable, since they were the property of Avco Inc. Two rotameter type flow meters have been ordered, one for measuring fuel flow (35 lb. to 350 lb. per hour capacity) and one for measuring water flow (45 lb. to 420 lb. per hour capacity); both meters have been ordered from Fisher-Porter Co., Hartboro, Pa., and the water flow meter has already been delivered.

The 250 h.p. electric motor for driving the air blower has been recovered and mounted on its stand, but the blower could not be reassembled as yet.

Preliminary runs were made with one of the 8-inch McDonnell engines. Only the Diesel compressors were used for starting air supply. The mount for the pulse jet engines is not satisfactory and will have to be redesigned, since instantaneous as well as average thrust measurements are necessary, and since the present engine mount measurements are very inaccurate because of the high inertia forces of the mount itself.

Design of a new type of engine mount, suitable for continuous thrust measurements by means of dynamic strain gauges, has been started at P.I.B.A.L. A pilot test-stand will be set up in our newly acquired Quonset hut for testing instruments for the full scale experiments.

Experimental

Progress. Preparations for the cold testing of the pulse jet model have been going on since January. Velocity and direction of airflow measurements will be made by means of hot wire anemometry. Basic designs of the apparatus for hot wire traverses have been completed although some detail dimensions must be determined by the final dimensions of the model.

Plans. All effort will be concentrated on completion of the inflow analysis between clamped reed valves after the technical report for the hinged reed valves is submitted. A new type of model suspension will be built at the Williamsport site. Hot wire calibration will commence after completion of a new bridge specifically designed for the new type hot wire anemometer. The low pressure gage for the cold test will be calibrated after completion of a specially designed carrier-type amplifier for the oscillograph. If satisfactory results are obtained, an order for additional low pressure gages will be issued. A portable stand will be built to hold the model while gages and instruments are mounted and also to provide for moving and storing the unit.

PHASE II

(1) To investigate causes of metal failure encountered by evaluation of use tests on developed materials, and (2) to investigate and develop new alloys to resist pressure, temperature, and erosion conditions existing in propulsion units by (a) modification of present alloys, (b) development of new alloys, and (c) use of powder metallurgy methods.

Summary

The design and construction of the tensile loading system of the variable temperature creep machine is nearing completion. Temperature distribution studies have advanced into the final stage of completeness. The status of work on the carbide and nitride series is reported.

Progress

Variable Temperature Creep Machine. During the past three months design and construction work has progressed toward the completion of the tensile loading system. The motor and loading screw drive have been assembled, and operation is satisfactory. At present, machine work is being undertaken for the fabrication of a sample test specimen, specimen grips, and a furnace carriage. Much work remains to be done on the instrumentation details before a creep test can be run.

Temperature Distribution Studies. Preliminary tests were performed on steel No.30 (C, 1.07%; Ni, 4.96%; Mn, 0.48%; Si, 0.41%) to determine its suitability for cold forming.

Tensile tests, bending tests, and drop forging tests indicated that the steel could be pressed into combustion chambers for temperature determination tests. Two straight tubes were produced by cold pressing. The first tube was formed in a rough jig and finished off by forging. This tube was not very successful. A second tube was fashioned with considerable success in a split die machined from cold rolled steel.

Various ideas were taken into consideration concerning the possibility of forming a tube with a reduced section. It was decided that the best method was to produce sections of the desired tube and to weld them together. To accomplish this a kirksite die (m.p. 785°F) was cast and a mandrel machined to give the desired contour as shown in Figure 2. The first attempts at forming in this die met with failure as the metal tore under cold pressing. To remedy this situation hot pressing was next attempted. The steel was heated to approximately 1250°F and then pressed. Four half-sections were produced in the desired shape by using this method. There was no sign of melting even though the melting point of the die was exceeded by roughly 500°F. The half-sections were then ground, fitted, and welded with 25-20 rod, see Figures 3 and 4. The tubes were then heat-treated to a predetermined martensitic structure. A spot check, by hardness measurements, was made on the tubes to see if they were in the martensitic state. The tubes hardness tested R_{45N} 65 to 66, which compared favorably with the standards R_{45N} 66 + 1 unit.

Five chromel-alumel thermocouples were made and attached to the tube wall at different stations, see Figures 5 and 6. The tube was fired by means of an oxygen acetylene

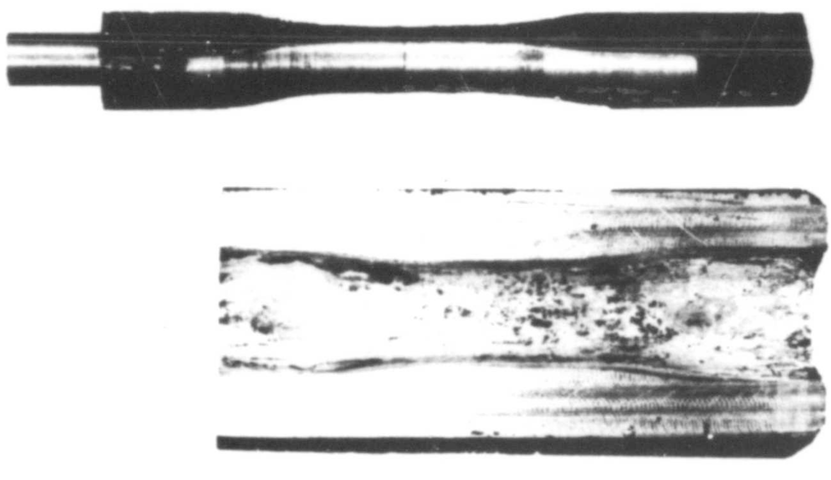
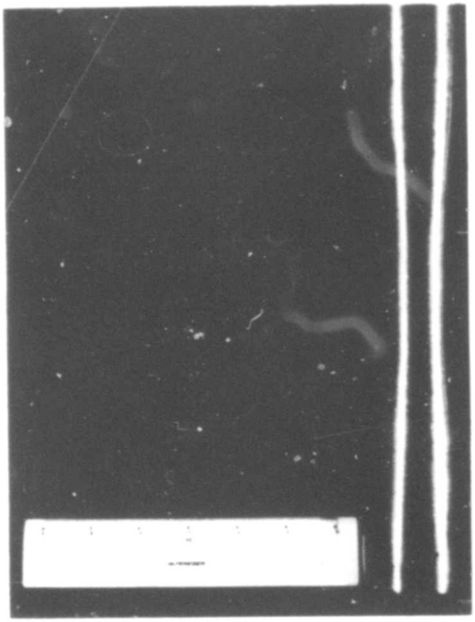
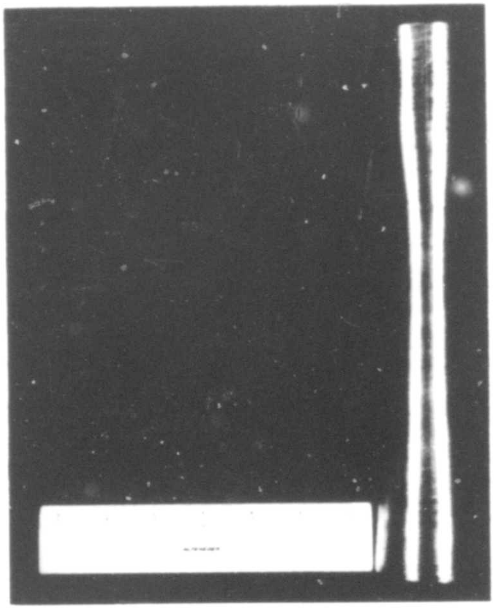


Figure 2.





Figures 3 and 4.

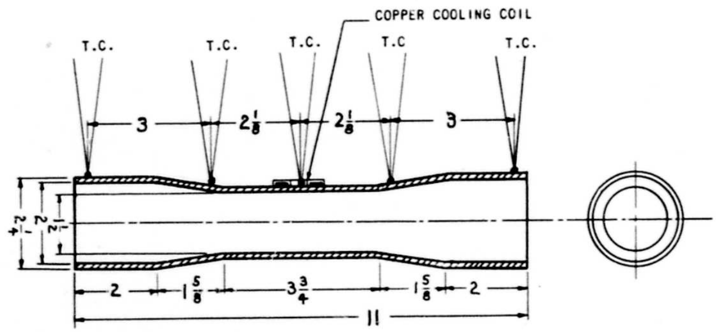


Figure 5. Diagram of thermocouples and tube.

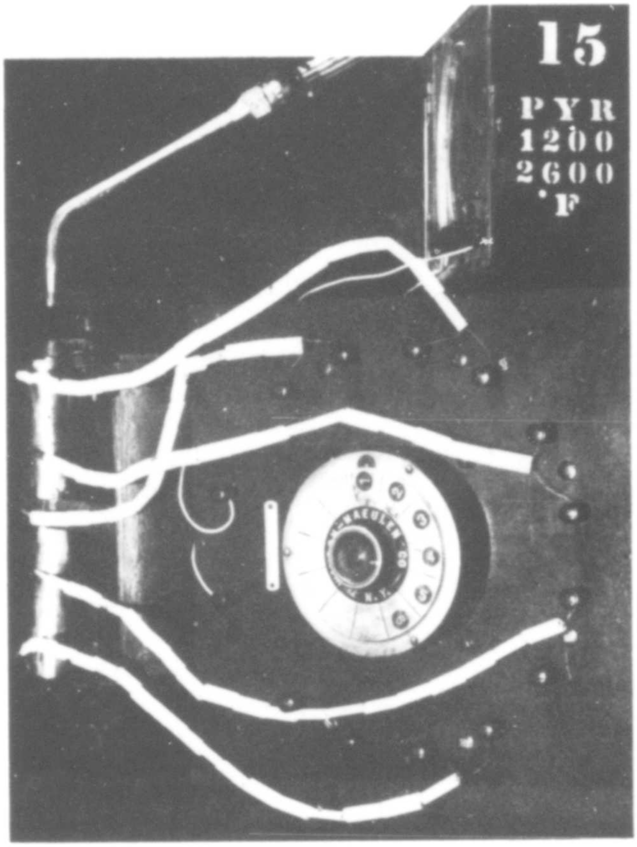


Figure 6.

flame for five minutes. Sectioning of the fired tube is now preceeding for metallographic and hardness studies.

Study of Carbides and Nitrides. Work was continued on the systems tungsten carbide-cobalt and titanium carbide-cobalt. These could be sintered in air without apparent deleterious effects. Density measurements were made on these alloys.

The titanium carbide-chromium samples were unsatisfactory as prepared in air because of reaction between the chromium and both oxygen and carbon monoxide. As this difficulty is expected to be encountered in many systems, a vacuum furnace and pumping system was designed and approval for the purchase of the components secured. The furnace and pumps have been delivered and are being assembled.

A micro-hardness study of the phases in sintered titanium carbide-chromium alloys revealed that the entire mass of one of the contaminated samples was extremely hard. The diamond point of the Microcharacter was destroyed after a few short microcuts had been made. Results with a penetration-type instrument, the Bergsman, confirmed the observations made with the Bierbaum machine.

A diamond-wheel cut-off machine was obtained to section the cones for slumping temperature determinations from the cylindrical bodies of the sintered slugs.

The design of a Nernst-Tammann carbon tube resistance furnace for very high temperatures has been completed.

Plans

On completion of the tensile loading system, work will commence on the instrumentation details to enable a creep test to be run.

