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UNITED STATES NAVY

PROJECT SQUID

ANNUAL PROGRAM REPORT

1 JANUARY, 1949

NEW YORK UNIVERSITY
 POLYTECHNIC INSTITUTE OF BROOKLYN
 PURDUE UNIVERSITY
 CORNELL AERONAUTICAL LABORATORY
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ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT

CONTRACTS AND NR NUMBERS:

NYU— N6-ORI-11, TASK ORDER 2, NR 220-040
PIB— N6-ORI-98, TASK ORDER 2, NR 220-039
PRF— N6-ORI-104, TASK ORDER 1, NR 220-042
CAL— N6-ORI-119, TASK ORDER 1, NR 220-041 and ~~043~~
PRIN—N6-ORI-105, TASK ORDER 3, NR 220-038
DEL— N8-ONR-74000 and 74001, NR 220-063

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ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION

FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ori-11, TASK ORDER II

New York University
New York, New York
1 January 1949

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PHASE I



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

Summary

Phase I was originally suggested by observations of combustion in pulse jets which showed that since the flame spreads out in turbulently distorted clouds, the burning would probably differ markedly from that occurring in bunsen flames. Because the factors affecting combustion are difficult to control in the actual engine, idealized laboratory experiments seemed desirable. During the last year the problem of how flame propagation in the flame tube, developed for this purpose, differs from that occurring in, for example, bunsen burners has been

solved. This does not mean that the hydrodynamic problems involved are in any way completely understood; however, the results of the interaction of flame and turbulent motions are known. Since a grid such as is used in this study does increase the rate of burning, it may be applicable to many types of combustion chambers. Several preliminary designs have been drawn up which it is hoped may be tried out during the coming year.

Progress

Moving Flame Experiments. Most of these experiments have been done with tubes similar to that shown in Figure 1. This tube has an approximate cross-sectional area of 16 square inches and is at present 6 feet long. The upper and lower surfaces are made of oak and the sides are

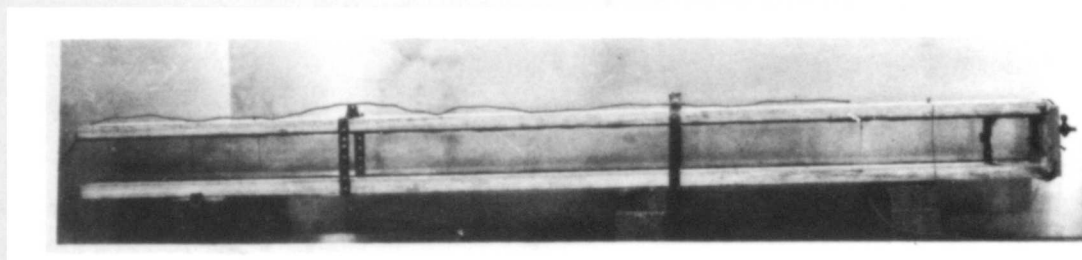


FIGURE 1

Flame tube used in the turbulent combustion experiments at N.Y.U.; the grid shown in Figure 2 can be seen in place approximately 4" from the closed end of the tube.

of glass sheets. The tube is filled with a mixture of propane (approximately 6.6%) and air (approximately 93.4%), and this mixture is ignited by a spark. The necessary turbulence is introduced by inserting a grid similar to that shown in Figure 2, a few inches down the tube from the closed end. Insertion of the grid raises the apparent flame velocity by a factor of ten and makes the movement of the flame from the grid to the open end of the tube more reproducible.

Work on this phase, therefore, has been directed toward gaining a better understanding of the combustion process in this configuration, many of whose combustion characteristics seem to indicate that it is at least analogous to the combustion occurring in pulse jets. Data has been recorded by luminous-flame streak pictures by schlieren movies and by other methods. Since the early schlieren pictures showed that a density difference, due to a small variation in temperature, was visible when unignited gas flowed through the grid as burning

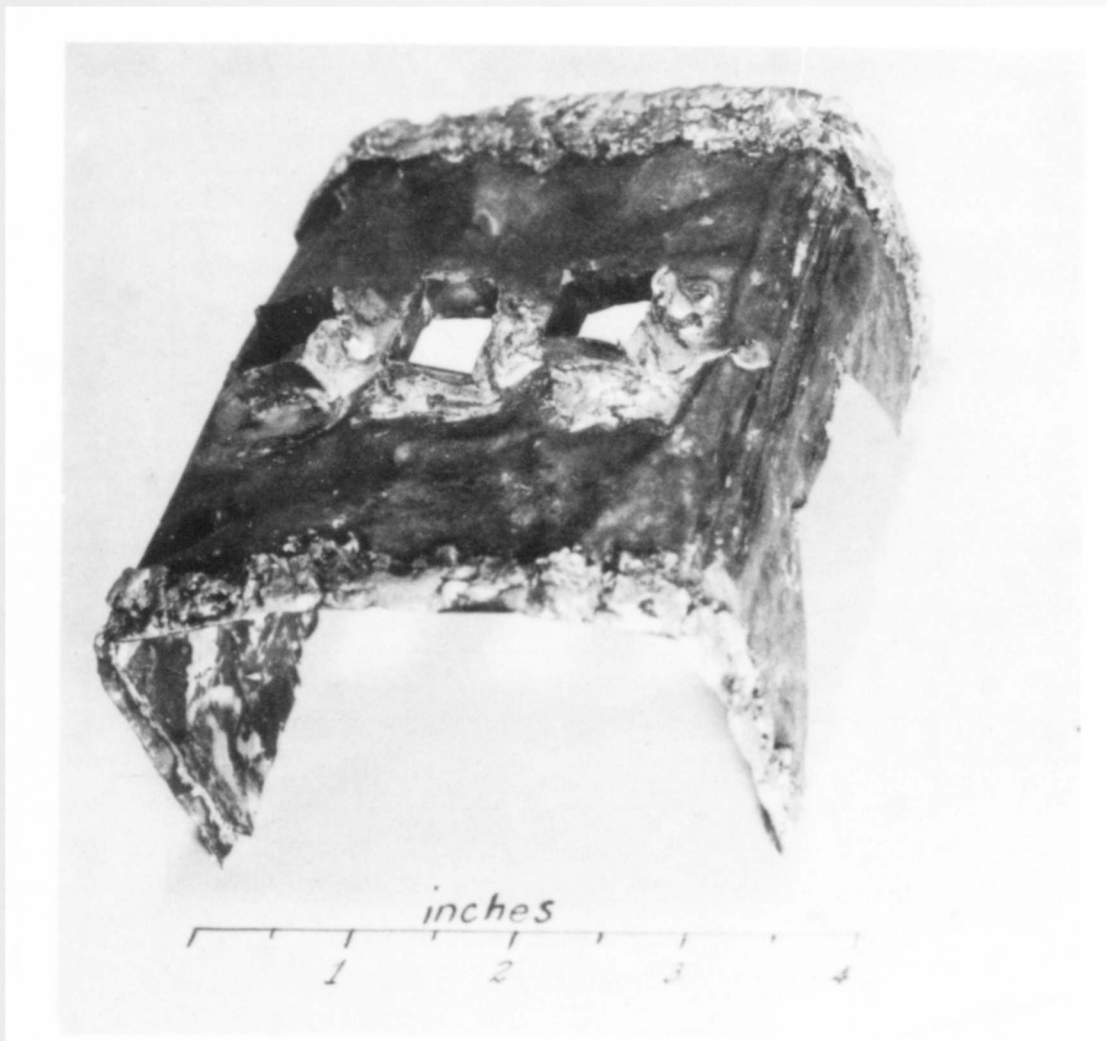


FIGURE 2

Grid used in flame tube to produce turbulent burning. This grid is the one that has been used for most of the combustion experiments during the past year.

progressed after ignition, a hot wire was used to earmark the mixture at various points within the tube to permit the measuring of mass flow in the unburned gas. The latest records made with local density gradients formed by this method have finally shown that the apparent, high flame speed is due to the very high rate of expansion of the burning gases between the grid and a layer of gas, initially located approximately 10 inches further down the tube. This in turn, is due to a very high rate of burning, which is caused by the large increase in reaction surface. The increase in reaction surface is the result of turbulent mixing produced by the jets of burning gas caused by the grid. A report is in preparation on this work which was the subject of a paper given at the Third Symposium in Combustion, Flame, and Explosion Phenomena at the University of Wisconsin, September, 1948.

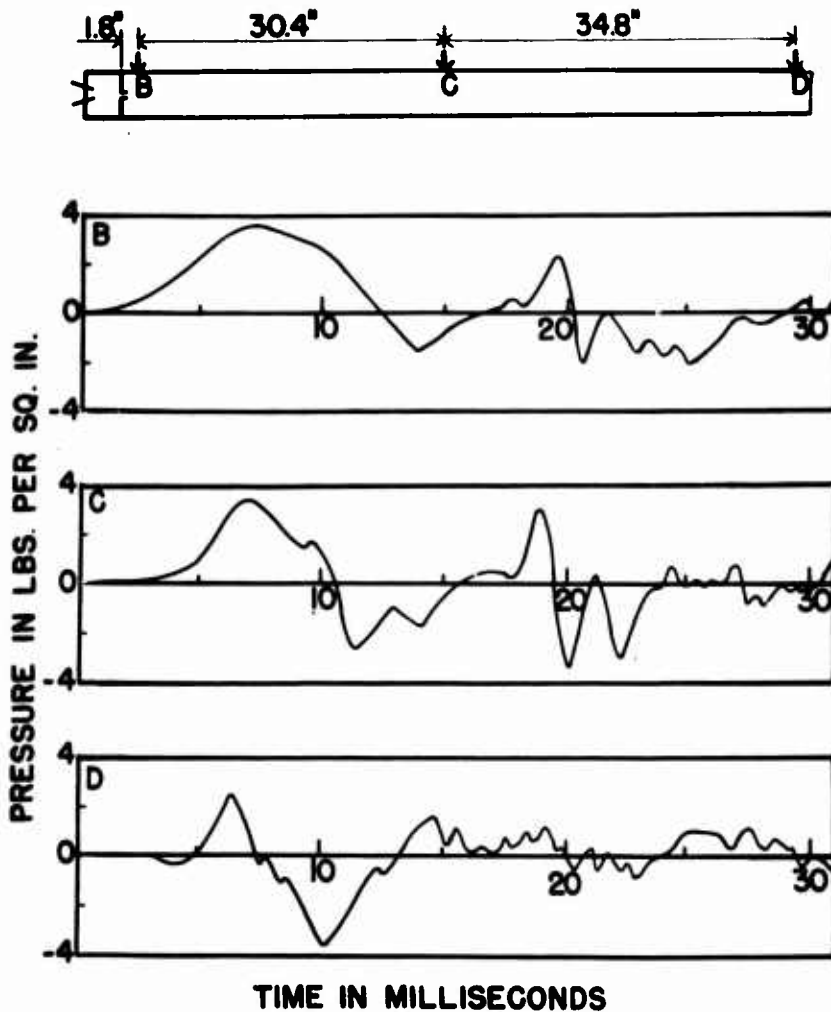


FIGURE 3

Pressure-time curves taken at the indicated points, B, C, and D in the flame tube. The zero position along the time axis is arbitrary and the three curves are not placed in true relation to each other with respect to time.

Pressure surveys have also been made with the pressure gauge system, developed under Phase 4, of the tube both with and without the grid. The results of these surveys, Figure 3, show the development of a pressure pulse in the tube in the region just beyond the grid. This pressure pulse is about 10 times greater than that which occurs in the tube without the grid. Experimental work requiring extensive instrumentation is now in hand to correlate the time of the pressure pulse with the events visible in the photographic records.

Since it has been shown that a properly designed augmentor increases the rate of combustion and the consequent pressure in an enclosed chamber, it is therefore probable that these augmentors may be effective in many types of combustion chambers where present burning rates and ef-

iciencies are low. Though preliminary designs for applications of these grids have been developed, in none of these cases has the device been tried.

Plans

It is expected that work under this phase will continue for at least several months along the present lines. Decisions on further work will be based on the results of these studies.

PHASE 2

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

Summary

This phase was undertaken because the heating of walls in rockets is not capable of theoretical expression at the present time. This is due to the fact that first, the variation of specific heats of steels at high rates of change of temperature is not fully known and second, because experimental determination of the temperatures present is subject to considerable error when these measurements are made with conventional thermocouple arrangements. During the past year two wedge thermocouples were completed and sent to other research groups for testing; also, the equipment for securing the data required on specific heats of steels at high rates of heating has been continually improved.

Progress

Wedge Thermocouples. It has been suggested by Macdonald of New York University and shown by Isaacson, Gaad and Singer (1) that the transient temperature which a thermocouple

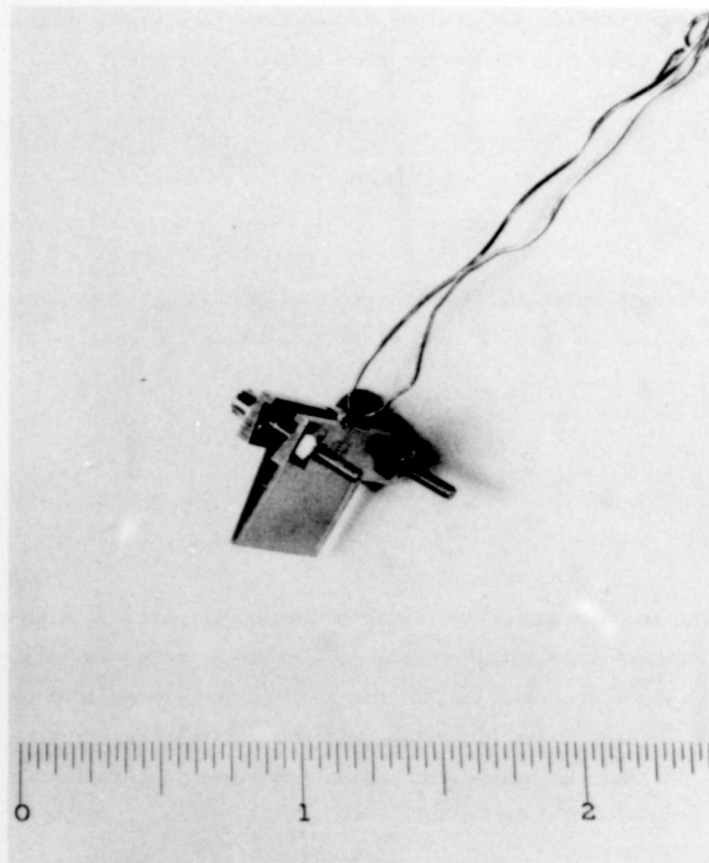


FIGURE 4

One of the wedge thermocouples constructed at New York University for use in determining the transient temperatures occurring in a rocket wall during starting. The vertex of the wedge is installed in a vee shaped slot in the rocket wall.

reads when inserted into the rocket wall and the temperature which would occur if the thermocouple were not present, may be markedly different. Since the error in temperature measurement due to a wedge shaped thermocouple is much more easily computed and the error is much smaller, quartz wedge thermocouples, Figure 4, were constructed and then surfaced with platinum and platinum rhodium by baking. The wedge angle chosen was 10° with the vertex $.010''$ wide, since it was not found feasible to grind the quartz wedges any thinner. Two wedges were completed, one of which was shipped to the Naval Ordnance Test Station, Inyokern, California and the other to Alleghany Ballistics Laboratory, for testing.

A report on this work was published as SQUID Technical Memo NYU-3, dated August 1948, and included a description of an improved design that would permit a true knife-edge contact.

Specific Heats of Steel at High Rates of Change of Temperature. Work was started on this problem in September 1946, and has continued without major interruption ever since. The problem has proven extremely difficult since it was necessary to construct equipment to record and amplify simultaneously not only the instantaneous values of the temperature of the specimen but also of the voltage and amperage of the heating current and to correlate these three factors. It has been necessary to reconstruct the apparatus a number of times to include in the various components those improvements for which the need had become apparent only as the experimental technique was successively improved. During the year 1948, it has been found necessary to construct new electronic switches and DC amplifiers. Runs have however, been taken, at high rates of heating up to 900° K although no inflection points in the temperature versus time curve have been observed to date. When the present modifications are completed, a run at a very slow rate of heating will be made to determine whether phase changes actually occur in this specimen and whether the apparatus will actually indicate them.

Plans

No further work is contemplated on wedge thermocouples, but work will continue along the present lines on the problem of measuring the specific heats of steel at high rates of heating.

PHASE 3

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

Summary

The objective of this phase is to obtain fundamental information and basic data concerning the operation of pulse jets and other jet devices for purposes of comparison with and use in a mathematical formulation of a theory of pulse jets.

During the past year work in this phase has been carried on along four major lines of investigation. First, the large-scale pulse jet equipment has been extensively modified, and has been used for making pressure and temperature records. Second, the small scale pulse jet experiments have been carried far enough to permit description of the cycle of operation of one type of small pulse jet engine. Third, a start on the study of augmentation in small pulse jets has been made. Fourth, some idealized experiments on and an investigation of the possibility of formulating a lumped parameter theory of the cycle of a pulse jet have been made.

Progress

Modifications in the Large Scale Pulse Jet Equipment. The thrust stand described in the last Annual Report has been completed, and various modifications have been made in the fuel injection system of the PJ-31 engine. These modifications included separation of the starting air system from the purge air line so that better control over starting conditions would be possible. In addition, the automatic fuel metering unit has been cut out and replaced with a remote-control valve, so that the operator has direct and continual control of the fuel flow. A thrust measuring device was constructed from a surplus aircraft hydraulic cylinder but has not yet been fully tested. Retempered and reshaped valve leaves are being installed in an old valve grill, and a source of unused leaves for this type of grill is being sought. A number of pressure and temperature measurement bosses have been installed on the engine, and a set of manometer pick-ups are being attached at the present time. During the past year the large scale pulse jet equipment has been used for testing the pressure and temperature instrumentation described in Phase 4.

Small Scale Pulse Jet Observations. A significant advance has been made in our knowledge of the flame and particle motions in small pulse jets of the Dynajet type. Using the transparent walled pulse jet described in the previous annual progress report, streak schlieren pictures were taken through the windows while the engine was operating. Some of the resulting pictures of different runs and of different portions of the engine are shown as a composite photograph, Figure 5, because of limitations in the size of the schlieren field. The streaks on the pictures are believed to be the traces of the images of tiny density inhomogeneities in the turbulent gas within the jet engine. These are due to local temperature gradients which are carried along with the prevailing gas velocity, and the streaks give, therefore, a graphical representation of position versus time for the gas 'particles' distributed throughout the engine. The reasoning on which this belief is based is as follows:

The schlieren pattern is sensitive to density changes (density gradients). If a density inhomogeneity in the gas were associated with a pressure wave, it would presumably be propagated with the speed of sound, which is much faster than the speeds indicated by the slopes

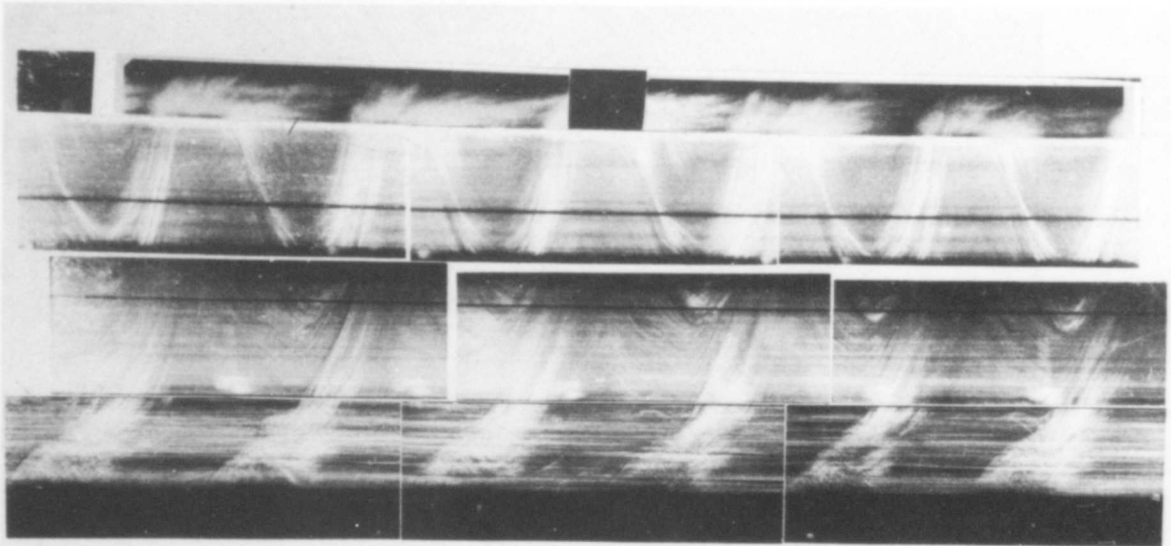


FIGURE 5

Matched schlieren pictures of particle motion in a small transparent-walled pulse jet. The valves are at the bottom and the flow is upward. Timing light marks are visible just above the bottom edge of the second row of pictures. These marks are $1/240$ of a second apart, and time proceeds from left to right. The horizontal block lines are located $10''$ and $15''$ from the valves.

of the schlieren streaks in the figure. If it were associated solely with visible flame propagation through the gas, then it should appear only when and where the flame does, which is not borne out on comparing the schlieren streak pictures with flame streak pictures, like those shown in last year's annual report. The schlieren traces seem to indicate an inflow of fresh gas-air mixture into the combustion chamber as soon as the valves open, where the flame pictures show ignition taking place in the midst of this mixture at a somewhat later time, just prior to the closing of the valves. This observation is confirmed by high speed motion pictures.

Clearly this argument is not completely conclusive, since there may be either invisible 'flames' present or pressure waves that interfere in such a way as to produce phase velocities of the density inhomogeneities differing from the particle velocities or sound velocities. However, the inference in question is at least probable.

By combining in various ways these observations with those made on flame travel, a graph of positions versus time for the particles and flames in the small pulse jet has been obtained. This is reproduced in Figure 6 which is a one-dimensionalized representation of the motions. Referring to this figure, we shall describe the pulse jet cycle, as far as we know it, in the next paragraph. We shall express the positions of events in terms of percentages of the length of the engine, measured from the valves (19 inches from the valves to the tailpipe exhaust port), and we shall express the times of events in terms of percentages of the cycle period, (about 4.6 ms.) measured from the instant the valves open.

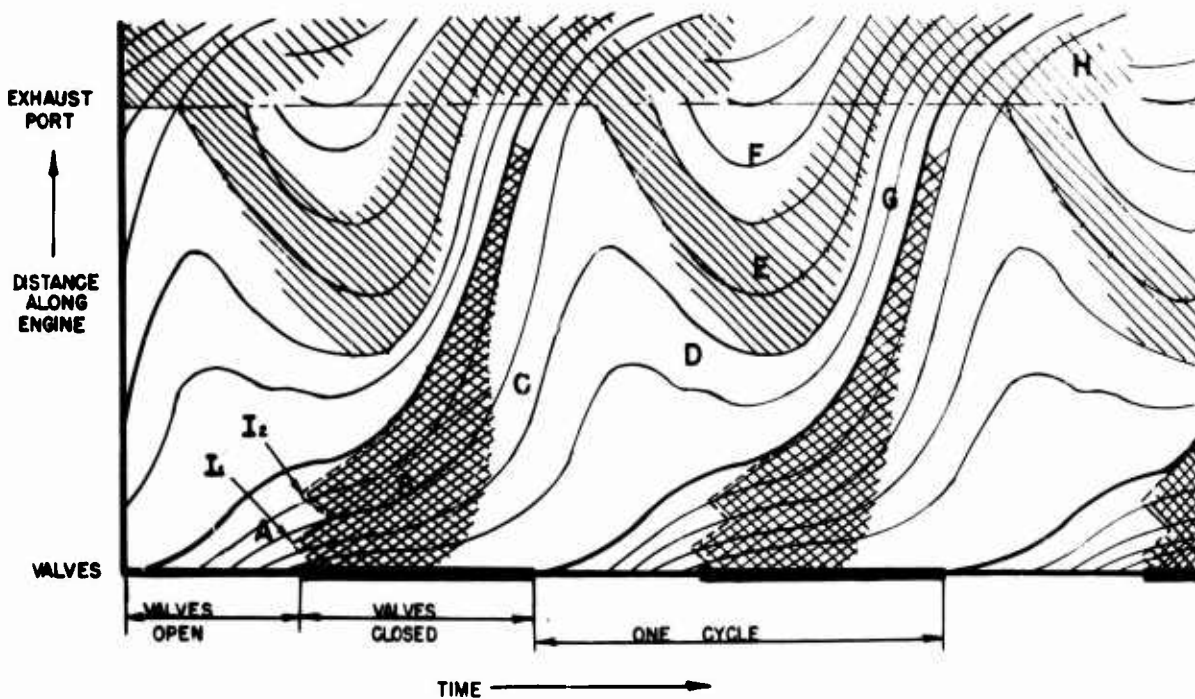


FIGURE 6

A sketch of two and a half complete cycles of flame and particle paths in a pulse jet engine.

- | | |
|---------------------------------------|---|
| A. Intake phase. | E. Possible secondary combustion phase. |
| B. Primary Combustion phase. | F. Inflow phase. |
| C. Expansion and first exhaust phase. | G. Second exhaust phase. |
| D. Compression phase. | H. Three dimensional flow region. |

- Interface between fresh mixture and burned mixture.
- +——+—— Interface between retained burned mixture and re-entrant gases from exhaust port.
- Primary combustion area.
- Region of possible secondary burning.
- Particle paths.
- Path of flame front.

At the moment the valves open, the mixture in the combustion chamber and tailpipe has reached a state of maximum expansion, and is, momentarily, uniformly at rest. The fresh gas-air mixture starts to flow in through the valves, attaining a speed of roughly 200 feet per second. At the same time the higher, outside pressure pushes air and some burned or burning mixture into the tailpipe exhaust port. This gas attains a speed of about 500 feet per second toward the valves and appears to undergo some additional combustion, particularly near the interface between the gases which have not escaped and those which have flowed in during

this 'inflow' phase. The gases in the engine, including the unburned fresh mixture, are then compressed as a result of the inertia of the inflow; and just prior to the moment of maximum compression, visible ignition takes place in the interior of the fresh mixture. This usually occurs in one or both of two regions, one at a point 3% of the engine length from the valves, the other, which usually occurs a little later, at a point 12% of the engine length. At the instant of visible ignition, occurring just before 50% of the period has passed, the valves are forced to snap shut, and the gases flowing into the tailpipe from the outside have reached a point 60% of the engine length from the valves, or 50% of the tailpipe length from the tailpipe exhaust port. The visible combustion spreads in both directions from the points of ignition, attaining speeds of roughly 70 feet per second with respect to the gas in the combustion chamber, which at this moment is moving relatively slowly. Because of this combustion, the pressure in the mixture rises rapidly, as does the temperature. The resulting pressure gradient down the length of the engine from the combustion chamber to the tailpipe helps initiate the 'outflow' phase. During this phase the gases in the combustion chamber expand rapidly. This forces the burning or partly burned mixture remaining in the tailpipe from the previous cycles and introduced, as described earlier, from the outside atmosphere to leave the tailpipe at a very high velocity of about 1500 feet per second. During this process, the flames have spread through the fresh mixture by the time the interface between the fresh mixture and old mixture (which at the time the valves closed was at a point 22% of the engine length) has reached the region where the tailpipe joins the combustion chamber, a point 25% of the engine length from the valves. Due to the inertia of this outflow, the gases in the engine overexpand, are decelerated, chiefly under the influence of the outside atmospheric pressure, i. e., by the pressure gradient extending from the higher outside atmospheric pressure to the lower combustion chamber pressure, and are brought momentarily to rest. Then the cycle is repeated.

Of course, all the pressure changes and the motions mentioned in this description, when examined in detail, must be brought about by the propagation of disturbances through the medium. A method of treating this problem is considered in *A Gas-Dynamical Formulation of Waves and Combustion in Pulse Jets* by MacDonal. However, the detailed correlation between even this idealized treatment and the experimental observations has not yet been accomplished, because of experimental and analytical complexities.

Less is known about the motion of the gases at and near the tailpipe. However, high speed schlieren and flame movies, studies of water and smoke analogies and smoke tracer studies have led to the following description of the non-steady flow patterns.

We must first distinguish between the case in which the tailpipe exhaust port is flared, usually with higher thrust being obtained, and the case in which it is not flared.

During the inflow phase, air from all directions, probably admixed with some burned or partly burned mixture previously ejected from the exhaust port, flows into the tailpipe. This flow, as indicated by the water analogy studies, is quite smooth when the tailpipe is flared and is similar to potential flow into a tube. When there is no flaring, however, it appears that a vortex is quickly set up just inside the opening. This, in effect, chokes off to a certain extent the inflow, as if the tube opening were actually constricted. Thus a straight tailpipe acts something like a Borda mouthpiece. This probably has the effect of reducing the compression attainable before ignition with a consequent loss in thrust.

As soon as the outflow phase begins, a fluid jet with a small angle of divergence from the axis of the engine is set up. The 'head' of the jet which pushes back into the surrounding atmosphere is observed to mushroom out and even to curl back, as if the fluid in the jet were flowing into a region shaped something like a torus. This is evidenced partly by the flaming vortex rings, seen in high speed movies of the flame from the PJ-31 tailpipe. (See Project SQUID Quarterly Progress Report dated 1 October 1948.) The flow in the atmosphere near the tailpipe is thus observed to resemble potential flow produced by the motion through the atmosphere of an object of changing shape, namely, the fluid jet itself.

When the gas inside the tailpipe tube becomes sufficiently rarefied so that its pressure drops below the outside atmospheric pressure, the outside atmosphere chokes off the fluid jet, which necks down, as described in previous reports, and the inflow begins. It should be noted that there is a small time interval in which the inflow is taking place around the jet proper, which is still flowing outward.

In the future we are planning experiments and observations to corroborate some of the above statements, which, it must be emphasized, should be regarded as mixtures of a few surmises with many conclusions attained from direct observations. Of particular interest to us is the study of the formation of the fluid jet, and the detailed study of the subsequent outflow and inflow. For this purpose certain idealized experiments are being carried out with an improved schlieren set up.

A 'Lumped' Formulation of a Pulse Jet Theory. A mathematical formulation of non-steady periodic flow of a compressible fluid within an open ended tube, together with an associated flow induced in the atmosphere outside the tube (treated as incompressible), has been set up, from the point of view of obtaining lumped parameters for such a system. The assumptions and approximations at the basis of this formulation are derived from the previously described observations of the flow near the small and large pulse jets, as well as from the water analogue studies. In this way, ordinary non-linear differential equations of motion are obtained for the fluid flow in and around propulsive devices employing a combustion driven or mechanically

driven resonating fluid column. It is hoped to obtain from this work engineering estimates of the relative orders of magnitude of various effects, due to such things as the presence or absence of vortices travelling with the end of the fluid jet set up during the outflow phase in each cycle.

Water Channel Analogues of Compressible Gas Flow. In last year's Annual Program Report there was discussed a theory of the analogy between the non-steady flow of water in channels having various cross-sectional shapes and the one-dimensional flow of gases having various values of the specific heat ratios. Previous water analogies had been limited to the study of gases having specific heat ratios of 2.0, and by varying the cross-sectional shape, this particular limitation was avoided.

Since then, experiments have been conducted which were designed to test a portion of this theory, namely the analogy between the propagation of small gravity waves in the water channel and the propagation of plane acoustic waves through the gases. Studied in particular were the analogy for a gas having a specific heat ratio of 2.0, which is a water channel having a rectangular cross-section, and the analogy for a gas having a specific heat ratio of 1.5, which is a water channel having a V-shaped cross-section. As a result, it was determined that the latter analogy is just as valid as the former.

At the end of the fiscal year, the study was dropped, on the recommendation of the Fluid Mechanics Panel. A final technical report on the subject by Probstein and Hudson, entitled *A Water Analogue of the Isentropic Flow of Compressible Gases which have Arbitrary Ratios of Specific Heats* has been submitted for publication. In this, the theoretical and experimental work has been presented in detail.

Idealized Experiments on the Formation and Properties of Jet Flow. Several experiments are being set up for the purpose of studying, mainly by schlieren methods, the formation and characteristics of steady and non-steady jet flow in air. These experiments are a continuation and an idealization of the work on the small transparent-walled pulse jet, and on the large flame tube.

Plans

Work will continue on gathering data from the large scale jet, and further experiments will be made on the small scale pulse jets. In addition, more theoretical work and idealized experiments will be carried out, as follows: (1) small scale flame tube studies; (2) two dimensional pulse jet studies; (3) studies of the steady and non-steady flow and mixing

of an air stream parallel to, and past the edge of a semi-infinite plane into an atmosphere initially at rest; (4) studies of jet formation by setting up small jets of air opposed to the ambient flow in the field of view.

PHASE 4

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

Summary

Since satisfactory measuring systems had never been developed for measuring fluctuating pressure and temperature at frequencies up to several hundred cycles per second, it has been necessary to design and construct these specialized instruments. Both the pressure and temperature measuring systems have been used on the PJ-31 and records have been obtained. In addition, during the course of the year the pressure gage system has been further improved by modifications on the transmitter, receiver, and the gage itself. The temperature measuring system has been more extensively modified to avoid the difficulties associated with the sodium D-line method.

Pressure Gauge. The condenser type gage developed during the past two years is of a type that responds down to and including zero frequency yet is able to follow transients up to several thousand cycles per second. Though during 1948 satisfactory records have been taken on the PJ-31 with this system, see Figure 7, some improvements have been found desirable and have been completed on both the transmitter and receiver units. In addition, the pressure gage head itself was redesigned to permit closer manufacturing tolerances, i.e., the air gap is now only .001" of which .0003" is filled with a mica sheet which increases the sensitivity of the unit. The detachable head, Figure 8, is also easier to machine and does not introduce residual stresses.

The problem of dynamic calibration by other means than bursting diaphragms still remains. Preliminary design is being undertaken on a siren type calibrator which will permit testing at high frequencies, and at higher pressures than the diaphragm method. As a test of the present gage system one of our pressure gages was installed in the throat of a Dilks loud

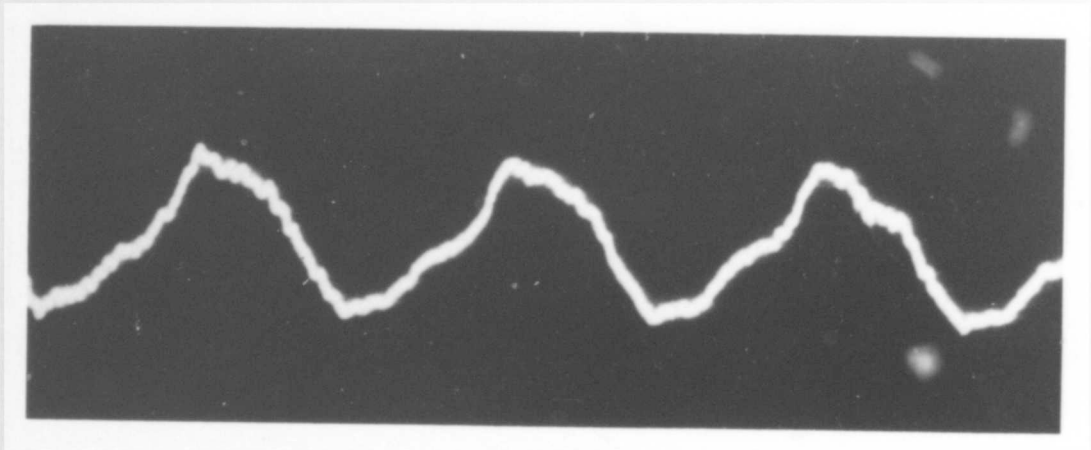


FIGURE 7

Pressure record of the PJ-31 at starting fuel flow, taken with condenser type pressure gage with integral head. The pressure range is approximately 20 psi. Pressure increases upward, and time runs from left to right.

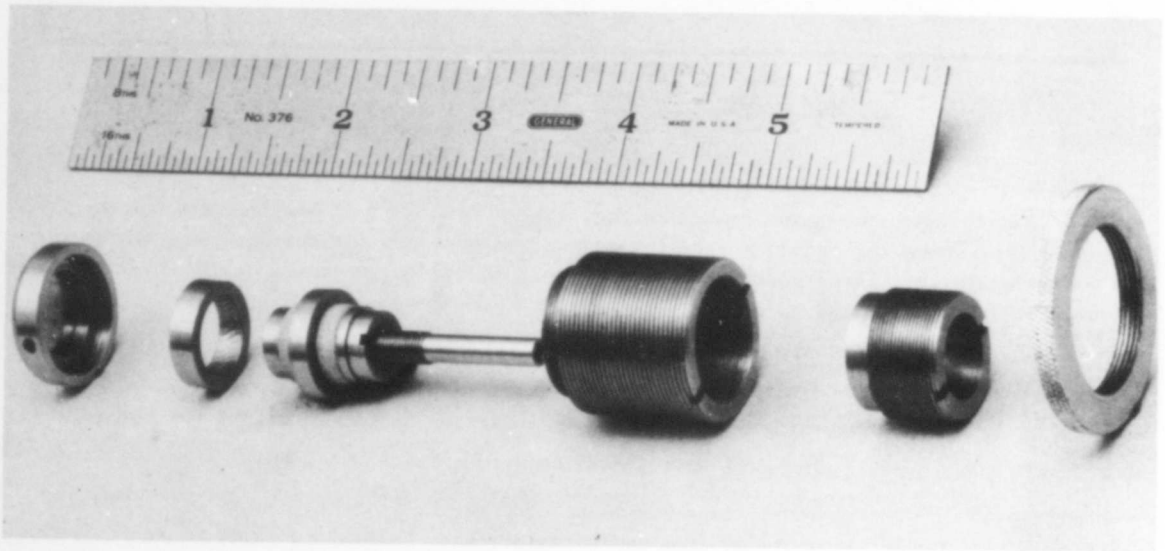


FIGURE 8

Head assembly with detachable diaphragm for condenser type pressure gage. This type of head will return to the original zero reading after being deflected in either direction.

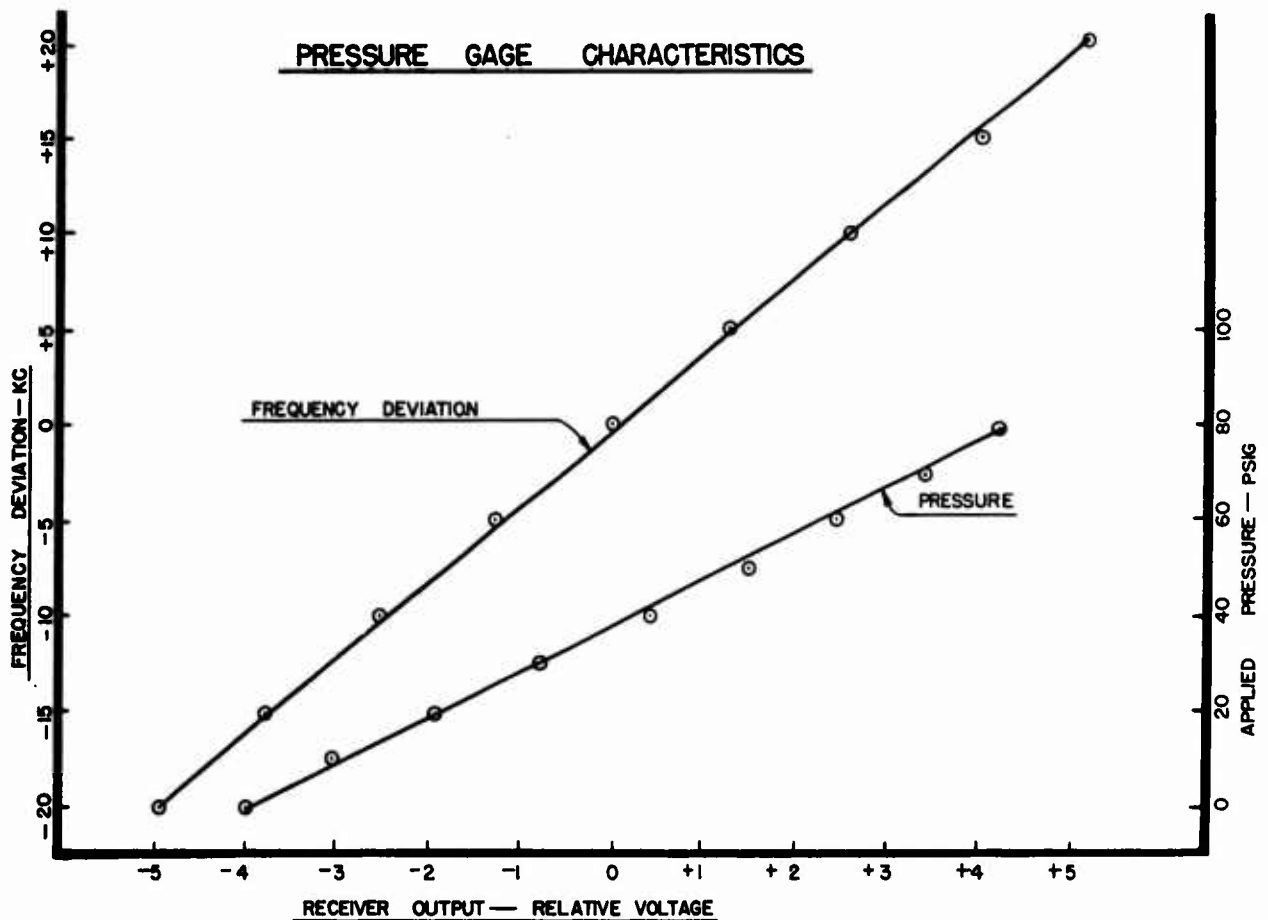


FIGURE 9

Characteristic curves for condenser gage system developed at New York University. The pressure curve shows the relative receiver-output voltages for various applied pressures for the complete system. The frequency deviation curve shows the frequency deviation from center frequency that produces the relative receiver-output voltages shown.

speaker. This speaker modulates an air stream under 15 pounds pressure by means of an electronically operated valve which gives a pressure variation in the throat of the speaker of approximately one pound. The gage unit showed no resonances up to 5 KC at this low amplitude. When a test was made with the cooling chamber installed in front of the gage, a resonance point occurred at 3 KC as expected from the calculations. Laboratory experiments have also been made showing satisfactory operation, when the gage is separated by a distance as much as five feet from the transmitter.

Optical System for Temperature Measurement. In the course of the year the temperature measuring apparatus was changed from a device for measuring the intensities of the sodium D line to a device for measuring the intensities of a part of the continuous spectrum of the gasoline flame.

This change was desirable because the intensity of the continuous background of the flame in the PJ-31 was found to be appreciable in the region of the sodium D-line, which led to the practical difficulty that either the calibrating burner must duplicate precisely the type of burning present in the jet or a monochromator would be required to isolate the center of the sodium line. This, however, would have reduced the ratio of signal to noise level to a very low value. The justification for trying the new method is based partly on the fact that a visual examination of the spectrum of the flame in the PJ-31 for the region between 5650 Å and 5800 Å indicates that the continuous spectrum is essentially free of emission and absorption lines in this region. This continuous background in hydrocarbon flames was ascribed by several earlier investigators to carbon radiation, and Schack (2) and has shown that the temperature and carbon particles follow the temperature of the gas within 1°C. We are at present investigating further the theoretical basis for this conclusion.

The two path method was retained since there is no information available on the actual radiation absorption coefficients of the continuous spectrum of gasoline flames at jet temperatures. As before, the output of each of the two photomultipliers is fed through the DC amplifier with a gain of about 700 to a 5" dual beam cathode ray tube which is photographed with a 35 mm. Fairchild camera. Both channels are calibrated against a strip lamp checked by the Bureau of Standards. This calibration is made without the windows and with the windows before each run and also once again with the windows after each run, to permit determination of the amount of carbonization. Additional temperature stations are being designed to obtain simultaneous measurement of temperatures at the beginning, middle, and end of the tailpipe of the PJ-31. It is hoped that this improved design will permit rapid collimation of both optical paths.

A paper on the theory of radiation by MacDonald and a description of this apparatus by Hett were given at a conference on Measurement of Temperatures of Pulsating Burning Gases (3).

Instantaneous Fluid Flow Velocity. In the course of the year a Bead type thermistor was mounted in a fuel flow line and tested in the laboratory. A compensating circuit was constructed giving satisfactory response up to 1 KC. Installation on the PJ-31 has been slowed up due to lack of personnel. It is also planned to try the thermistor in a bridge type circuit with compensating DC amplifier.

Observation Trailer. A 16 channel oscilloscope recording unit, using 8 dual beam 5 inch scopes and 4 monitoring tubes is being installed in the observation trailer. These channels will be used immediately for simultaneous pressure, temperature and gasoline flow readings on the PJ-31.

Plans

Work under this phase is expected to consist of development, completion, and application of the equipment herein described to the more extensive and accurate measurement of the values of pressure, temperature, and fluid and flame velocities occurring in the PJ-31 than has been possible in the past.

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ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ori-98, TASK ORDER II

*Polytechnic Institute of Brooklyn
Brooklyn, New York
1 January 1949*

INTRODUCTION

The research work on Project SQUID at the Polytechnic Institute of Brooklyn has been extended in some of its phases during the year 1948. Other phases have been terminated during that year. Phase one was terminated on October 1, 1948.

The analysis of air inflow through automatically operating reed valves has been concluded. For lack of funds no extensive numerical work could be carried out on this problem.

Within the framework of the problem dealing with the unified theory for pulse jets, analyses of the starting cycle and the operating cycle have been made. A continuation of this work is strongly recommended, since the method of analysis is simple as compared with the method used by other investigators, i.e., the linearized treatment of the aero-thermodynamic process in a pulse jet using the method of characteristics.

Two problems of phase one have been transferred to phase three and will be continued under this phase assignment. They are:

Problem PIB-1R7. Measurement of wall temperatures by means of λ -rays. This problem transferred as Problem PIB-3R3.

Problem PIB-1R8. Measurement of gas density and flow by X-rays. This problem transferred as Problem PIB-3R4.

The work on the second phase was terminated in June 1948. The continuation of investigations of some of its problems, particularly the study of carbides, nitrides and borides as materials for use in high-temperature applications needs careful consideration.

The analytical work on phase three has been extended to include the investigation of the laminar boundary layer of a compressible fluid flowing along a porous flat plate with fluid injected through the pores of the plate. The problems treated include the fully porous plate as well as the partial porous plate with both uniform and variable fluid injection. The experimental work on this phase consisted of designing and constructing the special apparatuses and of making the preliminary aerodynamic surveys to establish desirable flow conditions for the investigation of the stability of laminar boundary layer along the surface of a porous flat plate with fluid injection.

The detailed description of the work done is given below together with the reports published on each problem.

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

Theoretical investigations of the air inflow through reed valves were carried out. Two methods of analysis and their results were presented in three technical reports.

The unified theory for pulse jets was intended to provide an overall, reliable method for the prediction of performance of pulse jets. In the first submitted report a single duct engine is considered. By means of a general semi-inverse theory the waves of velocity, momentum, pressure, temperature, and heat input are derived exactly from a set of basic mass wave functions. The results of a first example are shown by sets of curves for each of the above enumerated variables.

The experimental work consisted of:

The determination of air intake efficiency of rotating sleeve valves, the continuous measurement of thrust of pulse jets at any moment, the investigations of strain gage type dynamic pressure detectors and their calibration, the investigations of the applicability of transverse supersonic pressure waves to the measurement of rapidly varying temperatures, and the measurement of pulse jet wall temperatures by X-ray diffraction method.

Technical reports described below upon the work done in each of the above problems were submitted for publication.

Progress

ANALYTICAL WORK.

Air Inflow Analysis Through Reed Valves. A detailed analysis of the air inflow through periodically opening reed valves has been made. Such valves have short operating life because of fatigue failure caused both by the high operating temperatures and the high impact forces on the tips of the reeds. The study has been devoted to the analysis of a non-steady, compressible flow, which was assumed to be non-viscous and isentropic. Hinged as well as clamped reeds were considered. The results of this analysis show that the centerline of the reeds to be employed must deviate very little from the average flow direction in order to avoid severe inertia and bending forces of the reeds. This means that the valve bank must be made up by a much larger number of individual valves than has been done in practice. The numerical work involved in the calculation of examples is laborious. This prompted the development of an 'approximate' theory of air inflow, where a quasi-steady flow (i.e., the neglect of the fluid inertia) and again a compressible, non-viscous, isentropic flow has been assumed. The presented results of the two theories compare favorably, if it is taken into account that in the example of the approximate theory the mass and stiffness distribution is different and supersonic velocities were avoided by the choice of the exit pressures. It is therefore thought that the 'approximate' theory yields satisfactory data for design purposes. It has the advantage of providing a simpler method and hence is more readily applicable to design than is

the 'exact' theory. The three technical reports on this work submitted for publication are: Technical Report No. 9: *Compressible Flow Through Reed Valves for Pulse Jet Engines. I. Hinged Reed Valves*, by Paul Torda, I. P. Villalba, J. H. Brick; Technical Report No. 10: *Compressible Flow Through Reed Valves for Pulse Jet Engines. II. Clamped Valves*, by Paul Torda; Technical Report No. 12: *Approximate Theory of Compressible Air Inflow Through Reed Valves for Pulse Jet Engines*, by Paul Torda.