When the fired tube is sectioned, metallographic and hardness studies will be made and the results submitted as a technical memorandum.

Future plans will involve the investigation of some of the carbide and nitride systems in the vacuum furnace. Attempts will be made to purify the metals and compounds by extraction of their oxygen content. Work under partial pressures of inert gases will be attempted.

PHASE III

(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.

Summary

A theoretical investigation of the laminar boundary layer of a compressible fluid flowing along a porous flat plate with fluid injection through the porous cells of the plate was made. The manuscript containing this material, which will be presented in the Heat Transfer and Fluid Mechanics Symposium in Los Angeles, is in the process of being written. The experimental investigation of the stability of the laminar boundary layer along the surface of a porous flat plate with injection is in progress.

Progress

A *theoretical* investigation of the temperature field in the laminar boundary layer (compressible fluid) on a porous flat plate with fluid injection has been made. The analysis for a compressible fluid under the same flow conditions as given in Technical Report No. 4 was carried out. In this analysis the inverse proportion between mass-density of the fluid and its temperature was used, and the viscosity was assumed to be proportional to both the square root and three-fourth power of the temperature.

In the solution of the laminar boundary layer equations, Prandtl's number is assumed to be equal to unity, then the temperature T can be expressed by a certain parabolic function of the velocity only, which satisfies both the equation of motion and the energy equation. The velocity profile was assumed to be linear and also as a polynomial of the fourth degree.

The solution of the above differential equations gave the relationship of length in the direction of flow to the boundary layer thickness for any given temperature ratio (free stream temperature to wall temperature). The relation between the wall temperature and the amount of coolant needed is also established for any given free stream and wall temperature ratio. The results of the investigation will be given in the manuscript mentioned in the summary.

An *experimental* investigation of the stability of the laminar boundary layer along the surface of a porous flat plate with fluid injection is continuing. The porous plate over which the flow is being investigated has been machined and mounted. It was decided that the elements that composed the plate had to be sealed off in the turbulence channel to insure uniform fluid injection. This has been done, and the porous plate is now ready for testing. It had also been decided to use 0.005" tungsten wire for the hot wire elements to give greater sensitivity for the velocity direction determination, a relatively important factor. This has necessitated the construction of a new Wheatstone bridge, which is now being built. Commercial nitrogen which will serve as the injection fluid, will be pressurized through the porous plate. This injection system design has been completed. Preliminary test runs will shortly be made to assure the precise operation of all instrumentation.

Proposed Work

Further investigations of the laminar boundary layer of a compressible fluid will be made. The investigation of the turbulent boundary layer of a fluid on a porous flat plate with injection is planned. The problems of flow of the fluid through porous metal and the temperature distribution will also be studied. Experimental verification of the above-mentioned theoretical investigations will be attempted.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-104, TASK ORDER I

PURDUE UNIVERSITY
and
PURDUE RESEARCH FOUNDATION
WEST LAFAYETTE, INDIANA

1 APRIL 1948

PHASE I

Statement of Problem. Development of a method of measuring instantaneous gas temperatures fluctuating at frequencies from 50 to 100 cycles per second in a range of temperatures from room temperature to 3000°F (pulse jet gases).

Progress. The researches of this phase are inactive at present.

PHASE II

Statement of Problem. To study continuous process combustion, defining effects of combustion-chamber size and shape, fuel and oxidizer distribution, and turbulence with available fuels and oxidizers.

Project Leader: H. J. Buttner, Professor of Automotive Engineering.

Summary

All of the activities on this phase were transferred to the new Combustion Laboratory at the Purdue Airport, where combustion studies were not limited by campus regulations against hazards and noises. As a result of this move, the systems for operating the burners had to be revised, and numerous difficulties resulting from the operation of the engine driven supercharger installations which supplied the air had to be overcome. Experimentation during this period was focused upon the flame-holding investigation to try to ascertain the parameters affecting flame stability. A preponderance of effort dealt with combustion of propane and air mixtures in an unconfined flame. Brief studies of the effect of enclosing the flame were made. Also some burning of heavy hydrocarbons instead of the gaseous propane was done in order to determine their applicability to heat power devices. The effect of turbulence on combustion was not studied during this period; however, preparations were made to obtain thermal evaluation of the effects of known intensities of turbulence applied to the unburned mixture.

Progress

Many experiments were conducted to find the effect of four variables on the stability of combustion in a burner where flame holding is obtained by means of an annular pilot flame surrounding the main jet. One of the variables studied (a) was the effect of mass rate of

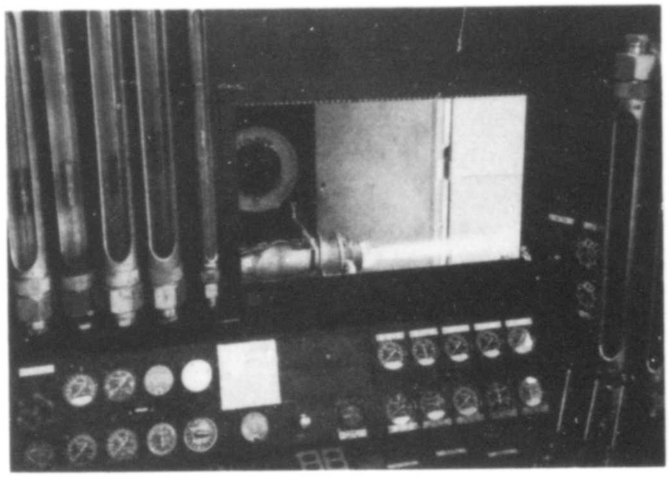
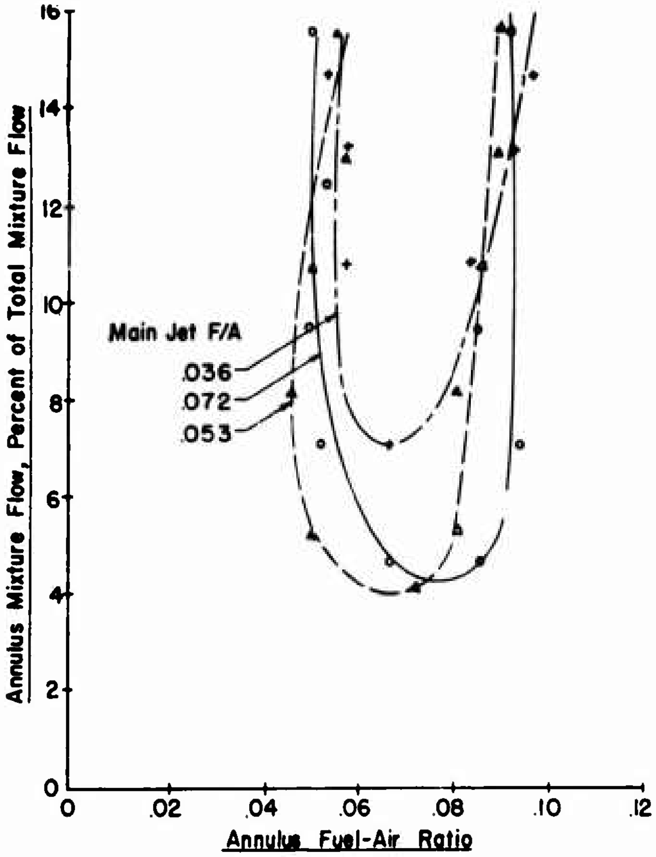


Figure 1. Combustion flame from intermediate burner with main jet mixture velocity of 500 feet per second.

flow or velocity of the main jet on the limits of stability. It was found that, with proper control of the other variables, over 1100 feet per second mixture velocity could be attained with stable burning. The remaining variables studied were (b) the effect of mass rates of mixture flow in the annulus, (c) the effect of fuel-air ratio in the annulus, and (d) the effect of fuel-air ratio in the main jet.

Within the permissible operational range studied at the previous location of the burner on the campus, no indications of instability of burning were found as long as the mixture velocities in the variable area annulus equalled the flame propagation velocity. Recent studies indicate this to be true up to the point where the rate of heat release from the annulus flame is insufficient to maintain continuous ignition of the main jet mixture.

Figures 2, 3, and 4 show the annulus fuel-air ratio requirements for a stable main jet flame for different rates of annulus mixture flow in terms of per cent of total mixture flow; the latter includes both the main and annulus flows. The curves for these three figures were obtained with mean velocities in the main jet of 500, 600, and 900 feet per second respectively and with various constant fuel-air ratios of the main jet mixture for each velocity. Each curve indicates the limits of stability as noted by audible and and visible means. The region within the configuration of each curve represents conditions



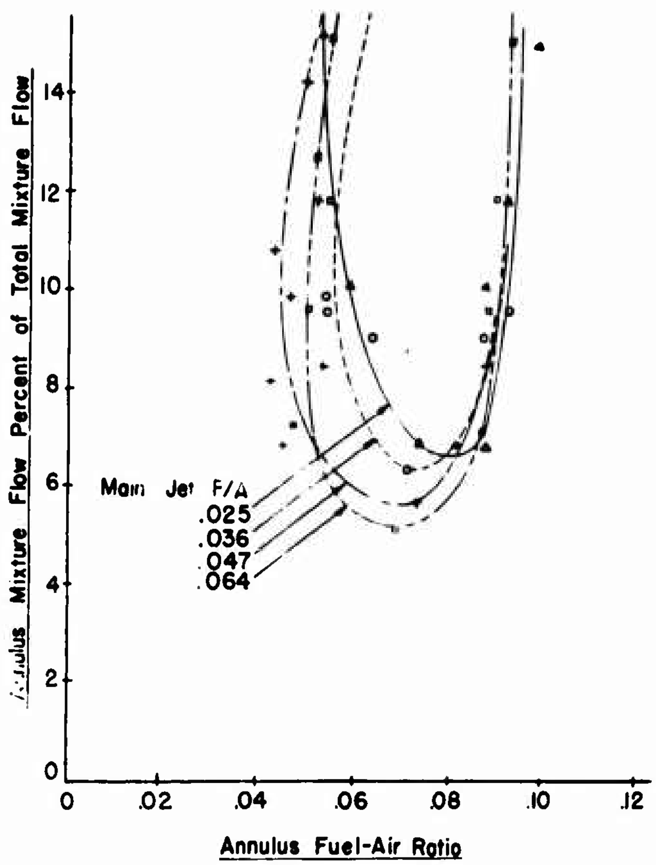


Figure 2. Stability limits of unconfined flame with main velocity of 500 feet per second.

Figure 3. Stability limits of unconfined flame with main jet velocity of 600 feet per second.

of stable burning within the main jet. The lowest point on each curve represents the minimum flow within the annulus, in terms of per cent of the total mixture flow, that will support a stable flame within the main jet. Any further reduction in the mixture flow through the annulus will result in an unstable main jet flame regardless of the annulus fuel-air ratio.

A minor change in the limits for stability and flame blow-out is evident from a comparison of Figure 12 in the Purdue section of the Annual Report, 1947, and Figures 2 to 5b inclusive. This difference is primarily due to more even distribution of the annulus mixture and more thorough mixing of the fuel and air for the series of experiments therein reported.

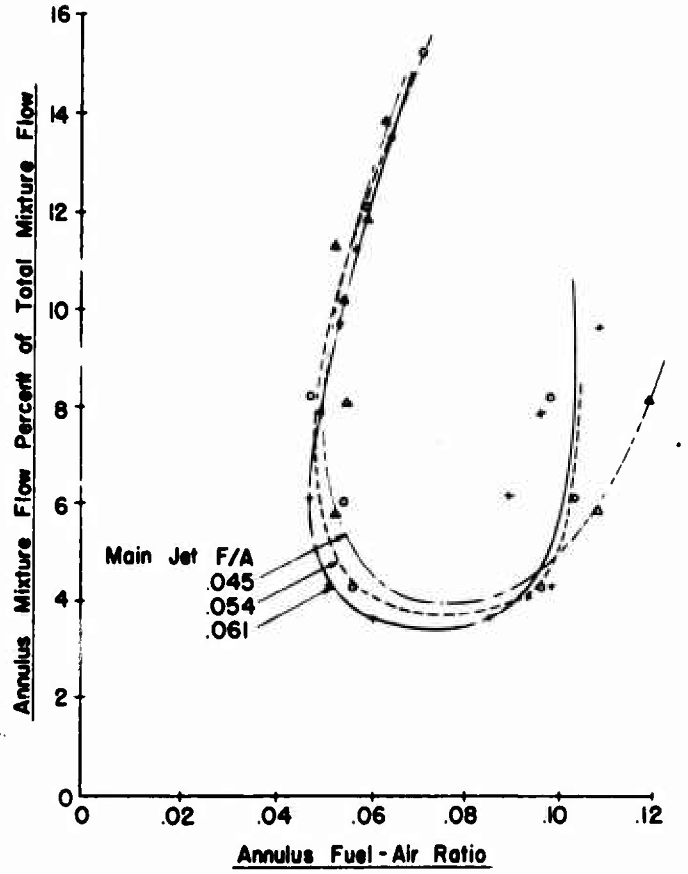
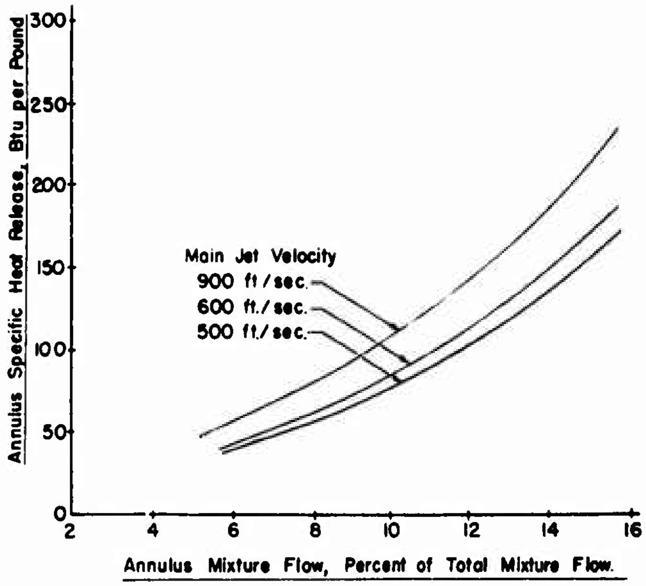


Figure 4. Stability limits of unconfined flame with main jet velocity of 900 feet per second.

Further reference to Figures 2, 3, and 4 will indicate that for flow-rates in the annulus above and below certain values the fuel-air ratio must be enriched to prevent instability. The critical condition can be determined by the leanest mixture which maintains stability. For flow-rates greater than the critical value the mixture strength must be increased to raise the flame velocity and counteract the increased velocity of flow through the annulus. For flow-rates less than the critical value, it becomes necessary to enrich the mixture, presumably in order to maintain a minimum rate of heat release.

Figures 5a and 5b show the variations of specific heat release necessary within the annulus to prevent blow-out of the annulus flame at the lean limit of combustion. For the lower rates of flow, the main jet flame blows out prior to the blow-out of the annulus flame, indicating that a minimum heat release is necessary for ignition of the main jet. With variable mixture strength from the lean-limit to the stoichiometric value in the main jet, it appears that no change in the heat release from the annulus is required to retain burning in the main jet.



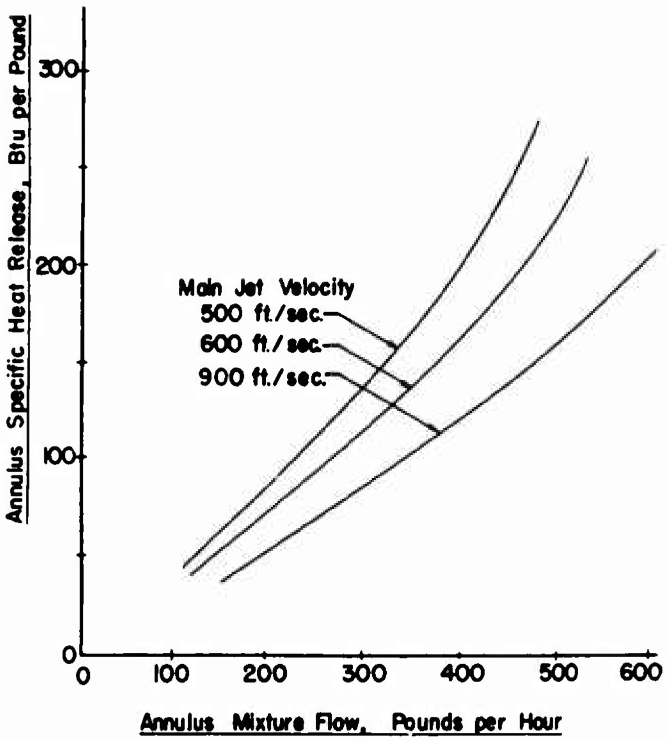


Figure 5a. Specific heat release of annulus flame at lean mixture blowout.

Figure 5b. Specific heat release of annulus flame at lean mixture blowout.

The term specific heat release, used in preparing Figures 5a and 5b is defined as the total theoretical heat release per unit of time within the annulus divided by the weight rate of flow within the main jet. Simplifying, it is equal to B.T.U. per pound. For a given specific heat release, a greater amount of mixture must flow through the annulus for increased velocities of the main jet. Three different main jet velocities are shown in the figures.

In an earlier study the high main jet mixture velocities (acoustic velocity range) for which stable burning was possible were observed. This study was repeated with the flame confined within a tube. Except for the apparent shortening of the flame length, no appreciable change occurred. The area ratio of the tube to main jet was of the order 13 to 1; thus there were no difficulties from thermal choking.

Plans

Additional experimentation with the present burner will be conducted to complete the study of the effect of the variables reported for this period. Studies will then be made of the effect of burning in a confined space. A second burner has been fabricated with identical configuration of the inner main jet contact surface, but with provision for the annulus flame to enter the main jet without the abrupt step now existing due to the great radial space between the bore of the inner jet nozzle and the inner surface of the annulus. This modification will permit enclosing the flame within a tube having a cross-section ordinarily of the same dimension as the main jet flame. This change will permit experimental evaluation of flame choking and other limiting conditions encountered with combustion at high velocities. The study of the effect on flame length, thus burning rate, by use of turbulence creators will be made. It is expected that the modified hot-wire anemometer soon will be available for an evaluation of the intensity of turbulence.

Studies of flame temperatures by the sodium line reversal method will be applied to turbulent flames. Correlation between the mean flame temperature obtained by integration of spot temperature traverses with partial flame coloration and the total coloration is being attempted to aid in the evaluation of the effect of turbulence on combustion.

PHASE III

Statement of Problem. This phase undertakes the study of corrosion in connection with jet propulsion. The purpose of the research is to identify the corrosion products and to investigate the process of corrosion and its dependence on the chemical and physical properties of the materials and on the conditions of exposure.

Project Leader: H. J. Yearian, Professor of Physics.

Summary

An anomaly in the X-ray diffraction from an alloy during its oxidation has been investigated further.

X-ray diffraction studies of the abnormal oxidation of an 11% chrome-iron alloy at 670°C give iron oxides with a small amount of chromite in solid solution in one case and only iron oxides in other cases. Microscopic and X-ray diffraction observations of the thick coating formed on the alloy during oxidation in air at 900°C reveal two light colored layers separated by a thin darker region. The inside of the inner layer shows only chromite; the outside of this layer shows that the chromite has a small amount of magnetite in solid solution accompanied by α Fe_2O_3 and possibly FeO rich in iron. Additional X-ray studies are discussed.

Electron diffraction measurements of the oxidation of a 27% chrome-steel give two reversals of the magnetite-spinel sequence of formation, which was found to occur over the whole temperature range of an 11% alloy. These are interpreted to mark the onset of new stable phases.

Progress

As discussed in the 1947 Annual Report for Project SQUID, an anomalous increase in the intensity diffraction from the base metal has been observed after the first short oxidation period. After eliminating the effects of recrystallization of flow layer as an explanation, it was proposed that the anomalous increase in the intensity diffraction could be due to a temporary depletion of chromium from the metal surface. A quantitative investigation of this effect shows that such a depletion would tend to give larger observed intensities, but could not be increased above the original values. The absorption of chromium in the form of oxide would decrease the observed intensity more than the intensity from the base metal would be increased.

Two other possibilities are being considered. The beam diffracted by the metal may be weakened by extinction as well as by absorption, and this extinction might be diminished during oxidation by an increase in imperfection of the metal crystals. This seems unlikely, however, since the absorption is very high with the radiations used and the crystals near the surface should already be very imperfect due to the polishing. A second possibility is that oxidation produces thin projections of metal through which diffraction can occur with less absorption than from a flat surface (the usual situation in the diffraction of electrons from "flat" surfaces). In this case it is difficult to understand the fact that the anomaly occurs only with iron radiation and not with copper radiation.

Attempts to follow the anomaly in reverse—that is, by stripping off the oxide and then polishing--have not been conclusive since no completely successful method has been found for removing the oxide layer with assurance that the metal surface is not altered. (Only a few tenths of a mil are effective in the diffraction.)

X-ray diffraction equipment for back reflection measurements of oxide structures has been set up. For iron alloys of high chrome content, chromium $K\alpha$ radiation is necessary. This has required special attention in the outgassing of the X-ray tube, the use of very thin aluminum windows, and the development of a satisfactory film covering material. Some measurements have been made on an 11% chrome-iron oxidized at $670^{\circ}C$ in one atmosphere of oxygen.

A sample which showed an abnormally rapid formation of a reddish-brown oxide (approximately 2 milligrams/cm^2 in 33 hours, as measured by the absorption method) gives Fe_3O_4 with 20 to 30% of $FeCr_2O_4$ in solid solution, and Fe_2O_3 with little or no Cr_2O_3 in solid solution. Other specimens which are rapidly attacked at the edges, forming a silvery grey oxide (Annual Report, 1947), give α Fe_2O_3, occasionally some additional Fe_3O_4, and no evidence of chromium. The patterns from these oxides consist of broad lines, indicating either very small particle size or non-homogeneous strain. The range of angles covered in the back reflection technique is too small to decide between these alternatives. It may be possible in some cases to remove a sufficiently large sample so that other powder diffraction methods can be used.

The normal protective layers formed in intervals of up to 330 hours at 670°C are not thick enough for back reflection photographs. During oxidation at 800°C of several samples of this material, plus specimens of commercial grades of 5, 13, 17, and 26% chrome-steel, the furnace overheated and burned out due to failure of the regulator. The oxides formed are being measured and analyzed.