Unified Pulse Jet Theory. This work was undertaken in February, 1948 in an effort to satisfy the request of the Office of Naval Research to develop an approximate, but still essentially reliable method of predicting the performance of pulse jets of different design. Besides this purpose, it was expected that a basis might be provided for coordinating the numerous and often disconnected experimental data on flame propagation and the travel of discontinuity surfaces in the combustion chamber with an overall theory for pulse jet engines.

A special procedure of a semi-inverse method by assuming a one-dimensional turbulent flow through the duct was found for the analysis of the effect of combustion, conduction, and convection of the waves in the combustion chamber and tailpipe, both of constant or varying cross section.

Different types of mass waves, i.e., mass flow multiplied by area $\rho A = f(x,t)$ were chosen for this method, partly based on data of experimental publications and partly based on appropriate reciprocating mass flow functions. In this way:

The velocity wave function follows from the mass wave function by the quadrature-integration of the continuity equation.

The pressure wave function follows from the quadrature-integration of the dynamic equation of flow.

The temperature wave function is given by the quotient of pressure wave and density wave.

The total heat input is derived from the energy equation, which contains the functions, determined above, of pressure, temperature, and density.

The net heat input of fuel combustion and eventually of leakage (negative) is derived by the subtraction of the contributions of convection and conduction of heat.

Until now, three wave patterns (ρA) have been assumed, namely:

- (1) A wave merely outflowing, such as to describe the first start of the pulse jet.

(2) A standing mass wave.

(3) A reciprocating mass wave as has been observed through the window of an operating pulse jet model.

The method of starting on the basis of an expected mass wave, in order to derive from it step-by-step velocity, temperature, pressure, heat input, and thrust function, has the great advantage of integrating exactly by quadratures without the necessity of linearization.

A Technical Report on case 1 was finished, but is not yet finally edited.

A Technical Report No. 13 on case 2 was submitted in July 1948, under the title *On Time and Space Functions of Heat Input Necessary to Produce, in a Tube, Waves of Density, Velocity, Pressure, Temperature, Momentum and Periodic Thrust of Required Character* by H. J. Reissner. It gives the explicit analysis and numerical examples in dimensionless form, so that each of the 6 variables indicated above are represented as functions of time and space by sets of curves.

A Technical Report on case 3 has been started but its completion depends on a final decision of the Office of Naval Research. It might be added that the above procedure described in several progress reports and in Technical Report No. 13 does not in any way overlap the investigations undertaken at other places, concerning shock waves and flame propagation, but as mentioned above, must rather be judged as a substratum in which the many scattered phenomena might be correlated.

EXPERIMENTAL WORK.

Rotating Sleeve Valve Pulse Jets. The inefficiency of the automatically working reed valves, as used on conventional pulse jet engines, gave the idea of the development of rotating sleeve valves which would be driven either by a windmotor or other source of energy. In order to increase the effective air intake area, the valve slots were placed on the circumference of the combustion chamber wall. In addition to increasing the air intake efficiency by the use of sleeve valves, an additional alternative was designed to place rotating sleeve valves also at the down stream end of the combustion chamber. Such an arrangement would allow the close approximation of constant volume combustion. It was realized, however, that the incorporation of this alternative design on the first model would increase the engineering difficulties on account of the unavoidable high temperatures. Therefore, it was decided to build the first model with rotating intake sleeve valves only and to start the development of the exit valves at a later date after the intake valves would have been brought to efficient operation.

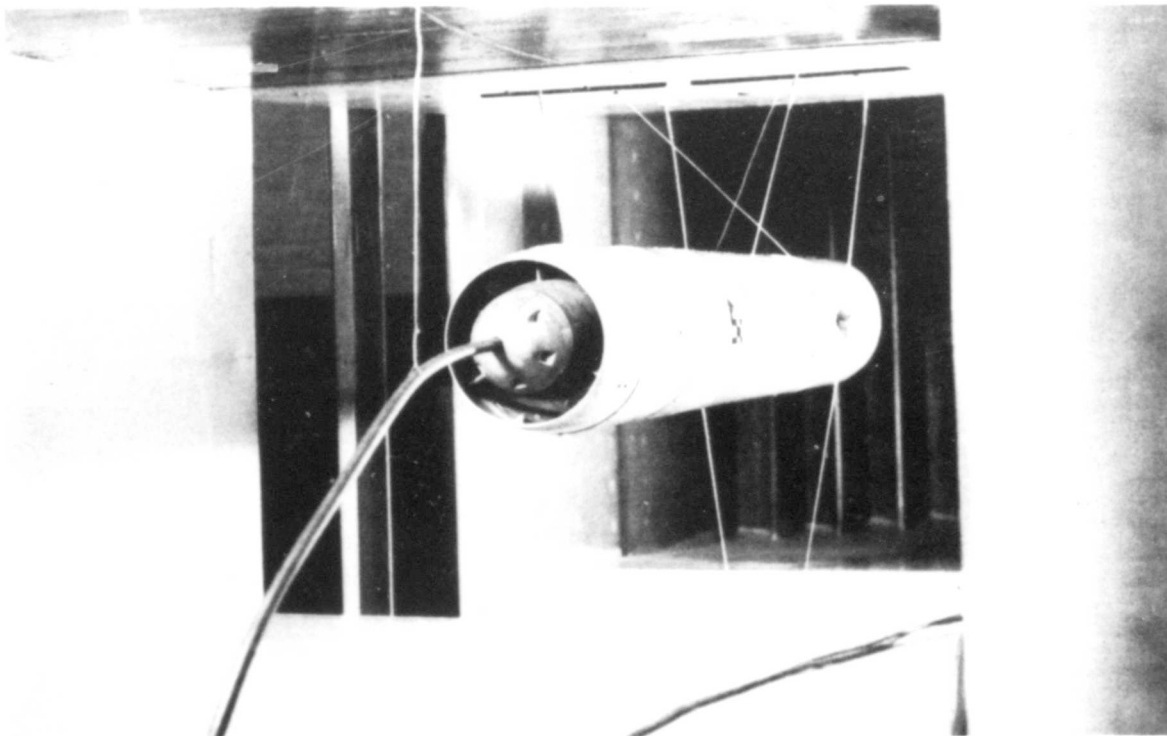


FIGURE 1

Rotating sleeve valve pulse jet mounted in the wind tunnel. Front view showing model suspension and flexible shaft drive.

Two test models of identical design were ordered according to our specifications at the IIE Circuit Breaker Co. in Philadelphia as subcontractor. The first model was to be finished, while the second one was to be final-machined at a later date after the required tolerances and correct slot size had been determined on the first model by tests in the PIBAL wind tunnel. Poor machining and inaccurate assembly on the part of the subcontractor necessitated extensive rework on the first model, and this circumstance greatly upset the planned test schedule. Figure 1 shows the front view of the test model mounted in the wind tunnel. Figure 2 shows a side view of the model together with the driving mechanism and test equipment. Hot-wire anemometers and strain gage type pressure detectors were used for the determination of the flow characteristics in various parts of the engine, such as intake duct, combustion chamber, tail pipe, and cooling duct. Figure 3 shows the schematic layout of the engine with the test points indicated. Termination of the work on Phase one prevented the planned tests from being brought to a satisfactory conclusion. It is intended to finish the work with the aid of thesis students. Such data as have already been determined are published in Technical Memorandum No. PIB-11, PIBAL No. 141 *Final Report on Phase I* by H. H. Reissner and Paul Torda,

Continuous Measurement of Pulse Jet Thrust Function. For the development of a satisfactory pulse jet theory, not only for the measurements of combustion chamber pressure and

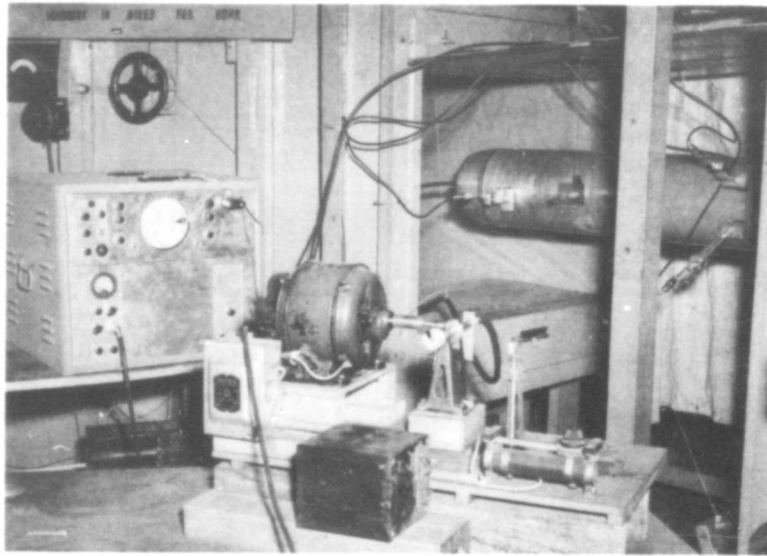


FIGURE 2

Rotating sleeve valve pulse jet mounted in the wind tunnel. Side view showing driving mechanism and test equipment.

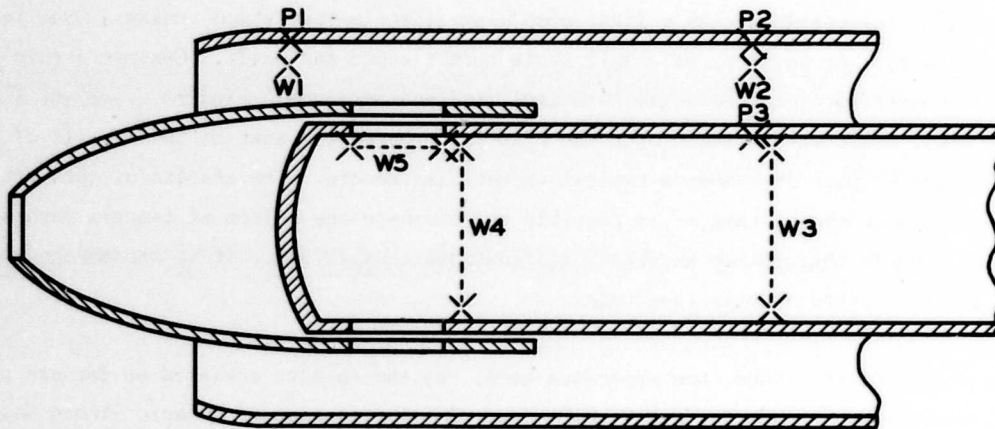


FIGURE 3

Schematic drawing of test model. Type of measurements carried out and their location on model.

W - Hot Wire

W1 Intake velocity

W3 Velocity across combustion chamber

W5 Velocity along combustion chamber port

P2 Wall pressure in cooling jacket

P - Pressure Detector

W2 Cooling Velocity

W4 Velocity across combustion chamber

P1 Wall pressure at intake

P3 Wall pressure in tail pipe

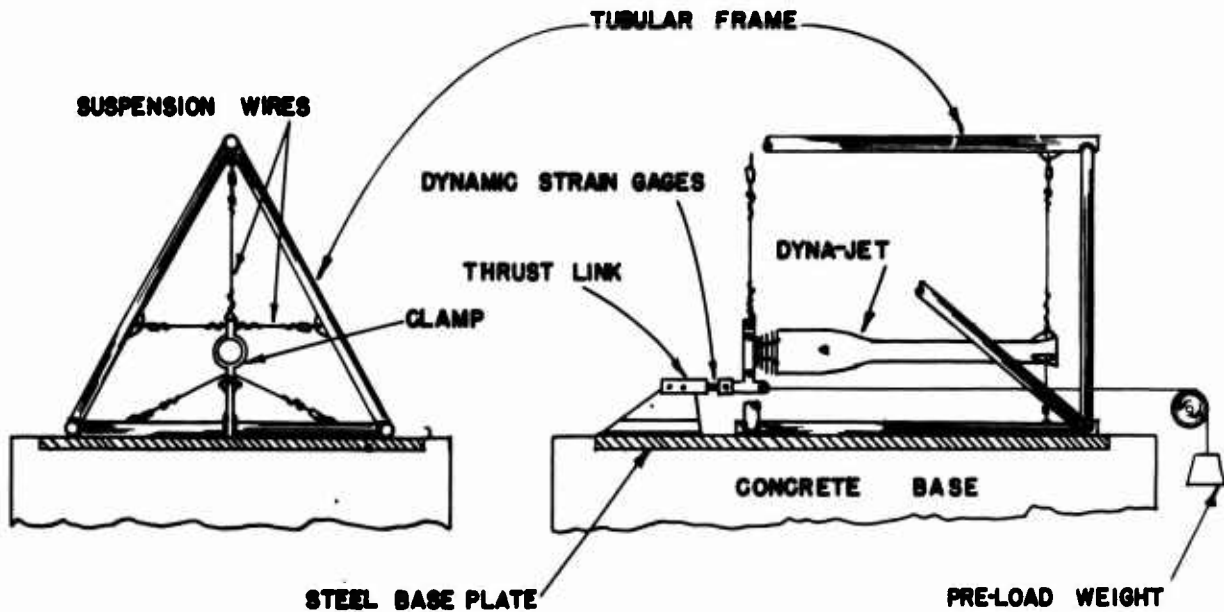


FIGURE 4
Pulse jet suspension.

temperature but also the measurement of the thrust as it changes periodically are of importance. In order to achieve the measurement of this time variation of the thrust, a new type of pulse jet suspension was designed. As a first step a small scale test stand, using a Dyna jet and incorporating all the features of a full scale thrust stand was built. Dynamic strain gages were used as detectors and the signal was amplified and recorded. Figures, 4, 5, 6, 7 and 8 show the small scale thrust stand with the Dyna jet mounted and some of the details of the setup. Figure 9, page 29, shows a typical thrust-time record. The results of this method of thrust measurement showed that it is possible to eliminate the effect of inertia forces of the suspension, and in this manner to obtain the instantaneous thrust. It is recommended to continue the work started at this Institute.

The design of the stand, the apparatus used, and the results achieved so far are published in: Technical Memorandum No. PIB-9; PIBAL No. 128, *Application of Dynamic Strain Gages to the Measurement of Continuous and Average Thrust of Pulse Jet Engines* by Paul Torda, Walter Ira Weiss, Erich Schatzki and Joseph Lovingham.

Measurement of Instantaneous Temperatures in the Combustion Chamber of a Pulse Jet Engine. An attempt was made to find a method for measuring the time variation of temperature throughout the cycle of a pulse jet engine.

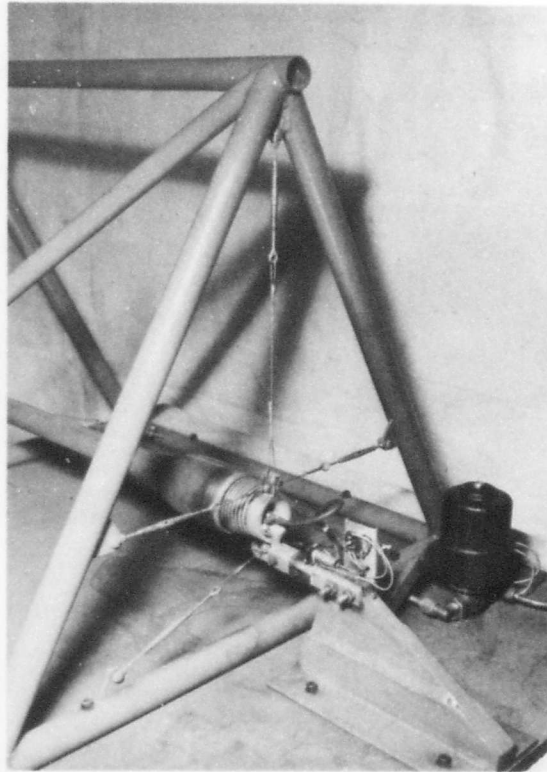


FIGURE 5
Pulse jet thrust stand detail of front suspension.

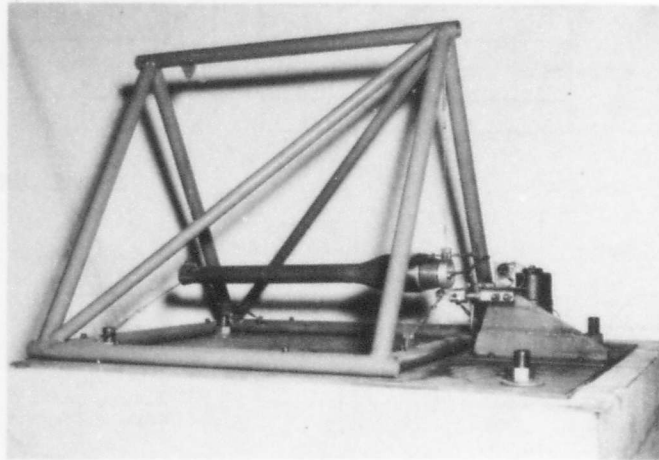


FIGURE 6
Small scale pulse jet thrust stand.

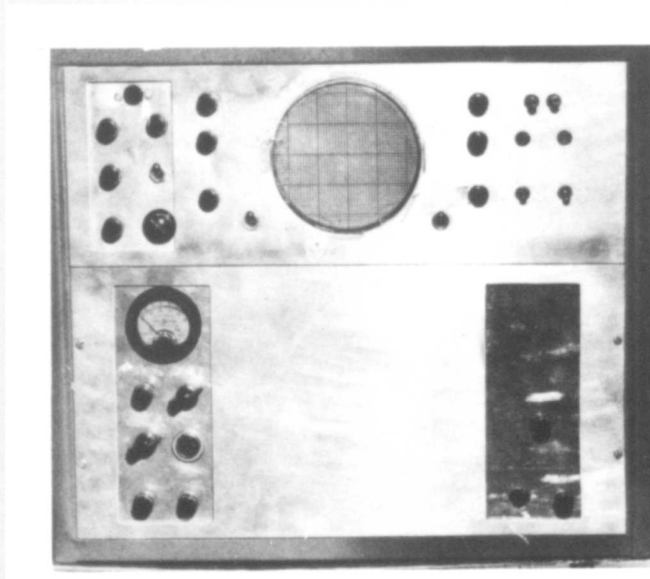


FIGURE 7

Two-gun oscilloscope used for thrust-time records of dyna jet.

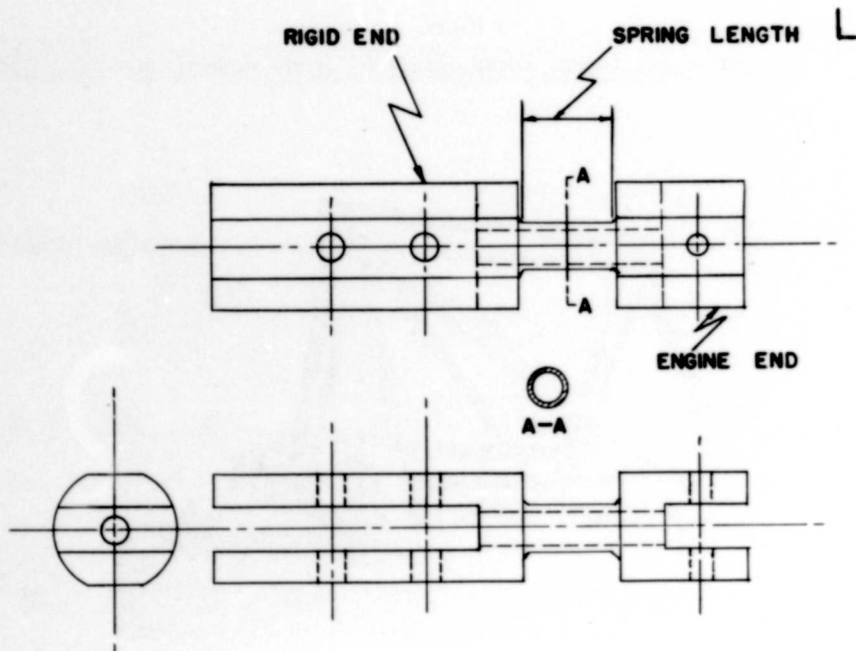


FIGURE 8

Thrust link.

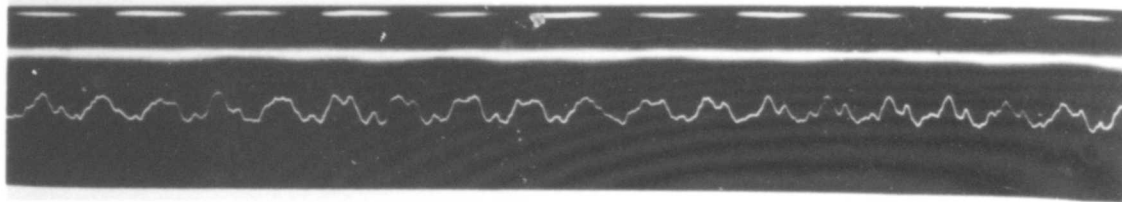


FIGURE 9

Typical thrust-time record of a dyna jet engine.

The measuring system has to be able to record temperature variations with negligible time lag because of the high frequencies at which pulse jets operate, and further, the system must withstand the high temperatures occurring.

A system measuring the transit time of an ultrasonic sound beam through the combustion chamber was chosen. The transit time is a function of the temperature of the medium. The time lag is negligible; the generating electromechanical transducers could be designed properly in order to withstand high temperatures and to avoid interference with the gas flow.

Investigations were begun along the following plan:

1. The development of an experimental supersonic generator,
2. The investigation of energy transmission in turbulent flow,
3. The construction of the final transducers, and
4. The actual measurements of temperatures.

Magnetostriction transducers seemed to unite all of the difficult requirements on the sound generating system. The experimental transducer was designed and built to operate at 10 kc. The magnetostrictive vibrating element consisted of an extremely thin nickel tube. Polarization was maintained by external D.C. excitation.

With the help of the experimental transducer valuable design data were found for magnetostrictive sound generators. Using the electric equivalent circuit, expressions were worked out for the efficiency as a function of the radiation resistance and internal mechanical dissipation. A method of design for optimum efficiency was developed. Radiation patterns for a vibrative piston radiating transversally into a cylinder were calculated by a wave guide analogy and measured.

The experimental transducer was used to investigate the possibilities of sound energy transmission through turbulent media. The measurements indicated that the scattering effect of turbulence lowered the energy of reception at the unusually high noise level.

At this stage of the development it became obvious that the power output of the transducers and the sensitivity of the receiving end should have been raised considerably. This had severe financial and technical limitations. Further considerations showed that even if satisfactory transmission could be established, all the variables involved in the measurements would not be separable, and the results would still be a function of the velocity and density as well as of the temperature of the combustion gases.

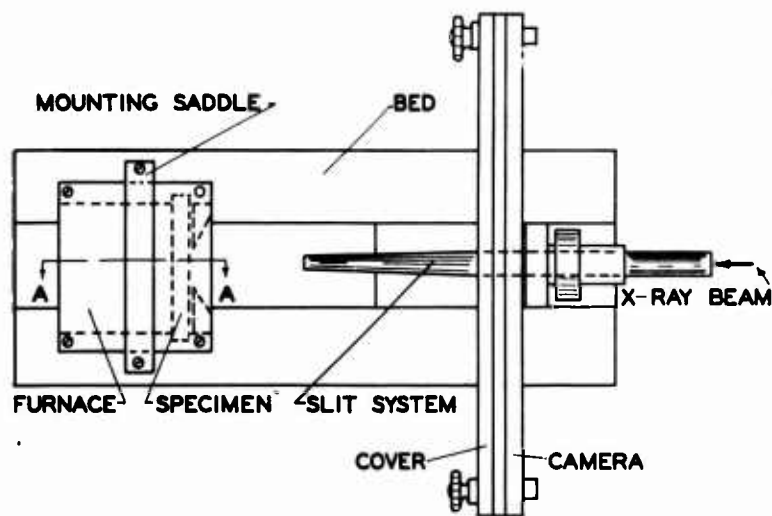
The theoretical considerations, the design of the apparatus, and the results achieved are published in Technical Memorandum No. PIB-7, PIBAL No. 126, *Measurement of Rapid Temperature Fluctuations in Pulsating Gas Flow* by Richard G. Lefeber.

Application of Strain-Gage Type Detectors to Combustion Chamber Pressure Measurements. Investigation of available dynamic pressure detectors have shown that the strain gage type instruments would be well suited for measuring the continuously varying pressures on the combustion chamber wall. Through the cooperation of the Statham Laboratories a satisfactory instrument has been developed. The necessary electric amplifying and indicating equipment has been developed and built at PIBAL. The work done on this problem has been described in Technical Memorandum No. PIB-6, PIBAL No. 125, *Application of Statham Pressure Transducers to the Continuous Recording of Instantaneous Pressures* by Walter Ira Weiss.

Calibration of Dynamic Pressure Detectors. A critical survey of the calibration methods of dynamic pressure detectors has shown the need for a standardized procedure. A sinusoidal and a square wave generator have been designed and built. Some comparative measurements were made using the Statham pressure indicator and the New York University capacitance type instrument. It is suggested that further investigations be made in this field. The work on this problem has been published in Technical Memorandum No. PIB-8, PIBAL No. 127, *Calibration Method and Equipment for Dynamic Pressure Detectors*, by Paul Torda and Walter Ira Weiss.

Work at Williamsport Test Stand. The work at the Williamsport test stand consisted mainly in reconditioning the plant and the badly neglected equipment. Several major and minor items, necessary for the efficient operating of the plant, had been removed before the facilities were transferred to PIBAL. Much time has been spent in restitution and replacement. During this work and after completion of it, routine tests were run on two 8 inch McDonnell pulse jets. An improvement in the support by a sleeve support at the combustion chamber only, instead of by the standard two spot fixation, was achieved.

On the termination of the contract the responsibility for the test facilities was returned to the Navy.



CAMERA SETUP, TOP VIEW

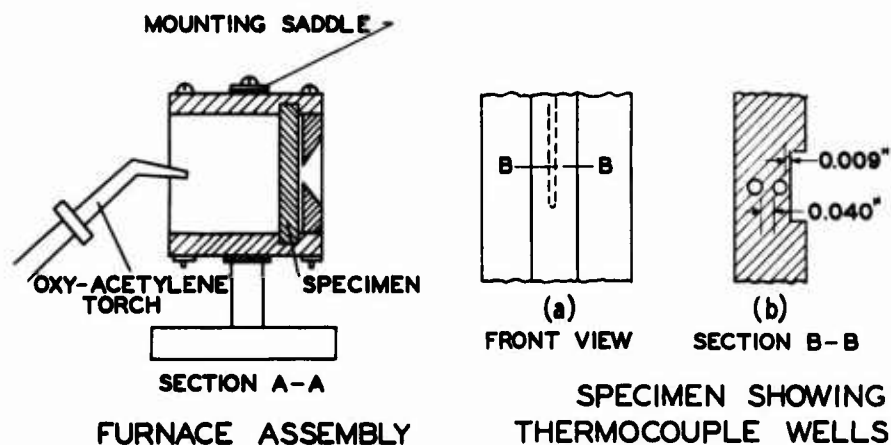


FIGURE 10

Measurement of Pulse Jet Wall Temperatures by X-Ray Diffraction Method. The basis for the measurement of surface temperatures by X-ray diffraction techniques is the fact that the macroscopic thermal expansion of solids is a consequence of the more fundamental expansions of the crystal lattice of the material with increase in temperature. Since the direction of X-ray scattering is a function of the changes of the lattice constants, this thermal expansion can be correlated to the temperature changes in the material. Pursuing this idea preliminary tests were started in 1947 on a sample of stainless steel with temperature changes from room temperature to approximately 800°F. These tests gave encouraging results and revealed the possibility of measuring temperatures within an accuracy of 20°F. However, for purposes of feasibility and instrumentation it was found necessary first, to start work with other materials and second, to design and build an X-ray camera and furnace suitable for the investigation of high surface-temperature measurements.

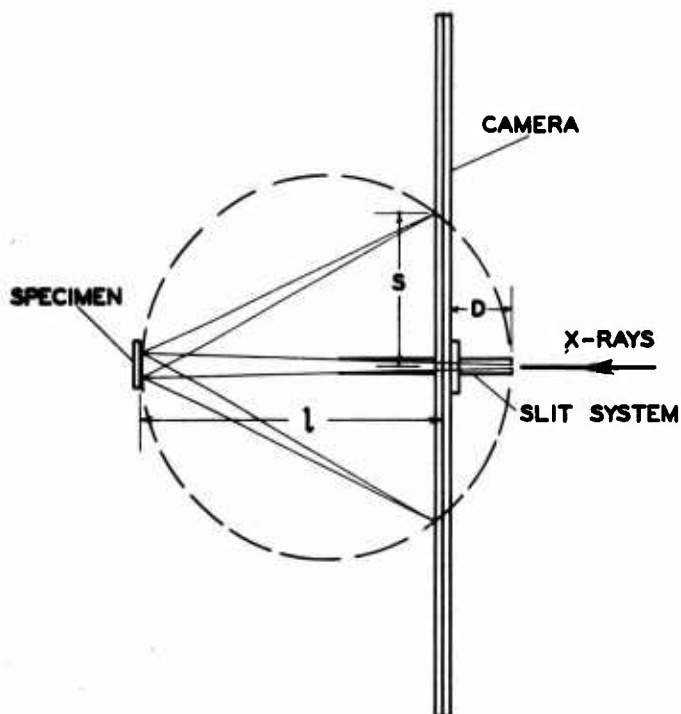


FIGURE 11

Focusing camera.

It has been shown that temperature measurements were possible up to 1700°F. and with greater accuracy than was achieved in the preliminary tests. Further, a Geiger-Muller counter together with an Esterline Angus automatic recorder was substituted for the photographic method of detection in order to speed up measurements.

Early in 1948 tests were started to determine the feasibility of the X-ray diffraction method of measuring surface temperatures on a specimen of a metal (AISI No. 347) used in the walls of a jet engine.

The method consisted of passing, through a suitable aperture in the film, a collimated X-ray beam which is scattered by the specimen placed parallel to the film and normal to this incident

X-ray beam. The scattered X-rays are reflected from the specimen and are intercepted by the film producing circular diffraction lines whose diameters are characteristic of the material and the temperature of the specimen. A change in temperature will produce a shift in the diameter of these diffraction lines.

The apparatus consisted of a small torch-heated furnace containing the specimen. A flat cassette type camera and the X-ray slit system were firmly mounted on the same support as was the furnace. This arrangement is shown in Figures 10 and 11. The X-ray source is a North American Philips X-ray diffraction unit employing an iron target tube. X-ray diagrams were taken at known temperatures of the specimen. The temperatures ranged from 77°F. to 1629°F. and were measured by carefully placed thermocouples. The results obtained are shown in Figure 12.

The solid line in Figure 12 shows the change in the radius of the diffraction line with increase in temperature for the iron $K\alpha_1$ line and the dotted line shows a similar relationship for the $K\alpha_2$ line. These lines substantiate closely the theoretical prediction of their essential linearity over the operating ranges. An examination of the graphs indicates that

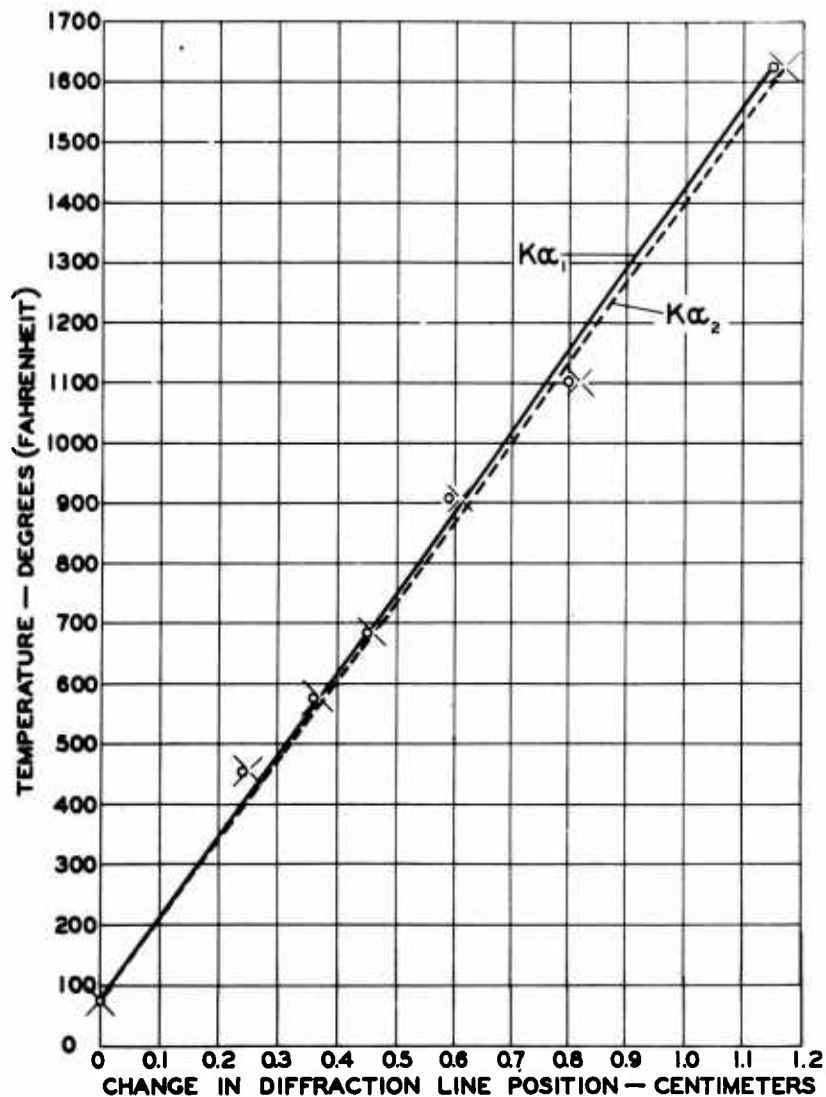


FIGURE 12

Radius change of diffraction ring pattern with temperature.

surface temperature can be measured to within 15°F. Experimental points lying off the line may be interpreted as caused by possible faulty temperature measurements by the thermocouples since the determinations were made over extended periods of time.

It can be concluded that surface temperature measurement of stainless steel AISI No. 347 is feasible by the application of X-ray technique over the range of temperature covered in these experiments with an accuracy of 15°F. Further, this method can be extended to the measurement of surface temperatures of material where thermocouples or other generally accepted methods cannot be readily applied either because of mechanical difficulties or because of the general dissipation of temperature field due to the presence of foreign material.

Work was then started to instrument this method as a temperature measuring device. It was felt necessary to set up a series of static experiments to determine the type of the overall design of a practical instrument. The film was supplanted by a Geiger-Muller counter as the method of determining the position of the diffraction lines. The G-M tube was used in conjunction with the 1500-A General Radio Company Counting Rate Meter and the Esterline Angus recorder.

The equipment was set up as a simple X-ray spectrometer, with manual control. Figure 13 illustrates the complete experimental arrangement. The G-M tube is supported on a universal arm and is mounted, along with the slip system, so that its distance from the specimen is readily adjustable. The G-M tube moves on an arc of the circle, the diameter of which is determined by the distance between the X-ray slit system and the specimen. The position of the slit system in front of the G-M tube is controlled by a worm gear mechanism. Thus, a shift in the diffraction lines, or a change in temperature, could be made a function of the degree of rotation of the gear system.

Preliminary experimentation in this direction revealed the presence of the diffraction lines. Figure 14 shows a typical X-ray diffraction diagram.

Plans

All problem assignments, except the measurement of wall temperatures by X-ray diffraction method, have been terminated. In this remaining problem the following work is planned.

A series of experiments will be made to obtain the relationship between the temperature of the stainless steel specimen and the position of the G-M tube. This is expected to provide sufficient data to begin the design of the direct reading 'X-ray thermometer'. Further, it is planned to make this device automatic in operation by making the G-M tube self-seeking by electronic means.



FIGURE 13

Experimental arrangement of temperature measurements by X-ray diffraction technique.

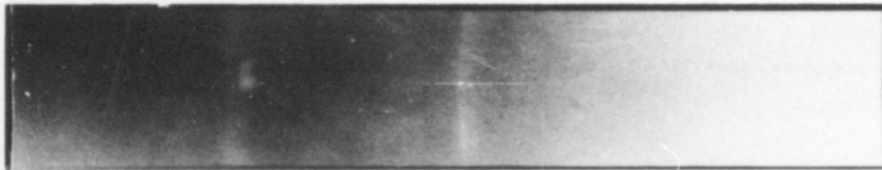


FIGURE 14

Typical X-ray diffraction diagram.

PHASE 2

(1) To investigate causes of metal failure thus far 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

This phase was concluded June 30, 1948. During the first half of 1948 the following work was done: The variable temperature creep machine was made ready for preliminary experiments. Temperature distribution studies by means of martensitic structure analysis were made and the studies of carbides, nitrides and borides bonded with refractory metals were continued.

Four technical memoranda were published and several others have been written and are now being edited for publication. Those issued were as follows:

1. *Problems Encountered in the Study of the Beryllium-Chromium System*, Technical Memorandum PIB-1, PIBAL Report No. 120.

2. *Changes in Martensite Structure as a Record of Temperature-Part I*, Technical Memorandum PIB-2, PIBAL Report No. 121.

3. *An Automatic Recording Extensometer System*, Technical Memorandum PIB-3, PIBAL Report No. 122.

4. *Changes in Martensite Structure as a Record of Temperature-Part II*, Technical Memorandum PIB-4, PIBAL Report No. 123,

Reports on the construction of a dilatometer and on the study of carbides and nitrides are now being edited.

The following tabulation contains a summary of the progress made on each topic as of July 1, 1948.

TABULATED SUMMARY OF WORK DONE IN 1948 ON PHASE 2

Original Topic	Code Number	Official Title	Achievements in 1948
Modified Creep Tests	PIB 2R1	Construction of a Dilatometer	Completed in 1947 Technical Memorandum to be published.
	PIB 2R2	Development of high temperature extensometers.	Completed November 1947. Technical Memorandum published.
	PIB 2R3	Variable temperature creep machine.	Machine completed. Changes made and instruments for measuring diameter during tests designed.
	PIB 2R4	Constant strain rate variable temperature testing machine.	No work done since basic frame was completed.
	PIB 2R5	Modified creep machine	Inactive
Temperature Distribution Studies	PIB 2R6	Changes in martensitic structure as a record of temperature.	Work complete Two technical memoranda issued.
Beryllium-Chromium System	PIB 2R7	Study of alloy system: Be-Cr.	Technical memorandum issued on difficulties encountered.
Carbides and Nitrides	PIB 2R8	Study of carbides and nitrides.	Technical memoranda being edited on literature survey and first systems studied: Alloy of titanium carbide and chromium carbide.

The results obtained in some parts of the program seem to warrant continuation of the work. Of particular interest are the phases dealing with carbides and nitrides and with the changes in martensitic structure as a temperature recorder. The martensitic structure study is now ready for tests with actual combustion chambers.

Progress

Construction of a Dilatometer. The dilatometer was completed in 1947 and a technical memorandum about this work is now being edited for publication. (See also Project SQUID Annual

Program Report, January 1, 1948).

Development of High Temperature Extensometers. The extensometer was completed in November, 1947. Complete details of its design and operation are reported in Technical Memorandum No. PIB-3, PIBAL Report No. 122, *An Automatic Recording Extensometer System*, by Flynn, R. and Stoll, M. (See also Project SQUID Annual Program Report, January 1, 1948).

Variable Temperature Creep Testing Machine. This machine was completed in 1948 and preliminary tests were made which are reported in the Quarterly Progress Report dated July 1, 1948.

As a result of these tests the driving motor was replaced with one having synchronous characteristics, and two instruments were designed to measure the diameter of the specimen at the necked section throughout the tests in order to enable the calculation of the true stress.

The basic design criteria of this machine are reported in the Project SQUID Annual Program Report January 1, 1948.

Constant Strain Rate, Variable Temperature Creep Testing Machine. The framework of the machine and a few of its basic parts were completed in 1947. No further work was carried out, however, since it was deemed desirable to employ the limited personnel for the completion of other parts of Phase 2. Since Phase 2 has been terminated this machine cannot be completed.

Modified Creep Tests. This problem has not been attacked at all due to lack of funds and personnel.

Changes in Martensitic Structure as a Record of Temperature. This study has been carried to completion and two reports, Technical Memorandum PIB-2, PIBAL Report No. 121, entitled, *Changes in Martensite Structure as a Record of Temperature-Part I*, by Schippereit, G. H. and Henry, O. H., and Technical Memorandum PIB-4, PIBAL Report No. 123, entitled *Changes in Martensite Structure as a Record of Temperature-Part II*, by Schippereit, G. H. and Henry, O. H., have been published and describe the procedures followed and the results obtained. The results of this study definitely confirm that temperature can be measured by observing the changes resulting from tempering of martensite. As a result it is possible to measure temperature in machine parts required to work at elevated temperatures.

Study of the Alloy System of Beryllium and Chromium. Due to health hazards connected with the manufacture of beryllia crucibles, and inability of securing these crucibles, the problem has been dormant for some time. A technical memorandum describing the problems encountered in the study of the system has been published, Technical Memorandum PIB-1, PIBAL Report No. 120, entitled: *Problems Encountered in a Study of the Beryllium-Chromium System*, by Schippereit, G. H.

Study of Carbides and Nitrides. Considerable work was accomplished on this part of Phase 2 in 1948 and some interesting results were obtained.

The study of the titanium carbide - chromium system, with samples produced in a CO atmosphere, was not very encouraging at first. As a result a vacuum system was designed and built. Since difficulties were encountered with the volatility of the chromium, it was decided to flush the furnace with hydrogen gas. While this gas protected the chromium, it attacked the titanium carbide, and the conclusion was reached that the components of this system are unsuitable for combination in a refractory alloy. Further examination of the compacts sintered in a CO atmosphere showed that the compacts containing less than 50 percent of chromium were the best from the point of soundness. The apparent interaction between chromium and carbon of the crucible at the outermost points of the compact and the resultant denseness led to the assumption that possibly a comparatively low-melting chromium carbide bonding the higher-melting titanium carbide was the answer to the technical difficulties encountered up to that point.

Several compacts of titanium carbide and chromium carbide were prepared and the expected hardness and soundness were confirmed. It was established, moreover, that the resultant specific gravity was uniquely lower than any other carbides experimented with so far.

The results of the investigations of the titanium carbide-cobalt and tungsten carbide-cobalt systems will be published shortly.

The study of carbides, nitrides and borides reveals the vastness of the field of materials which might be useful for high temperature applications. Therefore the problem deserves a careful and extensive investigation in the near future.

PHASE 3

(1) 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. (2) To study analytically and experimentally (a) the diffusion of fluids through porous media under high pressures and temperatures and (b) the effects (of this diffusion) on the internal aerodynamics. (3) To study problems in the field of physical-chemistry pertinent to (1) and (2) with consideration given to the clogging of pores, the use of catalysts imbedded in the liner walls and endothermic diffusion processes.

Summary

A paper dealing with the theoretical investigation of the laminar boundary layer of a compressible fluid flowing along a porous flat plate with fluid injected through the porous cells of the plate was presented at the 1948 Heat Transfer and Fluid Mechanics Institute. Further investigation of this problem with better approximation of the density and viscosity variation inside the boundary layer was also made. An experimental investigation of the stability of the laminar boundary layer along the surface of a porous flat plate with fluid injection is in progress.

Experiments were carried out to determine the flow conditions over a porous flat plate with fluid injection. The results of the experiments should serve for comparison with the results obtained from the theoretical investigations. The PIBAL two-dimensional turbulence channel was modified and appropriate hot-wire equipment was developed for these experiments. The results of the experiments are also presented.

Progress

ANALYTICAL WORK.

A paper entitled *Heat Transfer in Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection* was presented at the Heat Transfer and Fluid Mechanics Institute on June 23, 1948. The contents of this work are described briefly as follows:

Cooling of combustion chamber walls in rocket and jet motors, which are subject to extremely high temperatures, by means of injecting coolant through a porous wall is a new and effective cooling method. This is the so-called sweat cooling. On emerging from the wall the coolant first picks up heat from the wall and lowers the wall temperature, and then it forms a protective layer on the surface which is exposed to the hot gases, and thus diminishes the heat transfer from the hot gasses to the wall. Since the magnitude of the boundary layer thickness along the combustion chamber liner is known to be comparatively small, the problem can be treated by investigating the boundary layer along a flat plate under similar flow conditions. It is believed that this approximation allows qualitative conclusions to be drawn about the actual heat transfer process.

The theoretical study of the aero-thermodynamic problems involved was started by the investigation of the flow of a hot fluid over a porous flat plate under the conditions of

uniform fluid injection from the bottom of the plate. The assumptions made in the present investigations are as follows:

1. The mass density and temperature inside the boundary layer are inversely proportional and the viscosity is assumed to be proportional to the square root and three-fourth power of the temperature.
2. The Prandtl number is assumed to be equal to unity.
3. The flow is assumed to be laminar, and the fluid flowing along the wall and the coolant flowing through the pores are assumed homogeneous.

It must be borne in mind that in the turbulent boundary layer which occurs in actual practice the reduction of heat flow is probably smaller than it is in the laminar boundary layer. Moreover, the isolating effect of the coolant film is better in the case of a laminar boundary layer than in the case of a turbulent layer. Hence the calculations give an upper limit for the decrease of the heat transfer coefficient by sweat cooling.

In the solution of the boundary layer equation the Prandtl number is assumed to be equal to unity, then the temperature T could be expressed by a certain parabolic function only of the velocity; this function satisfies both the equation of motion and the energy equation. The velocity profile was assumed as a polynomial of the fourth degree.

By knowing that the quantity of heat per unit area removed by the plate is equal to the quantity of heat per unit area absorbed by the coolant at the surface of the plate, a relation between the wall temperature and the amount of coolant needed can be established. For a pre-designated wall temperature, the amount of coolant required per unit time can be determined provided that the temperature of the outer boundary layer and of the coolant is known. A comparison of the theoretical results with some available experimental data shows fair qualitative agreement. See Figure 15.

The results of the calculations show that the boundary layer thickness grows with the increase of both the Mach number and the temperature ratio (outer boundary layer temperature to wall temperature). Since the effect of compressibility is to increase the heat transfer through the wall, and since the amount of heat produced in the boundary layer increases with speed, the effect of both the increase of the Mach number and of the temperature ratio on the boundary layer thickness is the same. It should be noted that the temperature gradient at the wall increases as the Mach number increases and decreases as the velocity ratio (injection velocity to main stream velocity) increases. This behavior indicates that the heat transfer through the wall increases as the compressibility of the flow becomes more pronounced and decreases as the injection of coolant increases. On account of the injected velocity of the coolant along the plate, inflection points appeared in the velocity profiles inside the boundary layer. The instability of the laminar boundary layer may be interpreted from the inflec-

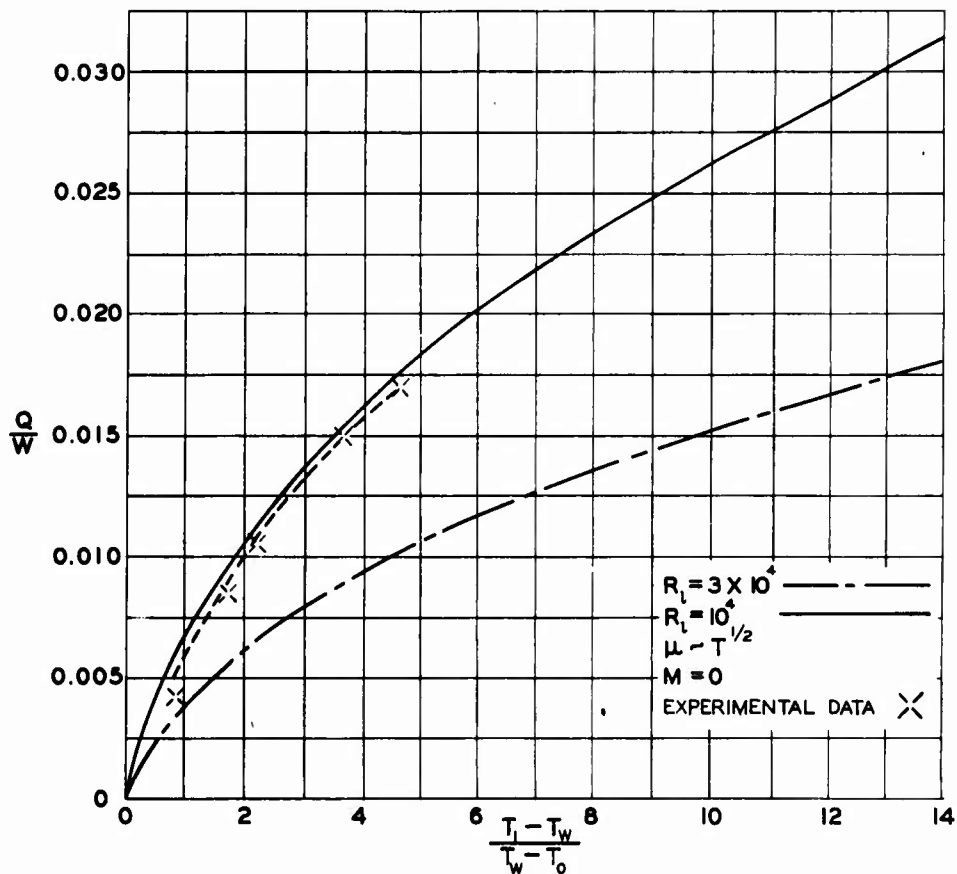


FIGURE 15

Temperature ratio vs. mass flow ratio for different Reynolds numbers.

tion points occurring in these velocity profiles.

The temperature ratios (the difference between outer boundary layer temperature and wall temperature to the difference between wall temperature and coolant temperature) as a function of mass flow ratios (coolant mass flow to main stream mass flow) were calculated at different Mach numbers and Reynolds numbers taking the viscosity variation with temperature into account. For a predesignated wall temperature it is shown that the rate of coolant discharge increases as the Mach number increases and decreases as the Reynolds number increases. It is also shown that larger amount of coolant is required to cool the wall as a predesignated temperature for $\mu \sim T^{\frac{1}{2}}$ than for $\mu \sim T^{\frac{3}{4}}$.

Further Investigation of Heat Transfer in Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection. In the analysis described in the previous section the mass density and viscosity of the fluid inside the boundary layer were assumed (for Mach number equal to zero) as follows:

$$\frac{\rho}{\rho_1} = \frac{T_1}{T} = \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \frac{y}{\delta} \right]^{-1} = \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \frac{y}{\delta} \right]^{-1}$$

$$\frac{\mu}{\mu_1} = \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \frac{y}{\delta} \right]^{\frac{1}{2}}$$

It is seen that the velocity profile inside the boundary layer in this case is linearly proportional to the distance perpendicular to the plate.

Further investigation of the problem described in the beginning of this chapter was made with the assumption that the mass density and the viscosity have the following forms.

$$(a) \left\{ \begin{aligned} \frac{\rho}{\rho_1} &= \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \left(\frac{2y}{\delta} - \frac{2y^3}{\delta^3} + \frac{y^4}{\delta^4} \right) \right]^{-1} \\ \frac{\mu}{\mu_1} &= \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \left\{ \frac{2}{1+\lambda} \frac{y}{\delta} + \frac{6\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^2 - \frac{2+8\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^3 + \frac{1+3\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^4 \right\} \right]^{-1} \end{aligned} \right.$$

$$(b) \left\{ \begin{aligned} \frac{\rho}{\rho_1} &= \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \left(\frac{2y}{\delta} - \frac{2y^3}{\delta^3} + \frac{y^4}{\delta^4} \right) \right]^{\frac{1}{2}} \\ \frac{\mu}{\mu_1} &= \left[\frac{T_W}{T_1} - \left(\frac{T_W}{T_1} - 1 \right) \left\{ \frac{2}{1+\lambda} \frac{y}{\delta} + \frac{6\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^2 - \frac{2+8\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^3 + \frac{1+3\lambda}{1+\lambda} \left(\frac{y}{\delta} \right)^4 \right\} \right]^{\frac{1}{2}} \end{aligned} \right.$$

With assumption (a) the general expression has been obtained from the solution of the boundary layer equations, and the results show the same trend as that obtained earlier, but the solution involved more complicated terms. In case (b) a non-linear differential equation has to be solved and only numerical solutions of limited cases were carried out.

Heat Transfer in Laminar Boundary Layer on a Partial Porous Flat Plate with Fluid Injection. The solution given in the first section was derived for a flow over a porous flat plate under the condition of uniform fluid injection from the bottom of the plate. However, the solution can be extended to the case where the region of injection begins at a distance $x = x_i$ from the leading edge of the plate. In the region $0 < x \leq x_i$ the solution of a boundary layer for an impermeable wall may be used. The above investigation has been published in Technical Memorandum PIB-10, PIBAL Report No. 135, entitled *Heat Transfer in Laminar Boundary Layer (Compressible Fluids) on a Porous Flat Plate with Fluid Injection*, by Yuan, S. W.

The results of the calculations show that for a partial porous flat plate smaller amount of coolant is required to cool the wall to a predesignated temperature than for the corresponding fully extended plate. The greater average boundary layer thickness occurring in the case of the partial porous plate explains the smaller heat transfer to the wall.

Heat Transfer in Laminar Boundary Layer in a Porous Flat Plate with Variable Fluid Injection. The general differential equation for the boundary layer thickness (δ) and the length in the direction of the flow (x) has been obtained for a laminar boundary layer on a porous plate with variable fluid injection. In order to solve the above differential equation of δ and x a linear variation of the injected fluid along the flow direction was assumed first. The analysis consists of the numerical solution of the non-linear differential equation.

All the investigations mentioned in the previous sections were based on a flow over a porous flat plate, i.e., it was assumed that the pressure gradient in the direction of the flow is zero. However, this is not true for a curved porous plate. A study of the laminar boundary layer along a porous, sweat-cooled wall with pressure gradient was made. A general differential equation was derived for flow in a laminar boundary layer along a porous sweat-cooled wall and numerical calculations are underway for the case with linear pressure drop in the direction of the flow.

EXPERIMENTAL WORK.

Experimental Investigation of the Stability of the Laminar Boundary Layer along the Surface of a Porous Flat Plate with Fluid Injection. The aim of the first experimental step was to determine the conditions of channel flow velocity and injection velocity under which instability occurs in a two-dimensional laminar boundary layer on a porous flat plate with fluid injection under isothermal conditions. The results of the experiments and the velocity profiles obtained would then be compared with the results of the analytical work carried out under this phase.

The experiments were carried out in the PIBAL two-dimensional turbulence channel, which was properly modified to enable the investigations mentioned above.

The porous plate (26 in. x $4^{5/16}$ in. x $17/32$ in.) had to be built up from six strips, $4^{5/16}$ in. x $4^{7/16}$ in. x $17/32$ in. each, since a sufficiently large plate was not available. The porous metal blocks were supplied by the Jet Propulsion Laboratory of the California Institute of Technology. The blocks were placed in a metal frame, and the joints were sealed with cement. The leading edge of the built-up plate was sharpened to a knife edge. The plate was mounted in the vertical wall of the turbulence channel.

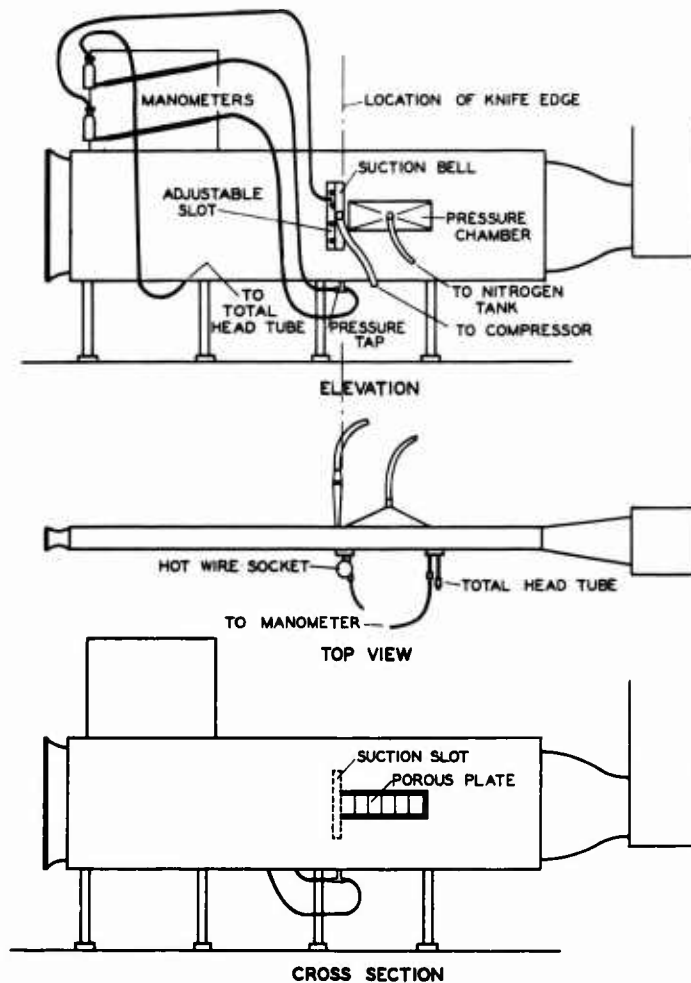


FIGURE 16

Experimental setup for studies of boundary layer stability with fluid injection.

In order to remove the initial boundary layer an adjustable vertical suction slot was cut into the wall of the channel at the leading edge of the porous flat plate. The slot was provided with a properly shaped suction bell to obtain uniform suction in the slot. The suction bell was connected to the intake of a supercharger. To boost the suction effect, the outlet of the supercharger was connected to a low pressure point of the turbulence chamber.

Injection was provided by commercially available bottled nitrogen. The outer side of the porous flat plate was covered by a pressure chamber connected to the nitrogen tank through a regulating valve

Figure 16 shows the experimental setup. The view at the bottom shows the porous plate inside the turbulence channel with the side wall removed.

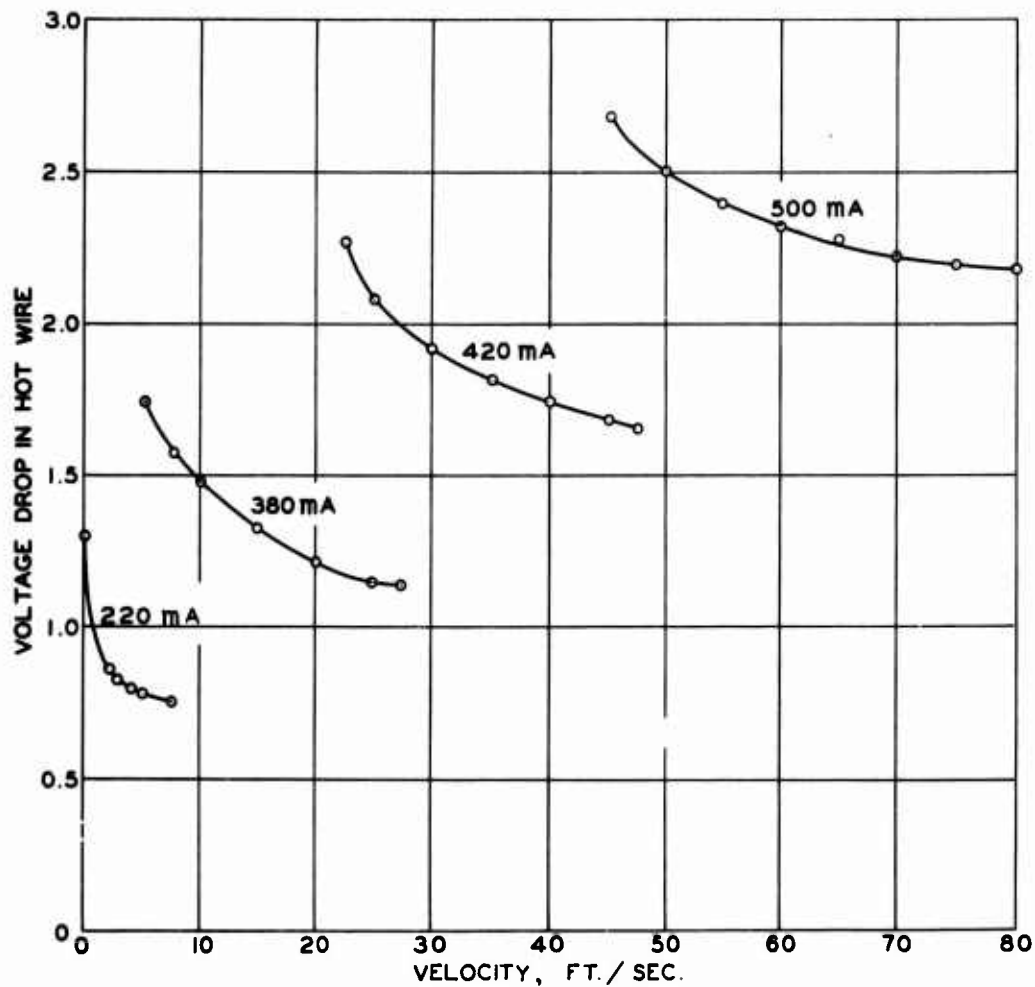


FIGURE 17

Calibration curves for hot wire.

The actual measurements were made by velocity profile surveys using the hot-wire-anemometer methods. Initial efforts to record flow directions in the boundary layer by means of the PIBAL two-wire hot-wire-anemometer were temporarily abandoned because of errors introduced by low V velocities and by the inherent assymetries of the wires. Single wires which recorded velocity magnitudes were used.

The electric equipment consisted of a simple volt-ammeter resistance measuring apparatus fed by a constant current generator. The hot wire anemometer itself was designed for convenient operation in the turbulence channel. The velocity sensitive element consisted of a 0.0008 in. tungsten wire, stretched between steel prongs. The hot-wire units were calibrated for voltage drop at various velocities. Blower equipment was used for the calibration. The wires had a working range of 0 - 80 feet/sec. A typical calibration curve is given in Figure 17.

For the investigation of the stability of the laminar boundary layer the knowledge of the injection velocity distribution over the porous plate is necessary. Therefore, measurements for the determination of injection velocity distribution were carried out. Some difficulties were encountered at low injection velocities, since the errors were of the order of magnitude of the velocities. Additional cooling of the wire by the cool plate during measurements very close to it produced an effect of a higher indicated velocity than the one which actually existed. This fact made corrections of the measured velocities necessary,

Figures 18 to 22 show the results of the experiments.

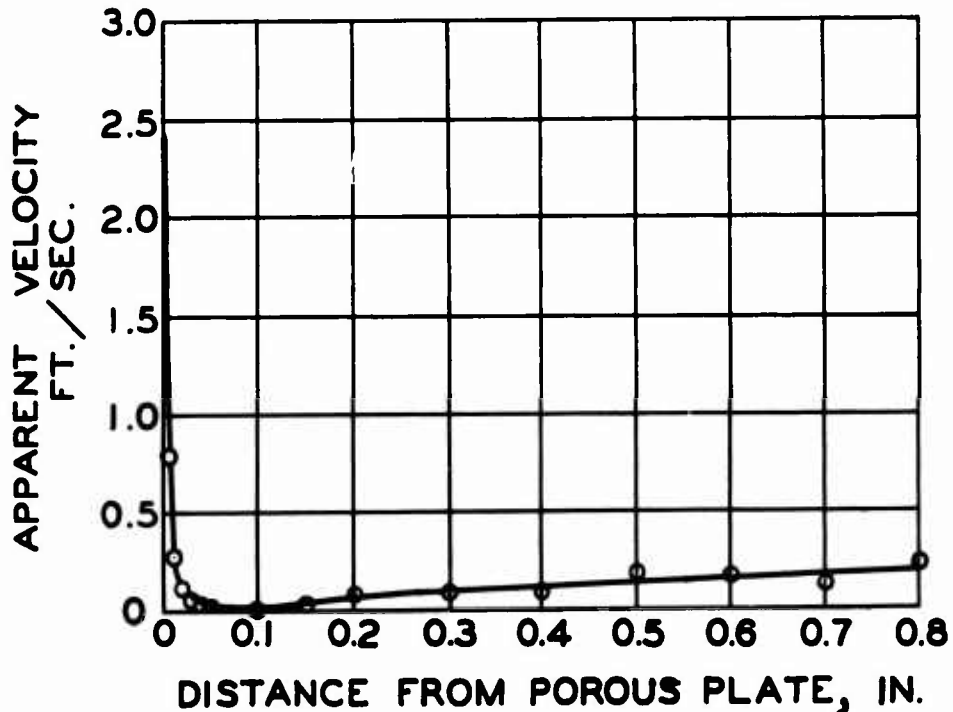


FIGURE 18

Apparent velocity as a function of distance from the plate.

Injection velocity = 0

Channel velocity = 0

Figure 18 shows the apparent velocity with no injection as a function of distance from the plate when there is no main flow in the channel. It is seen that the cooling effect is considerable in the immediate vicinity of the porous plate. This was remedied by using air from a compressor instead of the nitrogen from bottles. This additional cooling decreases to negligible magnitude about 0.1 in. from the plate. From here on, the natural convection currents introduce an error velocity which increases towards the center of the channel. These errors were taken into account in the following diagrams. Plans are being made to check the injection rate by metering the injection gas before it enters the injection chamber.

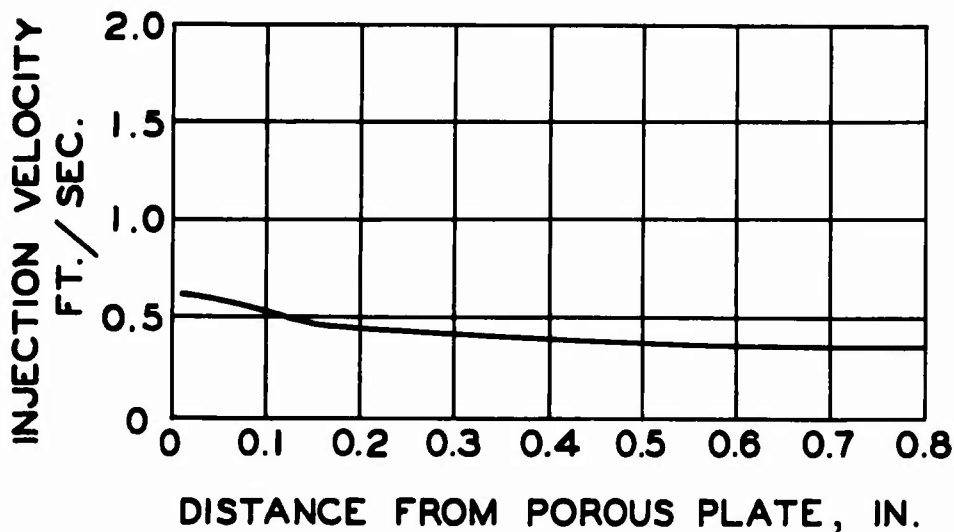


FIGURE 19

*Injection velocity plotted against the distance from the porous plate.
Applied pressure = 20 P.S.I.*

Figure 19 shows the injection velocities plotted against the distance from the porous plate with an applied pressure of 20 psi. The experimental values show fair agreement with the calculated value of 0.5 feet per second for 20.5 psi.

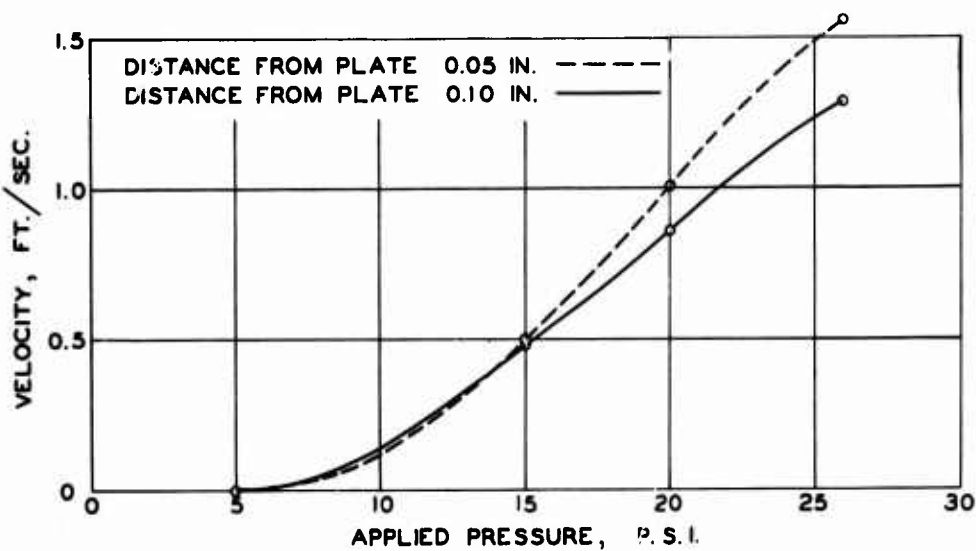


FIGURE 20

Variation of injection velocity plotted against applied pressure.

Figure 20 shows the variation of injection velocity versus applied pressure at 0.05 in. and 0.1 in. from the plate (corrected values).

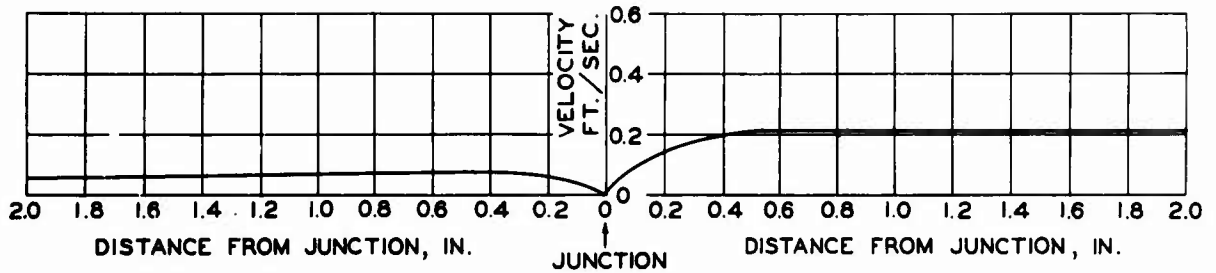


FIGURE 21

*Velocity along the porous plate - 0.01 in. from the plate.
Injection pressure = 20 P.S.I.*

Figure 21 shows a horizontal velocity survey along the porous plate on both sides of a junction of two strips at approximately 0.01 in. from the plate. The decrease in velocities on the left side from the junction and the jump at the junction is due to cooling errors introduced by the unevenness in the porous plate. It is seen that the velocity distribution is fairly uniform except at the junction, where the sealing cement prevents injection.

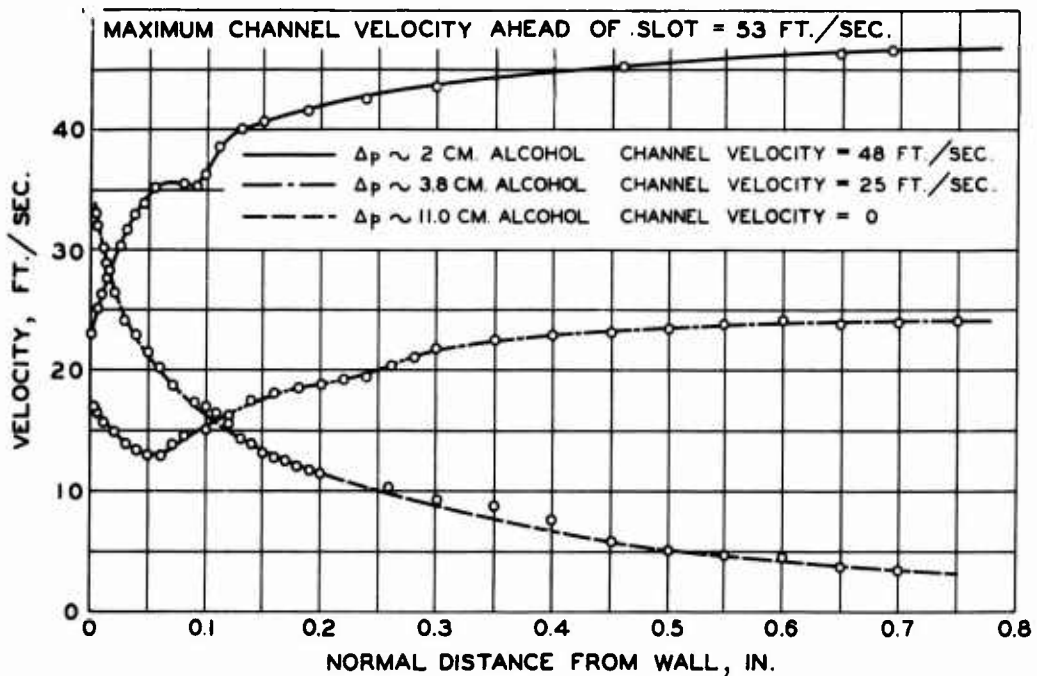


FIGURE 22

Velocity profiles at knife edge position.

Attempts were made to find the proper suction pressures corresponding to various channel speeds for complete removal of the initial boundary layer in the tunnel. Figure 22 shows ve-

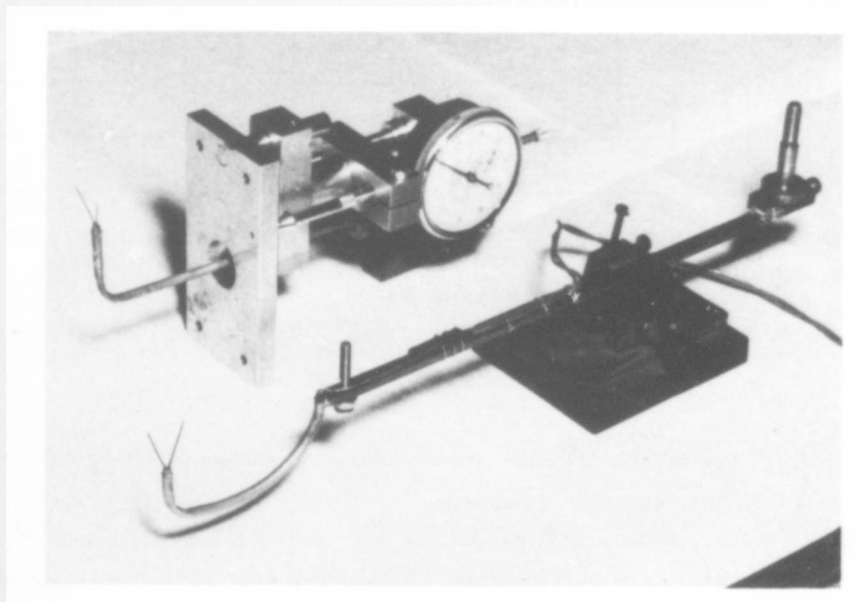


FIGURE 23

Hot-wire anemometers.

locity profiles at the knife edge at various ratios of channel speed to pressure drop in the suction slot. The aim of these measurements was to find the maximum channel speed for which sufficient suction was available in order to remove the boundary layer. For the present set-up this velocity would be between 25 feet per second and 50 feet per second. This channel velocity was not thought to be sufficiently high and therefore the compressor used to create the necessary suction was recently modified for higher suction capacity. At present experiments are run at elevated suction pressures to determine the proper ratio of channel velocity to pressure drop in the slot for removal of the initial boundary layer.

Figures 23 to 27 show the experimental setup and some of its details, such as the suction bell and the pressure chamber, the measuring equipment, the porous flat plate and the suction slot with a traversing hot-wire (side wall removed), and the hot wires used in the experiments.

Plans

The study of the turbulent boundary layer of a fluid on a porous flat plate with fluid injection will be continued.

Investigation of the situation that occurs when the molecular weight of the injected fluid differs from the molecular weight of the main fluid is planned.

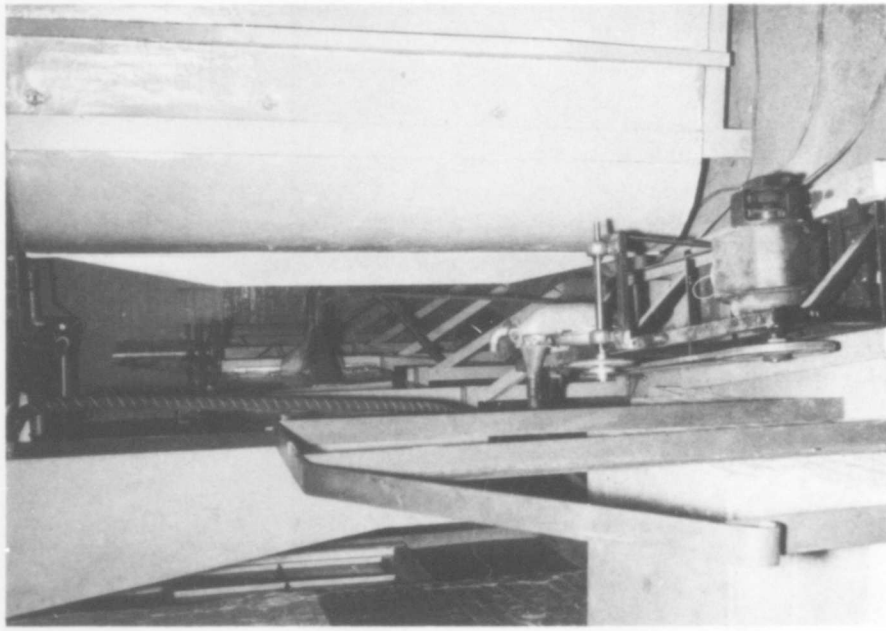


FIGURE 25

Turbulence channel showing compressor, suction bell and compression chamber.

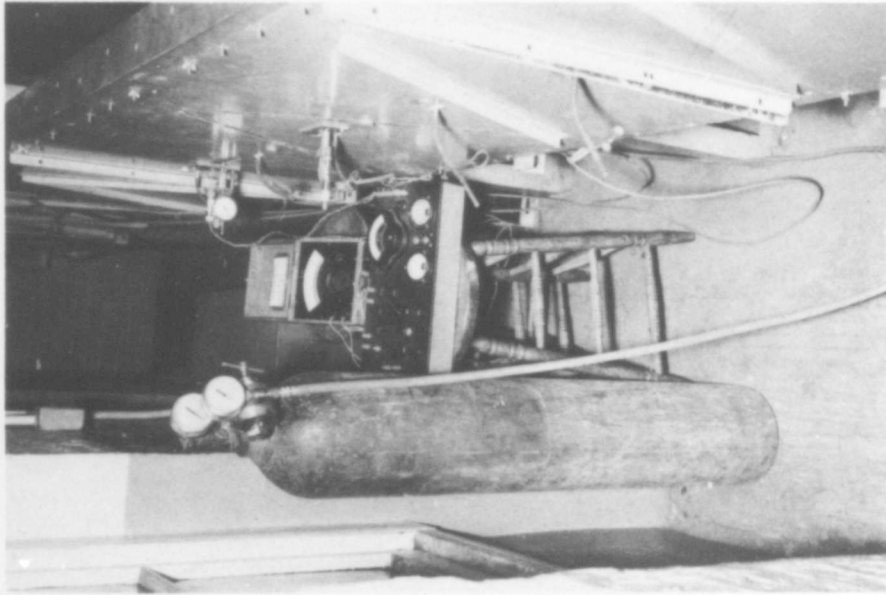


FIGURE 24

Turbulence channel experimental setup for determination of stability of laminar boundary layer over a porous flat plate with fluid injection.

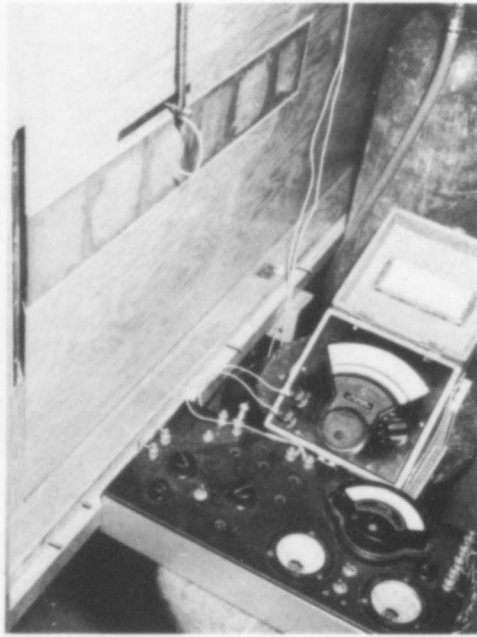


FIGURE 26

Detail of suction slot, porous flat plate, hot-wire anemometer (side-wall of turbulence channel removed) and electric equipment.

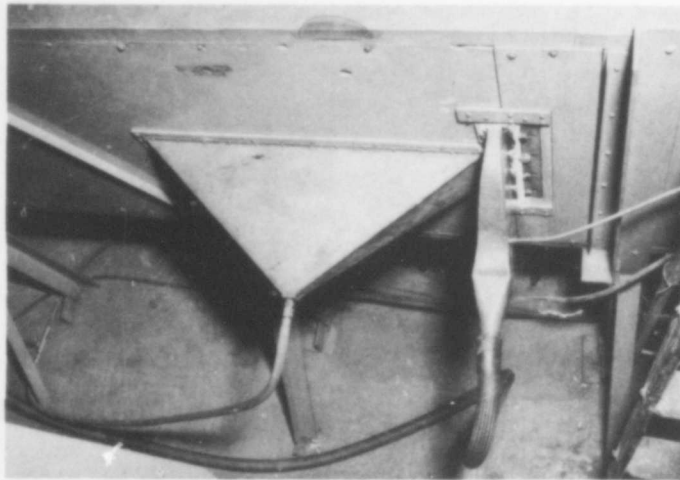


FIGURE 27

Detail of suction bell and compression chamber.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR 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 January 1949*

PHASE 2

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

Summary

All activities in this phase were transferred to the new Combustion Laboratory at the Purdue Airport where the facilities were designed for experimentally determining factors involved in continuous process combustion with emphasis on flame-holding. Other problems were studied on a limited scale. The investigation of flame stability and blow-off limits with an

annular-type of flame holder was extended to include mixture supply velocities in a low turbulence stream of Mach numbers up to unity. Some effort was made to create turbulence and to study its effect on parameters and limits established for mixture streams of low turbulence. Many modifications were made to hot-wire anemometer circuits to obtain suitable instrumentation for experimentally determining intensity of turbulence. Calculations were made of the thermodynamic properties of propane-air combustion products to permit determination of combustion efficiencies or the distance and/or volume required for attainment of a pre-selected combustion efficiency. A modified sodium line reversal technique employing a photographic method was developed for the determination of temperature gradients in a flame. Studies were also made of the temperature patterns in a turbulent burner, and a comparison was attempted with a non-turbulent burner.

Progress

Heat Release Requirements for Flame Holding in a High Velocity Stream. The determination of the heat release requirements for flame-holding developed from the study of the factors controlling the limiting velocity of a combustible mixture in a duct, above which combustion becomes unstable or flame blow-off occurs. Since the limiting velocity was believed to be appreciably affected by turbulence of the mixture, a contracting jet nozzle was used to eliminate this variable as far as possible by damping the turbulence in the nozzle upstream of the flame front. It was found possible to obtain stable combustion with or without the flame confined by a chamber as long as a stable secondary or pilot flame was maintained to serve as a flame holder for the main stream. Overall stability in the mainstream could be maintained over wide ranges of stream velocity and mixture strength, as long as stable burning existed in the secondary flame-holding mixture. Although mixture strengths in the main stream were outside the normal flame propagation ranges established for the particular fuel used, combustion was satisfactory if certain definite conditions were maintained in the flame holder. Fixed limits of mixture strength and rate of flow were found to be necessary for the flame-holding mixture to compensate for heat transfer and diffusion effects between the annulus mixture and the surrounding atmosphere. The experimental results indicated that less than 3 per cent of the total mixture was required for flame-holding under difficult conditions wherein excessive heat losses to the atmosphere occurred with unconfined burning.

There is apparently a very close relation existing between combustion stability and rate of heat release from the flame-holding mixture. Since minor modifications of the burner affect the introduction of the flame-holding mixture into the main stream, which alters appreciably the rate of heat release required, experiments were conducted to determine the design configurations required for an ideal burner. The ultimate objective was the fabrication of a two-

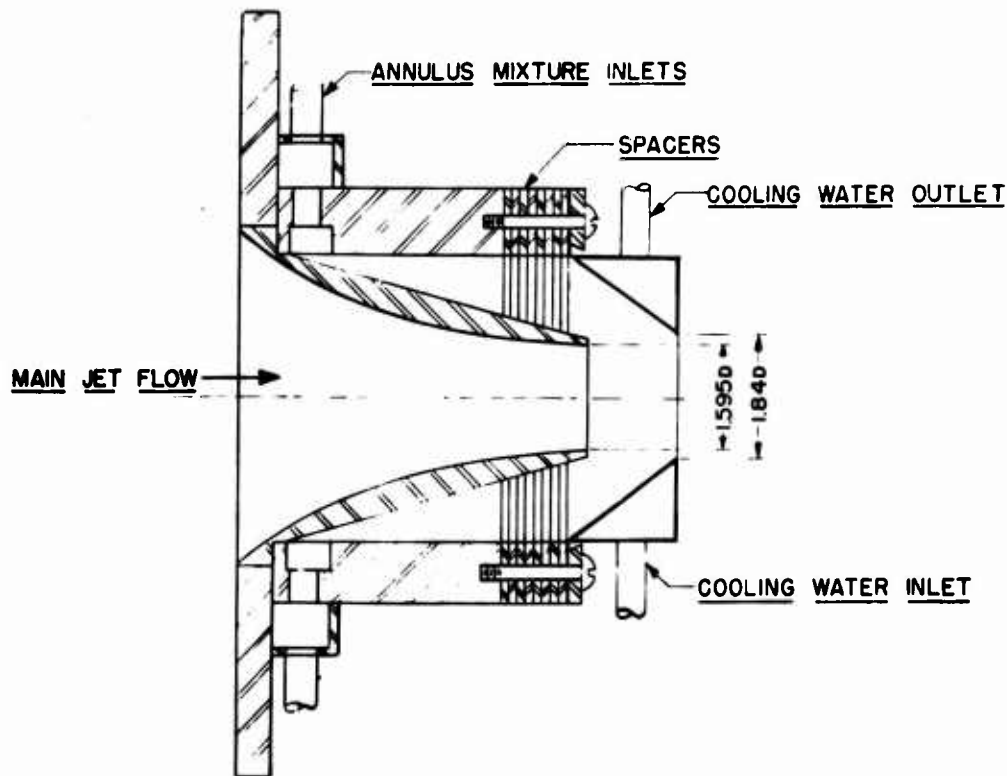


FIGURE 1

Variable Annulus flame-holder

dimensional, adjustable area, low-turbulence burner in which heated inert gases could be introduced in place of the burning flame-holding mixture. The experimental version, as adapted to the present burner, is shown in Figure 1. The principal modification of the burner, shown in the last Project SQUID Annual Program Report (1), consists of a water-jacketed contractor for the annulus flame-holding mixture which deflects the flame toward the main jet. By means of the spacers shown, the length of the hypothetical geometric interface between the annulus and the main jet streams can be altered. The experiments showed that the minimum heat release required of the annulus occurred with the minimum interface length. This is shown in Figure 2, page 56. These values were approximately one-third those required without confining the annulus flame where only a portion of the annulus flame could be expected to contact the main jet.

With the flame front appearing in the form of a cone, as in a Bunsen-type burner flame, it was possible to calculate the normal flame propagation velocity using any of several well known methods. The one selected for this study required a time exposure of a sensitized photographic plate and a measurement of the angle formed by the sides of the conical flame front. The normal flame propagation velocity was assumed to be equal to the product of the velocity of the unburned mixture and the sine of the angle formed between the mixture stream-lines and

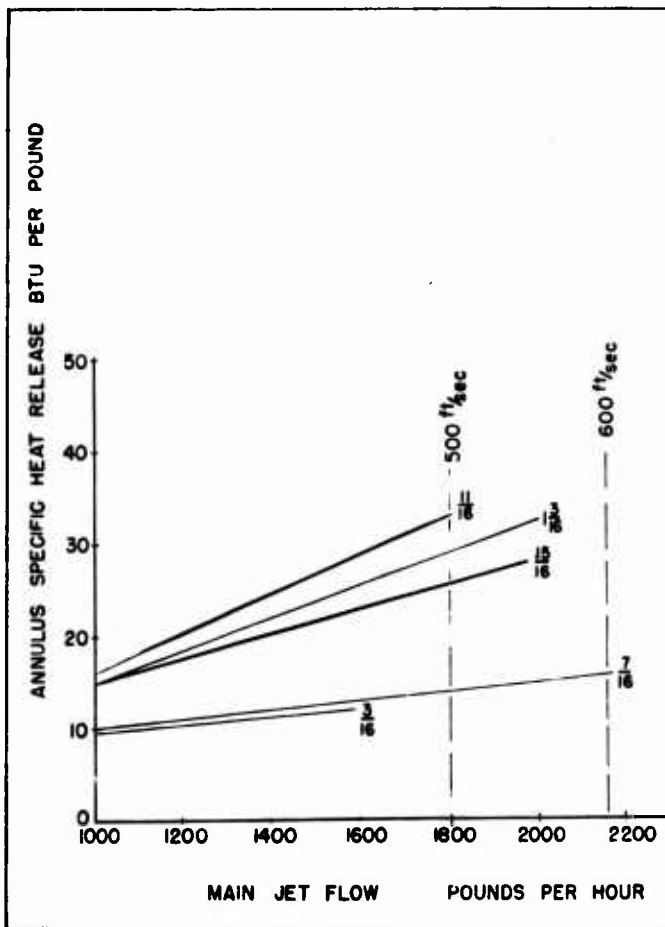


FIGURE 2

Annulus specific heat release for stability limits of main jet flow.

square velocity fluctuation due to turbulence, and \bar{V} is the mean gas velocity, were not determined. Relative differences, as indicated by a hot-wire anemometer, were observed in both the small Bunsen-type burner and in the intermediate size contracting-jet burner.

In the small burner, turbulence was created with a rotating rod in the axis of the burner. The magnitude of the axial velocity fluctuations due to turbulence was found to shift from the center of the burner toward the wall of the burner as rod roughness was increased. This effect was probably due to increasing vorticity of the stream. In any case, the flame velocity apparently increased, as evidenced by a change in area of the flame front determined spectroscopically and photographically.

In the medium-size burner, velocity and turbulence traverses were made. For mixture stream supply velocities in the main jet up to 1000 feet per second, the velocity pattern was constant across the jet. This velocity determination was obtained by means of a 0.028 inch diameter probe. Velocity traverses in planes normal to the stream axis and at selected in-

the flame front. An unusual relation was found to exist between mixture, supply velocity and the observed flame propagation velocity. The following empirical relation between the velocity limits studied was obtained:

$$S \sim V^{0.43}$$

where S = flame propagation velocity
 V = average mixture velocity.

This relation is shown in Figure 3. By extrapolation to the mixture velocities of small Bunsen burners, the flame velocities correspond quite closely to the measured values determined by numerous investigators.

Effect of Turbulence on Combustion.

The experimental determination of the effect of turbulence on combustion was delayed by inadequacy of the instrumentation being developed. Exact values of turbulence intensity, expressed as $\frac{\sqrt{(\bar{u})^2}}{\bar{V}}$, where $\sqrt{(\bar{u})^2}$ is the root-mean

crements of distance downstream from the lip of the nozzle showed velocity gradients increasing with an increase in the velocity through the nozzle. These gradients refer to the increments of velocity change with respect to unit change (radially) in axial position of the velocity probe. This change in gradient with velocity may be responsible for the change in flame velocity with jet velocity considered above.

The turbulence within the region of constant velocity, downstream from the lip of the nozzle (equal to the velocity in the minimum section of the nozzle), was of very low intensity as referred to relatively quiescent conditions in the room. The instrument indicated a very small increase in intensity with increasing jet velocity up to a Mach number of about 0.7. Further increase in velocity showed a reduction in turbulence intensity.

Very brief experimentation was conducted with a perforated disc turbulence-creator in combination with the contracting jet burner. This device was constructed to permit rapid removal for quick evaluation of the effects. These tests showed rather definite indications of greater specific heat release requirements from the annulus for stable combustion in the burner. The inference might be made that increased turbulence requires greater heat release for stable combustion.

Flame Temperature Patterns by Partial and Total Flame Coloration Using a Modified Sodium Line Reversal and Photographic Process. Experimentation with a modified adaptation (2) of the Fery method for line reversal determination of flame temperatures was conducted to determine possible empirical relationships between a partially and a totally colored flame using metallic salts for coloration. This method was developed to the point where it could be evaluated as to its limitations and potentialities. As a result of this work, it was deemed desirable to analyze the effect of the variation of salt concentration upon the indicated temperature of a flame. This analysis was made in terms of the Einstein emission and absorption coeffi-

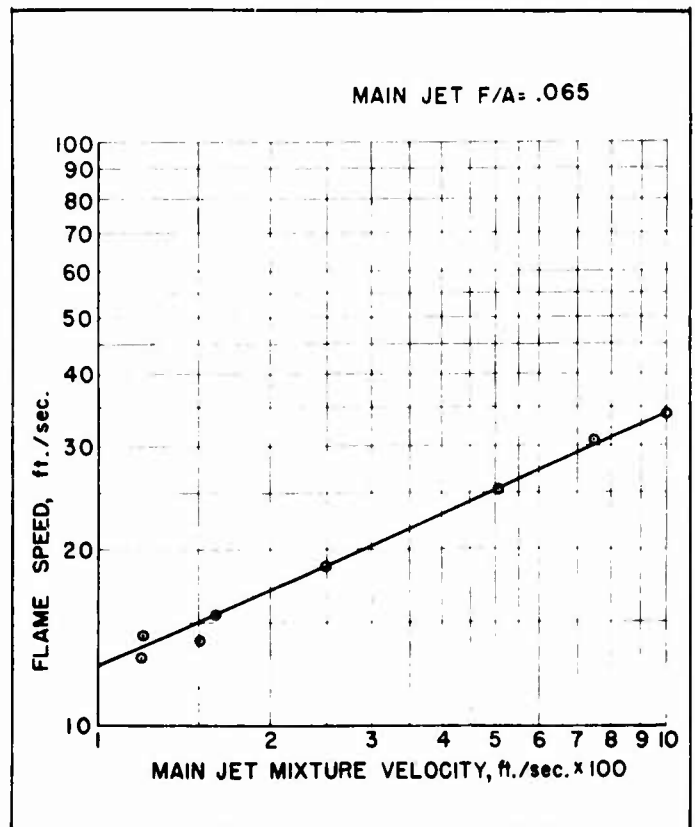


FIGURE 3

Flame propagation velocities of a propane-air mixture flowing at various speeds.

icients. An equation was developed and applied to experimental data with fair agreement. This work indicates the error of using totally colored flames for determining temperatures of the flame where thermal equilibrium does not exist. The assumption cannot be made that the temperature so obtained is the maximum or average for the particular flame.

Determination of Point Temperatures in Turbulent Flames Using Sodium Line Reversal Method.

In an endeavor to obtain suitable methods for evaluating the effect of turbulence on combustion, a modification of technique developed above was applied to temperature determinations and comparisons under turbulent and non-turbulent conditions. Because of the necessity of maintaining identical conditions for protracted periods, with the exception of the degree of turbulence, and also because of the necessity for positioning accuracy, the procedure has not been developed to the point where conclusions can be drawn.

Thermodynamic Properties of Propane-Air Flames. To permit a rational evaluation of the effects of changes in variables entering into the flame-holding function, a standard of comparison was selected. This standard was based on a consideration in the design of combustion chambers for obtaining as small a chamber as possible for a given rate of energy release. In special cases, consideration of factors, other than volume, such as the L^* value (or ratio of chamber volume to exit area) of rockets is of prime importance.

The term *volume effectiveness* has been selected to express the volume required to obtain a certain efficiency of combustion which may be pre-selected for a standard. This term is intended solely for use in a given configuration of combustion chamber wherein it is desired to investigate the effects of such factors as turbulence intensity on the volume required for completion of combustion to a certain percent of the theoretical heat capable of being released under existing conditions. No use has been made of this term because to do so would require the determination of the envelope of constant efficiency points. A number of means have been considered. These include direct temperature or pressure measurement and product gas sampling or spectroscopic analysis of the flames. An approximation, based on end of gas luminescence, could be used. In order that any of the methods mentioned may be used, the thermodynamic properties must be known.