Microscope studies of the oxidation of the 11% alloy in air at 900°C have been made. Two light colored layers are found which are spearated from each other and from the metal by thin dark layers. After several hours of oxidation the layers can frequently be separated at the dark regions. The inner light colored layer has been investigated by back reflection. The side next to the metal, carrying traces of dark red-brown material from the intervening dark layer seen in the microscope, gives a very poor pattern of broad lines identified as $FeCr_2O_4$ with little evidence of Fe_3O_4 in solid solution. The outside of this layer, which carries fragments of the dark region separating it from the outer layer, also gives broad lines. These are identified as $FeCr_2O_4$ with 10 to 20% of Fe_3O_4 in solid solution, αFe_2O_3 with little if any Cr_2O_3 in solid solution, and one line which agrees with FeO rich in iron.

The outside layer will be investigated similarly, and both layers will be studied by the Debye-Scherer technique.

A study of the oxide structures formed on certain Fe-Cr-Ni samples for which extensive data on corrosion resistance and mechanical properties are available (Annual Report, 1947) is under way.

The electron diffraction structure investigations of the oxides formed on an 11% chrome-iron alloy when oxidized in oxygen at a pressure of one millimeter of mercury (summarized in the Annual Report, 1947) show general agreement with the work of Hickman and Gulbransen on a 13% chrome-iron. There are significant differences at 600°C, so that a high chrome alloy has been studied (Armco 27: Cr 26.31%, C 0.14%, Mn 0.68%, P 0.020%, S 0.13%, Si 0.74%, Ni 0.33%, N 0.115%).

The results, within the limitations of distinction between iron and chromium oxides previously discussed, are shown in Table I. The entry at zero time of oxidation refers to the structure found on heating the sample to the oxidation temperature in the residual gas of the camera (5×10^{-5} mm Hg.). The last entry is the result after heating for 30 minutes in the camera vacuum following the 60 minute oxidation.

The initial structure marked "?" is not one of the common forms of iron or chromium oxides but is in good agreement with the hexagonal oxide found on iron by Jackson and Quarrell (Iron and Steel Institute, Special Report No. 24, 1939).

The reversal at 500°C of the 0 to X sequence of formation is similar to that observed by Hickman and Gulbransen on the 13% chrome-iron at 600°C but was not found on the 11% alloy. Presumably this corresponds to a change in type of oxide from iron-rich to chromium-rich, or vice versa. If so, this transformation occurs at a lower tempertaure with the higher chrome alloy. At the highest temperature the first positive electron diffraction evidence of a chrome-rich oxide is found. Coincident with the new phase is an additional reversal of the 0 to X sequence of formation. This confirms the suggestion that the similar reversals at lower temperature and percentages are probably associated with a change of phase from an iron-rich to chromium-rich oxide, even though the X structure found there is in better agreement with Fe_2O_3 than with Cr_2O_3. It will be noted that at 500°C the oxides formed are reducible in the camera vacuum, but not at the higher temperatures.

Plans

Further investigations of the anomalous behaviour of the X-ray absorption analysis will be made by removal of the oxide and by more detailed experiments on the effect of surface preparation. If the difficulty can be resolved, the measurements will be continued on other alloys and at higher temperatures.

The back reflection measurements will be continued on chrome steels of various compositions at higher temperatures both in oxygen and in air. These will, where feasible, be combined with Debye-Scherer investigations and optical and electron microscope observations.

Attempts to polish thin sections of the oxide layers for X-ray microradiographic photographs will be continued. Some promise of success in this work has been obtained recently.

TABLE I

Surface Structures Formed on a 27% Chrome-Iron Oxidized in Dry Oxygen at One Millimeter Mercury Pressure

Legend:
- ? = unknown hexagonal structure
- 0 = Fe_3O_4 (or other spinel, e.g. $FeCr_2O_4$)
- X = Fe_2O_3 (or solid solution with Cr_2O_3)
- X_c = Cr_2O_3 (or solid solution with Fe_2O_3)
- o = preferred orientation

Time of Oxidation	Temperature of Oxidation 400°C	500°C	600°C	700°C
0 min	0	?	?	?
1 min	0	?	?	X_c
5 min	0	Xo	0	X_c + trace 0
30 min	0	Xoo	0	0
60 min	0	0Xo	0X	0
30 min (vacuum)	0	?	0X	0

Tests of the low-power electron microscope for selective imaging of iron and chrome-rich regions of the oxide layers will be pressed as soon as the necessary X-ray tube is received.

A higher precision 50 kv. voltmeter than is now available has recently been completed and is being calibrated. This will increase the accuracy of the electron diffraction measurements to some degree and will therefore aid in distinguishing between the patterns of iron and chromium oxides. The electron diffraction studies of oxide growth will be extended to additional pure binary and commercial iron-chrome alooys.

The electrical properties of the protective oxide layers will be investigated. The immediate experiment planned is to determine the potential distribution across a thick-layered oxide structure when an electric current is passed through it. This will give a correlation of the resistance of the various layers and any potential barriers which may exist between them.

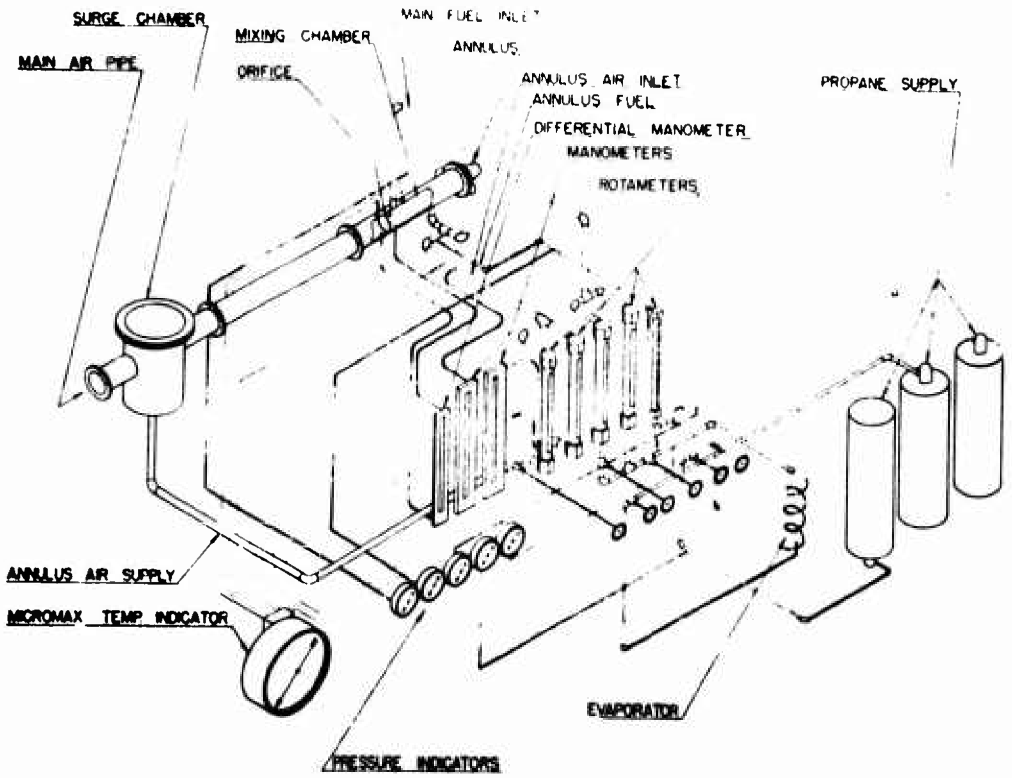


Figure 6. Fuel and air system for intermediate burner.

PHASE IV

Statement of Problem. The purpose of this research is to study, by means of bomb or continuous-flow experiments, temperatures, pressures, and concentration of reactants for various oxidation reactions of materials that may be of value as fuels for rocket or jet engines.

Project Leader: D. E. Holcomb, Assistant Professor of Chemical Engineering.

Summary

The equipment for carrying out constant volume experiments for this project has been completed and calibrated. The vapor pressure of hydrazine monohydrate has been determined over the temperature range of 60 to 100°C.

Progress

During this quarter the construction of the apparatus for determining the effect of surface upon the rate of the thermal oxidation of hydrazine monohydrate was completed. A heavier power line for the oil bath heater and a control panel for the apparatus were installed. A number of heating runs were made to determine the time required to reach certain temperatures and to determine the degree of temperature control in the isothermal reactor jacket. The degree of control attained was satisfactory. The entire reactor system was then given a thorough cleaning and adjusted until all leaks had been eliminated.

In order to determine suitable temperatures for the oxidation reaction, two runs were made in reaction bulbs immersed in a water bath maintained at constant temperature. Inaccuracies created during the charging of the bulbs and by condensation of the hydrazine monohydrate after the reaction had begun made the data obtained unreliable, but a measurable reaction was observed.

In order to obtain vapor pressure data for the hydrazine monohydrate, necessary for the selection of conditions which preclude condensation during the course of the reaction, a number of runs were made in the temperature range at which the reactions will be carried out. Having obtained these data, attention was turned to the determination of the degree of dissociation of the superheated vapor. One run was started, but mechanical difficulties developed during the course of the run and it became necessary to partially disassemble the apparatus. The mercury used as a confining liquid was cleaned and redistilled. Upon reassembly of the apparatus the reactor was recalibrated in such a manner as to facilitate the reading of the mercury level. A new charging device, which will improve the ease and the accuracy of charging hydrazine monohydrate, was made and installed.

Plans

Additional runs are to be made with superheated hydrazine monohydrate vapor in order to determine the amount of dissociation, if any. After these runs have been completed, the oxidation studies will be made.

PHASE V

Statement of Problem. The purpose of this research is to determine, for liquid-fuel rockets and pulse jet engines, the radiation factor and its contribution to heat transfer coefficients inside a pipe with gas flow at both low and high temperatures.

Project Leader: J. M. Smith, Associate Professor of Chemical Engineering.

Summary

The construction of the apparatus and preliminary calibration runs have been completed. The maximum design temperature of 2000°F was reached and control was maintained at this point. Runs at low temperatures are in progress so that the existing correlations for heat transfer to gases may be used to check the design and accuracy of the apparatus.

Progress

The resistance heaters in the test section were completed, and the test section wall thermocouples were welded to the tube. The apparatus was made air tight and then was insulated with two inches of diatomaceous earth followed by two inches of magnesia.

The calibration of the thermocouples was completed through 2000°F. The platinum thermocouple shields were assembled and suspended in the test section. During preliminary tests, control of the temperature within ± 2°F at 2000°F was found feasible.

Initial performance tests indicated that at a Reynolds number of 6810 a temperature of slightly over 2000°F can be attained in the gas entering the test section.

Runs are now being made using air at temperatures in the range 400-600°F so that the existing correlations for heat transfer coefficients may be obtained as a means of checking the design of the apparatus and accuracy of the method.

Plans

During the next quarter extensive determinations will be made of the film coefficients for air at various Reynolds numbers and at temperatures up to 2000°F.

PHASE 6-F

Statement of Problem. The purpose of this research is to determine experimentally heats of formation and combustion, specific heats, and other thermodynamic properties of various fuels and oxidizers used in pulsating jet engines. If possible, a correlation of thermodynamic properties of these fuels will be made so that calculations may be extended to include new fuels.

Project Leader: D. E. Holcomb, Assistant Professor of Chemical Engineering.

Summary

The heats of combustion of 2-nitropropane, 1, 1-dinitropropane, and 2, 2-dinitropropane have been determined experimentally during this quarter.