The composition of the product gases from the combustion of propane and air at one atmosphere pressure has been computed at fuel-air ratios from 0.02 to 0.12 and at 1800°R., 3240°R., and the maximum flame temperature. These are shown in Figures 4, 5, and 6. The products considered are nitrogen, water vapor, carbon dioxide, carbon monoxide, oxygen, hydrogen, the hydroxyl radical, nitric oxide, and atomic hydrogen; and the composition was computed by using the equilibrium constants of Lewis and Von Elbe (3).

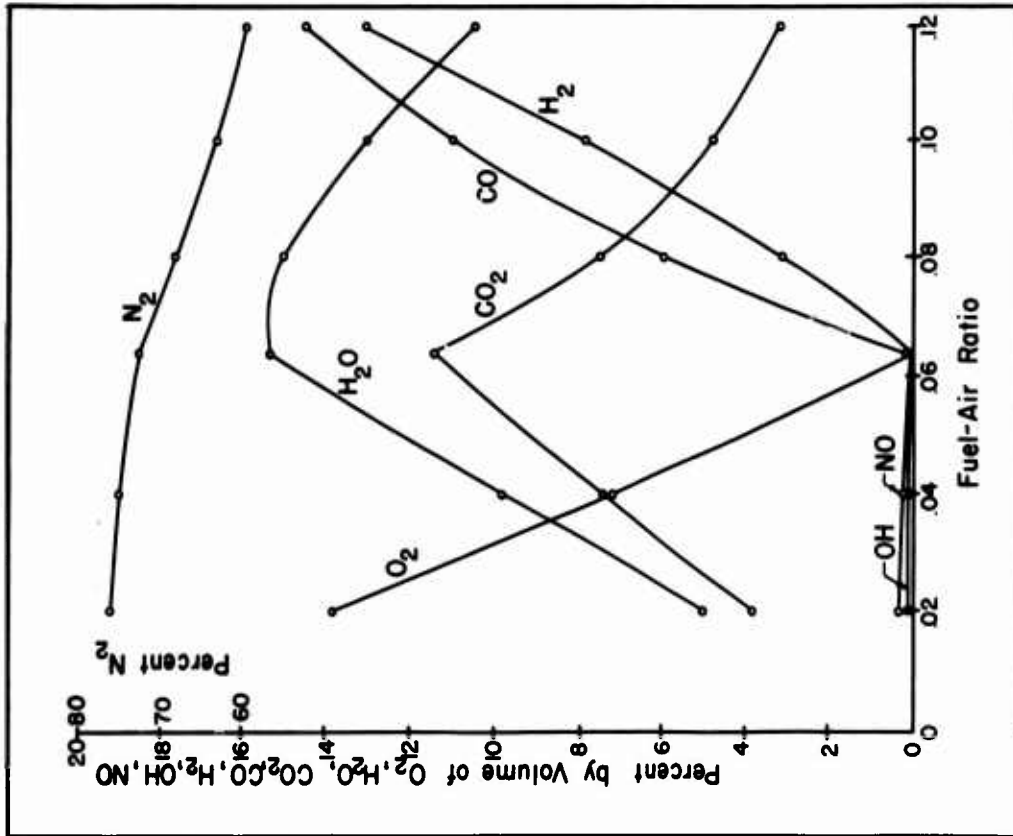


FIGURE 4

Products of combustion of propane and air at 1800°R. and one atmosphere.

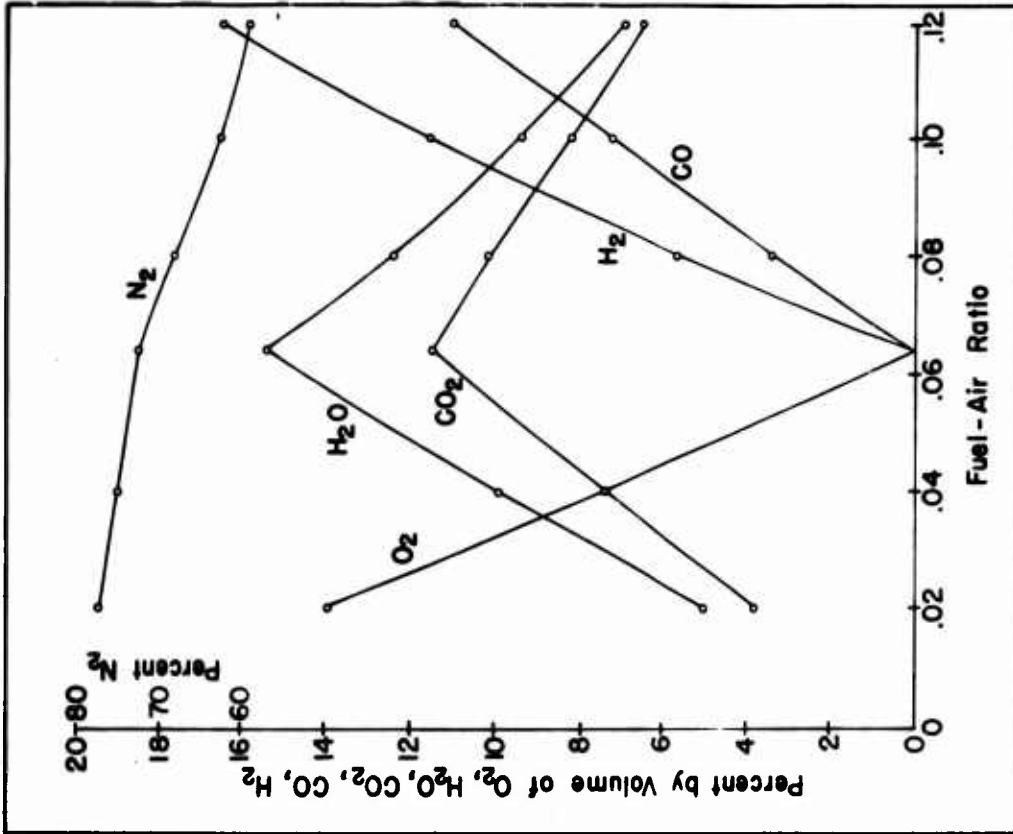


FIGURE 5

Products of combustion of propane and air at 3240°R. and one atmosphere.

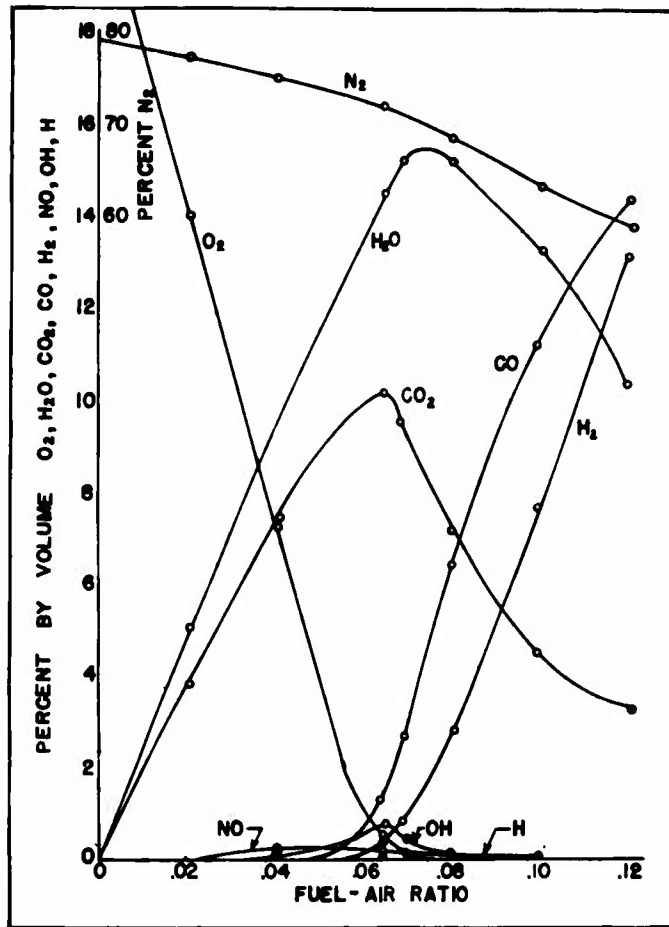


FIGURE 6

Products of propane and air at maximum flame temperature and one atmosphere.

By setting up a heat balance between the unburned mixture and the various product gas compositions, the heat release at maximum flame temperatures and the heat content of the product gases at 3240° R. and 1800° R. have also been computed. The heat content is defined as the amount of heat required to raise the product gases from the inlet temperature (610° R.) to the temperature in question. The heat release is the amount of heat required to raise the product gases to maximum flame temperature (or the lower heating value of the mixture). These values are shown in Figure 7. All values in this figure are referred to 18° C.

Figure 8 shows the heat release at maximum flame temperature expressed in B.T.U. per pound of mixture.

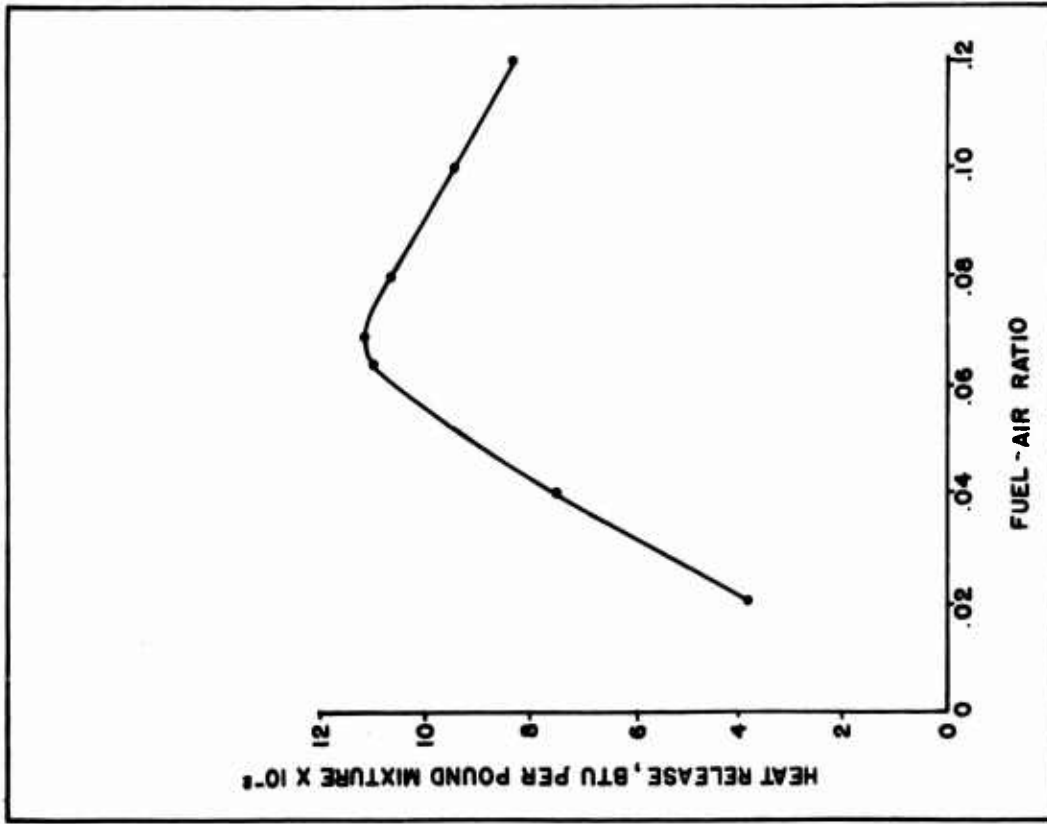


FIGURE 8

Heat release at maximum flame temperature in B.T.U. per pound of mixture.

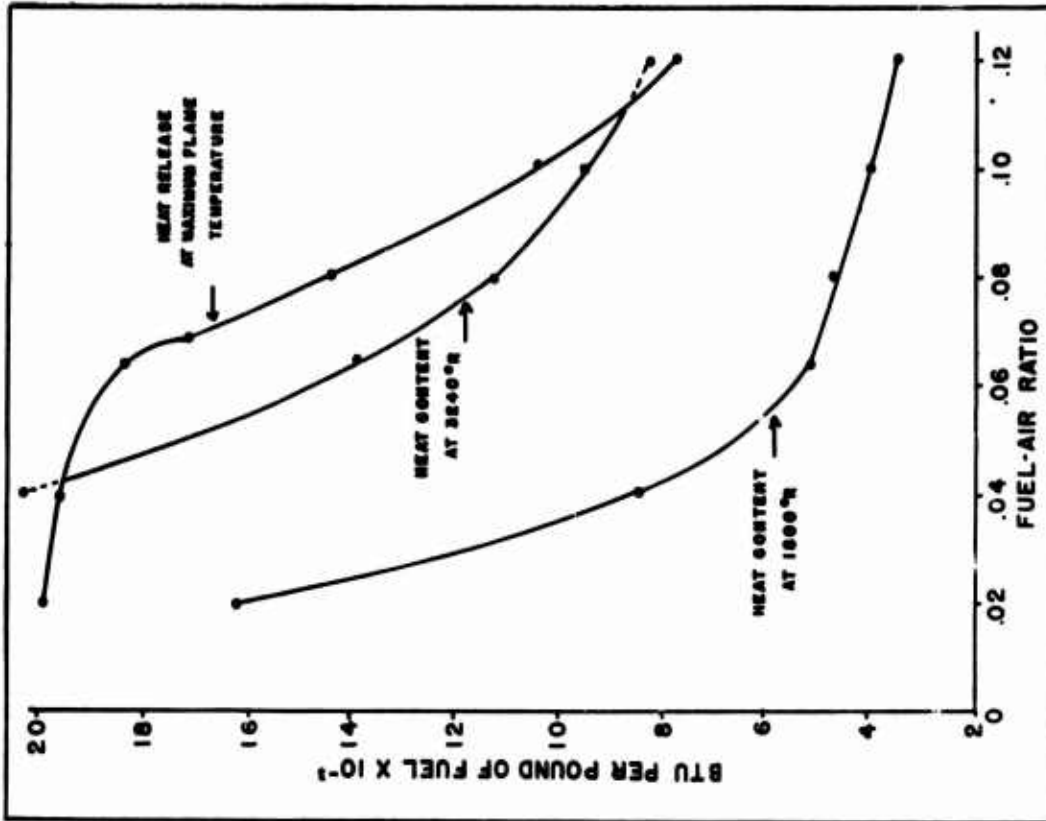


FIGURE 7

Heat release and heat content of product gases for constant pressure combustion of propane and air.

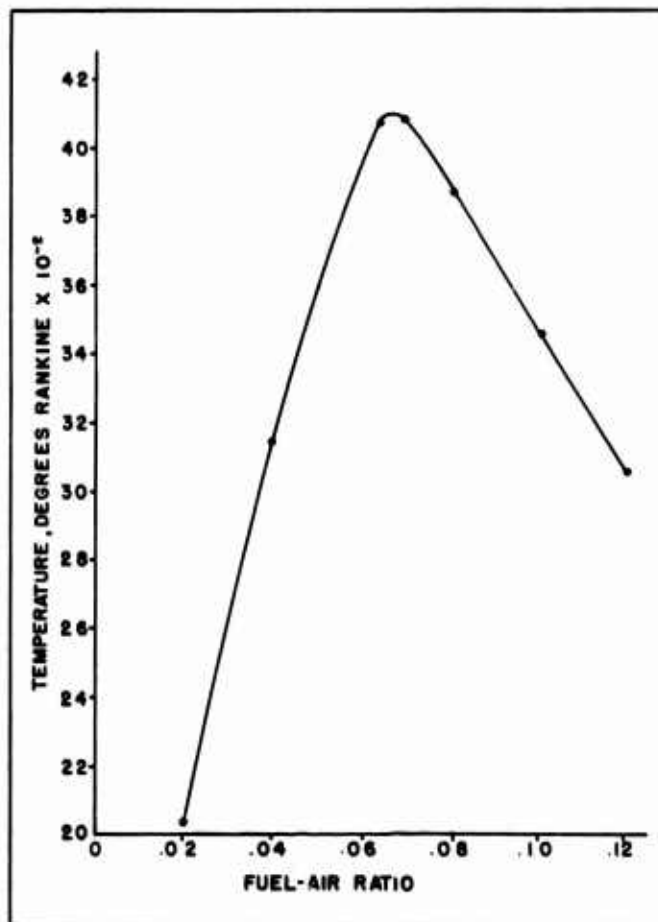


FIGURE 9

Maximum flame temperatures for constant pressure combustion of propane and air.

Knowing the heat release at maximum flame temperature and the product gas composition (and thus, the mean specific heat), one could compute the maximum flame temperature for the various fuel-air ratios. These are shown in Figure 9.

With the information gathered so far, it is now possible to present a thermal picture of the combustion process by considering a small unit of unburned mixture approaching the flame front and passing through it. This is illustrated in Figure 10 for the stoichiometric fuel-air ratio. Here the horizontal axes represent an as yet unknown time scale, which necessarily must be determined experimentally if the picture is to be quantitatively useful.

This unit of unburned mixture leaves the burner port at time zero and proceeds to the right in Figure 10. As it reaches the theoretical flame front (A), it is assumed to burn instantly to equilibrium at the maximum flame temperature (4070° R.), releasing 18,310 B.T.U.

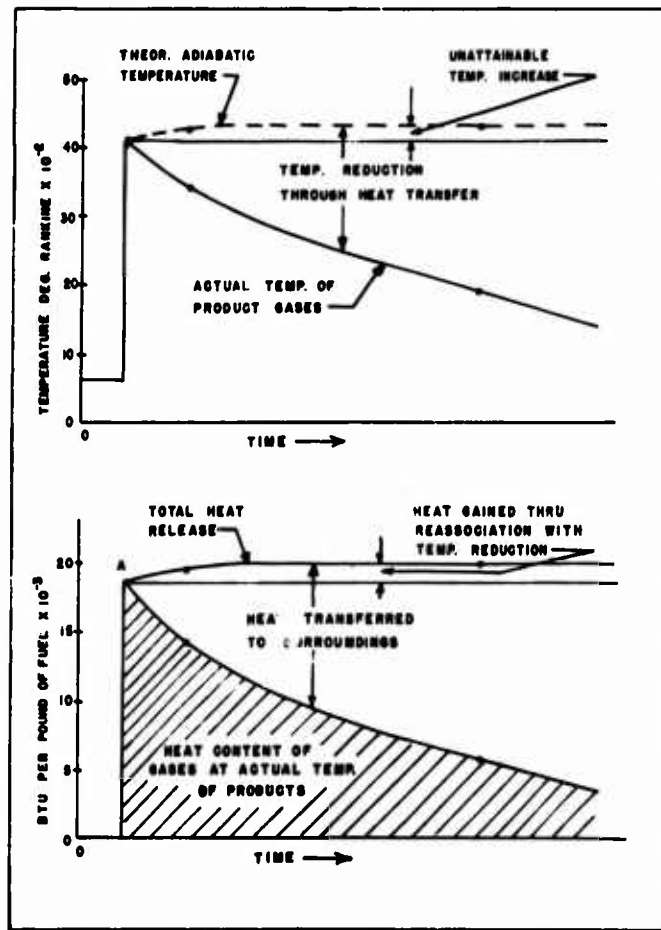


FIGURE 10

Theoretical constant pressure combustion of propane and air at the stoichiometric fuel-air ratio.

per pound of fuel. Continuing through the flame front, the unit, now consisting of burned gases, cools as heat is transferred to the surroundings. The cooling process, however, allows reassociation to occur, and as the temperature and heat content of the product gases decrease, the total heat release continues to increase until the full heating value of the fuel (19,800 B.T.U. per pound) is realized.

The theoretical adiabatic temperature in Figure 10 represents the temperature which would have been attained if the total heat release were all effective in raising the temperature with no heat transfer and no dissociation. This temperature, of course, is physically unattainable.

Diagrams of the type appearing in Figure 10, although they represent ideal conditions, would seem to provide a very interesting comparison with conditions along a flow line in

actual flames. It is intended to make such comparisons in the future.

Spectroscopic Studies of Laminar and Turbulent Flames. To obtain additional information on the effect of turbulence on combustion, a study was started of the spectra of small burner flames. These preliminary investigations of the differences in the spectra of laminar and turbulent Bunsen flames have been made with a Hilger medium quartz spectrograph. The small rotating-rod burner was used in this study in order that turbulence might be produced at will.

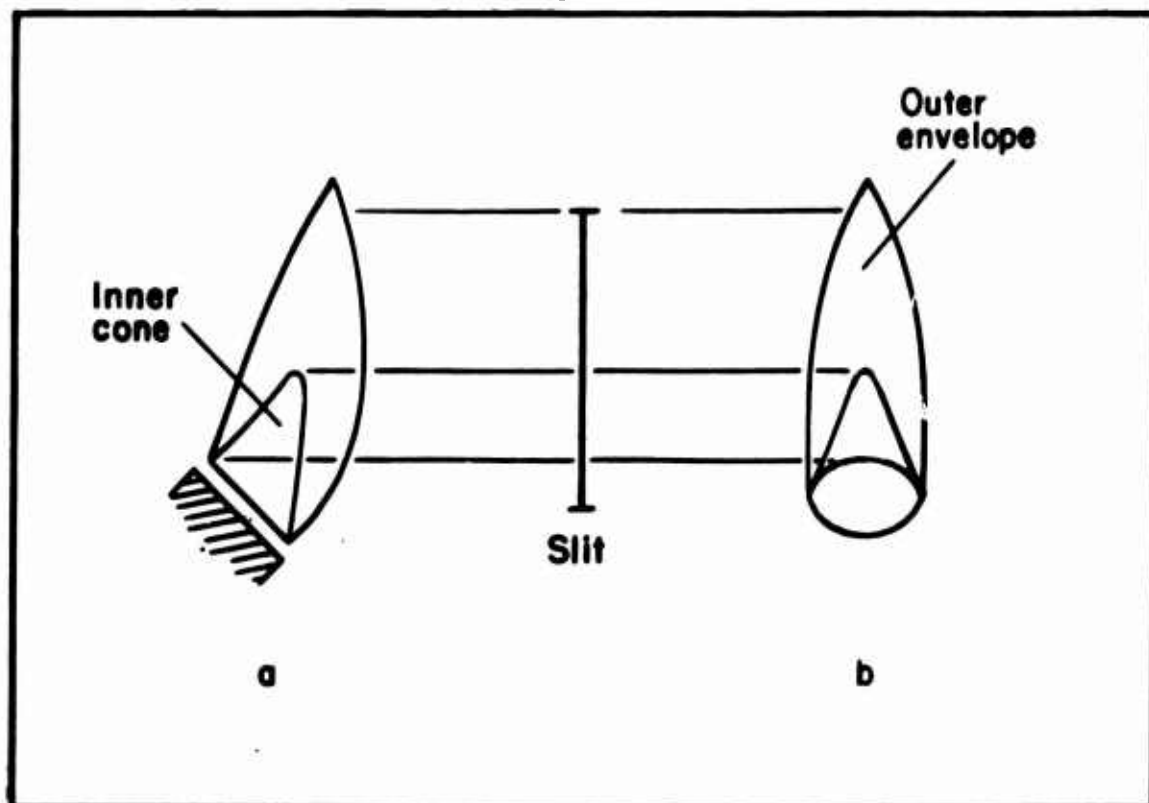


FIGURE 11

Position of flame for spectroscopic investigation of laminar and turbulent flame spectra.

The flame was viewed as shown in Figure 11. The side view is 11a, and the flame as seen by the spectrograph slit is 11b. The fuel was illuminating gas.

Figure 12 is a typical photograph of the laminar (top) and turbulent (bottom) flame spectra taken on a Kodak No. 40 plate with 40 minute exposures. Conditions of fuel-air ratio, mass-flow, position with respect to the spectrograph, and spectrograph adjustments were all

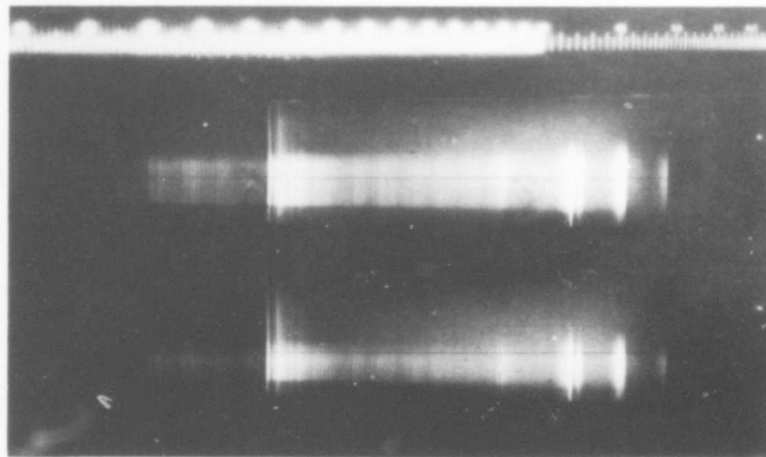


FIGURE 12

Comparison of laminar (top) and turbulent (bottom) flame spectra.

identical in the two spectra. The only difference was that the turbulence rod was rotating during the second exposure and not during the first.

Comparing the spectra of Figure 12, the following bands may be easily identified: (1) in the flame fronts, OH - 2811, 2064 Å, CH - 3900, 4312 Å, C₂ - 4382, 4737, 5165 Å; (2) in the outer envelope, OH - 3064 Å; and the continuous CO₂ radiation particularly strong in the region 3800 - 5000 Å.

The Kodak No. 40 plates had a rather high background density which made densitometer surveys difficult. However, a densitometer constructed by Dr. T. DeVries, of the Department of Chemistry, Purdue University, was used to read the densities of the principal lines in each band system. Background corrections were made as well as possible, and the line densities were converted to relative intensities by means of a plate calibration taken with a step sector.

The results showed no appreciable difference between the spectra of laminar and turbulent flame fronts. The differences were all within the experimental error. However, in the case of CO₂ radiation in the outer envelope, a decrease in intensity was noted for the turbulent flame which appears greater than the experimental error.

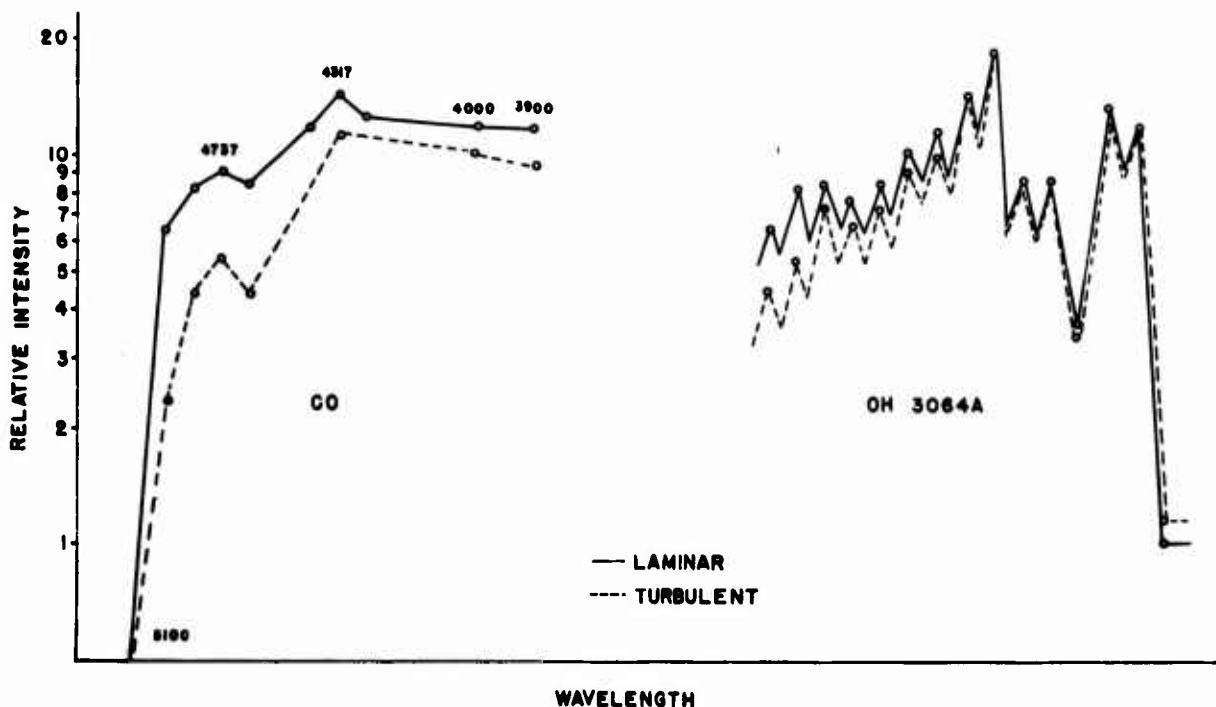


FIGURE 13

Comparison of spectra for laminar and turbulent flames. (Outer envelope just above cone.)

Figure 13 shows a typical intensity distribution found in the outer envelope of this flame. The vertical axis here represents *intensity of radiation* on a logarithmic scale, and the horizontal axis is a non-uniform scale of wave length. The circles represent observed intensities (at the wave length noted by the curves). Figure 13 is typical of distributions found throughout the outer envelope.

It must be noted that the study of the differences in laminar and turbulent flame spectra described here has been cursory in nature. The problem has been discontinued with no attempt to verify the conclusions which were indicated. It may be mentioned that the principal requirements for a more accurate study would be: (1) a more accurate densitometer; and (2) a more suitable photographic emulsion, principally one with less background.

Plans

It is intended to press actively the flame-holding experiments with early use of a two-dimensional burner now being designed. Adjustable nozzle segments are being considered to retain all of the advantages of a contracting jet with its low turbulence. The largest opening

of the throat of the jet will provide for more complete utilization of the great capacity of the air supply system. This will permit a better evaluation of the requirements of flame-holding in large size combustion chambers and will make it possible to study more accurately the effects of other variables which can only be estimated in small scale burners.

It is intended to introduce heated inert gases to determine whether flame-holding can be simplified to a single consideration of heat release. This is of considerable importance where it may be desirable to utilize a different fuel and oxidizer combination in the flame-holding stream from that of the main stream.

The studies of turbulence will be continued as soon as a hot-wire anemometer is developed to the point where it may be used with a reasonable degree of accuracy in the high velocity mixture streams with which a large portion of the researches of Phase 2 is associated. A good background has been developed for this investigation, and intensive development of hot-wire anemometers is being pressed at Purdue University.

The work on temperature determination with sodium line reversal technique will be restricted to the determination of point temperatures. All work accomplished to date on flame temperature patterns will be reported in a technical memorandum in the near future.

PHASE 3

To undertake the study of corrosion in connection with jet propulsion devices. The purpose of the research is to identify the corrosion products, and to investigate the process of corrosion as affected by the chemical and physical properties of the materials and the conditions of exposure.

Summary

The high temperature oxidation products formed in oxygen and in air on chromium steels ranging from 5 to 26 percent chromium content have been analyzed by X-ray diffraction. A quite regular variation of the phases present can be correlated with change in oxidation resistance. Identification of the oxide formed on several nickel-chromium steels over a limited range of temperatures has been completed.

The structure, formation, and growth of thin oxide films on chrome-iron and steels have been studied using electron diffraction and electron microscope methods.

Progress

With the general goal of elucidating the mechanism of high temperature oxidation resistance and the role of alloying elements in developing this resistance, a number of X-ray diffraction, electron diffraction, and electron microscope studies of oxide formation have been made. In order to simplify the interpretation of results, most of the work has been confined to the oxidation of chromium steels in pure oxygen and in air. A limited amount of work has been done on nickel-chromium steels oxidized in air.

X-ray diffraction has been used to identify the oxides formed on a series of chrome-steels of nominal 5, 11, 13, 17 and 26 percent chromium content when oxidized in pure dry oxygen of one atmosphere pressure at temperatures of 775, 825, 900, and 950° C. for 20 hours and at 1000° C. for 10 hours.

The samples were polished through 3/0 paper, vapor degreased, and oxidized in a quartz tube, a nichrome-wound furnace, regulated to $\pm 3^\circ\text{C}$. Tank oxygen passed through a copper oxide catalyst, *Askarite* and *Dryrite* was used. Diffraction patterns were taken with both back-reflection and Debye-Scherrer cameras using $\text{CrK}\alpha$ radiation. With the former technique, the pattern was taken with the oxide in place or in the form of flakes. In the second method, specimens were made by grinding samples scraped or chipped from the surface. In the case of the oxides formed on the lower chrome alloys at the higher temperatures, a rough separation of different layers was sometimes possible, so that these could be examined separately, but with the higher chrome alloys and at the lower temperatures, only total oxide samples could be obtained. In the latter case, the oxide usually consisted of a somewhat powdery scale, dark grey to black in color, which separated easily from a temper-color film on the metal. This film was too thin to be collected as a separate sample or to contribute appreciably to the X-ray pattern when included in the total sample. Electron diffraction investigations of these and other thin films will be described.

The structure found in repeated runs at each temperature is summarized in Table I. In this and the tables to follow, the symbol \cup indicates an Fe_3O_4 (spinel) structure type is present and X an α Fe_2O_3 (hematite) structure type. The number, if any, following this symbol indicates the percentage of the corresponding chromium oxide, FeCr_2O_4 or Cr_2O_3 respectively, in solid solution, as determined from the lattice parameters observed. Instead of X_{100} for pure Cr_2O_3 , the symbol XC is used for convenience. (Limitations encountered in determin-

TABLE I

STRUCTURES FORMED ON CHROME-STEELS IN ONE ATMOSPHERE OF DRY OXYGEN DURING 20 HOURS AT 775°C., 825°C., 950°C., AND DURING 10 HOURS AT 1000°C.

O = Fe₃O₄ Spinel type, a = 8.38 Å.
 O* = Fe₃O₄ Spinel type, a = 8.41 Å
 X = αFe₂O₃ Hematite type
 Xc = Cr₂O₃
 Xn = Fe₂O₃ Hematite type with n% Cr₂O₃ in solution
 () = sometimes found

s, m, w, vw = strong, medium, weak, very weak pattern
 C = probably Cr₃C₂
 +, u, u' = weak unidentified patterns
 Top, middle and bottom positions correspond to samples of outside, total, and inside scale, respectively.

Temp °C	Cr, %	5	11	13	17	26
775		C O-w, X-s	X-s, Xc-w	X-s Xc-m	X-ms, Xc-s	O*-w, X-w, Xc-s
825		O-w, X-s, C O-s, X-s O-s, X-s(m)	X-s, Xc-w X-s, Xc-mw	O-m, Xc-s, (X)	X-s, Xc-m	O*-w, X-vw, Xc-s
900		C O-m, X-s O-m, X-s	X-m, (Xc ?)	X O-m, X-s, (Xc-s) X	(O), X, (Xc-w) Xc, (X)	(O*), X-s, Xc-w
950		O-s, X-s, C O-s, X-s	C O-s, X-m	C O-m, X-s	O-m, X-s	O*-s, X75-s O*-s, Xc-s
1000		O-s, X-m, C, + O-s, X-m, +	O-s, X-m, C O-s, ++	O-s, X-w, C O-s, X-w	O-s, Xs O? X	O*-s, Xc-s

ing the degree of solid solution will be discussed later.) Where more than one phase is found in a given sample, the corresponding symbols are placed in horizontal rows and their relative amounts, as judged by the strong, medium, weak, or very weak intensity of their diffraction patterns, are shown by the letters S, m, w, or vw, following the type symbol. The vertical position of the symbols in the table box denotes the manner in which the sample was taken. The top of the box is associated with a sample taken from the outside of the scale, the middle with a total oxide sample (except as noted), and the bottom with a sample of the oxide next to the metal.

The symbol C indicates the presence of an additional structure which is found chiefly on the oxide surface. Auxiliary diffraction patterns with a Phillips recording spectrometer give one strong peak corresponding to a crystallographic spacing of $2.30\overset{\circ}{\text{A}}$, with no others evident. Grazing incidence photographs show the reason for this. The material is very highly oriented with a plane of $2.30\overset{\circ}{\text{A}}$ spacing parallel to the specimen surface. Measurements of this pattern are in good agreement with the structure of Cr_3C_2 . This is rather surprising since the material is most prevalent on the 5 percent chrome alloy and becomes evident on the 11 and 13 percent alloys at the higher temperatures. The source of carbon for its formation has not been completely determined; improved purification of the oxygen supply reduced the amount of this phase but did not eliminate it. Traces of CO or CO_2 may still be present, or the carbon may diffuse outward from the metal. The symbol + refers to the presence of two or three unidentified weak lines and, in the later tables, u or u' refers to more extensive unidentified patterns.

Table II shows the structures formed on these alloys in oxygen at 900°C . as a function of oxidation time, and Table III does the same for exposure to laboratory air.

Referring to these summarized results, and particularly to Table I, the most obvious effect of the chromium is to suppress the formation of FeO, even on the 5 percent alloy. This may be one of the chief functions of the chromium; it is not sufficient, however, since one must account for the great range of resistance to attack produced by varying the chromium content. If the protection is due in any way to the bulk oxide investigated, one must expect to establish a correlation between the structures found and the known changes in oxidation resistance.

The resistance to oxidation quite generally decreases as the chromium content of the alloy is diminished and as the temperature is increased. One thus expects to find a correlation of oxide type with position along the diagonal of Table I from upper right to lower left, this being the direction of decreasing resistance. The X structure, essentially pure $\alpha\text{Fe}_2\text{O}_3$, occurs in all parts of the table and is not, therefore, of primary importance. The O^* structure, which is the only spinel type found on the 26 percent alloy, is essentially different from the O

TABLE II

STRUCTURES FORMED ON CHROME-STEELS
OXIDIZED IN ONE ATMOSPHERE OF OXYGEN
AT 900°C. FOR VARIOUS TIMES.

Cr % Time hrs	5	13	17	26
5	C O-s, X-s O-s, X-s	X-s, Xc-m (O-m), X-s, Xc-m X-s, Xc-s	X-s, X25-w	X-m, Xc-s
20	C, u O-w, X-s	X O-m, (Xc-s), (X-s)	(O) X-s, (Xc-w) Xc (X)	(O*), X-s, Xc-w
100	C,X O-w, X-s O-w, X-s, (Xc)	X X-m, Xc-w X	X	X-s, X75-w [X-s, X75-w (O*), (X25), (Xc)]

structure in its lattice parameter and presumably different in its properties, so that the two should not be considered in the same category. Disregarding the O* phase, therefore, both O and Xc (together with the closely related high chrome Xn phases) show the expected correlation¹. The Xc phase occupies the field to the upper right and disappears on going downward to the left. Overlapping slightly with this field, the O phase appears and extends downward to the left. Thus one might attribute loss of oxidation resistance either to the disappearance of the Xc phase or to the appearance of the O phase. This transition region corresponds roughly to the composition-temperature contour which obtains for a rate of metal loss of 10 mg/cm²/day. This contour may be considered as marking the beginning of an excessive attack.

¹In preliminary reports of this work, the existence of Xc on the low chrome alloys at low temperatures had not been found, since in the earlier low temperature work only the back reflection method was used and the small amounts of this phase and the thinness of the oxide resulted in patterns too weak for its detection. More recently this work has been repeated using samples scraped from the surface and the Debye-Scherrer method, with the results shown in the table. Only after this completion of the table is the Xc correlation evident.

Which of the two processes is responsible for the onset of heavy attack cannot be determined from these data, since the fields of existence overlap. In order to see whether these relations change with changes in the overall thickness of the oxide layers, repeated runs were made at a fixed temperature and increasing times of exposure. The results are shown in Table II. At the 900°C. temperature used, the 5 percent alloy is non-protective, the 13 percent is in the critical region and the higher composition alloys are quite protective. In every case the rate of attack diminishes with increasing time. It is evident from the data shown in the table that over this range of time there is little change in the type of phases present. There are, however, definite indications that the Xc and other high chrome X phases become less prevalent with increasing time. This does not eliminate these structures as the possible seat of the protective mechanism, however, since it may only mean that they form a protective layer which does not grow in thickness as rapidly as does the X phase associated with them. There is little regularity in the variation of the O type phase.

TABLE III
STRUCTURES FORMED ON CHROME-STEELS
OXIDIZED IN AIR AT 900°C. FOR VARIOUS TIMES.

Cr % Hours	5	13	17	26
5	C O-m, X-m	X-s, Xc-s	O-w, X-m, Xc-s	O*-m, Xc-s
20	1. O-s, X-m, +, C 2. O-s, X-m 3. O-s, X-m,	O-w, X-s, +, C O-m, X-s, +	O-w, Xc-s	O*-s, Xc-s
100	1. O-s, X-w, u, C 2. O, u' 3. O, u'	C O-w, X-s O-vw, X-s	X X	O*-m, Xc-s

Note: Items 1, 2, 3 refer to an outside, middle and inner separable layer.

Table III presents the results of variable time experiments with air as the oxidant. The structures found are quite similar to those of Table II except that the O phase is noticeably more extensive. The fact that the 17 percent alloy is included in the O field, whereas at this temperature the alloy is quite resistant and certainly not less resistant than to one atmosphere

of oxygen, indicates that the mere presence of this phase is not necessarily detrimental. Thus, under conditions where the rate of attack is high, the O phase is found, but the converse is not necessarily true. In this connection it may be mentioned, that, in cases of abnormally rapid attack at specimen edges, imperfections, etc., abnormally large amounts of the O phase and abnormally small amounts of the Xc phase are found.

Additional experiments using reduced pressures of oxygen or partial pressures of oxygen in nitrogen, where the rate of attack is known to be less, may enable one to eliminate the O phase from consideration.

There is still the possibility that loss of corrosion resistance is associated with some change within the O phase not shown in these tables. It will be noted that two spinel types, O and O^* are found. Some of the patterns obtained have not yet been evaluated with sufficient accuracy for high precision determination of the lattice parameters, but they certainly fall into two groups in the neighborhood of $a = 8.38$ and 8.41 \AA for O and O^* respectively. One expects to find a decrease in the value of a with increasing substitution of Cr^{+++} for Fe^{+++} in going from Fe_3O_4 to FeCr_2O_4 , but the interpretation of the above values is not clear because of an apparent discrepancy in the published parameter for pure Fe_3O_4 . What appear to be equally reliable values range from 8.375 to 8.417 \AA . This seems too large a range to be due to experimental errors but, in all probability, is associated with a real difference in structure of some kind. The parameter values quoted for FeCr_2O_4 lie between 8.34 and 8.35 \AA . Thus, a change in structure which would increase the Fe_3O_4 parameter could very well compensate for the decrease due to solution of chromium. In this way the physical properties might be altered considerably without appreciable change in the parameter measured. There seem to be two alternatives for the compensation. The masking effect could be due to variations from stoichiometric composition of the oxide or to a rearrangement of the metal ions within the crystal lattice. Fe_3O_4 is known to be of the so-called *inverted* type of spinel, wherein half of the Fe^{+++} ions occupy the positions at which one would expect to find Fe^{++} ions. It may be that the presence of Cr^{+++} induces the normal form, and this may be more protective than the inverted form. The electrical resistance would almost certainly be increased, and according to the theories of the protective mechanism (4), this is beneficial. A literature search on these points is in progress.

An X-ray investigation of the oxides formed on a series of nickel-chromium steels has been undertaken and a limited set of data obtained. These samples (kindly supplied by Mr. Howard S. Avery, American Brake Shoe Company) are selected members of a large group for which extensive studies of high temperature mechanical properties and oxidation resistance have been published (5). The exposure conditions duplicate the latter tests, namely: exposure for 100 hours at temperatures of 1600 , 1800 , 2000 and 2200°F . in air saturated with water at a temperature of 90°F . The preheated air is supplied at a rate of 200 cc./min .

TABLE IV

OXIDE STRUCTURES FORMED ON NICKEL-CHROME STEELS
IN MOIST AIR FOR 100 HOURS
AT TEMPERATURES OF 2000°F. AND 2200°F.

Cr, %		10-11	15-16	21	25-26
Ni, %	Ni, %				
8	2000°F			O-w, X20-s, Xc-m	
	2200°F				
11-12	2000°F				O'-m, X25-s, Xc-vw O'-w, X25-s, Xc-m
	2200°F				O'-m, X25-m, Xc-s
19-20	2000°F				O'-m, Xc-s
	2200°F				O''-vw, Xc-s, (?)
35-36	2000°F		O'-s, Xc-m Xc, (?)		
	2200°F		O''-s, Xc-w, (?)		
63	2000°F	O', (?) Xc, (?)			
	2200°F	O''-m, Xc-s O''-w, Xc-s, (?)			

The oxides formed at the two lower temperatures were examined in place with a Wyland focusing camera, but they were too thin to give adequately strong patterns by this method. Samples of oxide were obtained at the two higher temperatures by scraping the ingots and were examined by the Debye-Scherrer method. The preliminary results are shown in Table IV.

Two types of samples are represented. The bulk of the scale frequently could be flaked off as one sample, and the remaining material next the metal could be scraped off to give a second sample. The data for the scale is entered in the table above that for the scraped sample. A single entry indicates the total oxide was taken. The result for the 2000°F. run is given in the upper half of each box and for the 2200°F. run in the lower half.

The spinels which were found can be divided into three groups according to their lattice parameter. These are designated by: 0 ($a = 8.38 \text{ \AA}$); 0' ($a = 8.35 \text{ \AA}$); and 0'' ($a < 8.35 \text{ \AA}$). The possible structures and interpretation of patterns is much more involved than in the iron-chromium case since spinels may be formed between Fe-Cr, Ni-Fe, Ni-Cr, and Ni-Fe-Cr. The lattice parameter changes produced by Cr and by Ni are nearly the same so that the first two types cannot be distinguished; the effect of Ni and Cr together, however, is to give a smaller parameter than does either Ni or Cr alone with Fe. Thus one may tentatively assign 0 to Fe_3O_4 or iron rich structures, 0' to a spinel approximating $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ or $\text{NiO} \cdot \text{Fe}_2\text{O}_3$, and 0'' to $\text{NiO} \cdot \text{Cr}_2\text{O}_3$ and solid solutions with the first two.

The (?) indicates a pattern not yet identified, but which is not NiO although it appears most often on the high nickel alloys. It is to be noted that no $\alpha\text{Fe}_2\text{O}_3$ is found, and that Cr_2O_3 and some form of spinel high in either nickel or chromium, or both, is present in nearly every case. The data are still too meager to draw any general conclusions regarding dependence on composition and temperature. The lower temperature runs will be repeated, and the measurements will be extended over a wider range of compositions.

It must be recognized that the protection afforded the metal by its oxide coating may not be due to the bulk oxide acting as a mechanical barrier separating the reactants but to some special properties of a relatively thin layer, presumably one next to the metal. In that case, the structures found in the bulk oxide by the X-ray investigations would be of only minor importance to the problem. For this reason, a considerable fraction of the research has been directed toward investigation of the formation, structure, and properties of thin oxide films, using electron diffraction and electron microscope techniques. This work has been confined to the study of chrome-irons and steels.

One line of attack has been to follow the structure changes on the surface of the thin oxide film during its growth by means of electron diffraction in reflection. Since this method is sensitive to very small surface effects, there is some danger that changes of the surface will occur between oxidation and examination. To obviate this possibility, a furnace attachment to the diffraction camera is used so that the specimens may be oxidized while in the camera, the atmosphere is pumped off at the desired intervals, and the diffraction pattern obtained without an intervening cooling cycle. In order to minimize the danger of oxide reduction during prolonged exhaust, oxygen pressures of only 1 mm. Hg have been used; the exhaust time is then about five minutes. Measurements on three compositions of chrome-iron at temperatures varying from 400°C . to 700°C . are given in Table V.

The entry for each material at 0 time is the structure found after the initial heating period of about five minutes in the residual gas of the camera (5×10^{-5} mm. Hg). The entry at 30 Vac. is the result obtained after 30 minutes in the camera vacuum at the conclusion of

TABLE V

STRUCTURES FORMED ON CHROME-IRON ALLOYS
IN DRY OXYGEN AT 1 mm. Hg PRESSURE

I = α FeXc = Cr_2O_3 (or solid solution with $\alpha\text{Fe}_2\text{O}_3$)O = Fe_3O_4 (or other spinel)

? = Hexagonal oxide (Jackson and Quarrell)

X = $\alpha\text{Fe}_2\text{O}_3$ (or solid solution with Cr_2O_3)

o = orientation

Oxidation Time	Min.	Chrome-Iron Sample	Temperature °C			
			400	500	600	700
0		11% Cr	I, O	I, O	I	O
1			O	O	O	O
5			O	O	X	O
30			X	O	X	O
60			X	O, X	X	O
0			18% Cr	O	O	O
1		O		Xoo	O	
5		O		Xoo	X	
30		X		Xoo	X	
60		X		Xoo	X	
30 Vac.		X		Xo	O, Xo	
0		27% Cr	O	?	?	?
1			O	?	?	Xc
5			O	Xo	O	O, Xc
30			O	Xoo	O	O
60			O	O, Xo	O, X	O
30 Vac.			O	?	O, X	O

the run. In only one case was there a serious reduction of the surface oxide so that reduction during the exhaust cycle is probably negligible.

The experiments have not been carried above this temperature range because the light from the furnace makes it difficult to adjust the sample for diffraction. The data on the 11 percent alloy has been reported previously (6).

The inherent accuracy of electron diffraction measurements is not sufficient to distinguish between some of the oxides and their solutions. Thus O may correspond to $\alpha\text{Fe}_2\text{O}_3$, Fe_3O_4 , FeCr_2O_4 or their solid solutions. Ordinarily it is not possible to distinguish between $\alpha\text{Fe}_2\text{O}_3$

and Cr_2O_3 or their solutions; these structures are recorded as X unless there is a definitely better agreement with Cr_2O_3 , in which case Xc is used.

On the 11 and 18 percent alloys there is a definite trend for the structure at the surface to pass through the sequence, αFe , Fe_3O_4 , $\alpha\text{Fe}_2\text{O}_3$. This is understandable in view of the decrease in the rate of metal ion diffusion to the surface as the film becomes thicker. The non-regular course of the time at which the higher oxide is first formed is probably the result of different rates of variation with temperature of film thickness, ion diffusion rates, and equilibrium constants. In similar experiments on a 13 percent chrome-steel, Hickman and Gulbransen (7) found a reversal of this *normal* sequence at 600°C ., the X phase appearing before the O phase. Presumably this reversal is associated with a change in the type of oxide from iron-rich to chromium-rich, or vice versa. On the 27 percent alloy we find two such reversals, at 500°C . and 700°C . The first of these transformations occurs at a lower temperature than on the 13 percent alloy. It will also be noted that the second transformation apparently involves formation of Cr_2O_3 , whereas at 500°C . it is an iron rich X phase.

It would be of interest to determine the structure of the inside of the film at the various stages of oxidation. One is tempted to assume that the inner structure remains the same as was first found on the surface, but this may not be the case, particularly for the conditions which give the reversed sequence of formation. In order to study this behavior, a technique of stripping the thin films electrolytically in a KCl solution saturated with hydrogen has been used so that they can be mounted for transmission examination by electron diffraction and in the electron microscope. These techniques have been successful in preliminary experiments and will be applied to films formed under the conditions of Table V. Mounting the removed films so that the inside surface can be examined directly by reflection diffraction is not yet completely satisfactory, but probably can be made so in the near future.

Two other methods of film removal have been utilized to examine thin films by transmission electron diffraction. Some success has been achieved with bromine dissolved in methanol, and it has been found recently that the films can sometimes be removed electrolytically in the same bath of perchloric acid and acetic anhydride used for polishing. The structures found for several films removed by these methods are shown in Table VI, page 78. The symbol F refers to a thin film produced in a short period of oxidation while T refers to the temper-color film remaining on the metal when the bulk scale formed in a longer period can be easily removed. The 20 hour and the two 5 hour films were from samples for which the bulk oxide structure is given in Table III. One finds the thin film structure is essentially similar to that of the scale within the accuracy of the electron diffraction method, i.e., $\text{Fe}_2\text{O}_3 \cdot 3\text{Cr}_2\text{O}_3$ could be Cr_2O_3 .

One may suspect that any of these violent methods, which are necessary to dissolve a chromium steel, may change the oxide film. In order to test this possibility, the struc-

TABLE VI
STRUCTURES OF STRIPPED OXIDE FILMS

<p>F thin oxide film</p> <p>T temper-color film under oxide scale</p> <p>K electrolytically stripped in KCl</p>	<p>P electrolytically stripped in perchloric acid + acetic acid</p> <p>B chemically stripped in bromine + methanol</p>
---	--

Alloy Cr %	Polish	Oxidation			Type	Removal	Probable structure
		time	temp °C	oxidant			
11	4/0	1 min	600	Air	F	K	Fe ₂ O ₃
11	4/0	2 min	900	Air	F	K	Fe ₂ O ₃ · 3 Cr ₂ O ₃
11	Met.	2 min	900	Air	F	K	Fe ₂ O ₃ · 5 Cr ₂ O ₃
26	3/0	20 hr	900	Air	T	B	FeCr ₂ O ₄ Fe ₂ O ₃ · Cr ₂ O ₃
26	3/0	5 hr	900	Air	T	B	FeCr ₂ O ₄
17	3/0	5 hr	900	Air	T	B	FeCr ₂ O ₄ Fe ₂ O ₃ · 3 Cr ₂ O ₃
5	elec.	3 min	900	Air	F	P	Fe ₂ O ₃

tures of identical films removed in each of the three ways are now being compared. If two or more methods give the same results, they will be assumed, tentatively, not to affect the structure, and these methods will be used in studies of the temper-color substrates formed under the conditions referred to in Table I.

Several series of electron micrographs, using the Formvar replica and manganese shadow casting technique, have been made of the oxide growth on chromium alloy steels. Commercial 27 percent and 17 percent chrome-steels have been used which have fine grain and well dispersed carbides and/or nitrides one to ten microns in diameter. These stand in relief on electropolishing. Replicas and photographs have been taken at frequent intervals during repeated one-minute cycles of heating in a furnace at 900° C. The maximum temperature reached during each cycle is 650°C. The temper-color changes from straw

through gold to a deep magenta. Beginning at the second cycle, crystallites of a few tenths micron diameter are formed on the matrix material in addition to a smooth layer, but not on the carbides. This continues throughout the runs, the smaller carbides gradually becoming covered over as the oxidized matrix builds up around them. There is a rather striking segregation of these oxide crystallites. They are quite regularly dispersed except that, as a carbide grain is approached, they become smaller and less frequent, leaving a completely smooth region surrounding the grain, as well as on the grain. Presumably this region is associated with chromium depletion of the matrix and it is therefore difficult to understand why this leads to a smooth oxide rather than one of relatively large crystallites, as might be expected of a matrix poor in chromium. On 11 percent and 5 percent chrome-alloys the growth of both film and crystallites is much more rapid, and the latter tend to have a tenuous vein-like appearance rather than consisting of isolated particles.

Systematic tests of the intensity anomaly observed in the X-ray absorption method of investigating the growth of thin films (6) are in progress. It had been observed that a lightly oxidized steel surface gave a higher X-ray diffraction intensity than did the original surface, in spite of the absorption of the diffracted beam in passing through the oxide film. Although an actual increase has not been observed in these tests, it has been demonstrated that the mechanical condition of the surface does influence the intensity observed. Surfaces rough polished on well used 3/0 paper give higher and broader peaks than do the same surfaces after two strokes on fresh 3/0 paper. The latter surfaces show very little change in intensity after twenty minutes of oxidation at 670°C. and after chemical stripping of the very light oxide layer. The changes produced, which are due to the differing effects of absorption in the surface irregularities, are being correlated with the surface condition by means of electron micrographs. The correlation will be extended through several cycles of oxidation and removal. Increasing times of oxidation will be used in order to establish the effect of the variation in intensity on the absorption measurements.

Test of the low power electron microscope apparatus for detecting the distribution of chromium and iron in an oxide cross section (6) has been interrupted twice by failure of the commercial copper target X-ray tube used to excite the characteristic electrons by which the image is formed. In the intervals between replacement of the tubes, tests were made with an iron target tube and a vanadium object, which gives photoelectrons of approximately equivalent energy. These tests were not very promising. Difficulties were encountered with distortions due to charging up of organically contaminated metal surfaces within the apparatus and, more seriously, by lack of sensitivity of the recording film for the low energy electrons involved.

Rather extensive measurements of the sensitivity of various plates have been made. With the low energy photoelectrons available (1000 to 4000 electron volts) the plate sensitivities are very low; a total charge of the order of 10^{-5} coulombs is necessary to produce unit optical

density. Various theoretical calculations have been made to estimate the exposure time that would be needed to develop an image. With this low sensitivity the times seem unreasonably long. Investigation of special ultra-violet sensitive plates and of oiled plates shows, however, that a 50-fold increase in sensitivity is possible and may make the experiments feasible.

The replacement copper tube was obtained but proved to be unsatisfactory, so that the equipment has been revised to accommodate one of our own continuously pumped tubes and is now ready for an operational test.

Plans

The X-ray structure determinations of the bulk oxides will be continued in one atmosphere of oxygen, particularly at temperatures below 775°C. on the low chrome alloys and above 1000°C. on the high chrome steels, to determine whether the trends established for the \bar{O} and Xc phases continue to these wider limits. The work with air and other reduced pressures of oxygen will be expanded to determine whether or not the existence region of the \bar{O} phase can be extended more definitely than was possible here, into the region where protective conditions obtain.

Further attempts will be made to identify the extra patterns, +, u, u' and (?), but the principal effort of this nature will be made to find the difference between \bar{O} and \bar{O}^* spinels and to look for possible variations within the \bar{O} type of structure. The literature search now under way has revealed little quantitative information on these points, but it is hoped that useful unpublished work may be available at the Phillips laboratories where a long-range program of research on oxide structures has been carried out.

The X-ray studies of the nickel-chromium steels will be continued at the lower temperatures and, if the samples can be obtained, over a wider and more continuously varying range of composition.

Some consideration is being given to the possibility of deciding, for a material such as the 27 percent chromium alloy which forms a temper-color film next the metal and a readily removable scale, whether the protection is due to the film or to the scale. If a sufficiently sensitive and essentially continuously indicating method of measuring the rate of attack can be devised, then a comparison of the rate obtained after removing the scale with the values originally obtained should enable one to make this distinction. Information pertinent to the problem should be obtainable by finding the variation in electrical resistance through oxide section by the probe method previously discussed (6). The apparatus for exploratory work has been built but, due to personnel changes, has not yet been used. This should go forward in the very near future.

The testing and comparison of different methods of stripping oxide films will be continued, and these methods of removal, combined with transmission and reflection electron diffraction and electron microscopic examination, will be used to study further the thin film structure and growth. As much application as possible will be made to the temper-color substrates formed under the conditions expressed by Table I.

It is now believed that the X-ray absorption analysis has been tested sufficiently, and that, with care in its application, productive work on the formation of the oxide film can be resumed.

PHASE 5

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

Summary

The initial construction of the apparatus was completed during this year. Calibrations of thermocouples and of the recorder-controller were made and analyzed. The maximum design temperature of 2000°F. was reached, and control was maintained at this point. Investigation of air film coefficients throughout the temperature range 500-2000° F. was initiated. The data up to 1000°F. may be considered complete; data in the range 1000°-2000°F. showed various peculiarities, and investigations to assign causes for these variations are still in progress.

Progress

During the early part of the year, the assembly and insulation of the apparatus was completed, though various modifications to improve operation have been made at later dates. The Brown Controller was adjusted and found capable of controlling the inlet gas temperature with a variation of $\pm 2^\circ\text{F}$. at 2000°F.

Several trial runs were made to determine heater performance. Typical data are shown as follows:

	Run A	Run B
Gas Heater	Off	On
Electric Heaters	100% On	97% On
Test Section Heaters	100% On	100% On
Air Flow Rate	118.8 lbs./hr.	103.5 lbs./hr.
Reynolds Number	12,000	6,810
Air Temp. Entrance to Test Section	737°F.	1999°F.
Air Temp. Exit Test Section (33.94 inches above entrance)	814°F.	1923°F.
Air Temp. Exit Gas Furnace	78°F.	1713°F.
Wall Temp. Test Section		
1.66 inches below entrance	815°F.	1929°F.
11.22 inches above entrance	896°F.	1949°F.
23.53 inches above entrance	939°F.	1883°F.
36.75 inches above entrance	772°F.	1718°F.

After the limits of performance were determined, the investigation of air film coefficients was begun. Low temperature data taken at 550°F. proved very consistent. These data showed good agreement (within 10%) with low temperature correlation advised by McAdams (8). A tentative correlation based on the mean film temperature with the Reynolds Number range 3,000 to 15,000 is:

$$\frac{hD}{K} = 0.034 \left(\frac{DG}{\mu} \right)^{0.74} \left(\frac{c\mu}{K} \right)^{0.4}$$

where h = the film coefficient of heat transfer

D = the tube diameter

K = the thermal conductivity

G = the mass velocity

μ = the viscosity

c = the specific heat

The experimental work was then extended to 950°F. and 1350°F. These data also checked with the McAdams correlation very well; however, as the temperature increased, more variability in the data was noted.

Approximately half-way through the year, a new type of wall temperature distribution became evident. The wall temperature, instead of steadily decreasing with an increase in distance from the entrance to the test section, fell and then, at the end, increased again.

The causes for this effect have been under investigation; however, no definite solution has yet been achieved. At present, a method of obviating the difficulty is being planned. It is thought that a disturbance of the flow pattern by the radiation shields and by contraction at the end of the test section is causing the peculiar wall temperature distribution. A mixing device is being constructed for the exit of the test section so that a mean mixed temperature may be read. By trial and error calculation, the mean temperature of the gas upstream from the shields will be obtained. Then the heat transfer coefficient may be determined for a section of undisturbed flow.

In order to have a better picture of the conditions in the test section, a method is now being developed whereby a temperature traverse may be made across the diameter of the test section at the entrance. As a by-product of these traverses, a mean-mixed temperature for the entrance air may be computed.

In conjunction with the attempts to ascertain the cause of the peculiar wall temperature gradient, data were gathered on the effect of wall temperature gradient on the film coefficient. During these studies, it became evident that the method of installation of wall thermocouples should be critically examined. As a result, several ways of attaching the thermocouple to the tube were tested. The effect of radiation shields and of convection losses on the junction were also surveyed. Typical results at a given point on the wall are:

<i>Type of Shield</i>	<i>Indicated Temperature</i>
Bare	1230.3
Platinum foil over junction	1234.7
Hemispheric saureisen layer with 0.25-inch radius over junction.	1229.3

At present, the method of installation consists of inserting a thermocouple into a pool of molten metal on the tube surface. No shield is used.

Several features of the auxiliary apparatus were changed during the year. Installation of new, high-output variacs provided a larger heat source for final air heating. Furthermore, the purchase of an electric heater for silica gel regeneration facilitated this operation. Certain changes in piping and valve arrangements were made to give steadier and more finely adjusted air supply.

Plans

After the construction of the mixing device and the traverse unit is completed, the investigation of air film coefficients will be continued. The system will then be modified for the introduction of steam as a test gas.

The data will be correlated on the basis of the bulk temperature, surface temperature, mean film temperature, a modified Reynolds Number (9), and possibly other considerations in order to ascertain the best type of correlation.

PHASE 7

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

Phase 7 has been broken down into several subsidiary problems and the progress of each problem is reported separately.

1. Design Construction and Instrumentation of a Rocket Test Laboratory²

Summary

The construction of the rocket test laboratory has been completed, and the instruments and piping for one test cell are being installed.

Progress

The construction of the rocket test laboratory was started in March, and the building was ready for occupancy in October. The essential elements of the testing facility are: (1) the main building comprising two test cells with a common control room, a work space, a chemical

²Project Engineers: W. J. Hesse, Instructor in Mechanical Engineering.
C. Beighley, Graduate Student.



FIGURE 14

Northwest side of rocket test laboratory.

laboratory, and a utility room; (2) an earth bunker into which the rocket jets will be directed; (3) six concrete slabs (20 x 12) for propellant storage; and (4) a metal shelter for housing the diesel-generator power unit and a small air compressor.

The details of design, construction, and instrumentation are available in a report entitled, *The Design and Instrumentation of the Rocket Testing Facility at Purdue University*, which was submitted to SQUID Headquarters in June. Figure 14 is a photograph of the northwest side of the building. The tanks shown are for storing the diesel oil, gasoline, and fuel oil for the various utilities.

Most of the instruments and flow lines for operating one test cell have been installed. The instrumentation and associated equipment are designed to provide accurate evaluation of the rocket motor performance parameters, including transients, up to chamber pressures of 3000 psi.

Figure 15 presents a view of one of the instrument panels. The panel is built around the test engineers' viewing window. The instruments grouped in the right hand section of the panel will be photographed during a test run by a slow speed movie camera. In addition, oscillograph

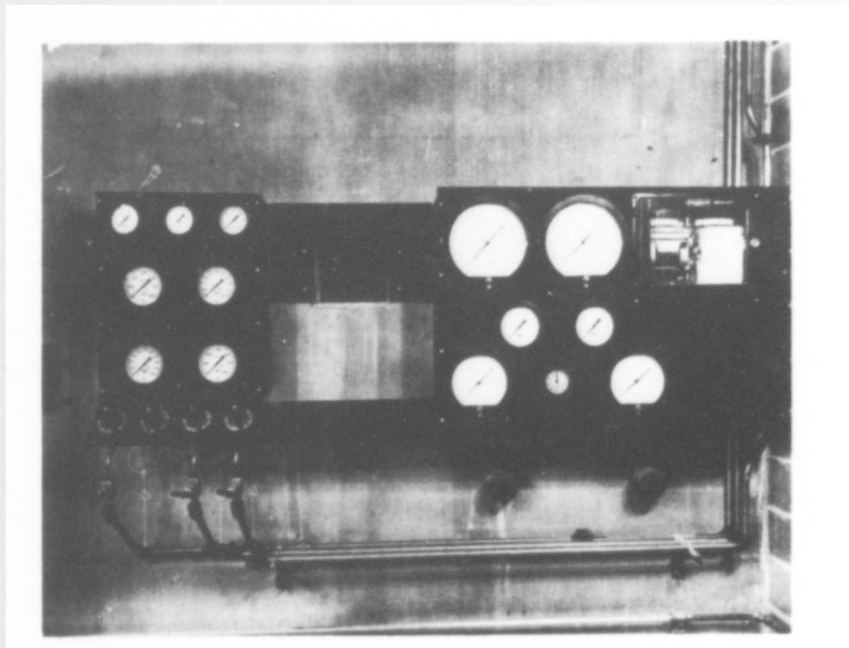


FIGURE 15

Instrument panel.

and recording potentiometer measurements will be taken of transient phenomena and temperatures.

Figure 16 is a schematic diagram illustrating the propellant flow and control systems. The propellant tanks, designed for an operating pressure of 3000 psia, will be filled by pressurizing the storage tanks located outside the building. Figure 17 shows four of these stainless steel storage tanks.

In addition to the method for measuring flow rates illustrated in Figure 15, a propellant weighing system has been incorporated. Figure 18, page 88, is a drawing of the weighing system. The dead weight of the tank is *balanced out* by lead ballast, and the weight of propellant consumed is measured by the reaction on a Hagan Thrust-Torq.

Plans

After the installation of the piping and instrumentation for test cell No. 1 has been completed, it is planned to check the system by trial runs on a 500 lb. thrust, uncooled

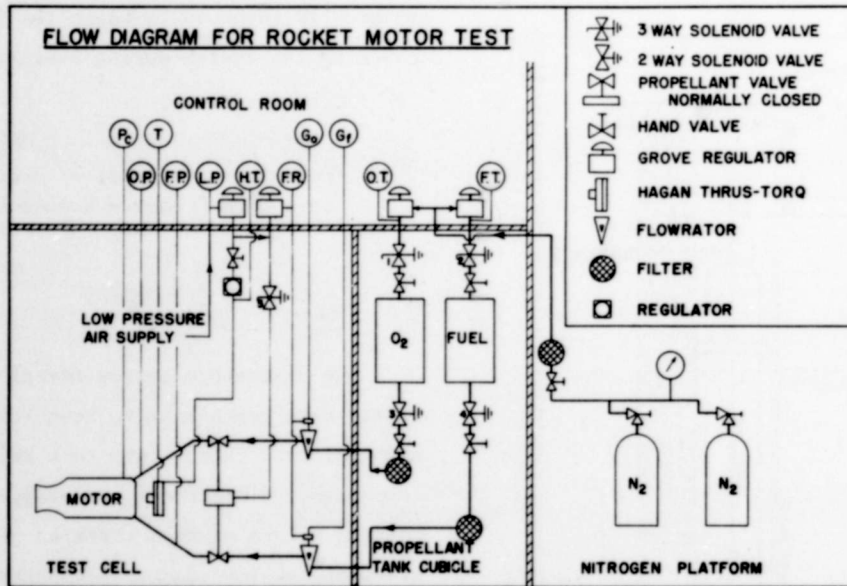


FIGURE 16

A schematic diagram of the propellant flow and control systems.

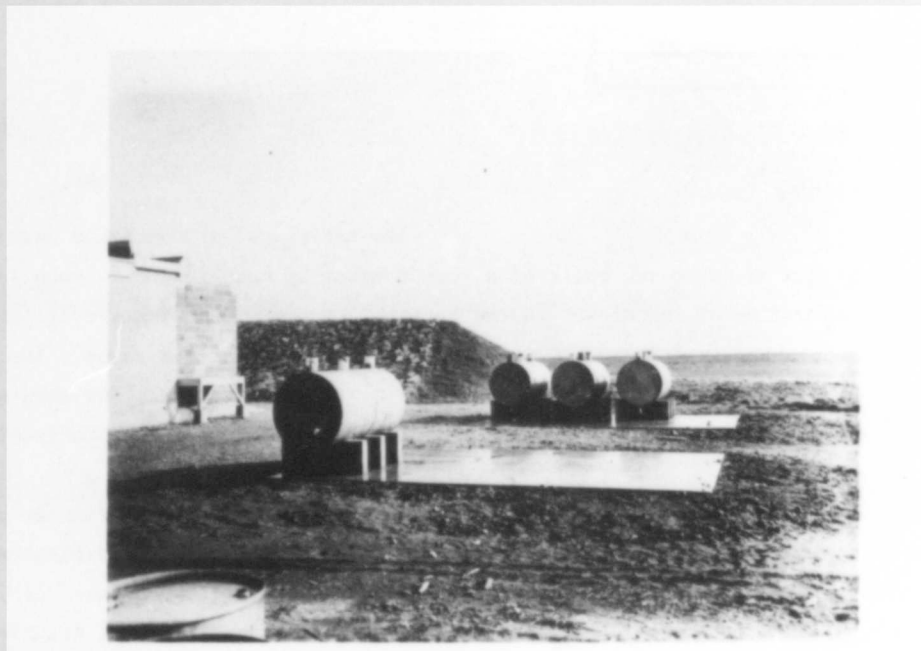


FIGURE 17

Propellant storage tanks.

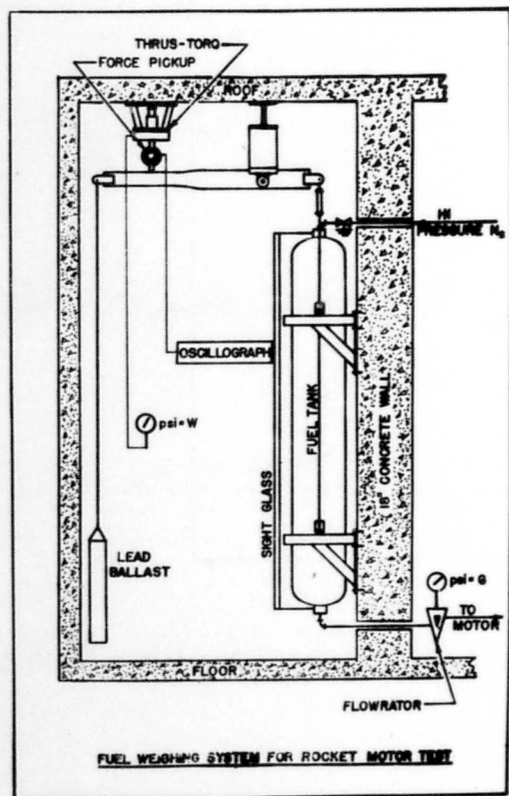


FIGURE 18

Propellant weighing system

from the combustion gases to the walls of a rocket motor is complicated by such factors as: the undetermined degree of turbulence in the chamber, the large temperature differences existing, the chamber shape, and the exact physical property data for the gases. The problem was simplified by assuming the heat transfer to be similar to that existing when a high temperature radiant gas passes in high velocity turbulent flow through a long horizontal tube.

A survey of the literature pertaining to high velocity convective heat transfer revealed that the flow Mach number has a negligible effect upon the heat transfer coefficient when the temperature difference is based upon the *impressed* or *adiabatic wall* temperature. (10), (11), (12), (13), (14). No data could be found which showed the effect upon the heat transfer coefficient of the large temperature differences encountered in rocket motors. Also, the question of the temperature to select in evaluating the physical properties of the gas could not be an-

³Project Engineers: C. F. Warner, Assistant Professor of Mechanical Engineering
G. M. Palmer, Instructor in the School of Aeronautics.

motor. It is hoped to begin the firings for checking the system during February 1949.

2. *Preliminary Analysis of Heat Transfer in a High Pressure Rocket Motor³.*

Summary

The literature survey revealed that little data pertaining to heat transfer from high velocity radiant gas to a wall at high temperature differences are available. Calculated values of heat transfer give good agreement, at low chamber pressures, with experimental values. Preliminary calculations indicate, as is to be expected, that the heat transfer problems will be aggravated if the combustion chamber pressure is increased.

Progress

The analytical study of the heat trans-

swered satisfactorily. In the absence of adequate information upon the subject, and with full realization that the calculated results would be approximate, equation 1 was selected for calculating the convective heat transfer coefficient.

$$\frac{hD}{K} = 0.0265 \text{ Re}^{0.8} \text{ Pr}^{0.3} \quad (1)$$

where h = convective heat transfer coefficient

Re = Reynolds number

D = chamber diameter

Pr = Prandtl number

K = thermal conductivity of the gas

The physical properties of the gas were evaluated at the static temperature of the gas. The latter temperature was obtained from thermochemical calculations.

The literature survey covering heat transfer by radiation from gases indicated that the methods due to Hottel and Egbert (16) are currently the most extensive, and the following equation was used for calculating the radiant heat transfer from CO_2 and H_2O .

$$q_r = 0.1723E' \left[E_g \left(\frac{T_g}{100} \right)^4 - a \left(\frac{T_s}{100} \right)^4 \right] \quad (2)$$

where q_r = heat transfer rate per unit area

E_c = emissivity of CO_2

E' = effective surface emissivity

C_c = correction for effect of total pressure upon CO_2 radiation

E_g = emissivity of gas mixture

E_w = emissivity of H_2O

a = absorbtivity of surface of rocket wall

C_w = correction for effect of total and partial pressure on water vapor radiation

T_g = gas static temperature

T_s = rocket wall temperatures

ΔE = correction for superimposed radiation

$$E_g = E_{c_g} \cdot C_c + E_{w_g} \cdot C_w - \Delta E_g$$

$$a = a_c + a_w - \bar{E}_s$$

$$\approx E_{c_s} \cdot C_c + E_{w_s} \cdot C_w - \Delta E_s$$

The subscripts g and s indicate that the quantities are to be evaluated at the gas and surface temperatures respectively. Curves for determining the values have been prepared by Hottel.

It was found that CO_2 and H_2O contributed the major portion of the heat transfer by radiation, and it was assumed that all of the radiant heat transfer in the rocket motor was due

to the CO_2 and H_2O .

The heat transfer was calculated for a five hundred pound thrust rocket motor having an aspect ratio $\frac{L}{D} = 2$, and $L^* = 100$, employing two propellant combinations: (1) white fuming nitric acid and aniline; and (2) white fuming nitric acid and octane. The flame temperatures and equilibrium products of combustion were obtained from calculations made by C. H. Trent at Purdue. An inner wall temperature of 1200°F . was assumed in all cases. The rates of convective heat transfer q_c were obtained by substituting values of h (from equation 1), evaluated for the combustion gas mixture at the calculated flame temperature, into the following equation:

$$q_c = h(T_i - T_s) \quad (3)$$

where q_c = rate of convective heat transfer per unit area

T_i = impressed or adiabatic wall temperature

h = convective heat transfer coefficient

T_s = wall temperature

By adding to q_c the value of q_r obtained from equation 2, the total rate of heat transfer per unit of area of wall, denoted by q , was calculated.

The rate of heat transfer in the throat section was obtained by multiplying the rate of heat transfer for the combustion chamber by the area ratio.

Figure 19 presents the results of the calculations. The values are in agreement with other experimental values for white fuming nitric acid-aniline at low pressures.

The study indicates that : (1) the rate of heat transfer increases appreciably with increases in combustion chamber pressure; (2) the throat heat transfer problem becomes more severe as the pressure is increased; and (3) the substitution of gasoline for aniline does not aggravate the heat transfer problem, but actually ameliorates it to a slight extent.

Plans

As thermochemical data become available for other fuels, the heat transfer study will be extended. The calculated values will be compared with experimental values as soon as data become available from the actual experimental results at Purdue.

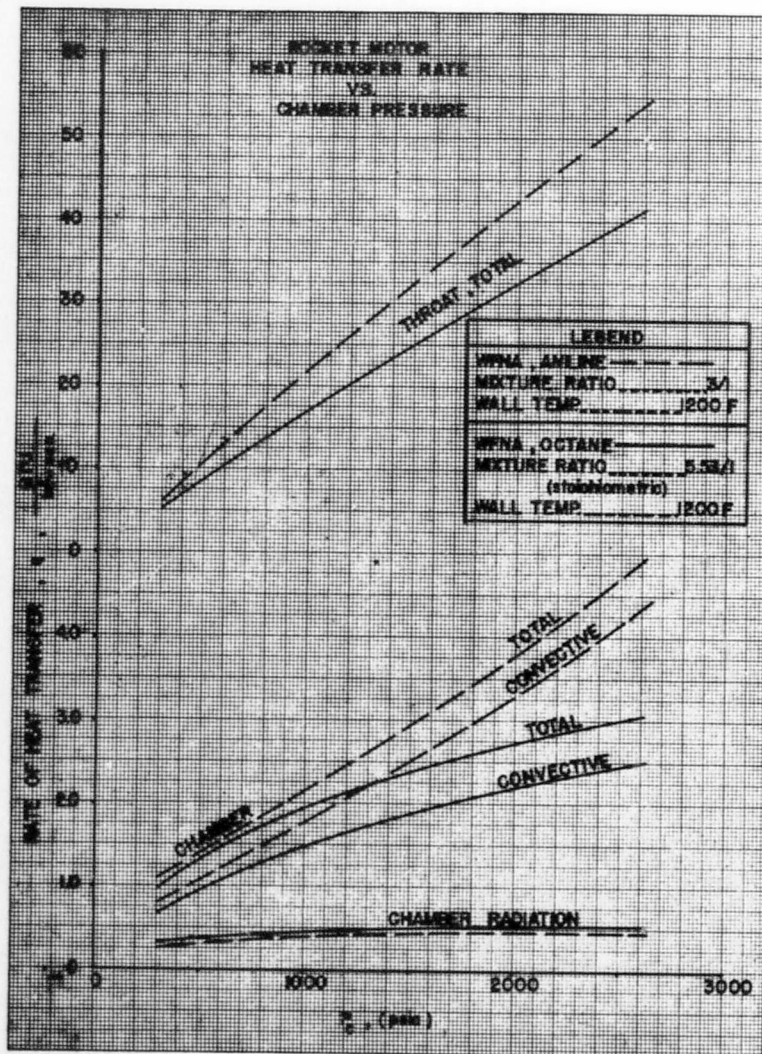


FIGURE 19

Rocket motor heat transfer rate versus combustion chamber pressure.

3. Ignition Lag Studies.⁴

Summary

An instrument for giving a direct measurement of the ignition delay time for rocket propellants has been designed and built.

⁴ Project Engineer: S. V. Cunn, Instructor in Mechanical Engineering.

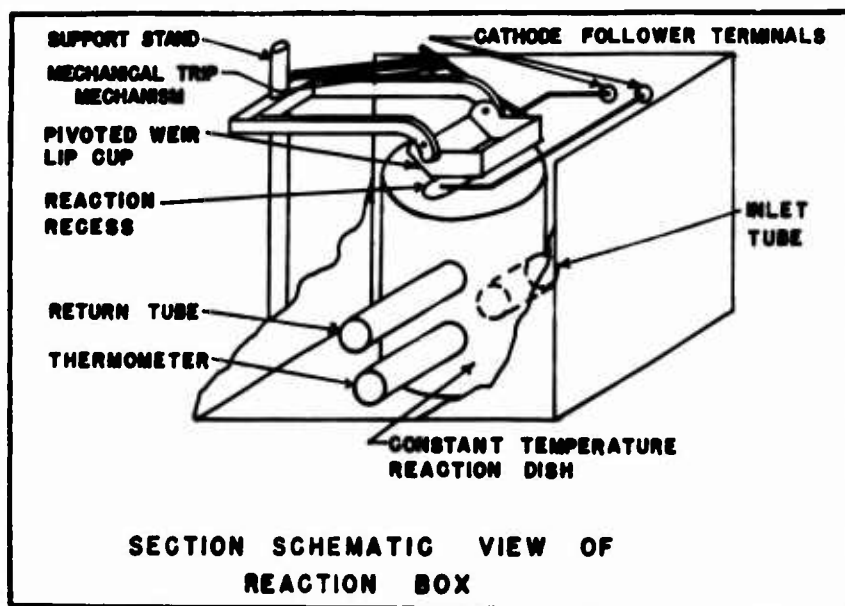


FIGURE 20

Schematic diagram of reaction.

PROGRESS

Early in January 1948, an agreement was reached with the Electrical Engineering School, Purdue University, which provided for the design and construction of an electronic ignition lag timer. For the purposes of design, the ignition lag of hypergolic propellants was defined as the elapsed time between the instant when the oxidizer and fuel contacted each other and the instant when the first visible light was emitted by the products of the reaction.

The apparatus currently being used functions as follows: one of the propellants is placed in a small, insulated, rectangular reaction cup, and the other is contained in a small, pivoted, stainless steel, box-like cup with a weir-type tip. The latter is suspended just above the reaction cut and is rotated by means of a bakelite arm as illustrated in Figure 20. A voltage of 67.5 volts is impressed between the pivoted cup and the reaction cup. When the former is tipped, one propellant flows, as a thin sheet, down into the other propellant. The contact of the propellants creates an electrical pulse signal of between 0.0001 and 0.01 volts, depending upon conductivities and dielectric constants of the propellants concerned.

The signal thus produced is placed upon the grid of a 1S5 pentode contained in a single stage, self-powered, enclosed, cathode follower circuit. This unit is placed within the explosion chamber, close to the reaction cup (see Figure 21). The low impedance output of the

cathode follower is then conducted through a shielded cable to a two state 6S17 pentode amplifier designed to give a differentiating effect to the pulse (see Figure 22). This differentiated and amplified pulse, when placed on the grid of a 2050 thyratron, causes the thyratron to fire. The instantaneous change in plate voltage of the thyratron is then utilized to charge a capacitor through a variable resistance and a constant current tube, giving an essentially constant rate of capacitor charging and a resulting fairly linear rise in voltage. The sweep voltage thus produced is put through two amplifiers, one being a paraphase of the other. The output of the one amplifier drives one horizontal deflection plate of a 241 Dumont oscilloscope positive while its paraphase amplifier drives the other plate negative at the same constant rate as the first amplifier. By use of an attenuating neon bulb coupling network between the two amplifiers, the instantaneous positive potential of one deflection plate is always numerically equal to the positive potential of the other plate. In this way a well-defined, linear timing trace is produced on the screen of the oscilloscope.

The recording of the first visible reaction light upon the timing trace is accomplished by use of a three stage phototube amplifier. The light incident upon a 922 low internal capacitance phototube initiates a signal. By use of a high-gain amplifier, consisting of two regular amplification stages terminated with a third cathode follower stage, the light signal is then placed on the vertical deflection plates of the oscilloscope where an appreciable vertical deflection of the timing trace occurs. The establishment of a time scale upon this trace is achieved by the impression of an arbitrarily fixed frequency oscillating signal from a Hewlett Packard Test Oscillator upon the Z axis of the cathode ray tube. Thus the timing trace appears as a dotted line, each dot representative of a small, easily calculated unit of time. This trace is recorded by a Dumont Recording Camera.

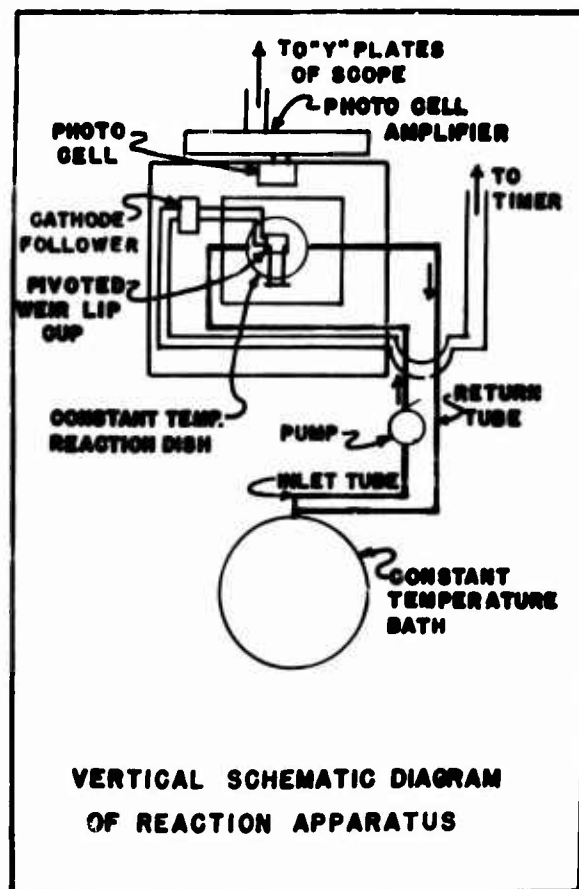


FIGURE 21

Schematic diagram of a reaction apparatus

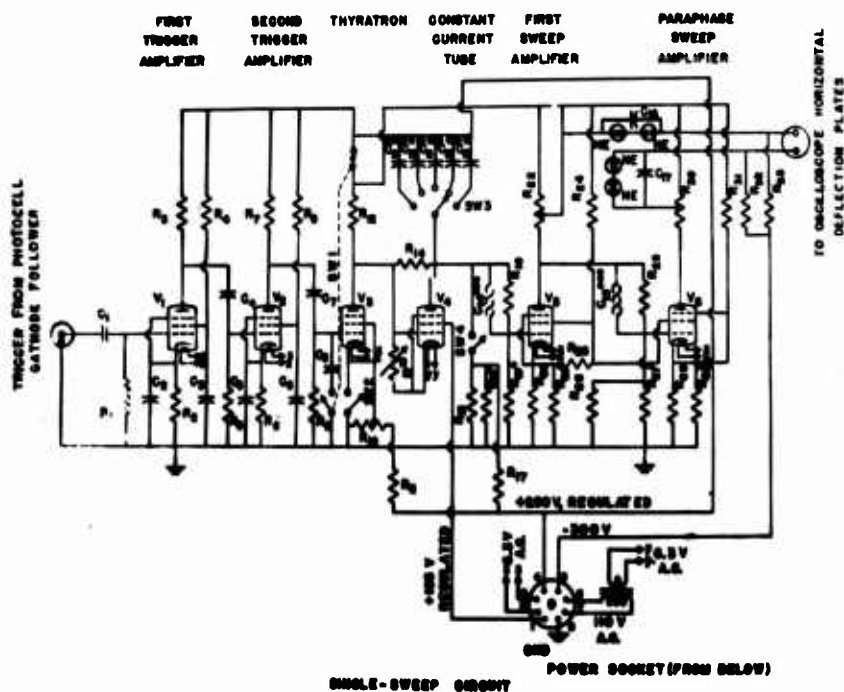


FIGURE 22

Circuit diagram for electronic timer.

The original timer was delivered in June 1948, and the apparatus set up in a temporary research laboratory. Initial tests with actual propellants soon revealed that the apparatus had several shortcomings, such as: inadequate shielding; an undersized power supply; and an exponential timing trace. To overcome these deficiencies, the timer was redesigned and rebuilt. By completely shielding all of the component parts and their interconnecting cables, by the use of a battery as a source of D. C. power for the phototube amplifier, and by redesign of the timing trace circuit to provide a linear trace, these problems were solved. By October, the redesigned instrument had been installed in the chemical laboratory of the newly completed Rocket Laboratory. Since then, several tests at ambient temperatures have been made, and the minimum quantity of reactants that must be used to give consistent ignition delay times has been determined.

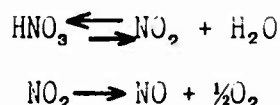
Plans

The ignition lag for hypergolic propellants is to be measured at various temperatures. After these tests are completed, a small rocket motor is to be developed to enable measurements to be made under conditions simulating the actual method of injection employed in rock-

In the first series of experiments, the gasoline was added dropwise into the open end of the combustion tube containing nitric acid vapor at about 350°C. The drops of gasoline ignited about 5 seconds after introduction. The nitric acid was produced by boiling white fuming nitric acid, 1.50 s.g., in the three-neck, round bottom flask, and heating the vapors to the desired temperature by allowing them to flow through the heated portions of the apparatus.

In the second series of experiments, the gasoline was introduced into the nitric acid vapor by means of a small nozzle inserted into the second side arm of the reaction tube so that the gasoline discharged in the direction opposite to the entrance of the nitric acid vapor. The gasoline entered the tube as a very fine stream and ignited immediately, producing a sharp report. The experiment was repeated several times without damage to the glass reaction tube. The temperature of the nitric acid vapor was about 420°C.

It is assumed that the reaction between nitric acid vapor and liquid gasoline is that between gaseous oxygen and gasoline, since nitric acid vapor dissociates when heated. Among the possible dissociation reactions, these reactions occur:



At elevated temperatures, the dissociation of nitrogen dioxide is quite appreciable, and at 619.5°C., nitrogen dioxide is completely dissociated (17).

Plans

It is planned to pursue this investigation further to obtain quantitative data on the minimum ignition temperature for the reaction between nitric acid vapor and liquid gasoline. It is also planned to determine the minimum temperature necessary to cause combustion between liquid nitric acid (1.50 s.g.), liquid gasoline, and liquid jet fuel. After these objectives have been attained, research on methods for catalyzing the reaction will be undertaken.

5. *Effect of Ambient Pressure on Ignition in a Rocket Motor.*⁶

Summary

All aspects of this project are as yet in the initial planning stage.

Progress

A tentative experimental program for the investigation of the effect of ambient pressure on ignition in a rocket motor has been arranged. The preliminary plans for the construction of a test motor and the requisite electronic measuring equipment are in progress.

Plans

When the test motor and other necessary instrumentation are complete, the experimental study will be undertaken.

6. *Investigation of Various Methods for Calculating Propellant Performance at High Pressure.*⁷

Summary

The thermochemical study has been completed covering the thermodynamic properties of the gases produced by the combustion of saturated hydrocarbons oxidized by white fuming nitric acid at various chamber pressures and oxidizer to fuel ratios. The values of specific impulse for heptane (C_7H_{16}), octane (C_8H_{18}), decane ($C_{10}H_{22}$), and eicosane ($C_{20}H_{42}$) oxidized by white fuming nitric acid have been calculated at a fuel-rich mixture ratio (4.8/1), the stoichiometric mixture ratio, and an oxidizer-rich mixture (6.32/1), and at chamber pressures ranging from 300 psia (20 atmospheres) to 2058 psia (140 atmospheres).

⁶Project Engineer: S. V. Gunn

⁷Project Engineer: C. H. Trent, Instructor, School of Mechanical Engineering.

Progress

In the search for a method for quickly and accurately calculating the equilibrium composition of the gases produced in combustion processes, the graphical method of Rudolph Kassner was found satisfactory. This method was employed in all of the calculations presented herein. The results of the calculations are presented in Table VII.

The hydrocarbons, heptane, octane, decane, and eicosane, were chosen because their C/H ratios are representative of the fuels that may be used as rocket fuels; e.g., gasoline, kerosene, etc. The variation in the C/H ratio of the fuel oxidized exerts a very small effect on the specific impulse for all the mixture ratios investigated; however, the effect on the characteristic velocity is more pronounced.

Increasing the pressure at which the combustion of the fuel and oxidizing agent occurs produces an overall favorable result. An average increase of 20.9 percent in the value of specific impulse for the four hydrocarbons studied may be obtained by increasing the chamber pressure from 300 psia to 2058 psia.

The variation of the characteristic velocity C^* , which is a thermodynamic function of the propellant gases independent of the chamber pressure, calculated at different pressures is quite small for a given mixture ratio. By increasing the chamber pressure from 300 to 2058 psia, an average increase of 1.83 per cent is produced in the value of C^* ; whereas, the thrust coefficient C_p , which is dependent solely upon the specific heat ratio and the chamber pressure, is increased by 18.43 per cent. These conclusions are represented graphically in Figure 24 and 25.

The values of specific impulse listed in Table VII are all based upon the assumption of frozen equilibrium. The values of specific impulse of octane oxidized by white fuming nitric acid at an O/F ratio of 4.8 were calculated on the basis of shifting equilibrium to serve as a comparison between the two assumptions. The results are tabulated in Table VIII. It was assumed that the increase in specific impulse for the other hydrocarbons and at other O/F ratios would be of the same order. A report covering the results of this project has been completed.

Plans

No further work is contemplated at this time.

TABLE VII

THEORETICAL PERFORMANCE DATA FOR SEVERAL HYDROCARBONS OXIDIZED BY WHITE FUMING NITRIC ACID - FROZEN EQUILIBRIUM.

<i>Fuel</i>	<i>C/H</i>	<i>O/F</i>	P_c <i>psia</i>	T_c °R	<i>k</i>	C^* <i>ft/sec</i>	C_T	I_{sp} <i>lb-sec/lb</i>
Heptane	5.25	4.8	300	5425	1.21	5061	1.41	221.3
Octane	5.33	4.8	300	5445	1.21	5060	1.41	221.2
Decane	5.45	4.8	300	5422	1.21	5041	1.41	220.4
Eicosane	5.71	4.8	300	5418	1.21	5033	1.41	220.0
Heptane	5.25	4.8	1000	5598	1.21	5121	1.59	253.0
Octane	5.33	4.8	1000	5616	1.21	5130	1.59	253.4
Decane	5.45	4.8	1000	5594	1.21	5105	1.59	252.1
Eicosane	5.71	4.8	1000	5575	1.21	5100	1.59	251.9
Heptane	5.25	4.8	2058	5693	1.21	5151	1.67	267.8
Octane	5.33	4.8	2058	5708	1.21	5154	1.67	268.0
Decane	5.45	4.8	2058	5684	1.21	5137	1.67	267.1
Eicosane	5.71	4.8	2058	5681	1.21	5126	1.67	266.5
Heptane	5.25	5.56	300	5364	1.21	4960	1.41	216.8
Octane	5.33	5.53	300	5382	1.21	4969	1.41	217.2
Decane	5.45	5.50	300	5391	1.21	4966	1.41	217.1
Eicosane	5.71	5.47	300	5395	1.21	4947	1.41	216.3
Heptane	5.25	5.56	1000	5535	1.21	5025	1.59	248.2
Octane	5.33	5.53	1000	5544	1.21	5040	1.59	248.7
Decane	5.45	5.50	1000	5553	1.21	5019	1.59	248.1
Eicosane	5.71	5.47	1000	5557	1.21	5012	1.59	247.5
Heptane	5.25	5.56	2058	5663	1.21	5060	1.67	263.0
Octane	5.33	5.53	2058	5670	1.21	5050	1.67	263.5
Decane	5.45	5.50	2058	5670	1.21	5052	1.67	262.6
Eicosane	5.71	5.47	2058	5675	1.21	5032	1.67	261.6
Heptane	5.25	6.32	300	5245	1.21	4822	1.41	210.8
Octane	5.33	6.32	300	5247	1.21	4830	1.41	211.1
Decane	5.45	6.32	300	5240	1.21	4825	1.41	210.9
Eicosane	5.71	6.32	300	5238	1.21	4805	1.41	210.0
Heptane	5.25	6.32	1000	5400	1.21	4880	1.59	241.2
Octane	5.33	6.32	1000	5414	1.21	4886	1.59	241.3
Decane	5.45	6.32	1000	5409	1.21	4884	1.59	241.2
Eicosane	5.71	6.32	1000	5411	1.21	4880	1.59	241.0
Heptane	5.25	6.32	2058	5490	1.21	4916	1.67	255.6
Octane	5.33	6.32	2058	5499	1.21	4921	1.67	255.8
Decane	5.45	6.32	2058	5485	1.21	4908	1.67	255.2
Eicosane	5.71	6.32	2058	5481	1.21	4892	1.67	254.4

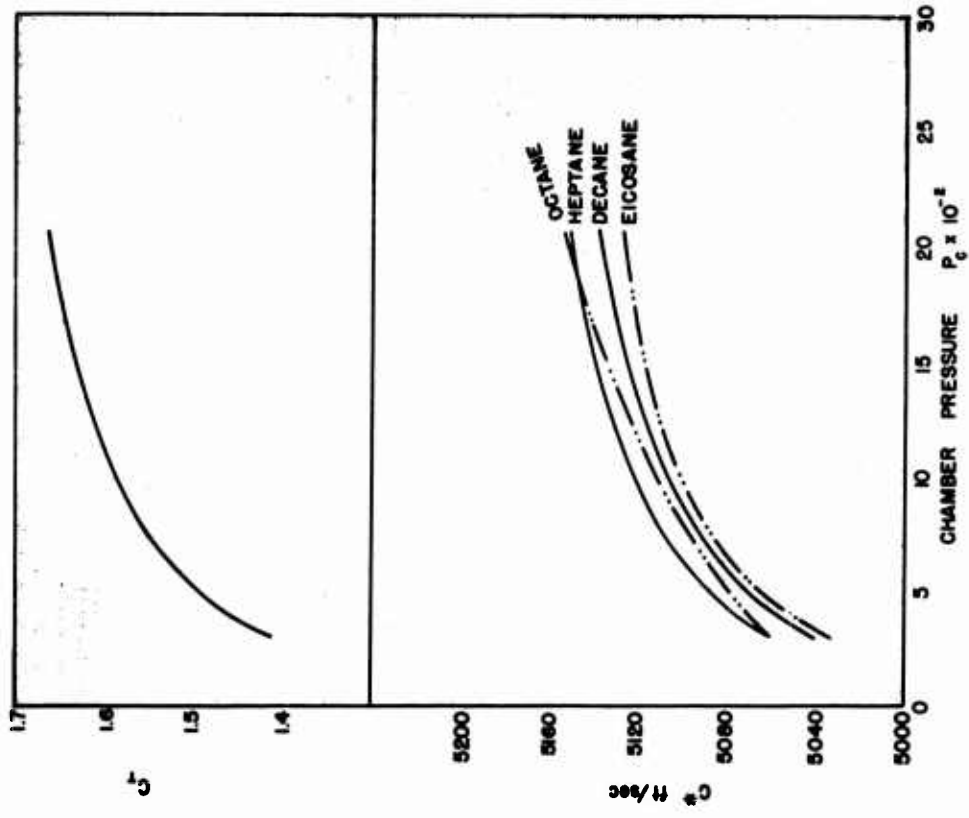


FIGURE 25

Variation of C^* and C_t with chamber pressure for an oxidizer-fuel ratio of 4.8.