Progress

Experimental determinations of the heats of combustion of the nitroparaffins have been initiated. The heats of combustion of 2-nitropropane, 1,1-dinitropropane, and 2, 2-dinitropropane have been determined with a precision of the order of 1.5 per mille.

Arrangements have been made to obtain samples of trinitromethane and hexanitroethane from another laboratory. The preparation of 1, 3- dinitropropane is now in progress in this laboratory.

A new firing system has been designed and constructed in order to facilitate obtaining more precise correction data of the heat contribution by the electric energy used to ignite the sample.

Latent heats and refractive indices will also be determined as the samples become available in the purified form.

Plans

The experimental determination of the heat of combustion, vapor pressure, freezing point, viscosity, liquid and vapor density, latent heat of vaporization, and refractive index of various nitroparaffins will be continued during the next quarter.

PHASE 6-G

Statement of Problem. The determination of heats of combustion of various chemical compounds suitable as high-energy fuels and oxidizers.

Project Leader: H. Hunt, Professor of Physical Chemistry.

Summary

Using the same equipment with which the heats of combustion of five aromatic amines were determined (as reported previously[1]), the heats of combustion of p-phenylene diamine, oxalyl dihydrazide, malonyl dihydrazide, and succinyl dihydrazide at constant volume and at 25°C have been obtained.

Progress

The heat of combustion at constant volume for each of the compounds listed has been determined by the nonadiabatic method using a Parr double valve oxygen bomb of 358 ml capacity using an oxygen pressure of 30 atmospheres at 25°C. The values of these heats of combustion are as follows, the standard deviation of each calculated in accordance with the recommendations of Rossini:[2]

p-Phenylene diamine	=	838.16	±	0.15	Kcal/mole
Oxalyldihydrazide	=	323.74	±	0.13	Kcal/mole
Malonyldihydrazide	=	476.91	±	0.13	Kcal/mole
Succinyl dihydrazide	=	630.88	±	0.11	Kcal/mole

To accomplish ignition of the samples of oxalyl dihydrazide and malonyl dihydrazide it was necessary to use a small pellet of benzoic acid (National Bureau of Standards, Sample 39f) as a promoter, thereby reducing slightly the precision of these two measurements.

Additional changes in the equipment being used, completed during the period covered by this report, include the installation of a new White double potentiometer and the assembly of a new audible timer which makes use of a synchronous electrical motor instead of a stopwatch.

A critical examination of methods whereby the heat input during ignition can be determined more accurately is being made. No startling revelations have been discovered.

Plans

Future work will continue on the measurement of the heats of combustion of selected compounds. Hydrazine nitrate, hydrazidicarbamide, and carbohydrazide are now on hand, and work with them will begin shortly.

References.

1. Project SQUID, Annual Report, December 1947, Purdue University, Phase 6-G.
2. Rossini, F. D., *J. Wash. Acad. Sci.*, 29, 416 (1939).

PHASE VII

Statement of Problem. Investigation of rocket motors and liquid propellants at high chamber pressure.

Project Leader: M. J. Zucrow, Professor of Gas Turbines and Jet Propulsion.

Summary

The current research activities have been divided into four categories, namely (1) Motor Design and Test Program, (2) Preliminary Analysis of Heat Transfer Problem,

(3) Propellant Thermochemistry, and (4) Completion of Test Pits and Their Equipment. The final plans and specifications for the rocket test building have been completed and the contract let. The investigators working in the aforementioned fields are conducting pertinent design studies and ordering equipment necessary to conduct the research program while awaiting construction of the test pits.

Progress

Motor Design and Test Program. The preliminary phase of the investigation of motor parameters has been started, and a breakdown of the overall program is nearing completion. This overall program will be divided into individual studies of the major components of a rocket motor, namely the injector, combustion chamber, and nozzle.

Design studies have been undertaken of the combustion chamber at various operating pressures to determine the proper size and shape. An attempt will be made to design motors so that a wide range of parameter studies can be made with a minimum number of motors. By allowing each test to serve as a point on the parameter curve, several parameters can be determined with a given arrangement.

Preliminary design of the first motor is now in progress. Heat transfer calculations for liquid cooling of the motor with water have been completed, and these indicate that there will be a sufficient quantity of water available to give satisfactory cooling. This motor is being designed so that the rate of heat transfer along the combustion chamber will be measurable within engineering accuracy.

Preliminary Analysis of Heat Transfer Problem. An investigation of the heat transfer problem at elevated temperatures and chamber pressures up to 2500 psi has been undertaken. Since the physical constants of the various gas mixtures are involved, the first phase of the problem consisted in predicting the physical constants of the individual gases composing the various mixtures. Theoretical extrapolations of existing experimental values combined with the application of the Kinetic Theory have been completed, and the resulting values have been reduced to a mole fraction basis, giving approximate values of the various thermodynamic constants for different gas mixtures at high pressures and temperatures.

The convective heat transfer coefficient has been computed for a range of chamber pressures from 300 psia to about 2500 psia. At 300 psia there is good agreement with published values of the convective heat transfer coefficient. It is believed that the computed values at higher pressure are at least representative of the convective heat transfer coefficients to be expected.

Currently the work in progress is concerned with predicting the radiant heat transfer at the elevated temperatures and pressures.

Propellant Thermochemistry. The theoretical calculation of the effect of increasing the chamber pressure from 300 psia to 2056.6 psia on the combustion of aniline oxidized by white fuming nitric acid has been completed. These results show an increase in specific impulse of 19.2% over the value obtained at 300 psia.

In addition to the calculations on the white fuming nitric acid-aniline propellant combination, similar work has been undertaken on various liquid hydrocarbon fuels to determine the effect on hydrogen-carbon ratio at chamber pressures up to 2000 psia. The ultimate aim of this research is to make available a plot of C/H ratio against specific impulse with chamber pressure as the parameter.

Completion of Test Pits and Their Equipment. The construction work of the test pits has been awarded to an acceptable contractor by the trustees of Purdue University. The electric power for the test pit will be supplied by a 30 KW Diesel driven generator. Shipping orders have been issued for this machine by JANMAT.

All major equipment needed for the research and test program has been ordered, and much of it has been received.

Personnel Changes. The following persons have recently been added to the staff of this phase: Mr. I. J. Weisenberg, formerly of Aerojet Engineering Corporation, concerned with the design of rocket motors (employed on a full-time basis), and Professor C. F. Warner, School of Mechanical Engineering, Purdue University, in the field pertaining to heat transfer and thermodynamics (employed on a part-time basis).

Plans

The design studies conducted under each category presented in the Summary will be continued for different propellant combinations with chamber pressures up to 2000 psia. The results of the design studies will be incorporated into the design of the experimental motors to be used in the main research program. Considerable work is planned on the investigation of catalysts producing spontaneous ignition of hydrocarbon fuels with acid oxidizers. Work is also planned for obtaining accurate data on the ignition lag of various propellant combinations over a wide range of temperature. The instruments for the test pits will be installed as soon as their construction has progressed to a permissible and feasible stage.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-119, TASK ORDER I

CORNELL AERONAUTICAL LABORATORY

BUFFALO, NEW YORK

1 APRIL 1948

PHASE I

In connection with jet propulsion engines: (1) to study the mechanism on non-steady 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.

Summary

Techniques are being developed to study the motion of flame fronts in tubes by means of the characteristics method. Instrumentation for the water analogy experiments is nearing completion. Valveless pulse jets have been built and are being studied. A number of Technical Memoranda have been prepared covering characteristics studies, acoustic jet investigations, and new forms of intermittent combustion devices.

Progress

Characteristics Study. The first phase of the study of the method of characteristics was completed and a Technical Memorandum on the construction of wave diagrams was completed. An attempt was then made to apply the method to the study of flame motion in tubes. Expansion of the burned gas produces pressure waves which travel ahead of the flame. When they are reflected from the ends of the tube, they meet the flame again and are then partly transmitted and partly reflected. At the same time, the velocity of the flame front is modified. On the basis of certain simplifying assumptions, general relations for the flame velocity and for the refraction of pressure waves were derived. A number of wave diagrams were constructed and these indicated the same behavior of the flame front as was described in published observations. In view of the simplifying assumptions made, and since the variation of the burning velocity with the conditions of the unburned gas is not well known, the wave diagrams should not be expected to give quantitative results but they should be valuable to estimate local pressure developments or to compare the effect of igniting the mixture at different points.

Water Analogy Experiments. The instrumentation of the water analogy experiments is nearing completion. After successfully building a depth gauge mentioned in previous reports an attempt was made to build a velocity gauge based on the principle of a hot-wire anemometer. Tungsten wires of 0.0008 and 0.0005 in. diameter are being used. At first the wire formed part of an a.c. bridge the output of which was amplified and recorded by means of a cathode ray oscilloscope. Frequency response and sensitivity appeared to be satisfactory within the required range, but certain diffulties of balancing caused by harmonics were encountered. In order to eliminate these, the a.c. bridge was replaced by a d.c. bridge and the output was interrupted mechanically. This system appeared to be satisfactory. By operating the interrupter at 60 cycles per second it was possible to utilize the same timing arrangement which was used previously for the depth gauge. A small calibration unit was built consisting of a circular dish filled with water and rotated at a suitable speed. It is necessary to use water from which the air has been removed by boiling. Otherwise, air bubbles form on this wire and cause erratic readings.

A number of runs were carried out on the water table using the depth gauge. The water level in the channel at first was higher than outside. The gauge was placed at one end, and the other end was suddenly opened. The depth recordings were well reproducible. The depth versus time plot was compared with theoretical results obtained from wave diagrams and they agreed very well for the beginning of the cycle but a discrepancy was observed betwe e lowest depth measured and that calculated. It is possible that this is an effec viscosity and further experiments are required to explain the difference.

Jets Produced by Oscillating Systems. A Technical Memorandum describing the experiments carried out with a system consisting of a tube attached to a loudspeaker has been issued. It appears that systems of this type may yield values of specific impulse which are very much higher than those obtainable from conventional pulse jets. It is believed that these high specific impulses are due to effective energy utilization as a result of wave reinforcement in the system and to the creation of definite types of flow patterns at the exit. Figure 1 shows a typical type of flow pattern observed at the exit of the small acoustic jet when maximum thrust was obtained. A second part of this Technical Memorandum is being prepared and describes the experiments with an acoustic jet where the loudspeaker was replaced by a mechanically operated piston.

Similar experiments were carried out under water using a small, mechanically driven piston. The specific impulse of this small system was higher than that claimed for hydro-pulses. Specific impulse values of the order of 200,000 seconds were obtained. Flow patterns similar to those obtained in air were observed. Maximum thrust was developed at definite frequencies although these frequencies do not appear to be related to the acoustic resonance frequency calculated from the speed of sound in water.

The flow pattern studies are being carried out by means of two-dimensional water models as shown in Figure 1. A large table has been constructed for more refined studies of flow patterns.

New Forms of Intermittent Combustion Engines. An analysis of the pulse jet cycle by means of wave diagrams indicated that intermittent combustion could be sustained without the use of flapper valves, and that these valves may be one of the most important factors contributing to inefficient operation. Studies of wave reinforcement in acoustic jets indicated that maximum thrust may possibly be obtained at frequencies other than those for self-sustained flapper valve operation.