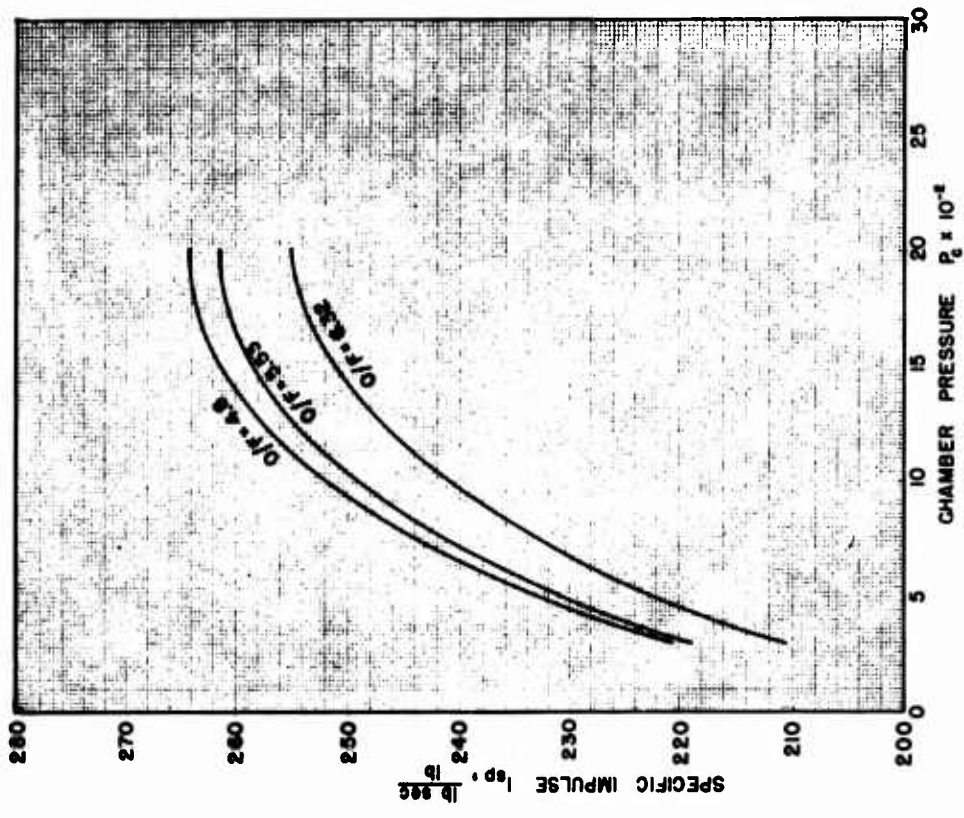


FIGURE 24

Average performance of hydrocarbon fuels oxidized by white fuming nitric acid.

TABLE VIII

SPECIFIC IMPULSE OF OCTANE OXIDIZED BY WHITE FUMING NITRIC ACID BASED ON SHIFTING EQUILIBRIUM.

Propellant	P_c psia	O/F	Specific Impulse lb-sec/lb		Increase
			Frozen Equilibrium	Shifting Equilibrium	
Octane WFNA	300	4.8/1	221.2	226.6	2.44%
Octane WFNA	1000	4.8/1	253.3	263.6	4.06%
Octane WFNA	2058	4.8/1	267.9	279.7	4.40%

7. *Experimental Investigation of Effect of Combustion Chamber Pressure Upon Rocket Motor Performance.*⁸

Summary

A program has been set up for determining the effect of chamber pressure on the basic design parameters of a rocket motor. Several uncooled rocket motors have been designed for this project, and the rocket motors for test at 300 psia chamber pressure are to be released for manufacture in a few days.

Progress

In February of 1948, a test program was decided upon. These tests were designed to determine the effect of increasing the combustion chamber pressure on the basic parameters pertinent to rocket motor design and on the interdependence of these parameters.

The test program was divided into four major phases as suggested mainly by the principal components of a rocket motor. These phases are as follows: (1) injectors, (2) combustion chambers, (3) nozzles, and (4) propellant reaction phenomena. The fourth phase consists of studies on the effect of changes in propellants, mixture ratio, and initial temperature.

⁸Project Engineer: G. M. Palmer, Instructor in the School of Aeronautics.

Each phase of the program will consist of a series of performance tests at different chamber pressures where all the variables that can be controlled will be held constant except one. The first tests will be conducted at 300 psia, and the motors for these 300 psia tests cover a series of L/D ratios, L^* 's, injectors, and nozzles, which can be interchanged in equal diameter motors

A cooled rocket motor is being manufactured for heat transfer studies. A large number of thermocouples are to be installed in the cooling passages, and the experimental heat transfer data are to be correlated with the heat transfer calculations.

Plans

The motors now being designed and fabricated are for tests at 300 psia chamber pressure. After completion of the tests at 300 psia, the motors designed for the next chamber pressure in the series will be tested. The results of tests at 300 psia will be the basis for determining the effect of increasing the chamber pressure on rocket motor operation.

8. The Cooling of Rocket Motor Nozzles by Transpiration Cooling Through Parallel Disks.⁹

Summary

Work has been initiated on the design of a suitable test section and testing apparatus for the purpose of analyzing the cooling effect of flow between parallel disks. Initial plans have been made concerning the method of carrying out the actual testing program.

Progress

Figure 26 is a sketch of the proposed test section. The test section is composed of a half section of $3\frac{1}{2}$ inch I.D. stainless steel pipe surrounded by a manifold and covered by

⁹Project Engineer: C. Beighley, Graduate Student, School of Mechanical Engineering.

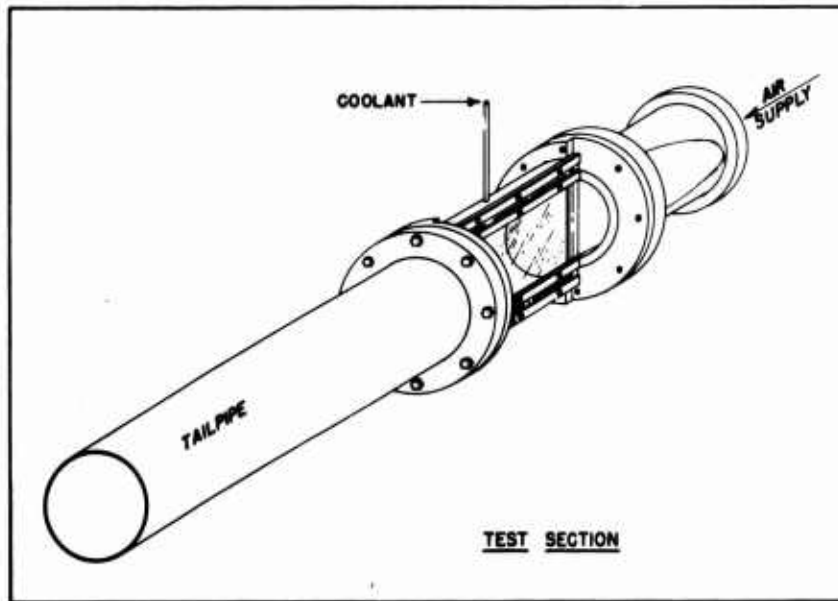


FIGURE 26

Sketch of proposed transpiration cooling test section

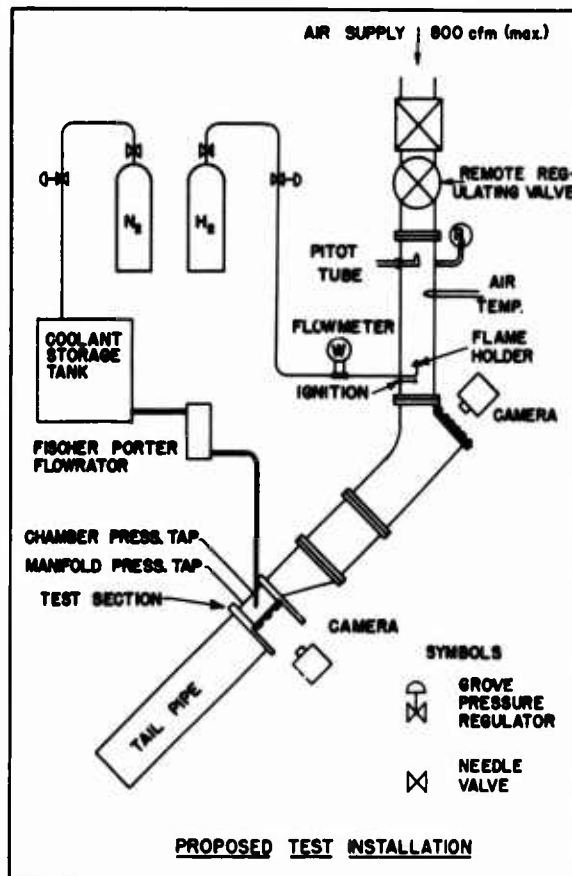


FIGURE 27

Test arrangement for transpiration cooling study.

a quartz window. The pipe is separated by an adjustable slot at approximately the mid-point of the test section. Figure 27 is a diagrammatic sketch of the proposed testing apparatus showing the instrumentation, controls, and method of heating the air.

Plans

The actual testing program will be divided into two parts. Part one will be carried out with unheated air. The purpose of this study will be to acquire a physical picture of the flow issuing from the slot at various velocities through the slot and Reynolds numbers through the pipe. Part two will be carried out with heated air. The purpose of this study will be to determine the temperature profile along the pipe downstream from the slot at various velocities and Reynolds numbers through the pipe. An attempt will then be made to correlate the data from these studies into a design parameter for the actual construction of a disk type rocket motor.

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ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ori-119, TASK ORDER I

Cornell Aeronautical Laboratory Inc.
Buffalo, New York
1 January 1949

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

The tools which have been used for the study of non-stationary gas flow are, in addition to experimental observation of actual phenomena, the analogy between surface gravity waves in shallow water and pressure waves in gases, and the method of characteristics. Both methods have been used extensively, and both have their advantages and disadvantages. Water analogy

experiments are comparatively easy to carry out. Satisfactory instrumentation has been developed to record water depth continuously at a selected point. Alternately, the whole flow pattern may be made visible by suspending suitable particles in the water. The water analogy gives useful qualitative results and is therefore a good tool to use, particularly in the early stages of an investigation when little or nothing is known about the flow. The method of characteristics should give quantitative results but requires a large amount of time for the solution of each individual problem.

Both the method of characteristics and the water analogy were applied to simple transient phenomena and the limitations of the analogy could be evaluated from a comparison of the results. The water analogy was also used to study flow patterns of acoustic jets and is still being used for a study of ducted pulse jets.

An attempt was made to develop a theory of acoustic jets and relations for thrust and specific impulse were obtained on the assumption of harmonic piston oscillations. This work is being extended to other types of piston motion.

A number of possible designs for intermittent combustion devices, both jet engines and turbines, were suggested. Actual work has been concentrated on experiments with small valveless pulse jets (about the size of a dynajet). A number of configurations and fuels were tried in an attempt to isolate significant design parameters. The highest specific impulse values observed were about 2400 lb. thrust per lb. fuel/sec. for thrusts of about 3 lb. No definite conclusions have been reached so far, and work is proceeding.

Towards the end of the year the work on fluctuating back pressures in diffusers (stability of shock waves) was resumed. Analytical relations could be derived for the motion of a shock produced when a steady flow is interrupted by the sudden closing of a valve which is opened again a short time later. A characteristic diagram for the same case agreed well with the analytical solution.

Progress

Study of Pulse Jet Shapes by Means of the Analogy between Surface Gravity Waves in Water and Gas Waves in Ducts. It is well-known that the surface in a shallow water channel follows laws quite analogous to those applying to pressure waves in gas. In this analogy, the water depth corresponds at the same time to gas density and temperature. This corresponds to a hypothetical gas for which the ratio of specific heats is 2; the analogue of gas pressure is then the square of the water depth.

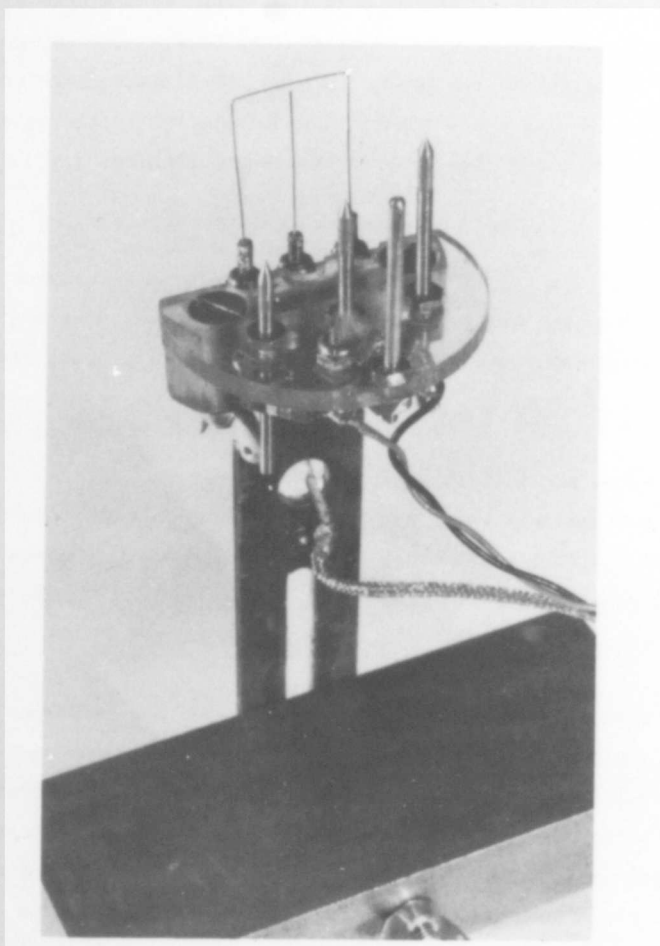


FIGURE 1

Depth gage for water analogy experiments.

Before applying the analogy to a study of pulse jet shapes, it was necessary to investigate, in general, its application to problems of non-stationary gas flow and to develop suitable instrumentation. This preliminary phase has essentially been completed. The problem of recording instantaneous water depths was solved satisfactorily. The probe, shown in Figure 1 consists of a U-shaped outer electrode which is grounded and a straight center electrode. The purpose of the U-shape is to eliminate as much as possible the effects of the proximity of a channel wall or bottom. This is particularly important for the new calibration procedure described below. The electrodes are made of platinum wire. An oscillator producing alternating current of about 800 cps. was constructed as current supply for the probe. The relation between the reciprocal resistance of the immersed probe and water depth is approximately linear. A constant voltage will, therefore, produce a current approximately

linearly related to depth. Originally, a single-sweep cathode-ray oscilloscope was used for recording. However, the required recording times were too long for satisfactory resolution of the record, and a small recording oscillograph was then used. Satisfactory recordings are being obtained with it when the oscillator current is rectified by means of a small instrument rectifier. Ordinary tap water is being used for all experiments. The conductivity of water varies about 1% per $^{\circ}\text{C}$, and in order to eliminate errors due to changes in temperature of the small water container that was used for calibration of the depth probe a different arrangement was set up. A large amount of water (about 25 gallons) is stored in a drum at room temperature. A small pump is used to raise the water level in a vertical 4" diameter glass tube at an unknown but constant rate. The probe together with

three known reference points which may also be seen in Figure 1 is placed inside and near the top of the tube. The water level is allowed to rise and is recorded on the oscillograph. A second channel is used to show the position of the reference points by means of a simple electrical circuit which indicates when the water surface makes contact with them. This procedure considerably reduces the time required to calibrate the probe and also the time required to evaluate the recording of some phenomena. Having a water pump already attached to the water table will make it possible in the future to extend the experimentation to problems involving continuous flow.

Attempts to measure the flow velocity of water by means of a hot-wire type instrument were not successful since the readings obtained were not steady. However, it was possible to take motion pictures of the water surface with small particles floating on it. Both aluminum powder and ink have been used.

The water analogy was first applied to the following problem:

A tube of constant cross section contains air which has been isentropically compressed from the outside condition. One end of the tube is suddenly opened and the gas discharges in an oscillatory manner. One is then interested to determine the gas pressure at various points of the tube as function of time.

The analogue model consists of a channel of constant cross section; one end is permanently closed while the other one leading to a large reservoir may be opened or closed at will, by a shutter type gate. Initially, the inside level is higher than the outside level which is maintained constant by means of an overflow. Sudden opening of the gate produces the analogue transient. The water depth is recorded at a point near the closed end. For comparison, several characteristics diagrams were prepared assuming a specific heat ratio of 2 as required for the water analogy. The experiments, except those of high initial pressure ratios, which will have to be repeated, were well-reproducible and gave all the same results: The head of the disturbance wave travelling into the channel moves with the anticipated speed. From then on, however, only a qualitative agreement between theory and experiment is obtained. The level drops more slowly than expected and not quite as low. The discrepancy could not be explained as a boundary layer effect, even with the assumption of a 3 mm. boundary layer thickness, which would of course be an unreasonably high value under the prevailing flow conditions. It is now felt that the disagreement may be attributable to a heretofore accepted oversimplification in the treatment of the phenomena that occur at the gate at the time of opening. The assumption which is usually made in the drawing of the characteristics diagram is that the pressure (water level) at the open end of the channel be constant and equal to the outside pressure under all outflow conditions except when the outflow Mach number is one. This assumption implies perfect reflection of any wave reaching the open end while, actually, a portion of it is transmitted

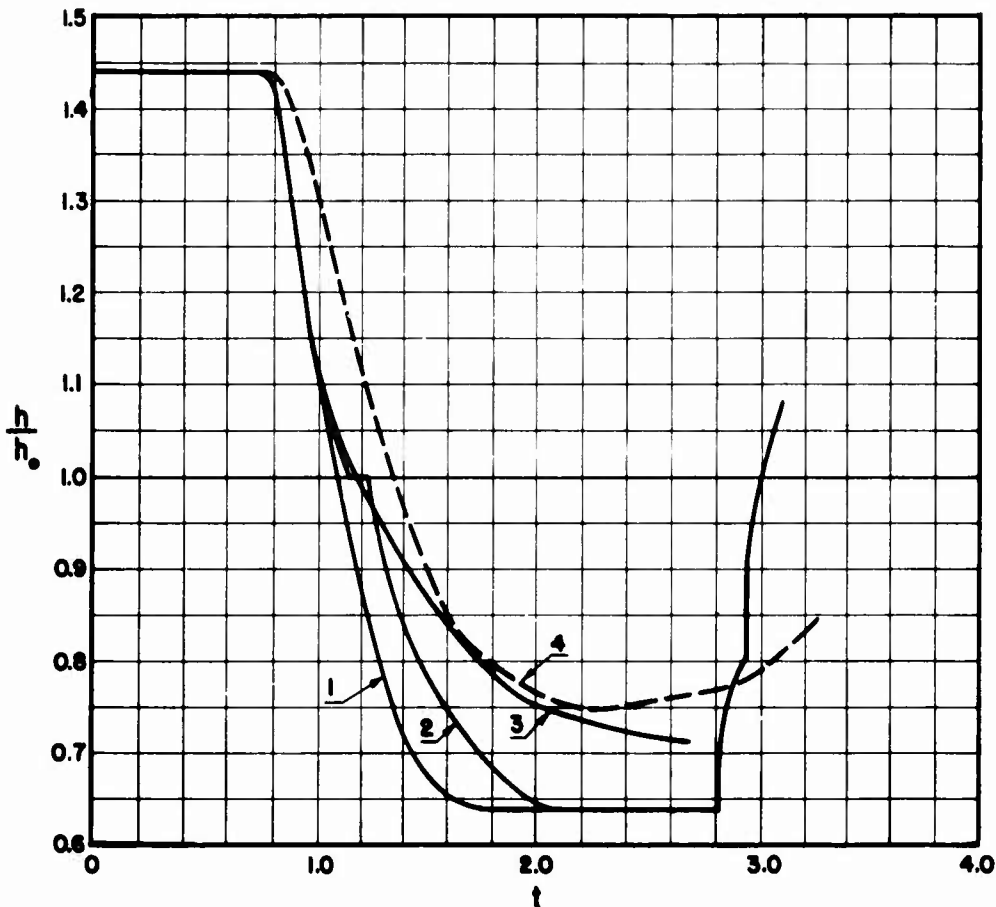


FIGURE 2

Water depth at closed end of constant cross section channel as function of time (in non-dimensional units). Curves 1, 2, 3, give theoretical results for different boundary conditions (see text), curve 4 shows the experimental results.

to the outside region. The outgoing wave, being free of constraint after it leaves the channel, propagates in all directions in the surrounding medium and therefore its intensity decreases as it progresses. As a result of this gradual loss of intensity of the outgoing wave, the depth at the open end of the channel will asymptotically approach the level of the surrounding ambient. A first attempt was made to account for the fact that the change of level at the open end, following the opening of the gate, is gradual and not instantaneous, by assuming an 'effective end' downstream of the actual end of the duct. In a second attempt to approximate the actual transient at the boundary, the outgoing wave was taken into consideration, dispensing with the concept of an effective end. In this treatment simplifying assumptions had to be made concerning the propagation pattern of the outgoing wave and the profile of the free surface between the two waves originating at the open end. The results are shown in Figure 2. The water depth at the closed end is h and the ratio h/h_0 (h_0 is the constant depth out-

side the channel) is plotted versus time t (in non-dimensional units). Curve 1 refers to the standard boundary conditions, curve 2 gives the results obtained on the assumption of an effective length, while curve 3 is the result of accounting for the outgoing wave. The experimental results are plotted as curve 4. Although the closest agreement is obtained with curve 3, showing that an allowance for imperfect reflection must be made, it appears that even this allowance does not reduce the discrepancy between theory and experiment in the early part of the transient. It must be remembered, however, that the water analogy, which only holds for shallow water, probably does not hold under the conditions prevailing at the gate for a short time after opening, when there is a large curvature of the surface.

The effect of the outgoing wave is of considerable importance in the two-dimensional case of a water channel, but it could be shown that in the three-dimensional case (actual gas discharge from a duct) the effect would be considerably smaller and possibly negligible.

The conclusions reached from this analysis is that water analogy experiments should in general, not be expected to give quantitative results. The qualitative results obtainable should, however, still be very useful particularly in the early stages of investigations when little or nothing about the flow conditions is known. The water analogy is now also being used in connection with other problems under this phase.

Study of the Mechanism of the Acoustic Jet.

The term 'acoustic jet' has been applied to jets produced by a piston oscillating in a tube. Experiments with such jets, which were started during 1947, were continued and described in Technical Memoranda CAL-13 and CAL-18. The experiments with an underwater model were described in the Technical Memorandum CAL-19.

An attempt was made to develop a theory for acoustic jets. Assuming an infinitely long tube closed by an oscillating piston, the instantaneous pressure on the piston may be calculated on the assumption of isentropic changes of state for a known motion of the piston. The mean thrust and energy input may then be calculated by integration of the instantaneous values. For sinusoidal piston motion and a specific heat ratio of 1.4 the thrust T is given by

$$T = 10.5 \cdot S \cdot p_0 \cdot k^2 \cdot \left(1 + \frac{5}{4}k^2 + \frac{5}{24}k^4\right).$$

where:

S = piston area

p_0 = atmospheric pressure

$$k = \frac{1}{5} \cdot \frac{x_0 \omega}{a_0}$$

x_0 = amplitude of piston motion

ω = circular frequency

a_0 = speed of sound in undisturbed gas

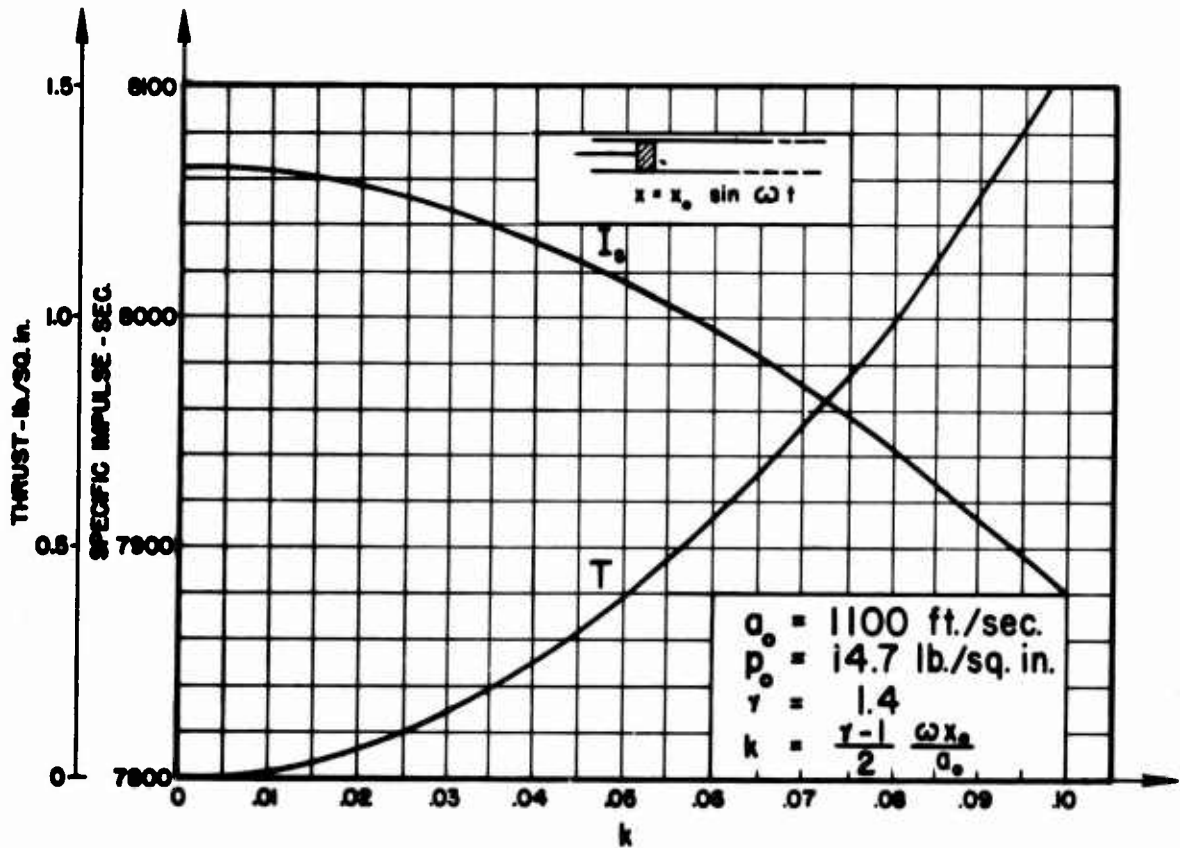


FIGURE 3

Thrust and specific impulse for an infinitely long acoustic jet.

The specific impulse, I_S (ratio of thrust and power input) becomes:

$$I_S = 8063 \left(1 - \frac{5}{2} k^2 + \frac{185}{8} k^4 + \dots \right) \frac{\text{lb. thrust}}{\text{lb. fuel/sec.}}$$

assuming an energy release of 19,000 B.T.U. per pound of fuel.

In Figure 3 values of T (in lb./sq.in.) and I_S are plotted as function of parameter k .

Thrust of a magnitude which is useful for propulsion purposes is of the order of 1.5/lb./sq.in. Since the corresponding value of k is equal to 0.1, this would require a maximum piston velocity of one-half the speed of sound (for an infinitely long acoustic jet tube).

A relation for the pressure exerted by a plane sound wave reflected from a wall was derived by Lord Rayleigh. If the same sound wave is produced by oscillating the wall, the radiation pressure is one-fourth of the value given by Rayleigh's formula. It may be shown that this value agrees with the one derived above for small values of k .

For a tube of finite length and a piston operating at resonance frequency, an estimate of thrust and specific impulse was obtained in the following way: Since in a tube of constant cross section, thrust can only be produced by pressure on the piston, the length of the jet tube is only important because the waves reflected from the open end may reinforce or weaken waves created by the piston motion. Maximum reinforcement of waves occurs at resonance. It is assumed that the pressure amplitude at the piston is increased by a factor f compared to the amplitude prevailing in an infinitely long tube. It may then be shown that thrust becomes proportional to f^2 while the specific impulse increases linearly with f . The unknown factor f was obtained from the previous experiments with acoustic jets as the ratio of experimental thrust to theoretical thrust for an infinitely long tube. The theoretical value of specific impulse using this factor showed good agreement with experimental data. Even with resonance, it appears that thrust values would be too small for purposes of propulsion, due to mechanical limitations. Higher values for thrust or specific impulse may possibly be obtained by a piston motion that is not sinusoidal but follows some other law. An analysis of a cycle with the piston moving forward and backward at constant but not necessarily equal speeds has been started. This work is still in progress and no conclusions have been reached as yet.

A similar analysis of the underwater jet indicated that the mechanism of such jets must be different from that of acoustic jets since water may be considered incompressible in these experiments. This preliminary analysis yielded values for thrust which were of the correct order of magnitude when compared with experimental results. No such agreement for the order of magnitude of the specific impulse values was obtained. However, both theory and experiments indicated that the specific impulse would be extremely high.

Study of Gas Flow in Half-open Pipes.

During 1947 a Technical Report No. 3 was issued where the outflow of compressed gas from a tube was analyzed. A number of characteristics diagrams were constructed corresponding to similar cases and a comparison of the results of the two methods showed that the agreement was poor. Since the characteristics method yields more accurate results, no further work on this particular analytical approach is contemplated.

Measurement of Gas Density in Non-Steady Flow.

This program was initiated primarily to obtain data concerning variations of state parameters under rapidly varying flow conditions for comparisons with theoretical work. Since an apparently satisfactory pressure gage has become available, this problem has temporarily been suspended.

Study of the Method of Characteristics for One-dimensional Non-steady Flow.

The method of characteristics is the most important theoretical tool available to solve

the equation of one-dimensional, non-steady gas flow. A systematic study of this method was started during 1947. The method is a graphical-numerical procedure to calculate state and flow parameters point by point in a position-time plane. Pressure waves which propagate along characteristic lines may be computed from the known initial and boundary conditions. The characteristic lines may be considered either as lines along which certain parameters behave in a known way, or as lines across which the state and flow parameters undergo discontinuous changes as an approximation to the actual flow condition. Both interpretations are being used and, for the sake of convenience, the corresponding diagrams are referred to as characteristics diagrams and wave diagrams, respectively. The procedures for wave diagrams were described in a SQUID Technical Memorandum CAL-14. Wave diagrams are limited in their use to isentropic flow although they may account for entropy discontinuities. A treatment of flame propagation where flames are represented by entropy discontinuities was described in SQUID Technical Memorandum CAL-23. Although it has been more and more necessary to concentrate on the use of characteristics diagrams, it was found that wave diagrams were of great value for initial instruction purposes.

The general study of the method was stopped at the middle of the year and no further systematic work is planned. The method, however, is continuously being applied to a number of problems.

Stability of Shock Waves in Supersonic Diffusers.

This program was inactive for most part of the year and was only taken up again during November. At first, the motion of a shock was studied which was produced by interrupting, for a short time, a steady flow in a duct of constant cross section.

Closing of the gate produces a shock wave of such strength that it produces a change of flow velocity equal to the initial flow velocity, V . If after a short time t_0 , the gate is opened again an expansion wave is created which, gradually, catches up with the shock and weakens it. Since a weaker shock travels more slowly, the path of the shock will be some curve in the x, t -plane. A successful attempt was made to obtain analytical relations for the shock motion using the following assumptions:

1. All changes of state are isentropic.
2. The gate interrupting the flow is closed and opened instantaneously.
3. For the shock velocity W_S an approximation of the Rankine-Hugoniot relation derived in SQUID Technical Memorandum CAL-14 was used:

For air, this formula becomes

$$W_S = U + A (1 + 3 dA/A + 3.5 (dA/A)^2)$$

where U and A are the velocities of flow and sound, respectively, of the medium in which the shock travels and dA is the increment of A across the shock. At each point of the shock, there

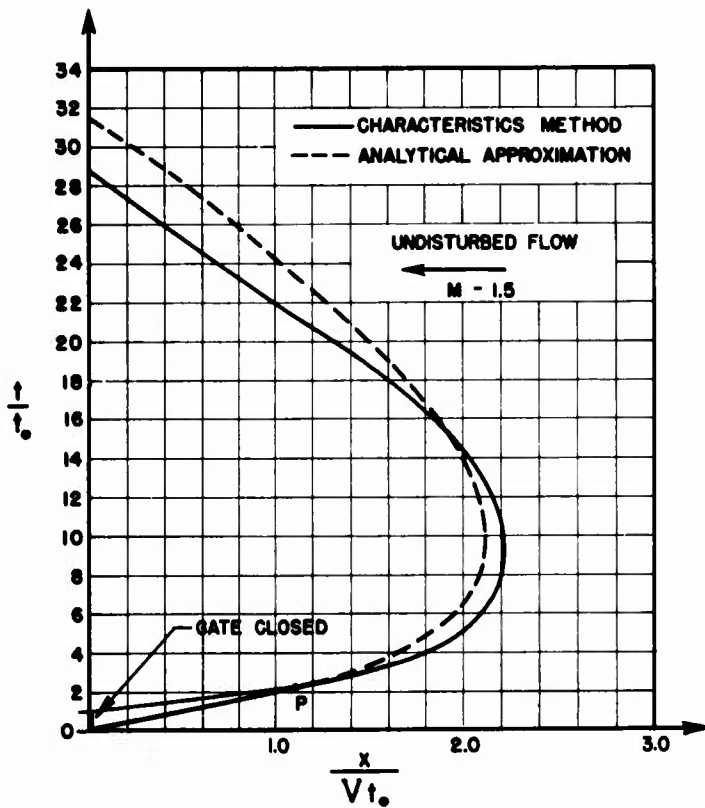


FIGURE 4

Interruption of a steady flow of $M = 1.5$ for a time t_0 . Path of the resulting shock wave as obtained by method of characteristics and an approximate analytical method.

maintaining the assumption of isentropic flow. The result is shown as the solid curve in Figure 4 and it is seen that the approximate analytical treatment agrees well with the more accurate characteristics method. The analytical relation may be utilized to calculate the maximum distance of upstream travel of the shock, the time of re-establishment of the initial flow, and other quantities of interest with an accuracy of a few percent provided the Mach number of the initial flow does not exceed 1.5. For higher Mach numbers, the analytical relations may be expected to rapidly become very inaccurate.

For Mach numbers of less than about 0.5 the last term in the equation for W_S becomes insignificant and in this case the shock path may be shown to be a parabola.

The analysis of the effect of small fluctuations of back pressure at Mach numbers near one which was carried out during 1947, is being completed by a comparison of the analytical results with those obtained by means of the method of characteristics, and a report is being prepared.

is a relation between shock velocity, W_S and strength, dA , given by the above relation, and for the characteristic line going through the same point, a relation between U and A is supplied from the condition of isentropic flow. These conditions may be combined to give a non-linear differential equation of first order for the shock path. It was possible to solve this equation and the result is shown as the dotted curve in Figure 4 for the special case of an initial flow of Mach number 1.5 from right to left. The head of the expansion wave reaches the shock at point P. It is seen that as the shock becomes weaker from then on, it also becomes slower and eventually reverses its motion. After a time of about $30 t_0$ the initial flow is re-established. In order to check the accuracy of the analytical treatment, a characteristics diagram for the same case was prepared without main-

Investigation of Valveless Pulse Jets.

Studies of characteristics diagrams and of acoustic jets indicated that it should be possible to build valveless pulse jets. After some experimentation successful intermittent operation was obtained when air and fuel was injected continuously.

Since such devices should have a long operating life, they could be used for various forms of intermittent combustion engines. A number of possible designs was suggested in SQUID Technical Memoranda CAL-15 and CAL-16. Nearly all experiments were carried out with small models, approximately the size of a dynajet but successful operation of a six inch valveless pulse jet was also achieved.

The models were made up of a number of units which could be assembled to give various configurations. The combustion chamber diameter was varied from $2\frac{1}{2}$ to 4 inches with a fixed length of 4 inches. By means of a short conical section, tailpipes of $1\frac{1}{2}$ inches diameter were attached. The length of the tailpipe could be varied continuously between 12 and 16 inches. Both propane and methane were used as fuels. Fuel consumption was measured by means of a small rotameter and thrust was determined on a small thrust stand and with the aid of a spring balance.

The highest values of specific impulse which could be obtained were about 2400 lb. thrust per lb. fuel/sec. for thrusts of the order of 3 lbs.

The operating frequency of these jets depended not only on the configuration but also on the air/fuel ratio. The highest values of specific impulse were obtained at frequencies which were lower than those at which an ordinary dynajet of the same shape would operate. So far, no definite conclusions as to the importance of various design parameters have been reached. It became apparent, however, that slight changes in design, air/fuel ratio or fuel injection system might have appreciable effects. For instance, it was observed in one instance that the specific impulse and thrust changed by 30% when the tailpipe length was changed by one quarter inch. Still larger variations were due to changes in air/fuel ratio.

Some of the preliminary experiments with such jets were described in SQUID Technical Memorandum CAL-20.

Recently a pressure gage of the type developed by NYU has become available and after some initial difficulties appears to operate satisfactorily. Experiments are now being conducted to determine the influence of various parameters on the pressure cycle.

A two-dimensional model of a valveless pulsejet has been constructed. The sidewalls are made of vicor glass. This model will be used in connection with a schlieren system to study the internal flow pattern under various conditions.

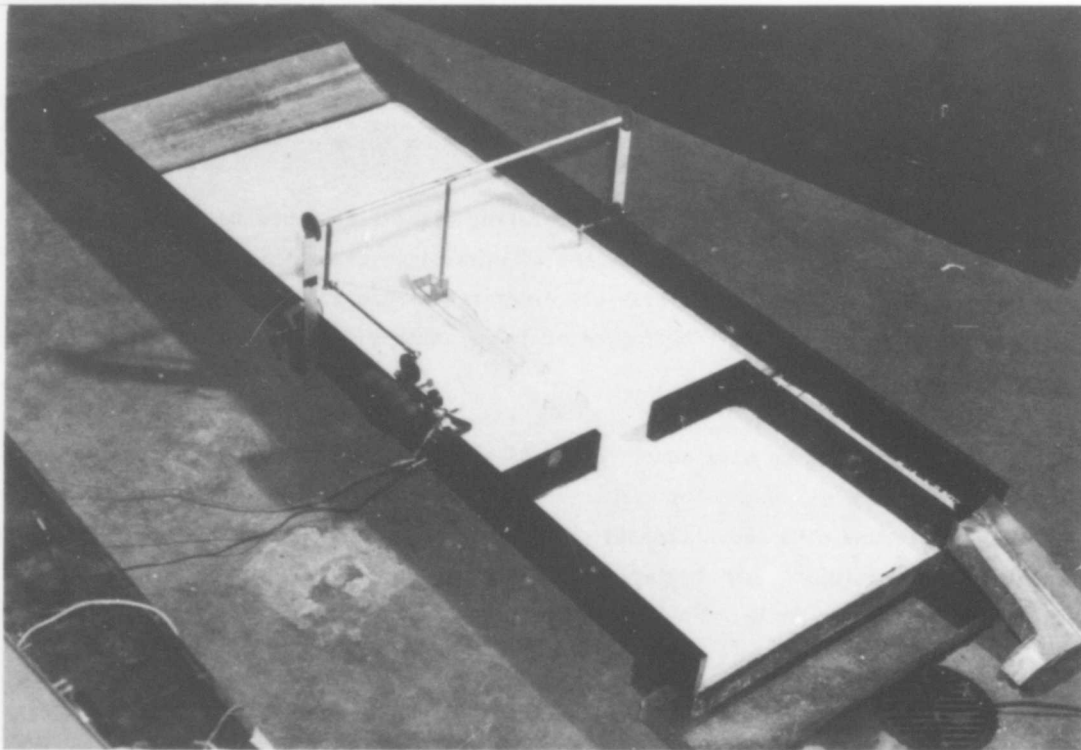


FIGURE 5

Water table for the study of shrouded pulse jets.

Study of the Operation of Shrouded Pulse Jets.

This program was only started during the latter part of the year. Enclosing a pulse jet in a duct produces effects on the flow about which very little is known. The preliminary approach to this problem was to determine whether the water analogy would provide useful information. Figure 5 shows the water table on which the pulse jet operation is simulated by a motor-driven pendulum. The flow in the duct enclosing the tail pipe is made visible by ink injected through capillary tubes.

In order to compare the flow pattern on the water table with that of an actual shrouded pulse jet, high speed motion pictures were taken of a valveless pulse jet surrounded by a two-dimensional duct. The flow was made visible by oil smoke. These films show that the flow pattern on the water table is essentially the same as for an actual pulse jet. It should, therefore, be possible to obtain information regarding the effects of duct shape, pulse jet frequency and flight Mach numbers by means of the water analogy.

Plans

Study of Pulse Jet Shapes by Means of the Analogy between Surface Gravity Waves in Water and Gas Waves in Ducts.

Water analogy will be applied to a study of pulse jet shapes. Information on desirable valve operation and ignition timing should also be obtainable from this investigation.

Study of the Mechanism of the Acoustic Jet.

The study of various acoustic jet cycles will be continued. The information obtained should in general be of value to pulse jet theory.

Study of Gas Flow in Half-open Pipes.

The pressure gage will be used to measure transients in half-open pipes. A comparison of these measurements with characteristics diagrams may lead to the establishment of proper boundary conditions for pressure waves of large amplitude.

Measurement of Gas Density in Non-steady Flow.

Temporarily suspended.

Study of the Method of Characteristic for One-dimensional Non-steady Flow.

No future work is being planned

Stability of Shock Waves in Supersonic Diffusers.

The present investigation will be continued and extended to ducts of variable cross section and to mixed supersonic and subsonic flows.

Cases of particular interest will be checked experimentally.

Investigation of Valveless Pulse Jets.

It is planned to continue experiments with small scale valveless pulse jets in the hope of isolating significant parameters that influence the performance of these devices.

Study of the Operation of Shrouded Pulse Jets.

The water analogy will be used to study the effect of shrouding a pulse jet. Parameters to be investigated particularly will be the shape of the duct, flight Mach number and pulse jet frequency. After some experience with these problems, it may become possible to develop theories of operation.

PHASE 2 (1)

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

Combustion Chamber Experiments.

The purpose of this work is to study stationary combustion in a duct, simulated by means of an ignition source moving with predetermined speed through a still combustible gas mixture. A spark between parallel-wire electrodes driven along the chamber by the field of a permanent magnet serves as ignition source. It is intended to study flame propagation under controlled conditions of gas pressure, temperature, composition, and flow. Design and construction of the combustion chamber and associated equipment has been finished. Preliminary tests of the chamber were performed with schlieren mirrors which were on loan from another department and are at present not available. Further tests had to be suspended therefore until a new pair of mirrors can be procured.

Burner Experiments.

This study is concerned with the effects of disturbances on flame shape and stability. Experimental techniques have been improved by applying spark photography and high speed motion pictures in combination with schlieren methods. Phenomena investigated include the effects of sound on flame stability, flame distortion caused by a vibrating wire, spontaneously oscillating inverted flames. The observed increase of amplitude of disturbances introduced into flame fronts is interpreted as an instability of the flow with respect to small disturbances. A theoretical study of this problem has been initiated. Flow visualization by means of particle injection is being attempted.

Flame Tube Experiments.

In this study, the velocity of flame-travel in a tube is measured by means of an electronic timing device connected with a number of ionization gaps along the tube. The original purpose of this work was to investigate the influence of constrictions and other obstacles on flame propagation. Preliminary tests showed that the electronic circuit functioned properly, but the results lacked sufficient reproducibility. The discrepancies were found to be caused partly by slight variations in the effects of pressure waves generated by the flame front and reflected at the ends of the tube. Only under changed experimental conditions, by

damping the reflection of pressure waves with glass wool pads at the ends of the tube, was it possible to improve reproducibility.

During these tests it became apparent that mere correlation of flame-travel data with experimental conditions would not contribute much toward understanding the basic phenomena involved. Investigation of the structure of flames propagating in tubes seemed essential for obtaining this information. Schlieren photography and cinematography were selected for this purpose. Schlieren movies taken with axial illumination of the flame in the tube showed very complicated structure, difficult to interpret. Further work was planned to separate the influence of pressure waves, stream turbulence, etc. on flame structure. It was found that even in the absence of such disturbances, flames in tubes assume a cellular structure. This result lends strong support to the assumption of an inherent instability of flame fronts, suggested by the results of the burner studies. In agreement with theoretical considerations, tests at reduced pressure showed the cell size to increase with decreasing pressure, a result considered to be of considerable practical importance.

Progress

Combustion Chamber Experiments.

Design and construction of the combustion chamber and associated equipment were finished during the first and second quarters of the year. The equipment includes a high voltage supply for the moving spark a condensed spark light source with its power supply, and a thyratron timing unit for the synchronization of spark light and camera shutter with ignition. The spark light source and the timing unit were designed flexibly enough to be also used in other applications, particularly in connection with the burner experiments.

Preliminary tests of the combustion chamber showed that on the whole the equipment functioned as anticipated. Timing of the spark movement by means of a number of auxiliary electrodes placed along the main electrodes was not satisfactory when combustion occurred in the chamber because of disturbances caused by flame ionization. These electrodes were therefore replaced by a single one which can be placed anywhere along the chamber. It serves the dual purpose of tripping the spark light and of allowing measurement of the average velocity of spark motion between start and exposure of the schlieren image of the flame front.

Exploratory tests of the chamber indicated that at least in the beginning the flame front followed the movement of the igniting spark and the flame surface appeared fairly smooth. It was noticed further in these tests that the velocity of spark travel had decreased over a period of several months, which indicates a gradual loss of field strength of the permanent magnet.

These experiments were performed with a pair of schlieren mirrors obtained on loan from another department. Since the mirrors were no longer available during the third and fourth quarters of the year, work had to be suspended during that period. It is expected that a pair of mirrors for this purpose will be procured early next year.

Burner Experiments.