Experiments were conducted with a small dynajet to verify these assumptions. The valves were elminated and air and fuel were injected continuously into the combustion chamber through a small opening. It was found that intermittent operation could be sustained without the use of valves and that after initial ignition a spark was not required. No difficulties were experienced with starting and thrust could be varied from zero to maximum by controlling the rate of fuel injection. These experiments also indicated that stable operation was possible both at 150 and 300 cycles per second, while the standard dynajet operates in the vicinity of 300 cycles per second. The modified jet yielded maximum thrust at 150 cycles per second.

Two Technical Memoranda have been completed discussing these possibilities and an additional Memorandum is in preparation describing the initial experiments.

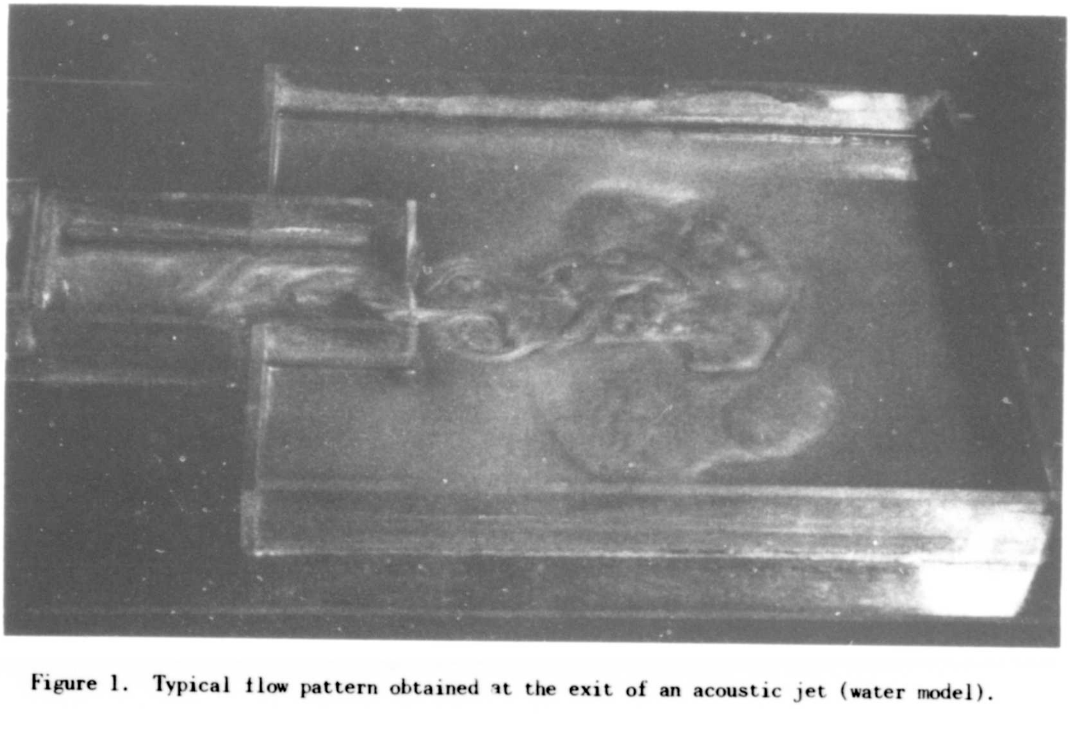


Figure 1. Typical flow pattern obtained at the exit of an acoustic jet (water model).

Possible methods of obtaining intermittent fuel injection were described in another Memorandum. Intermittent fuel injection may be utilized to obtain wave reinforcement in suitably designed systems and by this means it may be possible to obtain high values of specific impulse.

Plans

A Technical Memorandum will be prepared on the method of studying flame motion by means of wave diagrams.

The instrumentation for the water analogy experiments will be completed and described in a Technical Memorandum. The present improvised water table will then be redesigned to permit a study of the effects of shape of pulse jets on their performance to be made.

A Technical Memorandum will be prepared describing the experiments with an underwater model of an acoustic jet. Experiments are planned with a larger model to verify the possibility of obtaining very large values of specific impulse. The flow pattern studies will be continued.

Experiments will be conducted using larger models of valveless pulse jets. The possibilities of increasing the specific impulse of a jet by means of intermittent fuel injection will also be investigated. Experiments will be carried out with engines utilizing intermittent combustion and having no moving parts. A discussion of the possibilities of developing such engines will be given in a Technical Memorandum.

PHASE II

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.

Summary

For the purpose of taking instantaneous shadowgraphs or striae photographs of flame fronts in rapid motion, a condensed spark light source has been built. Shadowgraphs and striae photographs of disturbed flames have been taken with this device, and the results indicate that this technique offers advantages over the stroboscopic methods of recording which have been employed previously. The device will also be used for recording the flame motion in the combustion chamber.

An electronic stroboscope, making use of an infrared image converter tube, has been designed, and preliminary tests have been performed. It is expected that this instrument will furnish qualitative information on temperature fluctuations in the burned gas of disturbed flames. The ease of synchronization by means of electrical pulses should make it also a valuable tool for the study of flame motion in pulsating jet devices.

Construction of the combustion chamber and associated electrical equipment and of the electronic timing device for the flame tube has continued.

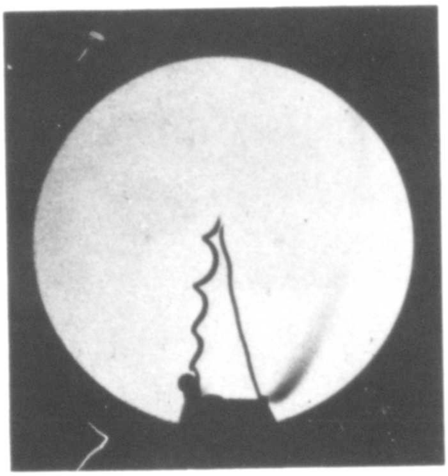
Progress

The main purpose of the work carried out in this phase is the study of interactions of flame propagation and flow disturbances. In the burner experiments this aim is achieved by observing the changes of shape and the motions caused by periodical or transient disturbances acting on otherwise stationary flame fronts. In the combustion chamber and flame tube experiments the propagation of a flame through a combustible gas and the influence of obstacles and other disturbances on this propagation is being studied. In both the burner and combustion chamber experiments, photographic registration of the flame is employed. For the purpose of taking instantaneous shadowgraphs or striae photographs of flame fronts in rapid motion, a condensed spark light source has been built. The spark energy is provided by four 0.1 microfarad condensers charged to about 7000 volts. Three small auxiliary spark gaps are connected between the condensers in such a way that when these gaps break down, the condensers are effectively connected in series, so that more than 20,000 volts appear across the main gap in the instant of discharge. It was found that an induction coil spark from an auxiliary electrode placed close to one of the small gaps is sufficient to start the discharge without any measurable delay. The duration of the discharge is estimated to be of the order of fractions of a microsecond. Since a small point source of light is needed, the spark is viewed axially through a hole in one of the electrodes.

Since this device will be used in the combustion chamber experiments in which the mixture will be ignited by the magnetically driven spark described previously, in order to obtain a record of the flame front at a selected instant during its motion an adjustable time delay must be introduced between the start of spark travel and tripping of the light source. For this purpose a circuit utilizing the time delay of opening of a relay has been designed. Delays in the range of 4 to 26 milliseconds could be obtained by shunting the relay coil with resistors of appropriate values. By adding a second relay the circuit was adapted also for the purpose of synchronizing the spark light with a solenoid-operated camera shutter.

With this arrangement a number of spark photographs of disturbed burner flames have been taken. The spark technique appears advantageous with respect to the stroboscopic methods employed previously, because of the better definition owing to the extremely short exposure time and the elimination of the synchronization circuits for the stroboscope. In addition, transient as well as periodic phenomena can be recorded by the spark method.

Both the shadowgraph and striae methods have been tested and compared. The latter seems to be better suited because it is free from optical distortions inherently present in the shadow method. These become objectionably large at the steep density gradients present at flame fronts. The striae method enables in addition a superposed exposure of direct flame photograph and spark image.



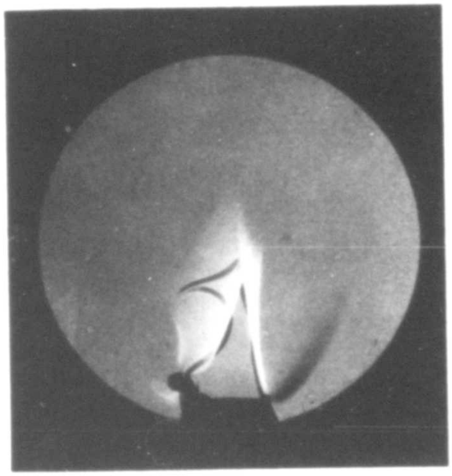


Figure 2. Spark striae photograph of a burner flame disturbed by a vibrating wire.
Figure 3. Superposed spark and direct photograph of disturbed flame.

Figure 2 shows a spark striae photograph of a burner flame into which a periodic disturbance was introduced by a vibrating wire. Figure 3 shows a superposition of a direct photograph (exposure time 20 sec.) and a spark striae photograph of a flame similarly disturbed with a lower frequency. In both cases the burner orifice was rectangular, so that the undisturbed flame fronts formed approximately plane surfaces perpendicular to the image plane. The wire, which was also perpendicular to the image plane, is visible in the lower left part of the figures. Figure 2 shows the increase of amplitude of the flame front distortion during its upward travel; this had been observed in previous work. It can be seen that the flame front waves become sharply pointed toward the burned gas in the upper part of the flame, a feature that was not very clearly visible on stroboscopic photographs owing to lack of definition.

These striae photographs were obtained with a small circular hole as a stop, instead of the customary knife edge. This accounts for the fact that the flame front appears always as a dark line, irrespective of its orientation.

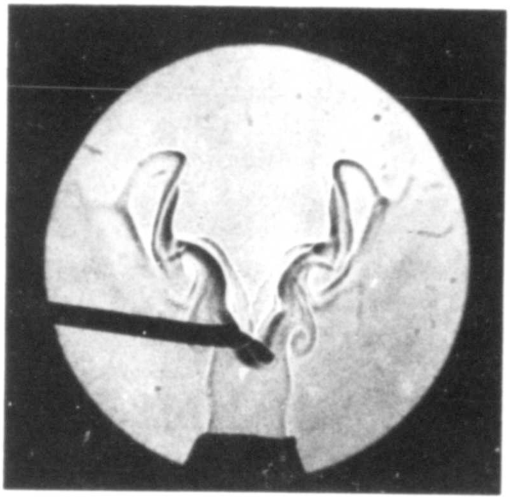


Figure 4. Spark shadowgraph of oscillating inverted flame.

A spark shadowgraph of a spontaneously oscillating inverted flame, held on a rigid wire inserted into the gas stream, is shown in Figure 4. In addition to the flame front, which is folded and apparently split into several branches, rolled-in vortices in the unburned gas below the flame are visible.

In order to observe temperature fluctuations probably present in the outer cone of disturbed flames, an instrument has been designed and built which allows stroboscopic observations in the infrared. The device, which is based on an electronic principle, utilizes the infrared image converter tube 1P25. Stroboscopic operation of the tube is achieved by applying periodic rectangular voltage pulses to one or several of the electrodes in such a way that the image appears only during the duration of these pulses. Since this instrument can be synchronized by means of electrical pulses without being subject to any of the inertia effects which are always present in mechanical stroboscopes, it is felt that it may be a valuable tool for the study of flame motion in pulse jet devices.

Plans

Systematic studies of periodic and transient disturbances in burner flames will be continued, using the techniques of spark photography and the infrared stroboscope in addition to the stroboscopic methods previously developed. Application of high speed motion pictures to these studies is also planned.

Work is continuing on the construction of the combustion chamber and associated electrical equipment, and on the electronic timing device for the flame tube.

PHASE II (2)

In connection with jet propulsion engines: to study the mechanism of combustion and attendant reactions through the application of spectrographic and other techniques.

Summary

Catalytic Influence of Combustion Chamber Wall Materials. In evaluating the catalytic effect of various substances in the combustion of premixed fuel and air in tubes of small diameter, the metering system of our special burner has been recalibrated on the basis of chemical analyses of the effluent gases from the burner. Blow-out velocity measurements have been continued on unlined quartz tubes.

Determination of Heat Release during Combustion. In the study of methods for determining heat release, especially by the use of refrigerated probes, the assembly of a special furnace for the establishment of a satisfactory carbon dioxide/carbon monoxide-oxygen equilibrium for checking the efficiency of the probe hss been completed.

Spectrographic Methods. The study of the application of spectrographic methods to the elucidation of combustion mechanisms has progressed to the data recording stage. The assembly and calibration of the burner and manostatic control system have been completed. Sustained combustion has been obtained at pressures as low as 20 mm. of mercury over a wide range of air/fuel ratios. The intensity of the flame seems sufficiently high so that good plates can be obtained with relatively short exposures.

Progress

Catalytic Influence of Combustion Chamber Wall Materials. In the study evaluating the catalytic effect of various combustion chamber wall materials, the metering system for our special burner has been recalibrated on the basis of chemical analyses of the effluent gases from the burner. Samples were taken of various air/fuel mixtures as they emerged from the burner without combustion. These samples were completely analyzed in an Orsat apparatus and an empirical air/fuel ratio was established. The calibration of the metering system was then corrected correspondingly. Some deviations from the original calibration were found. The original calibration of the system indicated that more fuel was being passed through the system than was in reality being passed. Hence the air/fuel ratios previously reported were too low.

As a measure of the catalytic activity of the combustion chamber wall mass flow, blow-out velocities were determined for a series of silica tubes in order to establish a mean against which other materials could be compared. Some difficulty has been encountered in establishing a constant blow-out mass flow for a given air/fuel ratio. The difficulty arises from the fact that successive runs in the same tube require successively higher mass flows to produce a blow out. This observation is undoubtedly related to changes in the surface characteristics of the quartz tubes which are induced by recrystallization of the quartz. In this connection it has been observed that with use the quartz tubes become increasingly fragile and brittle. Runs are presently in progress to establish the relative effectiveness of swabbing the tube with a hydrofluoric acid between runs in order to establish surface uniformity from run to run.

In an effort to establish the flow pattern downstream from the fine grid flame arrestor, the characteristics of gas flow through a rectangular duct with transparent sides have been observed by schlieren techniques and by shadowgraph techniques. Flow patterns have been observed visually, but as yet no satisfactory photographic records have been obtained.

Determination of Heat Release during Combustion. In the study of methods for determining heat release, especially by the use of refrigerated probes, the assembly of a furnace for the establishment of a satisfactory carbon dioxide/carbon monoxide-oxygen equilibrium for checking the efficiency of the probe has been completed. The adaptation of existing electrical equipment for use with this furnace has also been completed.

The furnace is comprised of a hollow globar with an internal diameter of 3" and an overall length of 36". Graphite contacts separate the globar from water-cooled copper electrodes. Contact pressure is maintained by spring loading. The manufacturer recommends the globar element for continuous operation at 2800°F, and it is entirely possible that 3000°F can be maintained for short periods of time. In order to provide the necessary current for this furnace, and at the same time maintain flexibility in applying the voltage, three 100-amp. transformers are being interconnected so that the voltage may be applied in small steps.

An Alundum tube 1-5/8" internal diameter and 36" long has been inserted inside the hollow globar and held in a central position by the use of carbon spacers. This gas-tight tube has an adapter at one end for connection of a feed line through which purified carbon dioxide will be fed. At the other end, a long water-cooled sampling probe will be inserted to a point of maximum temperature within the furnace. Preliminary tests in a small scale outfit showed that temperatures above 2800°F could be maintained within the gas-tight tube at the region immediately adjacent to the end of the sampling probe. By use of the small scale equipment, the effect of gas input rate was established and it was found that for a given diameter tube and for a given size probe an optimum gas flow rate exists.

Spectrographic Methods. In the study of the application of spectrographic methods to the evaluation of combustion mechanisms, the recording of data in the ultraviolet region is in progress. Calibration of the manostat control assembly has been completed, and preliminary tests with the burner have been made. Sustained combustion has been effected at pressures ranging from atmospheric to 20 mm. of mercury. Preliminary observations indicate fairly high intensity at low pressures. A number of runs are being performed so that the limitations of the method and the apparatus can be evaluated. In these runs the various parameters which will affect the spectrographic record are being varied without the benefit of the ultimate refinements which the apparatus is capable. From these it is hoped to obtain a generalized idea of the species which will exist in the low pressure flames.

As a result of a conference with Dr. S. H. Bauer of Cornell University, consultant on this project, a specific program has been outlined in which the initial studies will be conducted in the ultraviolet region and the investigation ultimately continued in the infrared region. In addition, consideration is being given to methods for sectioning the flame for determining the extent of the inner cone, luminous mantle, and envelope of the flame, and to the determination of various temperatures therein.

The technical progress on this project has been somewhat retarded because it was necessary to redeploy personnel to the other SQUID projects, and because a graduate physicist, hired to act as technical leader for project, failed to report. In the place of the latter it has been necessary to retain a consult nt, and a satisfactory empirical program has been outlined with the consultant's assistance. The initial studies will be made in the ultraviolet region and ultimately continued in the infrared region, where it is expected better band structure definition will be obtained.

PHASE III

To study the properties and behavior of materials for high-temperature application in connection with jet engines.

Summary

In the process of evaluating various sheet stock alloys for jet engine service applications in the temperature range of 1200 to 1800°F, study of deformation characteristics has been made through the use of true-stress true-strain tensile data. Correlation of such results has revealed that much can be learned of the mechanism of deformation of these heat resistant materials under conditions where strain hardening, recrystallization, precipitation, and phase changes are occurring.

The high-temperature fatigue properties of 25-20 + 2% silicon stainless steel, Regular Inconel and S-816 alloys were determined on the pneumatic fatigue tester. Experiments using frequencies other than natural material frequencies were conducted. Determination of a means of measuring strain on the critical area of the fatigue specimen at high temperature is being evolved.

Initial check of the optical system of the high-temperature metalloscope with a movie camera showed that the relay lens gave a poor optical image. A new furnace with a water-cooled objective has been made. A vaccum system for the furnace of the metalloscope is being assembled.

Attempts were made to improve by heat treatment the high-temperature creep strength (for short-time service applications) of the 25-20-2 silicon sheet alloy. Marked improvement of the annealed stock was promoted by cold working plus ageing at 1600°F for 20 hours. The superiority of the heat-treated alloy was attributed to its finer grain size and carbide dispersion.

Progress

High-temperature Fatigue Test. The pneumatic fatigue testing machine was used to determine the fatigue curves for (25-20 + 2% Si) alloy at 1200°F, 1400°F, 1600°F, and 1800°F. The next alloy to be evaluated was Regular Inconel. It was found that at 1200°F extreme amplitudes of vibration were necessary to cause failure within the eight-hour time limit. The operation of the machine was erratic at these amplitudes and testing was discontinued at 1200°F. The curves for 1400°F and 1600°F were determined with little difficulty. When an attempt was made to evaluate the S-816 alloy, it was found that the difficulties encountered with Inconel were present not only at 1200°F but also at 1400°F and 1600°F.

It was thought that by replacing the resonant air columns with a variable speed rotary air valve that the machine would be capable of greater amplitudes and it might be possible to control frequency to some extent. The valve was constructed and tested. The tendency of the specimen to vibrate at its natural frequency could not be overcome. Vibration was possible only at multiples of the natural frequency, and this was complex. The specimen vibrated at its natural frequency at a large amplitude and at the frequency of the air valve at a small amplitude, both of these vibrations being superimposed. It was decided that a positive-drive machine will have to be used to study the effects of frequency at elevated temperatures and to supplement the pneumatic fatigue machine for those tests that are beyond its capabilities.

Work has been started on the evaluation of deflection in terms of strain. It is planned to attach two vertical arms to the specimen with knife-edge clamps. These clamps are to be located at either end of a 1/4" gauge length at the critical section. As the upper end of specimen is deflected the arm attached to the upper end of the gauge length will deflect more than the one attached to the lower end. The distance between them will be proportional to the strain over the gauge length. The two arms will be calibrated against a standard strain gauge at room temperature and when the strain gauge is removed the arms will be used to indicate strain at elevated temperatures. The strain will be measured under static conditions. A good approximation of stress will be available by interpolation from high-temperature tensile data.

High-temperature Metalloscope. Assembly of the optical system was completed and a number of frames of motion picture films were run off at room temperature. The quality of the image was poor and the magnification was low. Checking of the system revealed that most of the difficulty encountered was due to the relay lens which was apparently of inferior quality compared to the other lenses. There was considerable chromatic aberration in the image and the large aperture caused a relief effect due to conical illumination.

The quality of the image without the relay lens in the system was very good. It was therefore planned to either water- or air-cool the 16 mm. lens and focus through a quartz window directly on the heated specimen. A new furnace has been constructed and is complete except for the quartz window. The units of the vacuum system are now being assembled so that they will be ready when the quartz plates arrive.

High-temperature Tensile Tests. In the course of determining the conventional tensile properties at elevated temperatures of various heat resistant sheet alloys, modification of testing technique has been made to permit the determination of true-stress true-strain characteristics. For purposes of studying the deformation mechanisms involved in these materials, consideration of the true stress and strain conditions should yield more reliable results than are obtainable from the fictitious quantities normally calculated on the basis of the test specimen's original gauge length and cross sectional area.

True stress-strain tensile data have been obtained in the temperature range of 1200 to 1800°F over a 100 to 1 range of strain rates for the following alloys:

S-816 annealed
S-816 cold worked
Regular Inconel
Inconel "X" aged
1020 carbon steel

The 1020 steel was tested in the temperature range of 600 to 1200°F to provide background data on a relatively simple alloy for aid in interpreting the results obtained from the more complex heat resistant sheet materials.

The experimental technique consisted of recording simulataneously the quantities of load, elongation and time. From this data, true strain values were calculated according to the relation:

$$\varepsilon = \int_{l_0}^{l} \frac{dl}{l} = ln \frac{l}{l_0}$$

where l and l_0 represent the instantaneous and original gauge length respectively. Instantaneous values of cross-sectional area were determined on the basis of the previously established fact that plastic deformation occurs under conditions of constant volume, thus permitting the relation:

$$\frac{A}{A_0} = \frac{l_0}{l}$$

Where A and A_0 represent the instantaneous and original areas of the specimens. True stress values were then determined on the basis of the calculated A. Such a calculation of A is restricted to deformations of the specimen prior to necking or the onset of non-uniform strain conditions on the gauge length.

Stress-strain data of this nature for the alloys listed have been studied and it appears that much can be learned of the mechanism of deformation of these materials under conditions where strain hardening, recrystallization, precipitation, and phase changes are occurring during the course of the deformation process. A detailed analysis of such results will be forthcoming as SQUID Memorandum Report CAL 17 entitled "High Temperature Deformation Characteristics of Several Sheet Alloys."