The experimental techniques employed in this study of the effects of disturbances on flame shape and stability have been improved and extended to non-periodic phenomena by the application of spark photography and high speed motion pictures in combination with schlieren methods. A simple schlieren setup, Figure 6, consisting of a point light source, a lens of 11.25 inch focal

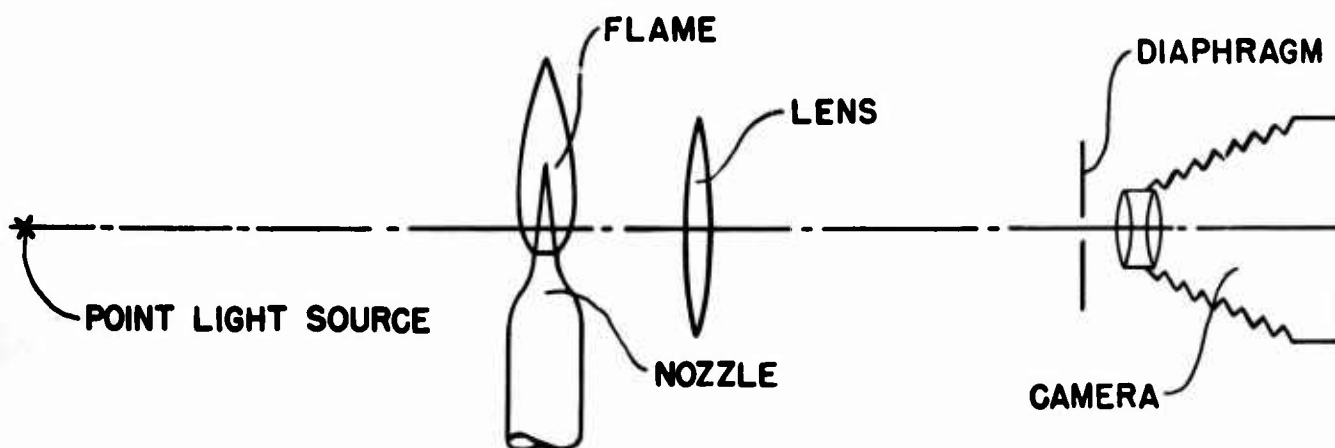


FIGURE 6

Schlieren setup.

length and 4-½ inch diameter and a diaphragm with a small circular hole serving as schlieren stop, proved to be entirely adequate for this work. The condensed spark light source developed for the combustion chamber study was used for spark photography. High speed motion pictures were taken with a 16 mm Fastax camera, using a 100W Western Electric Concentrated Arc Lamp as light source. Synchronization of transients with the spark light or with the motion picture camera was achieved by means of the thyatron timing unit designed for the combustion chamber.

Among the phenomena which were investigated by means of these techniques were the effects of acoustical disturbances on flame stability. Sound was found to have an adverse effect on the blow-off stability of seated flames, causing the flame to lift under the influence of a sufficiently intense acoustical disturbance at one of the resonance frequencies of the gas column in the burner pipe. This effect may possibly provide a means for defining and measuring, at least in some arbitrary way, the amount of stability of burner flames. It was found

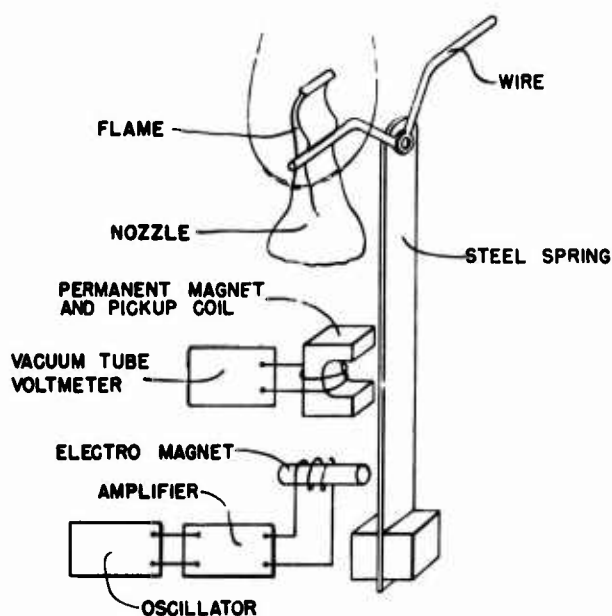


FIGURE 7

Vibrating wire arrangement.

further that a stabilizing effect of sound is present as soon as the flame has lifted from the burner port under the influence of the disturbance; when the disturbance is removed; the flame does not return to the burner, but blows off completely. A plausible explanation of this effect, confirmed by motion picture studies, was found in the increase of vortex motion in the boundary of the emerging gas jet caused by the acoustical disturbance.

Figure 7 shows the vibrating wire arrangement which was used for introducing disturbances of known initial amplitude into the flame. Vibration of the steel spring carrying the wire is caused by the electromagnet, energized by the oscillator-amplifier com-

bination. A convenient means for measuring the vibration amplitude was provided by the output of the pickup coil, which had been calibrated against the amplitude measured by a micrometer microscope. Figure 8, page 124 shows schlieren motion pictures, taken at approximately 3300 frames per second, of the effect of the wire vibrating at 2 frequencies on a burner flame. The increase of amplitude of the distortion of the flame front, as the waves travel upward from the wire, is clearly visible. It can be seen further that the distortion is unsymmetrical: the wave crests are smoothly rounded toward the unburned gas, while they are sharply pointed toward the burned gas. This is the type of deformation to be expected if it is caused, as has been inferred previously (1), by a flow disturbance, superposed over the main flow. It can also be seen that the flame front on the right side, undisturbed by the wire, follows in its upper part, to a certain degree, the deformation of the other flame front. This confirms further the presence of a flow disturbance penetrating from the directly distorted flame front into the unburned gas.

Attempts to visualize and measure the disturbance velocities by means of particles injected into the gas stream have not yet been successful, owing to the difficulties caused by the non-steady nature of the flow phenomena to be studied. Since it does not seem possible to deduce with sufficient accuracy the disturbance velocities from the distortion of the flame front alone, work on the particle method is being continued.

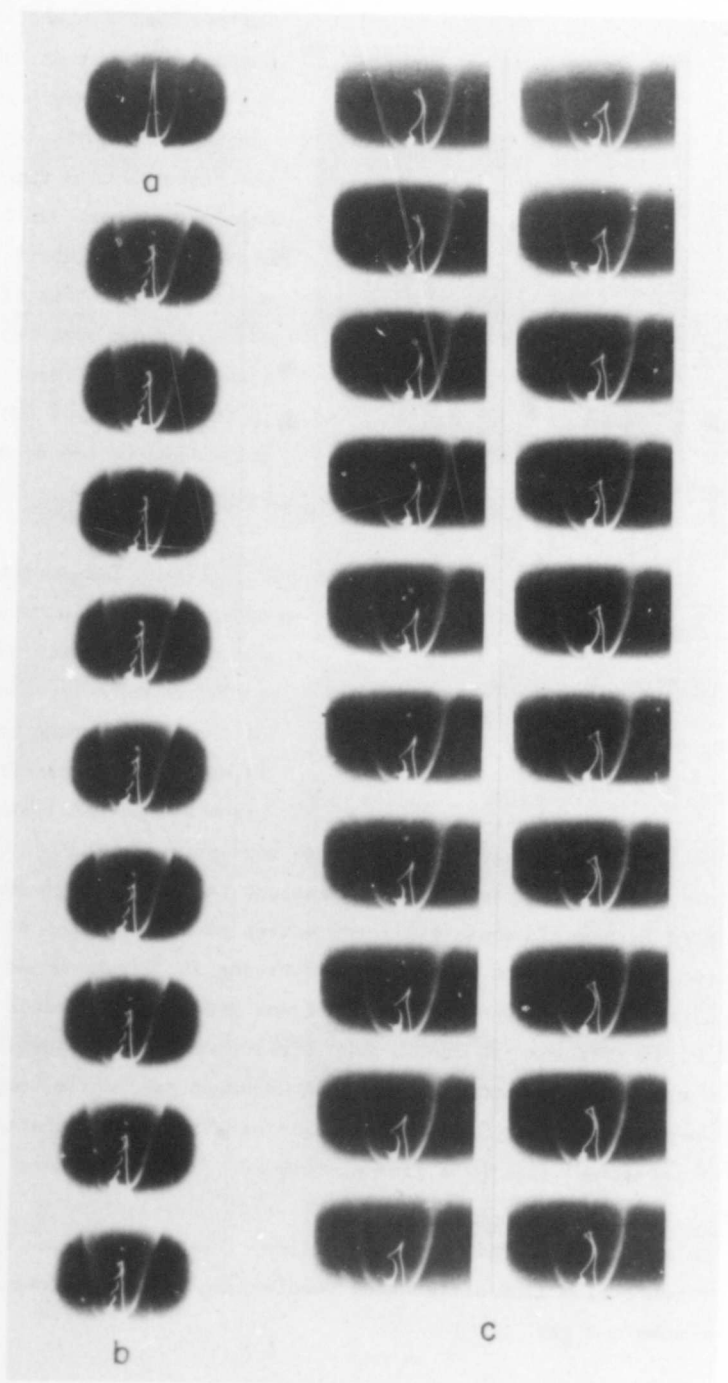


FIGURE 8

Effect of vibrating wire on Bunsen flame. 330 frames per second.

(a) without disturbance.

(b) frequency 430 cps. amplitude 0.3 mm.

(c) frequency 175 cps. amplitude 0.75 mm.

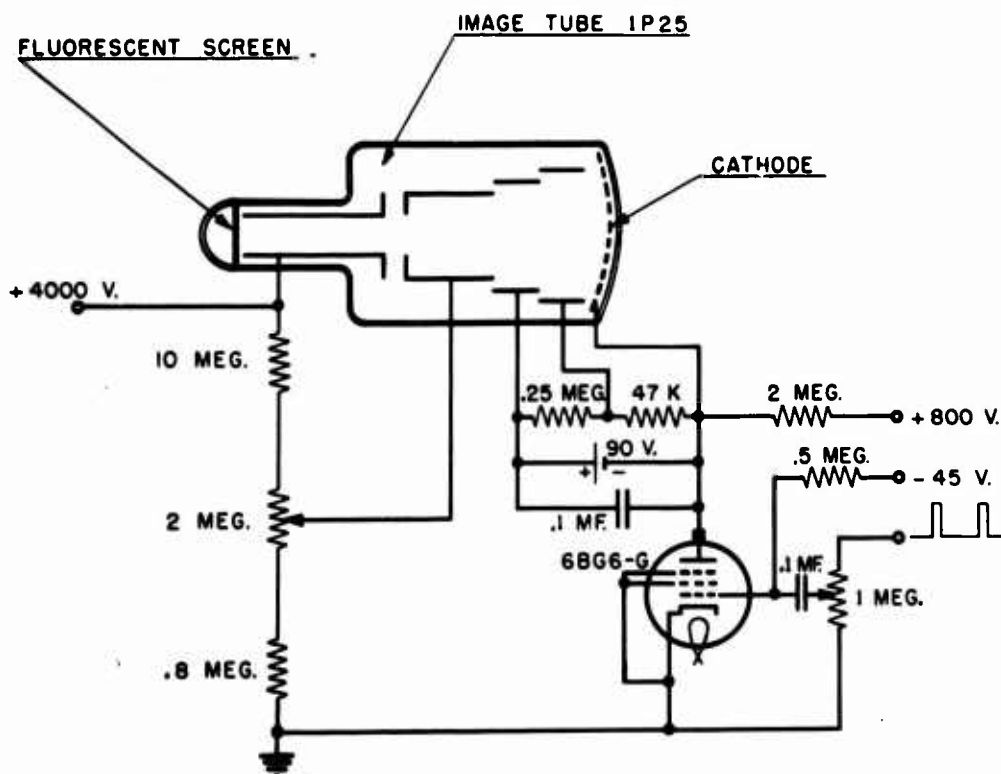


FIGURE 9

Circuit for stroboscopic operation of image tube.

It appeared of considerable further interest to investigate the temperature field in the vicinity of a disturbed flame front. An attempt was made to observe periodic temperature fluctuations stroboscopically by viewing the flame with an infrared image converter tube 1-P-25 operated with periodically varying electrode potentials. Figure 9 shows the circuit which enabled the use of the tube as a stroboscope by applying rectangular voltage pulses to the grid of the 6BG6-G tube. Visual observation of the fluorescent screen definitely indicated that temperature fluctuations were present in the burned gas behind periodically distorted flame fronts, at least at frequencies below about 200 cps. Photographic registration of the image was difficult, however, due chiefly to the inadequate light output of the fluorescent screen. In order to make this instrument of value for pulse jet studies and similar problems, the quality of the image would have to be improved by designing a special tube for the purpose.

The most important single result of the burner flame studies appears to be the observed increase of amplitude of disturbances introduced into flame fronts. This phenomenon is quite similar to the growth of disturbances in the laminar boundary layer (2) and is thus indicative of an instability of the flow through the flame front. (For further support of the assumption of instability, see the next section.) The two phenomena are distinguished, however, by the

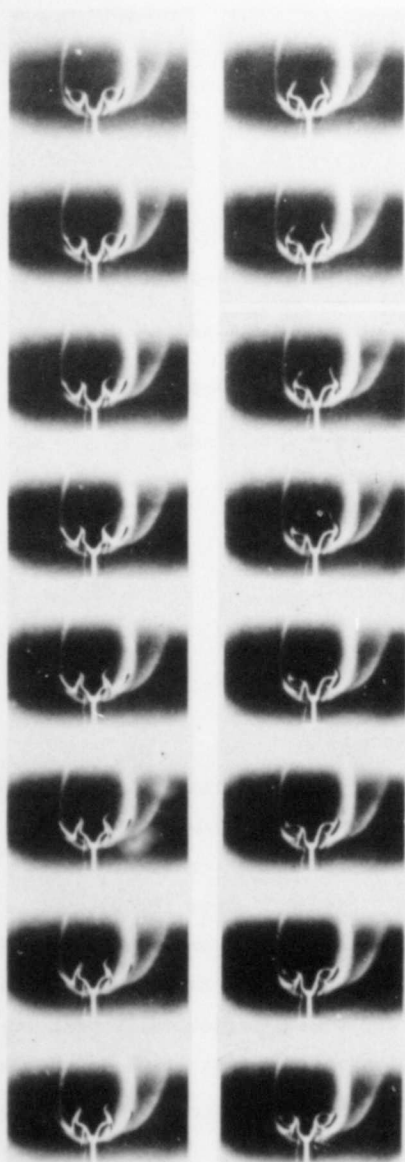


FIGURE 10

*Spontaneous oscillating
inverted flame.*

*330 frames per second,
frequency 250 cps.*

direction of the velocity gradients in the undisturbed flow: In the boundary layer, the gradient is perpendicular to the streamlines and is caused by viscosity; in the flame front, the gradient is parallel to the streamlines and is caused by the expansion of the gas due to the temperature rise. Accordingly, while the transfer of energy from the main flow into the disturbance is due to viscosity in the case of boundary layer flow, it appears reasonable to assume that in the case of the flame front, part of the thermal energy is diverted into the disturbance instead of causing only an acceleration of the main flow.

The excitation of spontaneous vibrations in inverted flames seems to confirm these views. A study of this phenomenon has also been initiated. Figure 10 shows schlieren motion pictures of an oscillating inverted flame held on a wire inserted into the gas jet. The vortex motion in the unburned gas is seen to be greatly amplified by the flame. The oscillations are apparently maintained by acoustical feedback from the flame to the gas jet. Similar acoustical phenomena may occur frequently in flame holding devices, and may often be responsible for unexpectedly large effects on performance of minor changes in flameholder design.

Because the experimental results clearly indicate the importance of the hydrodynamical stability of flame fronts, a theoretical investigation of this problem has been started. Previously (3) instability of plane flame fronts had been proved under the assumption of incompressible, non-viscous flow, taking the flame front as a surface of discontinuity of normal velocity. The latter assumption appears to be open to serious criticism; therefore, the treatment has been extended to a flame front of finite thickness with a continuous change of flow velocity. It was found, however, that a purely hydrodynamical treatment in this case does not lead to non-trivial

solutions for the disturbance. Physical considerations show that a valid treatment must include thermal as well as flow phenomena. Starting with the Euler, continuity and heat balance equations, a system of differential equations for the first order velocity, pressure, temperature and density perturbations has been derived. Solutions of these equations have not yet been found, owing to the considerable analytical difficulties involved.

Flame Tube Experiments.

The original purpose of this study was the investigation of the influence of constrictions and other obstacles on flame propagation in tubes.

It will be recalled that a steel tube of 2-1/4 inch i.d., made up of sections of 2 ft. length, between which the obstacles could be inserted, is used for this work. An oscillographic record of flame travel is obtained by means of ionization gaps placed at 1 ft. intervals along the tube, each of which upon passage of the flame causes a thyatron to be tripped and thereby transmits a voltage pulse to the oscilloscope.

After completion of the thyatron unit, preliminary runs of the tube without obstacles were performed. Operation of the electronic circuit was entirely satisfactory. The results showed, however, a serious lack of reproducibility, both in runs with the ignition end open and the other end closed and vice versa. Climatic influences may have been partly responsible for the discrepancies between experiments performed on different days. However, a major influence on flame propagation in tubes is exerted by pressure waves emitted by the flame front and reflected on both ends of the tube. Due possibly to slight variations in the early development of the flame following ignition, the intensity of these disturbances seems somewhat different in each experiment, thus causing appreciable changes in the overall course of flame travel. Only in runs, where experimental conditions were changed fundamentally by damping reflection of pressure waves with pads of glass wool at the ends of the tube, could the reproducibility be improved considerably.

During these exploratory experiments, it became increasingly evident that a mere empirical correlation of flame travel data with experimental conditions would contribute little towards an understanding of the basic phenomena involved. Since it is generally agreed that increases of flame speed beyond the laminar burning velocity are primarily caused by increases of flame surface area, an investigation of the structure of flames propagating in tubes appeared to be essential for obtaining this basic information. The need for this type of work becomes even more apparent when it is realized that in spite of the large amount of work which has been done on flame propagation in tubes, practically no information on flame structure can be found in literature.

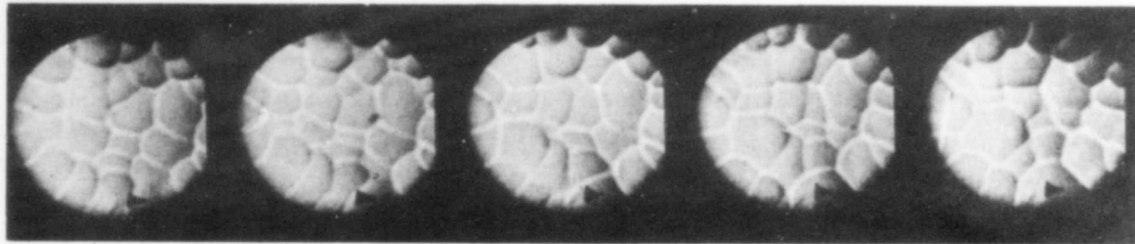


FIGURE 11

Cellular flame in tube of 2- $\frac{1}{2}$ inch inner diameter. 64 frames per second.

The methods of schlieren photography and cinematography were selected for this purpose. Exploratory work was done with the flame tube made up of 5 sections of 2 ft. length. Ignition was at the open end, the other end was closed with a flat plate of Vycor glass. High speed schlieren motion pictures of flames propagating in the tube were taken by means of a parallel beam of light passing axially through the tube.

These movies showed the flame structure to be very complicated and continuously changing. The effects of oscillations of the gas column, increasing and decreasing in intensity several times during flame travel, were plainly visible.

Because of the complicated nature of the observed structure, which made interpretation difficult, further work was planned with the purpose of studying the influence of pressure waves, stream turbulence, etc. separately. Visual observation of flames in a vertical glass tube of 2- $\frac{3}{4}$ inch i.d., which were kept practically stationary by proper adjustment of flow velocity and mixture composition, lead to a somewhat unexpected result. In spite of the lack of stream turbulence because of the small flow velocities used, and the absence of acoustical disturbances, the flame assumed, over a wide range of compositions, a 'cellular' structure. The structure observed here seems to be quite different from the cell structure obtained in the experiments at New York University. In these experiments, after the flame passed through the grid, a considerable length of the tube appeared to be filled simultaneously with small cells, while here comparatively few cells were distributed side by side in one layer. Each of the cells consisted of an approximately hemispherical cusp, convex downward towards the unburned gas and separated from the neighboring cells by rather sharp ridges pointing upwards into the burned gas. The cells were in continuous irregular motion. (Note that the deformation of flame fronts subjected to artificial disturbances, described in the preceding section, is of the same nature.) Schlieren motion pictures of this structure were taken with a slightly different setup in which the flame was kept stationary by a converging-diverging section close to the top of the vertical flame tube of 2- $\frac{1}{2}$ inch i.d. Figure 11 shows a few frames, taken at

64 frames per second, in which the cells seem to be generated at the wall and move towards the center. Whether this is due to the particular experimental conditions, or whether it occurs also in straight tubes, has not yet been determined.

The appearance of a cell structure even in the absence of stream turbulence and other disturbances seems to lend strong support to the assumption of an inherent instability of flame fronts, which has been discussed in the preceding section. Cell formation in the case of convection from a lower hot to an upper cold plate (4) has been treated successfully as a stability problem (5). In the case of the flame, as well as in the case of convection, the cells must be caused by flow disturbances of the nature of vortex rings, superposed over the main flow. The average size of the cells, which was experimentally found to be about 1/2 to 3/4 inch for propane-air mixtures, should be obtained in the theory as the wave length of the disturbance for which instability is a maximum. Though the theoretical problem of flame front stability has not yet been solved, an important result of the theory has been confirmed experimentally. Dimensional analysis shows that the size of the cells should be proportional to the thickness of the (laminar) flame front, under otherwise equal conditions. Since, as is well-known, the thickness of the flame zone is essentially inversely proportional to pressure, exploratory tests at reduced pressures were performed in the CAL Altitude Chamber. These tests completely confirmed the theoretical conclusion that cell size must be essentially inversely proportional to pressure.

Apart from its theoretical significance, this result has also considerable practical importance. Even in the presence of turbulence and other disturbances the instability of flames leading to breakdown into cells may still play an important role. It is thus reasonable to assume that the properties of flames will be markedly different depending on whether the apparatus (duct, flameholder, etc.) is large or small compared with the average cell size. The dependence of cell size on pressure may thus explain some of the difficulties experienced in high altitude burning, and may suggest means for overcoming them.

Plans

Combustion Chamber Experiments.

As soon as a pair of schlieren mirrors can be obtained, tests will be resumed.

Burner Experiments.

Future work will be concerned primarily with flow visualization by means of particle injection. The theoretical study of flame stability is continuing.

Flame Tube Experiments.

Study of flame structure and effects of disturbances on flame travel in tubes will continue.

PHASE 2 (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

During the year 1948 the work carried out under Phase 2(2) at Cornell Aeronautical Laboratory may be classified under the following problems:

- a. *Theoretical Studies of and Determination of Heat Release during Combustion,*
- b. *The Possible Catalytic Influence of Combustion Chamber Wall Material, and*
- c. *Investigation of the Effect of Combustion Conditions on the Spectra of Hydrocarbon Flames.*

Theoretical Studies of and Determination of Heat Release during Combustion.

From heat transfer considerations it was shown that the time required to cool a gas sample between any two temperatures in a small-diameter water-cooled probe is independent of the sampling rate and is proportional to the square of the tube diameter. For a tube of 0.010 inch internal diameter, the time required to cool hydrocarbon combustion gas from its flame temperature to 1000°F is about 30 microseconds. Special refrigeration is of little advantage. A water-cooled sampling probe was designed, constructed and tested. Results showed that the cooled probe prevented the reassociation of carbon monoxide and oxygen when these gases were in equilibrium with carbon dioxide at 3000°F at the instant of sampling. Strong evidence was obtained that the reassociation of carbon monoxide and oxygen and of hydrogen and oxygen was prevented in samples removed from flames at 4200°F.

The Possible Catalytic Influence of Combustion Chamber Wall Material.

The possible catalytic effect of various wall materials and surface conditions on the combustion of premixed fuel and air has been investigated in heavily insulated tubes of small internal diameter. In comparison with Inconel, various metals and their respective oxides exhibited no appreciable difference. Silica, however, exhibited a positive effect. No significant effects could be traced to the internal surface condition of the tube.

In making microphotometer tracings of the densities of the CH bands in the region 4315 \AA , it was observed that maximum emission was obtained at a pressure of approximately 27 mm. When the actual photographs of the flame were densitometered to obtain the total intensity of emitted light as a function of pressure, a maximum was found at about 30 mm. These observations together seem to indicate that the CH radical may be the primary source of emission in these low pressure flames.

The present experimental work is comprised of further more detailed study of these effects, especially the affect on the C_2 radical concentration

Plans

Theoretical Studies of and Determination of Heat Release during Combustion.

Discontinued as of June 30, 1948. A Technical Memorandum, CAL-8, has been issued, which summarizes the result of this investigation.

The Possible Catalytic Influence of Combustion Chamber Wall Material.

Discontinued as of June 30, 1948. A Technical Memorandum, CAL-12, which summarizes this work has been drafted.

Investigation of Effect of Combustion Conditions on the Spectra of Hydrocarbon Flames.

With regard to the determination of the concentration of radicals in the flame from emission spectroscopy, it may be possible to find this value. If the fraction of the total light which enters the spectroscope can be established for a given band, and if an absolute calibration of density versus intensity for the plates used at the frequency of the given band can be made, then the total number of emitters can be calculated by dividing the integrated energy in the band by $h\nu$. However, before the number of emitters so calculated can be traced to the number of radicals which would emit, excitation and radiation probabilities must be established. This is not an easy matter, although some progress has been made through absorption measurements.

The foregoing emphasizes the desirability of having available instrumentation for making absorption measurements in the infrared region, and to this end the design of a pulsating infrared source similar to that reported by Silverman and Herman (7) is underway.

A scanning unit is also in the process of construction, which will permit measurement of the total emissivity of the flame.

The scanning mechanism proper is a revolving perforated disk which optically permits examination of the flame in twelve horizontal sections, through intervals of 30 seconds per section.

Pick-up of variations in the flame intensity is made by a photoelectric device, amplified and then recorded directly on a Brown Electronic recorder. Completion of this unit is expected soon.

Attempts are also being made to determine the relative order of appearance of the various transient species in the flame. Here again the sectioning feature of the scanning disk will be utilized.

A general outline of the program of attack on the project problem has been formulated in a series of progressive experiments, outlined on the basis of the preliminary results. These are outlined below:

A. With the oxygen-fuel ratio held constant.

To study:

1. Effect of pressure on OH concentration.
2. Calibration of the OH bands.
3. Energy involved; possible pressure affects on equipartition.
4. Possibility of quantitative measurements of the OH concentration.

B. With the oxygen-fuel ratio held constant.

To study:

1. Effect of pressure on CH concentration.
2. Calibration of CH bands.
3. Energy involved; possible pressure affects on equipartition.
4. Possibility of quantitative measurements of the CH concentration.

C. With the pressure held constant.

To study:

1. Effect of varying oxygen-fuel ratio on OH concentration.
2. Effect of varying oxygen-fuel ratio on CH concentration.
3. Effect of varying oxygen-fuel ratio on C_2 concentration.

D. To study:

1. Effect of pressure on flame intensity.
2. Effect of oxygen-fuel ratio variation on flame intensity.
3. Estimation of life time of the CH radical.
4. Effect of pressure on flame temperature.
5. Effect of oxygen-fuel ratio variation on flame temperature.
6. Temperature of various areas in the flame.
7. Pressure gradients within the mantle in the vicinity of the orifice.

The search outlined above would require expenditure of considerable effort in excess of that presently provided for, however, all phases were included to emphasize the broad scope and continuity of the program.

Investigation of the Effect of Combustion Conditions on the Spectra of Hydrocarbon Flames.

In the study of combustion phenomena at low pressure, spectrographic examinations of stable flames, burning over a wide range of pressures and oxygen/fuel ratios have been made in the ultraviolet region of the spectrum. Preliminary results indicate that the OH radical concentration may be related to the pressure through the relation $[OH] \approx A \log p$. The CH radical concentration in the flames exhibits a similar behavior. Extensive broadening of the reaction zone has been observed with reduction of pressure in the burner.

Progress

Theoretical Studies of and Determination of Heat Release during Combustion.

To obtain experimental evidence, gas of known composition and temperature was studied. This study was difficult because of difficulties encountered in finding materials capable of withstanding the high temperature. To obtain significant amounts of CO by dissociating CO_2 , thereby having a known composition, a temperature of the order of $3000^\circ F$ is necessary in order that the amount of CO be even a moderate fraction of one percent. Containing the samples in refractory tubes heated externally by flames proved unsatisfactory because of discrepancies in the resultant analyses which indicated that the tubes were quite porous to the products of combustion.

Of the various methods tried, heating CO_2 in a 1-inch I.D. Sillimanite tube inserted in a hollow Globar element proved the most satisfactory. Temperatures in excess of $2800^\circ F$ could be attained for short periods of time, and a section 16-inches long in the center was maintained at constant temperature. By keeping a slow flow of CO_2 into one end and inserting the sampling tube from the other, it was safe to assume the gas temperature at the point of sampling was the same as that of the walls as measured by a calibrated platinum-platinum rhodium thermocouple. The thermocouple was near the end of the cooled sampling tube and, therefore, its direct reading needed a correction added to it. The correction was determined by placing the thermocouple-sampling tube assembly in a muffle furnace and calibrating against the known temperature of the furnace. The furnace temperature was known by means of the thermocouple measurements confirmed by optical pyrometer measurements.

The excellent agreement between the temperature at which the gas is in equilibrium with constituents found in the sample and the measured temperature indicates that no appreciable re-association of CO and O_2 occurred in the sampling tube after cooling.

Due to the great difficulty encountered in maintaining materials at known temperatures only as high as $3000^\circ F$, no attempt was made to treat the H_2O dissociation in a manner similar to that of CO_2 , for it would have required a temperature approximately $1000^\circ F$ higher in order to produce

appreciable quantities of hydrogen and oxygen by dissociation.

The Possible Catalytic Influence of Combustion Chamber Wall Material.

In further evaluating the catalytic effect of various wall surfaces on the combustion of premixed fuel and air in tubes of small diameter, additional combustion experiments have been made under conditions designed to eliminate dissimilar heat transfer effects between tubes of various compositions. In these tests the relative activity of different surfaces was evaluated by measuring the mass-flow required to cause the flame to blow out of the tube at a given air-fuel ratio. The effects of surface roughness were similarly investigated.

Copper or silver films deposited on stainless steel produced no appreciable change in the mass flow required to produce blow-out. However, when silver was deposited on silica, the mass flow required to produce blow-out was reduced 25% from the value normally found for silica. These results substantiated previously reported results. (6)

Sandblasting and coarse shotblasting of stainless steel tubes did not result in any appreciable change in the mass flow required to produce blow-out. It was concluded, therefore, that surface roughness of the magnitude here introduced did not affect the combustion.

Investigation of Effect of Combustion Conditions on the Spectra of Hydrocarbon Flames.

Schlieren photographs of these low pressure flames failed to yield any satisfactory negatives. It is apparent that the density and temperature gradients are so slight that no schlieren photographs are possible with our present equipment. Caydon and also Broeze have also noted this absence of schlieren effects at low pressure.

An initial series of spectrophotometer exposures was made of the methane-oxygen flame in the region $2875\overset{\circ}{\text{A}}$ to $4871\overset{\circ}{\text{A}}$. These exposures were taken at progressively low pressures beginning at a maximum burner pressure of 47 mm. and progressing down to a minimum burner pressure of 12 mm. with a constant oxygen-fuel ratio of 2.2. Simultaneously conventional photographs were taken of the flame at each of the pressure settings.

The exposures were made with the intent of investigating the effect, if any, of pressure on the concentration of the OH, CH, and C₂ radicals in the flame, since in this region numerous bands of these emitters are present. Microphotometer tracings of the densities of the OH bands in the region $3064\overset{\circ}{\text{A}}$ make it appear that the OH concentration is proportional to $A \log p$, where A is a constant (in this instant A was 1) and p the pressure at which the burning is taking place. However, the curve has not been corrected for the geometry of the experimental setup, i.e., for the difference in the volume of a flame reaction zone which was focused upon the slit.

PHASE 3

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

Summary

Work under Phase 3 during the year 1948 has centered upon an investigation of: 1. *Construction of a high temperature Metalloscope*, 2. *High temperature tensile testing of sheet materials*, 3. *High temperature short time creep testing of sheet materials*, 4. *High temperature fatigue testing of sheet materials*.

Construction of a High Temperature Metalloscope.

The current high temperature metalloscope has been used satisfactorily on 24 ST aluminum specimens up to 1000°F under 10^{-4} mm. of Hg vacuum with excellent visual observations of the microstructures. A description is given on the vacuum furnace, vacuum system, and the optical system.

High Temperature Tensile Testing of Sheet Materials.

On the basis of data obtained for a number of heat resistant sheet materials, a high-temperature mechanism of deformation was described similar to that encountered in metallic diffusion. Such an interpretation was reached through determination of the activation energies associated with high-temperature flow and particularly the variation of these energy values with stress. At the present time additional high-temperature deformation tests are being conducted on pure copper, iron, and aluminum to compare the activation energies of deformation extrapolated to zero stress with those of self-diffusion for these metals.

High Temperature Short Time Creep Testing of Sheet Materials.

The factors affecting the creep strength of austenitic stainless steels are being investigated with current emphasis upon utilizing the sigma phase as a hardener for these alloys. By proper combination of cold working, aging temperature and time, it is possible to control the pattern of sigma phase formation so as to materially harden the structure while still retaining sufficient ductility. Creep tests on the microstructures tested to date indicate that marked increase in strength may be attained up to 1400°F for short life periods.

High Temperature Fatigue Testing of Sheet Materials.

An apparatus has been constructed for conducting high-temperature creep tests under fluctu-

ating tensile load conditions. In preliminary tests, conducted in the temperature range of 1200 to 1800°F on 24 Cr - 20 Ni - 2 Si steel, the frequency of load fluctuation was found to be an important variable affecting the creep rate obtained. Further testing will be made to investigate the variables of temperature, frequency, static load, and fluctuating load magnitude.

The pneumatic fatigue apparatus, using a cantilever type specimen, has been used for comparing the relative resistance of sheet materials to high-temperature bending fatigue failure at the short-life end of the scale. Under these test conditions it was not possible to determine the stresses involved but comparison of three materials under similar conditions indicated the following order of superiority; S-816, regular inconel, and 25 Cr - 20 Ni - 2 Si.

Progress

Construction of a High Temperature Metalloscope.

The three main problems required satisfactory solution in order to obtain photomicrographs of metal structures at high temperatures; namely

1. A vacuum tight furnace.
2. A vacuum system capable of obtaining 10^{-5} mm. of Hg vacuum.
3. A suitable optical system consisting of microscope and camera.

Figure 12, page 137 illustrates the currently developed high temperature metalloscope.

The vacuum furnace consisted of a platinum wound, refractory cylinder surrounded by a water cooled outer chamber. A transite washer separated the surface of the heated specimen from the quartz window. The temperature of the specimen was measured with a chromel-alumel thermocouple placed in a hole 1/32" below the surface to be studied. Visual observations have been made of specimens heated to temperatures as high as 1800°F.

The vacuum system consisted of a Cenco-Megavac forepump, a two-stage oil diffusion pump, a manifold for introducing the ionization and Pirani gages into the system, and the furnace. The sealing materials used were De Khotinsky's cement, rubber tubing with Celvacene, and rubber gaskets with Celvacene. Acetone was used very satisfactorily to detect leaks. With previous outgassing of the furnace and specimen, a vacuum of 7×10^{-5} mm. of Hg was obtained with this system.

During a period when delays were experienced in obtaining parts for the vacuum system, an alternate method for controlling atmosphere was tried. By connecting a forepump and an argon

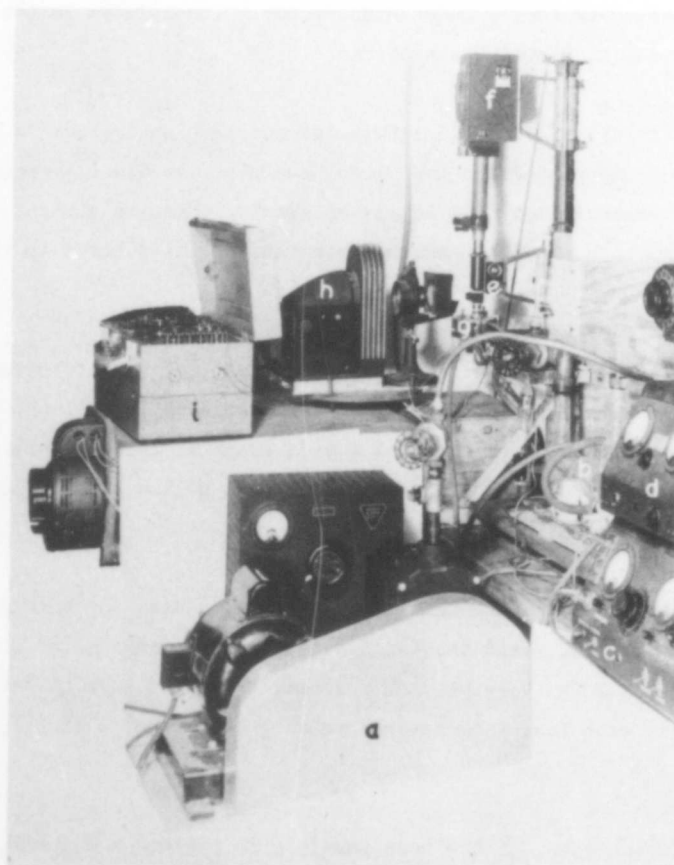


FIGURE 12

High Temperature Metalloscope.

- | | |
|----------------------------------|-------------------------|
| (a) Cenco-Megavac Vacuum Pump | (f) 16 mm. Movie Camera |
| (b) Two-stage Oil Diffusion Pump | (g) Furnace |
| (c) Ionization Gage | (h) Illuminating Unit |
| (d) Pirani Gage | (i) L & N Potentiometer |
| (e) Microscope | |

gas cylinder to the furnace, alternate purging and pumping, and then holding the furnace under argon gas pressure, a 24 ST aluminum specimen was heated to 1000^oF with excellent visual observations of the microstructure. Since commercial purity argon caused oxidation difficulties, a spectroscopically pure argon gas was required.

The optical system caused difficulty when a relay lens of poor quality was used. By eliminating this lens and air cooling the 16 mm. objective while it was brought close to the quartz window, satisfactory results were obtained. The present optical system consists of a 16 mm. objective a 10X ocular, and a partially silvered prism which permits 10% of the light to pass to an observation eyepiece and 90% to the 16 mm. movie camera. Satisfactory moving pictures were taken of 24 ST aluminum at room temperature. Additional movies were taken of

aluminum specimens heated to 1000°F under high vacuum. The film is in the process of being studied and correlated with visual observations.

Recent experiments using 24 SI aluminum specimens with an average vacuum of 10^{-4} mm. of Hg enabled one to view and photograph the microstructure. In order to remove the outgassing in the furnace, the temperature had to be raised slowly. Results indicated a change taking place in the microstructure at 950°F, which is tentatively attributed to eutectic melting.

High Temperature Tensile Testing of Sheet Materials.

In conjunction with the study of the sheet materials for high temperature jet engine service, data have been gathered involving the basic variables of stress, strain, strain rate, and temperature. By suitable correlation of a wide range of these quantities controlling the deformation characteristics of a material, some features of the high temperature deformation process have been defined.

The short-time high-temperature tensile test has been used for this purpose and was conducted in such a manner as to yield true stress-true strain diagrams at constant temperature and strain rate. Strain rates varying from approximately 0.02 to 5.0% per minute have been used for all materials with test temperatures ranging from room to 1800°F, depending upon the alloy under study.

On the basis of such data, it has been possible to picture a deformation process for a metal at high temperatures as similar to that of metallic diffusion in which relative displacement of the atoms occur by their individual shearing actions past their neighbors. As indicated in a paper (3) presented to the American Society for Metals, this concept is prompted by determination of the activation energies associated with the high-temperature deformation process and comparison of their magnitudes with those associated with diffusion in the same alloys.

Figure 13 illustrates the variation of activation energy with stress found for several of the sheet materials tested. The fact that such energy values decrease with increasing stress may be interpreted to mean that the increased elastic dilation of the lattice structure due to increased applied stresses permits easier transposition and squeezing of the atoms past their neighbors from one position to another. If such a curve be extrapolated to zero stress, the activation energy so obtained should be representative of that associated with diffusion of the atoms involved. This latter point is being examined more critically by high-temperature deformation tests being conducted on pure metals for which the activation energies of self-diffusion are known.

High Temperature Short Time Creep Testing of Sheet Materials.

The many qualities of the austenitic chromium-nickel stainless steels from the procurement,

EFFECT OF STRESS ON ACTIVATION ENERGIES AT THE CONSTANT STRAIN VALUES INDICATED

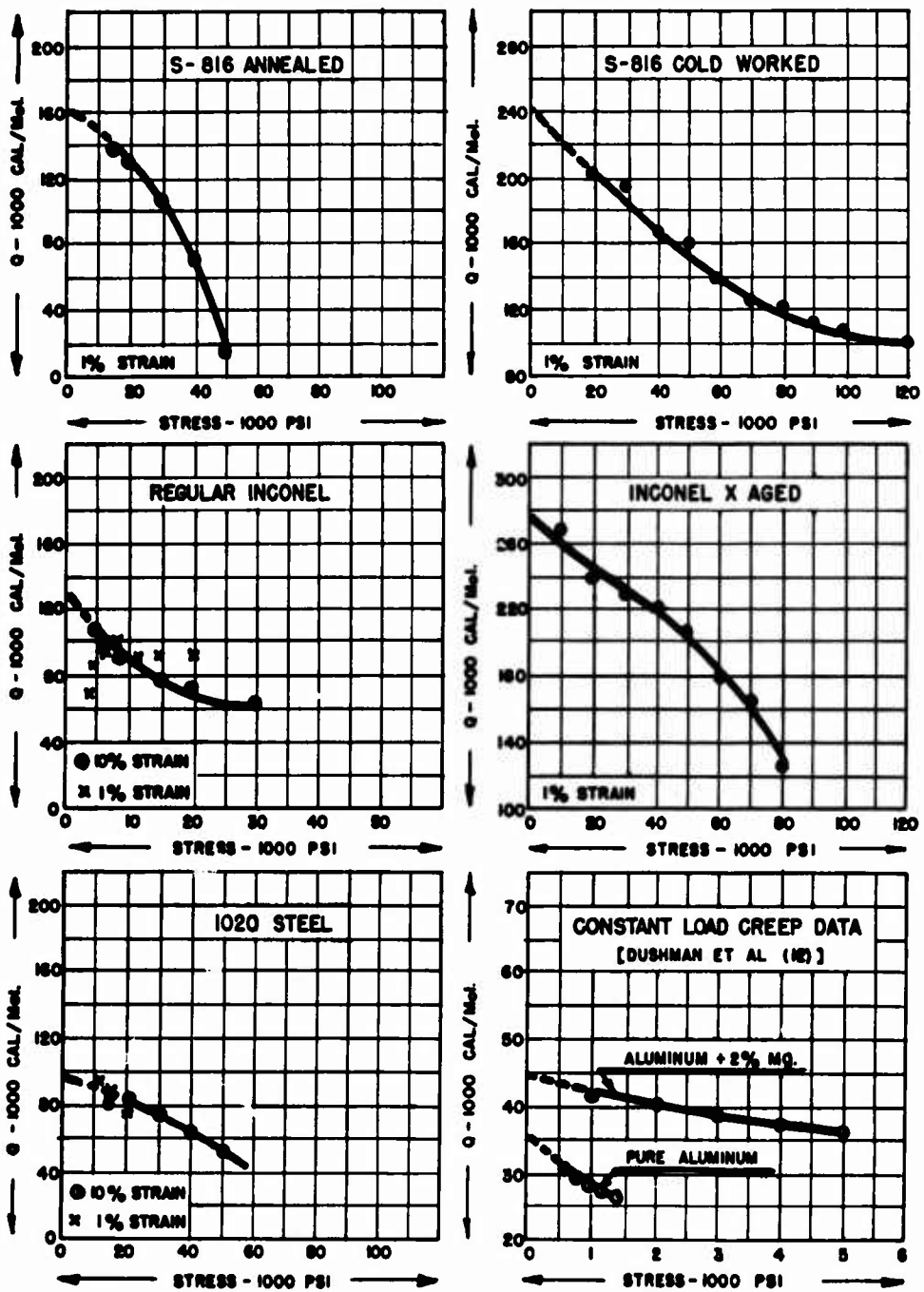
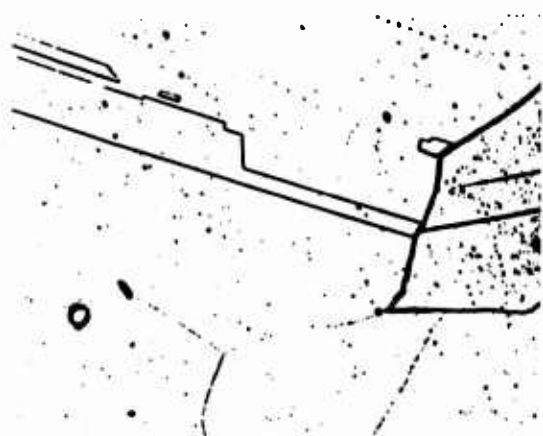


FIGURE 13

Effect of Stress on Activation Energies at the Constant Strain Values Indicated

25 Cr - 20 Ni - 2 Si Stainless Steel



EB 70 500 X
2000° F - 30 Min. - A.C.



EB 92 500 X
2000° F - 30 Min. - A.C.
1600° F - 200 Hr.



EB 95 500 X
25% Cold Work
1600° F - 15 Hrs.



EB 98 500 X
50% Cold Work
1600° F - 15 Hrs.

FIGURE 14

Microstructures of Heat Treated 25 Cr-20Ni-2Si Stainless Steel

fabrication, and service standpoint would dictate this type of material to be a desirable one for jet engine construction. Consequently some effort has been devoted to improving its high-temperature creep characteristics through heat treating methods. While such steels are not susceptible to heat treatment in the normal sense of the word, marked variations in properties may result from such treatments causing cold work, recrystallization, carbide and sigma phase formation. Emphasis has been placed on studying the effect of sigma distribution on the high temperature properties of such steels using a 25 Cr - 20 Ni - 2 Si sheet material.

Preliminary to a mechanical testing program, a metallographic study has been made of this alloy initially in the annealed, 25% cold worked, and 50% cold worked condition and treated at

HIGH TEMPERATURE PROPERTIES OF 25 Cr-20 Ni-2 Si STAINLESS STEEL

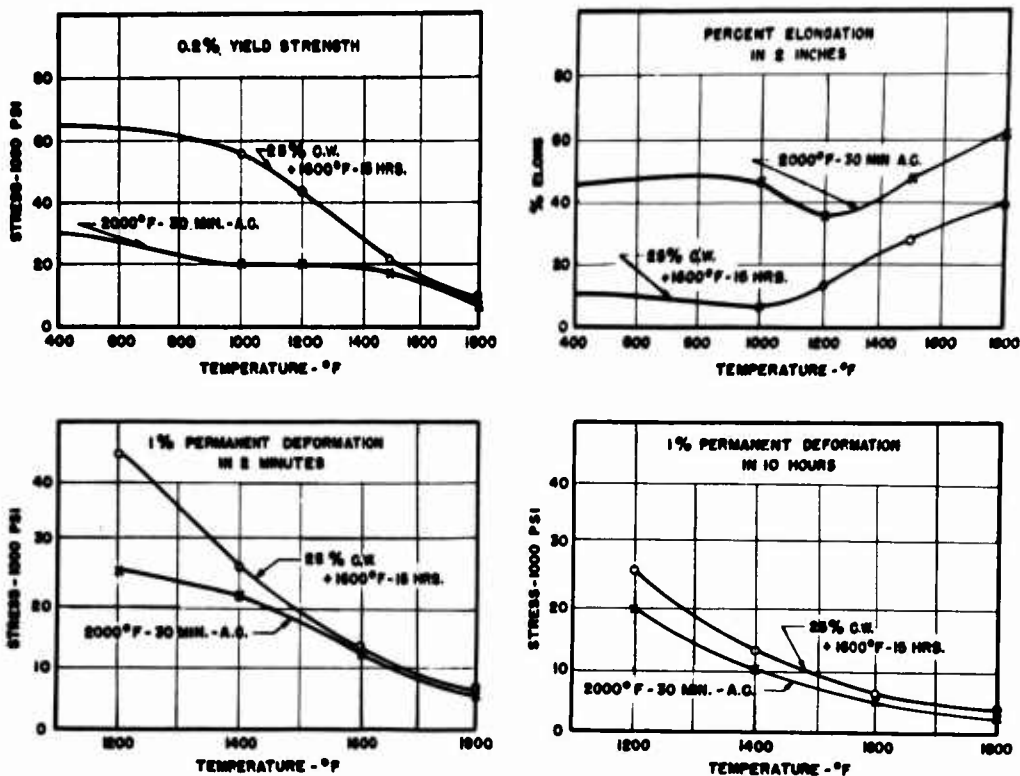


FIGURE 15

High Temperature Properties of 25 Cr-20 Ni-2 Si Stainless Steel.