High-temperature Creep Tests. While considerable test data and service experience exists for the use of many heat-resistant alloys in long time high-temperature service installations, a need has arisen for design data capable of evaluating such materials for shorter time applications of the order of minutes or several hours. Because of the common use being made of the 25-20-2 silicon grade of stainless steel for short-life service, determinations already have been made of the limiting stress values for producing specified deformations in time periods up to two hours.

In an attempt to improve the short-time creep properties of the annealed 25-20-2 silicon sheet stock, further evaluation has been made of this alloy after cold working and heating at 1600°F for 16 hours. Such a treatment was found to produce two major microstructural changes as compared to the annealed material, namely a refinement of grain size and precipitation of a constituent tentatively identified by etching techniques as a carbide phase. The micrographs and X-ray diffraction patterns of Figure 5 illustrate these phase and grain size differences.

Time-deformation measurements were made at constant load and temperature on the cold-worked and heat-treated material over the range of 1200 to 1800°F. At temperatures up to and including 1400°F the heat-treated material showed a stress advantage of approximately 25 per cent for a limiting total strain of 1 per cent in 2 minutes. This advantage was reduced slightly for the longer life period of 1 per cent total strain in 60 minutes. At all temperatures the heat-treated material was superior, but the advantage was of no practical interest at temperatures above 1400°F.

While long time creep and rupture tests have indicated coarse grained 25-20 to have superior strength to fine grained in the temperature range of 1000 to 1800°F, it is not surprising to find the reverse true for shorter life periods and more rapid rates of strain. According to our present qualitative conceptions of creep, rapid deformation occurs mainly by a slip process which would be hindered by fine grain size. Undoubtedly the large quantity of randomly distributed carbide in the finer grained material also contributed to its higher short-time creep strength.

Further experiments of a more fundamental nature would be warranted to isolate and evaluate the influences of grain size and type of microconstituents on the strain mechanism at elevated temperatures.

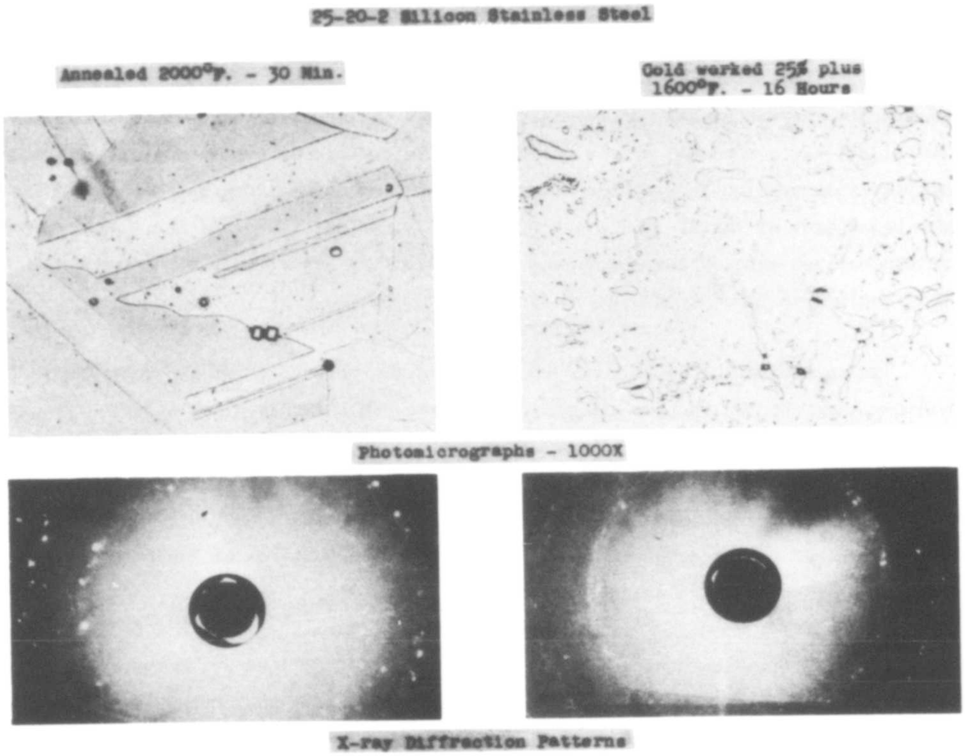


Figure 5. Micrographs and X-ray diffraction patterns of 25-20-2 silicon stainless steel.

QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH

ON LIQUID ROCKET AND PULSE JET PROPULSION

FOR THE

BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6ORI-105, TASK ORDER III

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY
1 APRIL 1948

PHASE I

Statement of Problem. In connection with liquid rockets and pulsating jet engines; to investigate theoretically and experimentally (1) the stability of laminar boundary layer, (2) the interaction of boundary layer with external flow field at supersonic velocities as it affects pressure distribution around bodies of revolution, airfoils, etc., and (3) interaction of shock waves in channels and diffusers.

Progress

Main Supersonic Tunnel. With the details of the quick-closing valve and blow-out panel installation settled, all important components of the main supersonic tunnel and the air supply system are either installed or in process of fabrication. The main physical progress recently has been the installation of the "headers" linking the air flasks to the valve control room.

Pilot Tunnel. During the last three months, the construction of the pilot tunnel and air supply system has been finished, the unit assembled with the $M = 3.01$ nozzle, and installation of pressure gages and schlieren mirrors completed. Recently, several trial runs were made up to stagnation or settling chamber pressures of 65 psi. The performance of the regulator valves has so far met all expectations. The rest of the schlieren system and the cameras are being installed and calibration runs will begin shortly.

Future Prospects. Once the pilot tunnel is functioning satisfactorily, the efforts of the staff will be concentrated on placing the main supersonic tunnel in operation. After several disappointing delays, it now appears that the regulator valves and control system will actually be delivered in early June. All other components now being fabricated are expected to arrive before that time.

So far as the pilot tunnel is concerned, the full program outlined in the Quarterly Progress Report for 1 October 1947 can now be initiated. Our machine shop is fabricating a "universal" test section assembly that will permit considerable flexibility in mounting flat plates, wedges, etc. for the study of boundary layer shock wave interactions and other problems.

Theoretical Studies.

Stability of Supersonic Laminar Boundary Layer. There is in progress a theoretical analysis of the stability of the supersonic laminar boundary layer in an "accelerating" flow field, such as the flow over a convex supersonic airfoil. The stability theory shows that the minimum critical Reynolds number, or "stability limit" depends only on the local distribution of velocity and temperature across the boundary layer. The first task, then, was to develop a method for the calculation of the mean boundary layer flow. After several attempts to develop a new method, it was found that a slight modification of Dorodnitzyn's procedure greatly simplified the calculations. Computations utilizing this modified procedure are now being carried out for the laminar boundary layer along the wall of the $M = 3.01$ nozzle. Later, the method will be applied to a supersonic circular-arc airfoil.

The theoretical analysis indicates in general that the supersonic laminar boundary layer can be completely stabilized by a sufficiently large negative pressure gradient in the flow direction. One of the objects of the calculations now in progress is to determine the conditions under which complete "laminarization" is possible, and then to compare the theoretical predictions with experimental observations.

Flow of a Gas When Departures From Perfect Gas Law Are Considered. Calculations are being made of the expansion of air through a supersonic nozzle from a high pressure air supply when the gas obeys the Beattie-Bridgman equation of state and the dependence of specific heats on both pressure and temperature is taken into account. The object of these calculations is to settle the question as to whether departures from the perfect gas law are significant. Preliminary results for a single case (stagnation pressure of 32 atm., stagnation temperature of $500^{\circ}R$) show that the effect of departures from the perfect gas law can be appreciable. For example, at $M = 4.0$, the pressure ratio p/p_0 is 0.0064 if air is regarded as a perfect gas with $\gamma = 1.40$, but $p/p_0 = 0.0080$ when the Beattie-Bridgman equation of state and specific heats derived from this equation are employed.

No experimental data on the specific heats of air directly has been found in the interesting range of pressures and temperatures, but Williams has utilized some data on Joule-Thomson coefficients to calculate the specific heats by a numerical-graphical process. His values will be compared with the results obtained from the Beattie-Bridgman equation.

PHASE II

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.

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

Progress

In connection with the use of aluminum borohydride as an ignitor for hydrocarbon-oxygen mixtures at room temperature, a study of the interaction of borohydride vapor and the mono-olefins, ethylene and propylene, has been made. Both these substances are ignited (in presence of oxygen) when dry, while the paraffin, n-butane, requires moisture. It is found that both olefins condense spontaneously with borohydride at nearly equal rates. There is no effect with n-butane. This suggests a mechanism for the olefin oxidation.

Ammonia gas is among the potential fuels of reasonably good theoretical efficiency, whose ignition is difficult. A study of the non-explosive (and non-catalytic) oxidation in glass and silica tubes has shown that reaction only occurs at an appreciable rate above 650°C. This should put ammonia in a class with methane.

Further work on the reaction between hydrogen atoms and oxygen molecules at 0.3 mm. pressure shows that the reaction is largely confined to the cold surface of the mixing chamber. With the chamber at liquid air temperature, the product is mainly hydrogen peroxide.

A review of the electrical properties of flames has been prepared and will be circulated shortly.

PHASE III

Statement of Problem. To study some of the problems involved in propulsion units of the ducted type. Specifically these problems are: (1) The mixing of primary and secondary streams in an ejector; (2) Methods to improve this mixing; (3) Combustion chamber problems in a ducted propulsive unit.

Progress

Theoretical Studies. A theoretical analysis of compressible gas flow in an ejector using a supersonic primary jet has been completed and is in process of publication. This paper will be issued as: Project SQUID Technical Report No. 9, and is entitled "Flow in Ejectors Driven by Supersonic Jets."

Two further theoretical investigations are being carried forward. The first is a study of the performance of an entire ducted propulsive device, which is about 30% completed. The second is a study of the performance of an ejector supercharged by an auxiliary air compressor. This latter study is still in the preliminary stages.

Experimental Apparatus. The two-dimensional mixing channel to be used in the first experimental phases of this program is in an advanced stage of assembly, and it is expected that preliminary tests will be made by the time that air is made available from the supersonic pilot tunnel.

Preliminary designs for a liquid fuel rocket motor installation are advancing rapidly, certain components of the system being already on order. Based upon the results of several initial tests, the construction of a liquid-fuel system using a pump rather than inert gas pressurization appears feasible. This will simplify the system greatly, and for this reason plans for a gaseous fuel motor system have been shelved.

Apparatus for the study of some of the problems of fuel injection and flame-holding is in process of construction.

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ABSTRACT: In connection with liquid rockets and pulse jet engines, progress was made with the schlieren observations of combustion details and flow through the grid of moving-flame tube, with high speed simultaneous schlieren and flame motion pictures of the small transparent walled jet, and with completion of development of pressure and temperature instrumentation. Theoretical investigations have been made in the linearized theory of aero-thermodynamics as applied to flame tubes and to pulse jets. The theoretical study of two and three dimensional non-steady jets was pursued intensively during this period. Further investigations were conducted to develop new alloys to resist pressure, temperature, and erosion conditions existing in propulsion units. Metallurgical, fabrication and design problems involved in cooling rocket and intermittent jet engines by diffusion of fluids through porous metal combustion chamber liners are analyzed.

DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

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Project Squid

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