1500, 1600, 1700, and 1800°F for various time periods. By use of various combinations of cold working, aging times, and temperatures it was found possible to control the quantity and distribution pattern of the sigma phase developed in this alloy. By development of a finely distributed sigma constituent considerable hardening of the alloy may be had while retaining suitable ductility characteristics.

Figure 14 displays several of the typical microstructures being compared with respect to their high temperature load-carrying-ability.

The high temperature yield strength, ductility, and short-time creep properties are illustrated in Figure 15 for the annealed microstructure and the sigma-tized one produced by 25% cold reduction plus 15 hours at 1600°F. The short-time strength properties of the annealed structure may be markedly improved at temperatures up to 1400°F as here shown. Other structures of different sigma and configurations and austenitic grain sizes are being considered.

**CREEP OF 25Cr-20Ni-2Si STAINLESS STEEL
UNDER STATIC AND FLUCTUATING LOAD CONDITIONS**

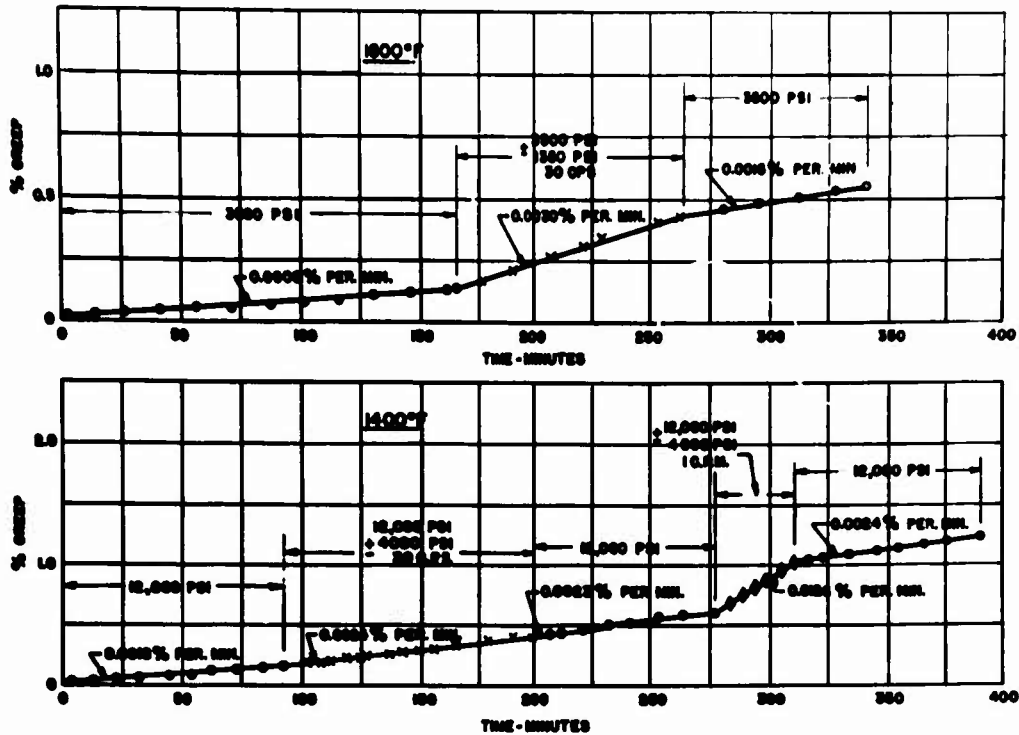


FIGURE 16

Creep of 25 Cr-20Ni-2Si Stainless Steel under Static and Fluctuating Load Conditions.

High Temperature Fatigue Testing of Sheet Materials.

While much of the material evaluation data determined by high-temperature creep testing is done under static load conditions, fluctuating loads are more commonly encountered in service. Therefore, an attempt is being made to determine the fluctuating load effect on the creep properties of materials. Apparatus has been constructed for such tests in which the specimen tension stress may be cycled at sine wave frequencies varying from 1 cycle per minute to 30 cycles per second while strain readings are being made on the specimen at temperatures up to 1800°F.

Typical of the results obtained from preliminary tests are those shown in Figure 16. In the test made at 1800°F, the application of a 30 cps load, fluctuating about the mean stress, caused accelerated creep as might be expected from consideration of the exponential relationship between creep rate and static stress. While a cyclic stress of the same frequency and proportionate magnitude applied at 1400°F had no effect on the creep rate, the same fluctuating stress cycled at 1 cpm did materially influence the rate of strain observed. It is felt that fluctuating load may or may not influence the creep properties depending upon the com-

ination of temperature and frequency of load cycling involved. Other variables such as mean stress level and amplitude of fluctuating stress may be of considerable significance.

The pneumatic type fatigue machine, with a cantilever type test specimen, was used to conduct high-temperature bending fatigue tests on several heat resistant sheet materials in the temperature range of 1200 to 1800°F at the time this testing machine was constructed and put into operation it was anticipated that test data would be obtained correlating maximum fibre stress with number of cycles to failure. Experience with this equipment at the high-temperatures and large stresses used to give relatively short-time failures had indicated that the stress quantity cannot be calculated or measured accurately. However, tests conducted under similar conditions with different materials are capable of providing qualitative comparisons of the relative merits of different alloys exposed to high-temperature bending fatigue conditions. Tests conducted to date on 25 Cr - 20 Ni - 2 Si stainless steel, regular Inconel, and S-816 indicate increasing resistance to hot bending fatigue life in the order mentioned.

Plans

Construction of High Temperature Metalloscope.

Future plans include the study of steel heated to produce the change to austenite, greater refinement in the vacuum system to provide higher pumping speeds and higher vacuum while specimen is at temperature, and use of a larger film size camera.

High Temperature Tensile Testing of Sheet Materials.

By conducting additional high-temperature deformation tests on relatively pure metals it should be possible to determine activation energies of deformation which when extrapolated to zero stress should compare in magnitude with energy values found by other investigators through self-diffusion experiments. To this end, sheet stock metals of copper, aluminum, and iron of approximately 99.9% purity have been procured and are being prepared for testing. While the data will be obtained primarily for the purpose of determining activation energy values, it will be further analyzed to see if other interpretations applying to deformation may be made.

High Temperature Short Time Creep Testing of Sheet Materials.

In the current series of creep tests being conducted, the possibility of using sigma phase as a strengthening agent is being investigated. If advantage can be gained by this means in the 25 Cr - 20 Ni - 2 Si steel being studied, similar studies would be extended to the other austenitic varieties such as the 18-8 and 25-12 types.

Other microstructural variations such as grain size and carbide distribution should be investigated for optimum properties.

High Temperature Fatigue Testing of Sheet Materials.

In view of the preliminary results obtained with fluctuating load creep tests, it is planned to investigate the effect of the variables of frequency, temperature, static stress, and fluctuating stress magnitude on the rate of creep observed for several heat resistant materials such as 310 stainless steel and Inconel X. It is felt that any effects produced by these variables may be used to further our general understanding of the high-temperature creep deformation process.

It is planned to use the available pneumatic fatigue equipment for comparing the high-temperature bending fatigue life of other materials such as Inconel X, GT-45, and 1020 carbon steel. The equipment may be applied to evaluating the relative fatigue strengths of welded joints and notched sections although in the latter case further effort should be made to estimate the magnitude of stresses involved.

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ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ori-105, TASK ORDER III
DESIGNATION NO. NR 220-038

*Princeton University
Princeton, New Jersey
1 January 1949*

PHASE I

In connection with liquid rockets and pulsating jet engines; to investigate theoretically and experimentally: (1) the stability of the laminar boundary layer, (2) the interaction of the boundary layer with the 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.

Summary

Phase I is no longer an active part of Project SQUID. Since 1 July 1948, this phase has been sponsored jointly by the Office of Naval Research, Fluid Mechanics Division, and the Bureau of Ordnance, Applied Physics Laboratory. Progress prior to this change of sponsorship was last outlined in the Project SQUID, Quarterly Progress Report dated 1 July 1948. In addition, reference is made to Project SQUID Technical Memorandum Number PR.-8, dated

29 May 1948, entitled *The Princeton Pilot Variable Density Supersonic Wind Tunnel* by Seymour M. Bogdonoff.

PHASE II

Under Joint Sponsorship of:

*Bureau of Ordnance
Navy Department
Contract NOrd-7920, Task PRN-3
Applied Physics Laboratory, Johns Hopkins*

*Project SQUID
Office of Naval Research
Navy Department
Contract N6ori-105, Task Order III
Designation No. NR220-038*

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 of ionization and flame, (4) observation of optical and mass spectra and (5) theory of adiabatic exothermic reaction.

Summary

Investigations in progress during the past year have been directed toward an understanding of the physico-chemical aspects of flame propagation, and of ignition. Examples include: (1) Kinetics of slow combustion of ammonia; (2) Kinetics of decomposition of diborane; and aluminum borohydride; (3) Interaction of aluminum borohydride and olefines; (4) Reactions of hydrogen atoms with hydrocarbon-oxygen mixtures; (5) Effects of electric fields on bunsen flame; (6) Explosibility of hydrogen-chlorine mixtures under strong illumination.

The bearing of such data on combustion in jet devices is discussed.

Progress

The essential feature of any jet propulsive device likely to be developed in the near future (excluding nuclear energy sources) is an efficient high-velocity combustion unit. It is therefore important to arrive at an understanding of the nature of the combustion process itself. It may seem surprising that such an understanding has not already been achieved, but the fact is that apart from purely thermodynamic aspects the development is still in its specu-

lative stages. The reason for this lies in the extraordinary variety of combustion phenomena, and the extreme complexity of the elementary processes of chemical reaction, radiation, conduction, convection, diffusion, and flow which are simultaneously involved. Obviously, the first effort has to be in the direction of isolation of variables.

Investigations conducted under this task order are limited primarily to chemical reaction mechanisms, and their relation to the problems of ignition and flame propagation. High-velocity fuel-air streams have been given less attention in this work not only because of the obvious complications due to purely aerodynamic effects but more particularly because combustion under such conditions ordinarily requires the use of a pilot or flame holder which has the effect of preventing the observation of ignition and propagation independently of one another. Most experimental work has been carried out in static systems, or under conditions of laminar flow. In this way studies are being made of:-

1. Kinetics of slow combustion of ammonia;
2. Kinetics of decomposition of diborane and aluminum borohydride;
3. Interaction of aluminum borohydride and olefines;
4. Reactions of hydrogen atoms with hydrocarbon-oxygen mixtures;
5. Effects of electric fields on the bunsen flame;
6. Explosibility of hydrogen-chlorine mixtures under strong illumination.

Some of the results of these investigations are discussed below in their bearing on combustion processes in jet propulsion systems.

It is first of all taken for granted that such combustion processes are fundamentally radical chain reactions. Hence any treatment which assigns a secondary role to the formation and reaction of free radicals, or no role whatever, is chemically inadequate. Secondly, it is believed to be essential that two aspects of the combustion process be distinguished - namely, the 'transient' phenomena involved in ignition (and extinction), and the 'steady-state' phenomena of flame propagation. In these terms, the combustion problem resolves itself into a consideration of what kinds of radicals may be present, how they are formed and destroyed, and how they interact with fuel and oxidant molecules both in the process of setting up the flame front, and in its subsequent propagation through the fuel-oxidant mixture.

Concerning the necessity of regarding combustion processes as radical chain reactions, there can hardly be any question at the present time. Such chains involve:-

1. a chain-initiating process,
2. the chain propagation,
3. a chain-ending process,

or alternatively in outline:-

1. $RX \rightarrow R + X$
2. $R + A \rightarrow B + R'$
 $R' + C \rightarrow D + R$
3. R (or R') \rightarrow Inactive species.

Radicals may be formed by normal dissociation processes in the medium or at the wall of a container; they may be supplied by dissociation of an added sensitizer; or they may arise from photochemical dissociation, or from collisions with electrons in an electric field. Provided the source is not too intense or the reaction too exothermic, an approach to steady-state reaction under isothermal conditions results. However, explosion is always a possibility if temperature and concentration gradients develop, or if a chain-branching mechanism enters into the reaction scheme. The above radical sources are then properly described as sources of ignition. Since explosion may develop so rapidly that temperature equilibrium and the like are not maintained, the phenomena are of a transient nature.

If the immediate source of ignition is in contact with a further supply of unburnt fuel-oxidant mixture, a new sort of steady-state may be set up corresponding to propagation of the explosion to give a flame front. In this case radicals are no longer supplied by an external source of the medium itself but come from the flame front by a process of diffusion, as Tanford especially has shown. Tanford assumes that radicals are present in thermodynamic equilibrium concentrations in the flame front of a bunsen type burner, and that the rate-controlling process is the back-diffusion of such radicals into unburnt gas. A fixed concentration gradient is set up which determines how fast the mixture can be fed to the flame front - this being equal to the propagation rate in the backward direction. The rate or flame speed is given approximately by the expression:-

$$\text{Rate} = \frac{(kC_{\text{ave}}C_0D)^{1/2}}{Q}$$

where k = reaction rate constant

C_{ave} = average concentration of reactant

C_0 = equilibrium radical concentration in the flame front

D = diffusion coefficient for the radical into unburnt gas

Q = quantity of combustible in unit volume.

By means of this expression it has been found possible to give a reasonable account of the change in flame speed with composition and with pressure.

Ignition and propagation are ingeniously combined in jet propulsion systems. Both turbo-jet and ram-jet engines are made capable of operating at feed rates far in excess of that characteristic of the bunsen type burner by the introduction of a pilot or flame holder which provides

a steady source of ignition. This juxtaposition of the two phenomena is especially to be emphasized when considering operations at high altitude. It is apparently well substantiated that both turbo-jet and ram-jet systems begin to fail when operating chamber pressures drop much below 1 atmosphere. Yet there is plenty of evidence that the bunsen-type burner will function at pressures approaching 0.1 atmosphere. Further, Tanford's theory and much experimental data indicate that flame speeds actually increase within limits as pressure is lowered, due to the fact that the diffusion coefficient, D , varies inversely as the pressure. The failure of the jet systems cannot therefore be ascribed to burning velocity. It must then represent a failure of the ignition agency. That this is likely to be the case is indicated by the data of Lewis and von Elbe on minimum spark energies where it is found that the minimum required rises rapidly as pressure falls. Evidently the solution to the difficulty must be searched for in more efficient flame holders and pilots, or in fuels requiring lower ignition stimuli.

The latter eventuality was recognized early in the development of this program, and remains a primary consideration. Several systems reported to be capable of spontaneous ignition at room temperature have been under investigation - among them nickel carbonyl, zinc dimethyl, boron triethyl, diborane, and aluminum borohydride with air or oxygen. Of these, boron triethyl was shown to be the most active at low pressures, with zinc dimethyl not far behind. Nickel carbonyl was indicated to have no practical value because of an excessively long induction period. Neither diborane nor aluminum borohydride (when dry) showed any marked tendency to react with oxygen until temperatures were reached approaching those for decomposition (100-200°C). All these substances could eventually induce the explosion of hydrocarbon-oxygen mixtures, however.

Early work was also done on the spark ignition of fuel-oxidant mixtures at low pressures. From this emerged the fact that ethylene oxide of all substances tested, had the broadest low pressure ignition limits in air or oxygen-much broader than various organic nitrogen compounds or propylene oxide, or any of the other organic oxygen compounds investigated.

Another conclusion drawn from the spark-ignition work was that mixtures of ammonia with air or oxygen were extraordinarily difficult to ignite, though visual observation indicated that once ignition had occurred, flame travel was quite fast. This has led to an investigation of the slow non-catalytic oxidation of ammonia, from which has emerged the conclusion that ammonia is an inhibitor for its own oxidation. The inhibitory action of ammonia on the photosensitized oxidation of hydrogen had previously been observed by Taylor and Salley, but no similar data on the thermal reaction were available.

The use of a spark source of ignition is complicated by the lack of a clear theory of the elementary processes occurring in electrical discharges, and by the fact that the electrodes themselves introduce extraneous effects. As an alternative, experiments have been undertaken

on photo chemical ignition with the system, hydrogen-chlorine. Preliminary data have only confirmed that explosion occurs under strong illumination (a photo-flash bulb), but there is great irregularity in the data at present. This method could be extended in principle to any system capable of absorbing radiation in a convenient range.

Another kind of study of ignition is under consideration. It is well known that a flame is itself a suitable source of ignition, but there has been as yet no systematic attempt to regulate or characterize the igniting flame. There is no obvious reason why this cannot be done, and it will be tried. Such a system would of course come close to that actually employed in jet engines.

Interesting results are being obtained on the interactions of hydrogen atoms (from Wood's discharge tube) with hydrocarbon-oxygen mixtures. The mixtures are found to be excited to reaction at room temperature and 0.3 mm pressure, thus indicating that normally the slow process is formation of active radicals rather than the subsequent reactions. Although the results are incomplete, it has been noted that the character of the product follows closely on the structure of the hydrocarbon. Thus n-butane seems to give mainly acetaldehyde, as though the split occurred at the middle bond (attack on secondary hydrogen); with iso-butane (branched structure) both acetone and formaldehyde were detected; with 1 butene an attack at the double bond gives propion aldehyde and formaldehyde; with 1-3 butadiene the identified products were acrolein, formaldehyde and glyoxal. Additional data for methane, propane and propylene lead to the conclusion that reactivity increases with increasing size of the molecule and is substantially greater for olefines than for paraffins.

Although data of these kinds have no immediate practical application on jet combustion systems, it is hoped that they will assist in interpretation of the elementary processes which are involved.

Some attention has been given to the problem of ions normally present in flames. Estimates of concentrations based on measurements of conductivity and of saturation currents give quite small values - of the order of 10^8 - 10^{10} ions per cc, rising to 10^{12} ions per cc when alkali salts are added. Although the magnitudes are quite uncertain due to difficulties of measurements and interpretation, there is little doubt that the numbers are small. However even these magnitudes are not easy to account for - in fact it would appear that for thermodynamic equilibrium the ionization potentials of the atomic or molecular species involved can only be a few volts, and much less than those of any known stable species. One possibility is that the values deduced from conductivity measurements do not represent equilibrium values but that the field applied in making the measurements itself contributes to the free energy of the dissociation process, that is, that normal coulombic attractions between ions are partially neutralized. Alternatively, the ions may be excited products of intermediate reactions.

Another aspect of the ion problem has to do with effects of electric fields on flame speeds. Speeds are increased by fields over a limited range. Calculations indicate that the effect may be mechanical - the phenomenon being allied to the so-called 'electric wind.'

Plans

All of the systems noted in the 'Summary' will continue under investigation. In addition, as mentioned in the body of the report, it is planned to study ignition by a pilot flame of controlled characteristics. More generally, the nature and mechanism of ignition will be emphasized, as it is believed that this, in contrast to propagation, is the least understood and perhaps the most critical feature of jet combustion systems.

PHASE III

To study some of the problems connected with the development of propulsive devices of the ducted type. Specifically, these problems are: (1) the mixing of parallel gas streams, (2) means of improving such mixing, (3) combustion chamber problems.

Summary

Phase 3 of Project SQUID at Princeton University is concerned with the theoretical and experimental investigation of certain of the fundamental problems associated with the development of ducted propulsive devices. This phase was initiated in July 1947 and is being carried out by the Department of Aeronautical Engineering under Contract No. N6-ori-105, Task Order III.

One of the basic problems in the functioning of such propulsive devices is that of ejector action, in which a high velocity primary gas jet entrains portions of the surrounding air and thus induces a secondary flow of air in the duct. The performance of a ducted propulsion unit, particularly in certain speed regions, will depend on the proper design of the ejector, which forms the core of the device.

For this reason, the staff assigned to this phase has chosen to concentrate, in the first portion of the program, on a study of the performance possibilities and limitations of gas-driven air ejectors. In any specific instance, the primary jet may be supersonic, or may lie in the high subsonic range. For most purposes, however, this jet may be considered to be supersonic, as in the exhaust from a rocket motor.

The program of study of this problem consists of the following theoretical and experimental investigations:

THEORETICAL AND ANALYTICAL STUDIES.

1. The study of the performance of constant area ejectors driven by supersonic gas jets.
2. A similar study of ejectors in which the mixing is accomplished at constant static pressure.
3. Preliminary studies of entire ducted units, such as the inducer-ramjet, based upon the results obtained above.
4. Such other studies as may be indicated in the course of the problem.

EXPERIMENTAL STUDIES.

1. An investigation of the performance of an ejector driven by a cold supersonic air jet.
2. A study of various schemes to improve the performance of such an ejector.
3. Fundamental studies of the two dimensional mixing of a supersonic stream and a subsonic stream.
4. Development of a reliable, fifty pound thrust rocket motor.
5. An investigation of the performance of an air ejector built around this rocket.
6. A study of the problems associated with the placing of afterburners or ramjet units behind this rocket ejector.

Progress

THEORETICAL AND ANALYTICAL STUDIES.

During 1948, the problem of performance estimation in both constant area and constant pressure ejectors has been studied in some detail. One-dimensional solutions to both cases have been obtained in terms of non dimensional parameters describing the character of the primary jet and the geometry of the ejector. The study of the constant-area ejector has been completed and issued as a Technical Memorandum. Computation of the solutions for spe-

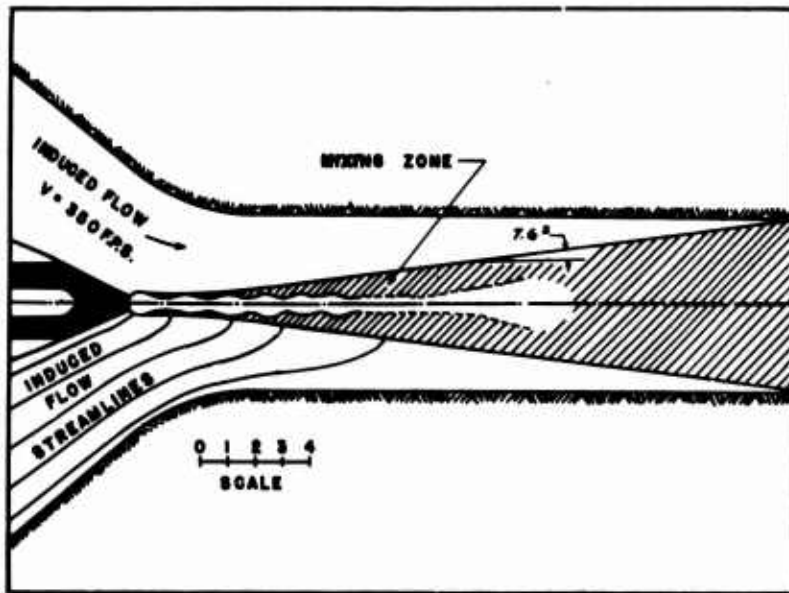


FIGURE 1

Flow in a straight ejector with jet Mach No. = 1.37.

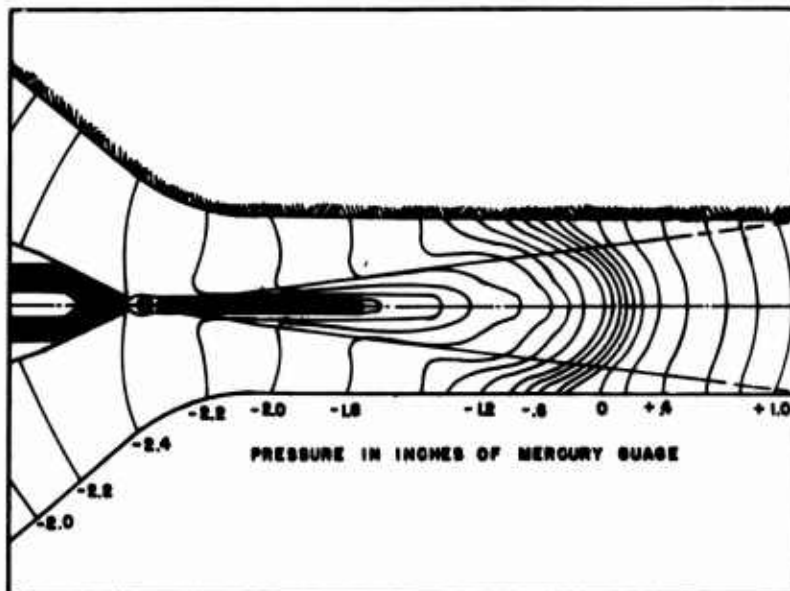


FIGURE 2

Static isobars for same ejector as in Figure 1.

cific constant pressure cases is currently in progress. When these data are assembled, a Technical Note on the results of these calculations will be issued.

Beyond a few preliminary calculations, the study of the over-all performance of ducted propulsion systems has been held in abeyance, subject to experimental checking of the simplified ejector theory.

EXPERIMENTAL ACTIVITIES.

Air Ejector. During this year, the two dimensional ejector driven by a cold supersonic air jet has been completed and a series of 38 tests conducted. This ejector, which has been described fully in previous reports, has yielded a considerable amount of basic information on the internal flow pattern of an ejector. Some of these results are presented in Figures 1 to 3.

Mass flow measurements have been made on both primary and secondary streams with various ejector geometries.

With one representative configuration a complete static pressure survey has been made with results indicated in Figure 2.

The flow pattern as shown in Figure 1 is the result of a combination of observational techniques. Since the initial Mach number of the jet in use in all tests to date is quite low (1.37), and since, up to the present, only a crude optical setup has been used, shadow-graph observation yields only the first few shocks in the jet. Induced flow streamlines were obtained by observing the paths of particles introduced in the inlet of the ejector. The central shock pattern and mixing zones were observable due to the fact that in long runs, the stagnation temperature of the jet falls well below freezing and a very clear frost pattern is deposited on the plastic sides of the ejector. These results, combined with the static pressure survey of the tube give an interesting insight into the flow in the ejector. The central supersonic core of the primary stream extends a relatively long distance into the tube. In certain cases of under-expansion, the shock patterns may be traced distinctly for a distance downstream of about 12 inches. The height of the two dimensional throat of the jet is $1/4$ inch. From this central core a zone of mixing spreads out symmetrically into the primary flow at an included angle of about 15 degrees.

The pressure in the tube rises slowly from the inlet valve until a point is reached where the mixing zone reaches the edge of the ejector tube. The pressure then rises rapidly to a value slightly higher than atmospheric. A gradual further rise is observed, followed by a tapering off to atmospheric at the exit.

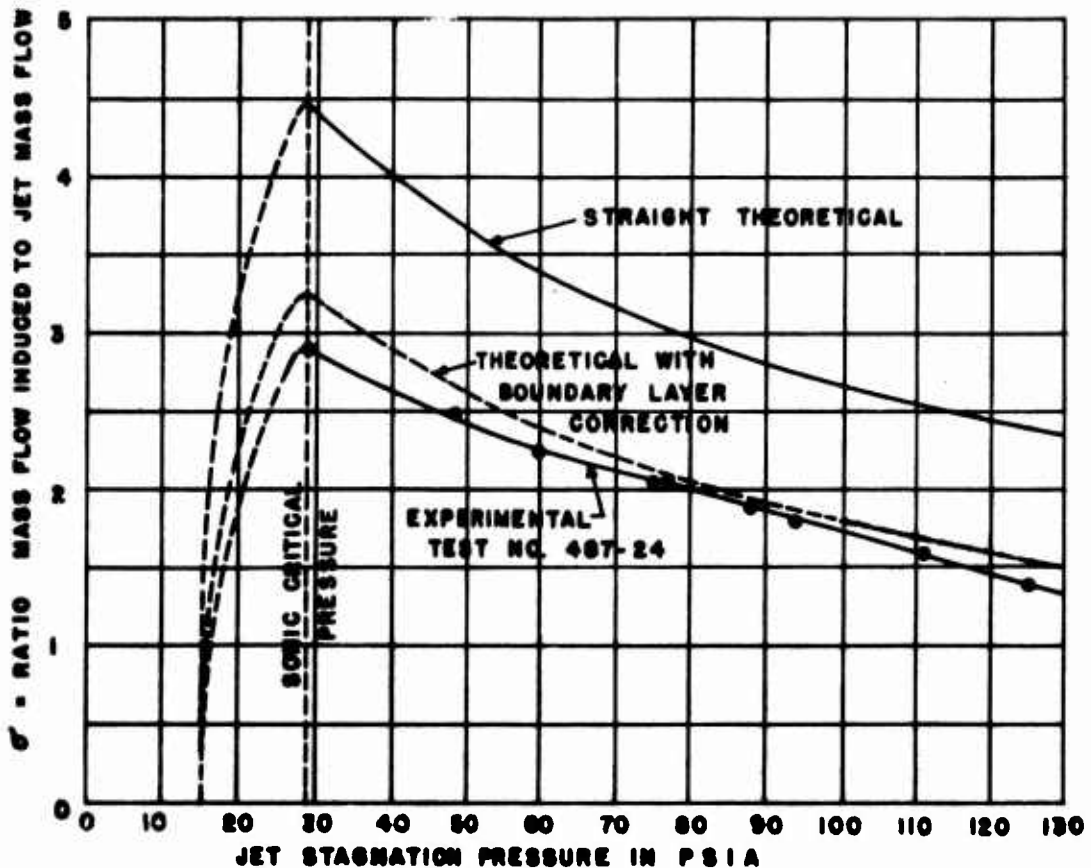


FIGURE 3

Results of test on 6'' x 1½'' straight ejector.

Figure 3 shows some of the quantitative mass flow data collected in one test. It will be noticed that the experimental data is not continuous, a sharp break being observed in the curve at about 75 lbs. pressure (correct expansion for this jet occurring at about 45 lbs.) This phenomenon is accompanied by a marked change in the noise of the apparatus, and is apparently associated with local sonic regions in the induced flow.

The top curve of figure 3 shows the theoretical values for the same conditions. Since the theory does not account for frictional effects, the quantitative agreement was not expected to be much closer than is shown. The qualitative agreement is, however, excellent.

No accurate velocity profiles have been established as yet and so no definite estimate can be made of the effect of the boundary layer on the ejector performance. The work to date has been largely of a rough exploratory nature but has served to yield preliminary data and to reveal the potentialities and limitations of the experimental setup. The problem of boundary

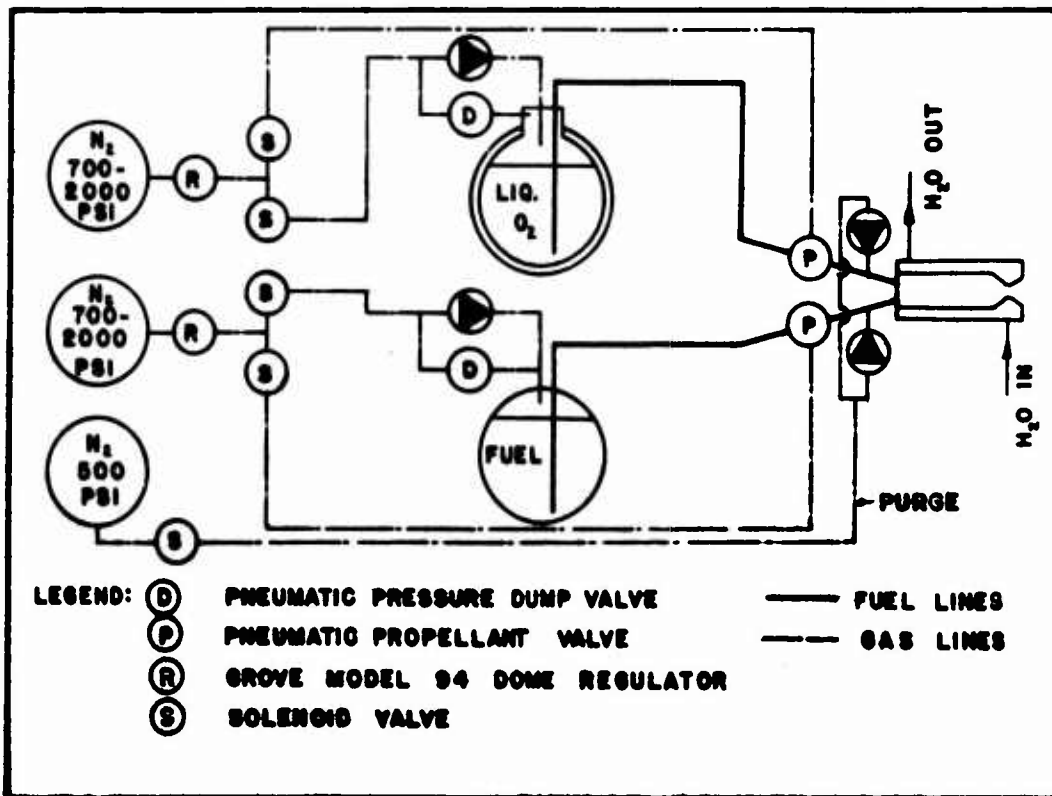


FIGURE 4

Schematic of liquid fuel rocket system.

layer growth is of course of primary importance and a study of this phase of the problem is now under way in order to help establish the limitations of the present experimental setup.

In a rough sense, the effect of the boundary layer will be to act as a restriction on the induced flow. In order to estimate the importance of this effect, a series of calculations were carried out to determine the mass ratio of induced to primary air as a function of jet stagnation pressure, considering the influence of the boundary layer to be a reduction in the effective exit area of the ejector. The assumption of a 25% reduction in exit area yielded the results shown in Figure 3. The validity of such assumptions must of course be justified experimentally and the velocity surveys now in progress will give detailed information on this point.

Rocket Motor Development. In line with the overall schedule for this phase, a small water-cooled liquid-fuel rocket motor system has been developed and placed in operation.

A schematic drawing of this system is shown in Figure 4. Liquid oxygen and a mixture of 75% ethyl alcohol and 25% water are fed to the rocket from tanks which are pressurized sepa-

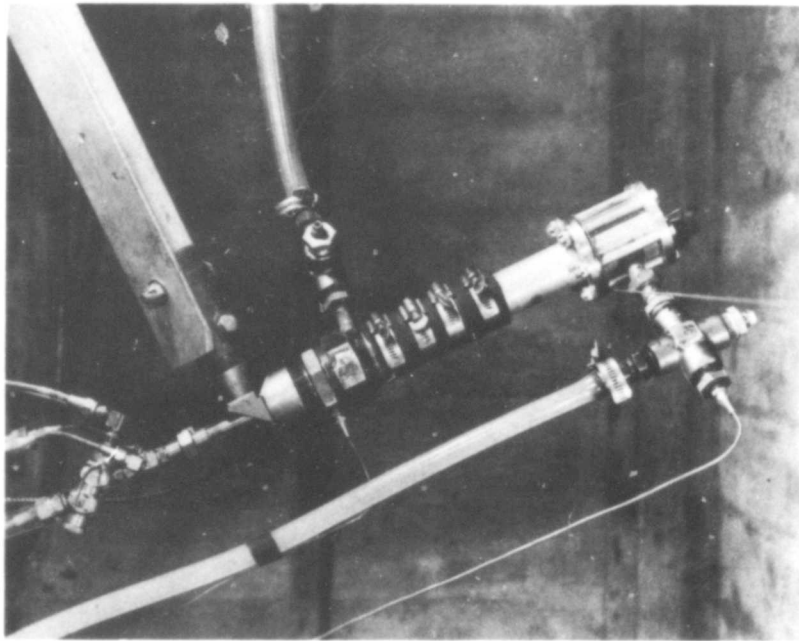


FIGURE 5

Side view of fifty pound oxygen alcohol rocket motor.

rately by an inert gas. Propellant cut-off and starting are accomplished by a pair of special pneumatic propellant valves developed at this laboratory. All operations are remotely controlled from the observation room, and performance has been very satisfactory.

The motor itself was designed for fifty pounds of thrust. The shell is water-cooled and is constructed entirely of threaded connections.

The design is such that a burn-out destroys only the central portions of the inner stainless steel shell and the outer casing. A replacement can be made in a few hours and at very little cost. This design lends itself very neatly to experimental work of this type because of the low cost and the ready flexibility of the system.

Ignition is accomplished by a spark from a wire introduced through the throat and arcing to the injector head. This system has operated satisfactorily in all tests to date.

At the present time the injector head contains but a single hole for each propellant, the center-lines intersecting on the center-line of the rocket in such a way that the resultant stream is as nearly axial as possible.

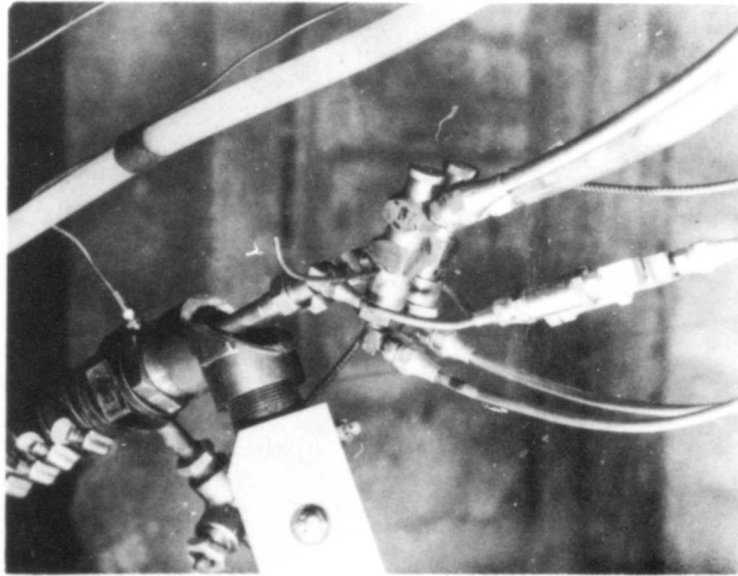


FIGURE 6

*Fifty pound alcohol oxygen rocket.
View of propellant valve assemblies.*

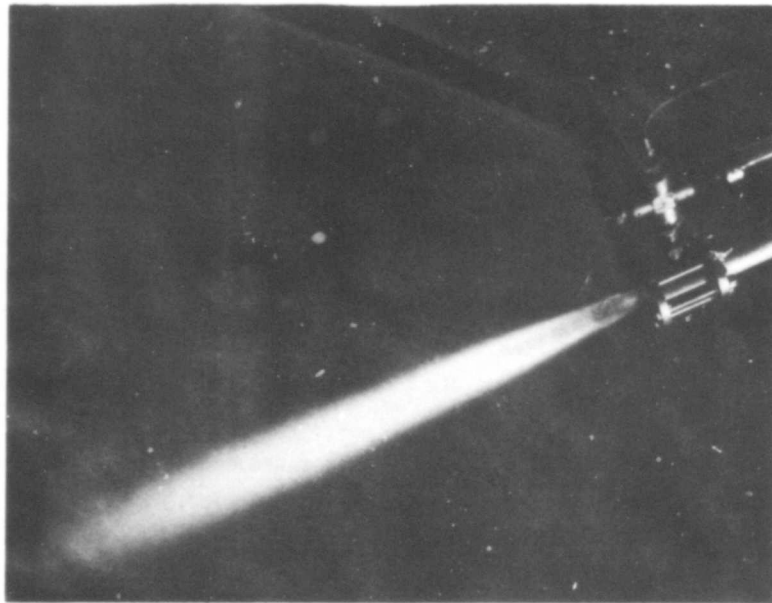


FIGURE 7

Flame from rocket motor during a test.

Since optimum rocket performance is not essential, this extremely simple injector head may prove entirely satisfactory. A four-hole injector is to be tried shortly in order to give a comparative performance check. Indications are, however, that the present injector is remarkably satisfactory.

The operation of the motor has been smooth and a specific impulse in the neighborhood of 195, at chamber pressures in the vicinity of 275 lbs. absolute, is estimated. The present motor shell has accumulated over 16 minutes of running in fifteen starts with various mixture ratios and chamber pressures. Aside from insignificant amounts of erosion in the throat, the motor is still in good shape. Figure 5 shows a side view of the rocket motor assembly as mounted on the rigid test stand. The motor is pointed down at 30 degrees to insure the carrying away of possible excess fuel accumulated in the starting process. Figure 6 shows a closer view of the propellant valve assemblies at the rear of the rocket. Figure 7 depicts the rocket in operation.

Plans

During the coming year, experimental work will be continued on both phases of this program.

An extensive series of tests on the air ejector is planned including a study of the effects of variation in ejector geometry and the Mach number of the jet. It is also planned to make some detailed studies of the mixing action of the supersonic and subsonic streams.

The rocket is to be tested on the thrust jack shortly. Once the calibration of the motor is complete, the installation will be reworked for installation in the duct. Ejector performance with the hot jet will be investigated prior to the initiation of experiments with the complete rocket-ram jet power plant.

PHASE 4

To investigate theoretically and experimentally a valveless intermittent jet engine.

Summary

During the latter part of 1947, the idea of an intermittent valveless jet engine, which would operate intermittently through cyclic injection of fuel was conceived at the Aeronautical Engineering Department of Princeton University. Thermodynamic efficiency calculations indicated that this type of engine might be a marked improvement compared with the ram jet engine. Funds were made available by Project SQUID on March 1, 1948, to theoretically and experimentally determine the possibilities of such an engine.

Theoretical studies of the combustion process have been made. Experiments in a 4 inch square jet tube of 8 foot length are being carried out. An air supply delivering a 550 feet per second 4 inch diameter jet has been set up. A combustion pressure ratio of about 2 has been obtained, indicating that high thermodynamic efficiencies are possible from a combustion point of view. An ideal thermal efficiency of 50% is shown to be possible at a flight Mach number of 1.8; the efficiency at $M = .3$ is shown to be 10 times that of the ram jet.

Progress

Description of Engine. The idea of an intermittent valveless jet engine, operating intermittently through cyclic fuel injection, was conceived at the Aeronautical Engineering Department of Princeton University during the latter part of 1947. The theoretical and experimental investigation of the possibilities of such an engine was actually commenced on March 1, 1948, when funds were made available through Project SQUIL.

It is visualized that the body of the engine consist simply of a tube open at both ends. The inlet portion of the subsonic engine would be an expanding diffuser. The inlet of an engine designed for supersonic flight would probably be the conventional supersonic diffuser. Fuel is injected cyclically somewhere near the center of the tube. The fuel system is composed of injection nozzles, fuel pump, regulation apparatus, and a pump drive. An ignition device also may be required.

It is well known that the ideal thermal efficiency of a ram jet depends upon the ram pressure rise which is a function of flight Mach number. It will be shown in a later paragraph that the proposed engine has a greater ideal thermal efficiency than a ram jet at the same flight Mach number, since, in addition to the ram pressure rise, a further increase in pressure occurs as a result of intermittent combustion. Furthermore whereas the efficiency of the ram jet is zero at zero speed, the proposed engine has a finite thermal efficiency, and therefore, static thrust may be obtained with proper design. Also, since flame stabilization is not required, the high stagnation pressure loss flame holders of the ram jet are not necessary.

Program of Investigation. A theoretical and experimental program was set up to investigate the possibilities of the intermittent valveless jet engine. The program is:

Theoretical:

1. Investigation of the combustion process of the engine.
 - a. Determination of the pressure rise obtained in a constant area tube.
 - b. Effect of change of tube cross section on combustion pressure rise.
2. Investigation of gas dynamical cycle of engine.
 - a. Cycle of constant cross section tube.
 - b. Effect of tube cross section on cycle and the determination of the proper tube shape.

Experimental:

1. Exploratory investigation of intermittent combustion in a flowing gas.
2. Investigation of maximum combustion pressure rise obtainable in constant area tube.
3. Investigation of effect of tube shape, operating characteristics of the engine, and determination of specific thrust and fuel consumption.

Of the studies indicated *Theoretical 1.a.*, and *Experimental 1* have already been carried out. The remainder of the theoretical program and *Experimental 2*, are now in progress.

THEORETICAL STUDIES

Combustion Process. In order to afford an insight into the processes taking place within the engine, and to make dynamic calculations of thermodynamic efficiency, theoretical studies of the combustion process occurring within the proposed engine have been made. A simple one-dimensional gas dynamical theory of the combustion process has been evolved. The assumptions of the theory are that (1) combustion takes place in a thin plane, flame front across which the value of the specific heats remains constant (suitable average values may be assumed), and (2) that the molecular weight of the burnt gases is the same as the unburnt mixture. In addition the air waves of finite amplitude, propagated as the result of intermittent combustion, are considered isentropic. This is a good approximation up to pressure ratios of about 2.

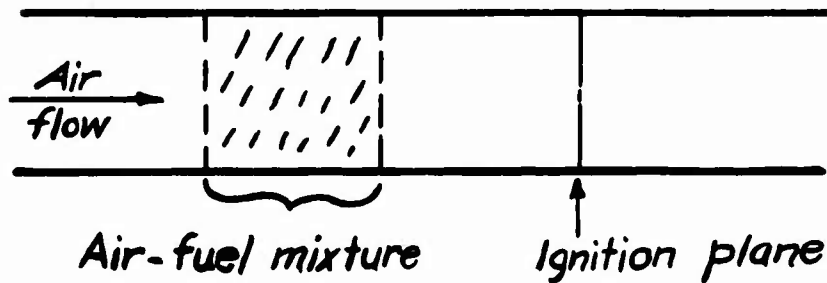


FIGURE 8

Motion of mixture in tube.

Consider the steady flow of air in the tube of Figure 8. Fuel is injected at some point in the tube mixing with a mass of air, and the resulting fuel-air mixture moves downstream. The downstream end of the mixture is ignited upon reaching the ignition plane, and a plane flame front is propagated through the mixture until it is completely burnt. The gas dynamics of the combustion process may be conveniently described on the time-distance (t, x) plane Figure 9. With the initiation of combustion, two shock waves are propagated up and down the tube. The burnt gas region is bounded on the upstream side by the flame front and on the downstream side by a plane of entropy (or temperature) discontinuity, on either side of which the fluid velocities and pressures are equal. The results of calculation of the pressure ratio across the upstream shock are shown in Figure 10 for various ratios of the normal burning velocity V_n to the velocity of sound ahead of the flame a_1 , and various air fuel ratios. It is interesting to note that the pressure rise depends very critically on the burning velocity ratio $\frac{V_n}{a_1}$ and is independent of the flow velocity in the tube. The theory is also applicable to flame motions in stationary tubes. A report on the general theory is being prepared.

Operation of Engine. The operation of the intermittent valveless jet engine results from proper utilization of the waves generated by the intermittent combustion process. The gas dynamic cycle of the constant area engine is schematically depicted in the t - x plane in Figure 11. The shock propagated upstream adiabatically compresses the fuel air mixture. This process is analogous to the compression of the mixture in an internal combustion engine by the piston. When the flame front reaches the upstream end of the mixture, the burning process is complete. Expansion waves are emitted in both directions from this intersection plane; the burnt gas and fresh gas regions here are separated by another plane of entropy discontinuity. The upstream and downstream wave systems are reflected with change of sign at the inlet and exhaust of the tube respectively. The downstream waves exhaust the previously burnt gases at high velocity. The geometry of the tube is arranged so that the burnt gases have moved downstream out of the combustion chamber when the waves return to the combustion chamber. Fuel is injected at this time and the cycle is repeated.

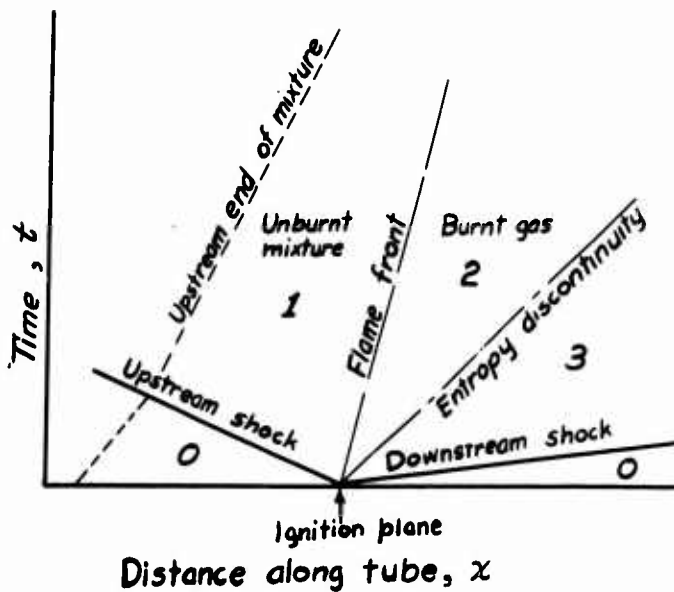


FIGURE 9

Gas dynamics of combustion process.

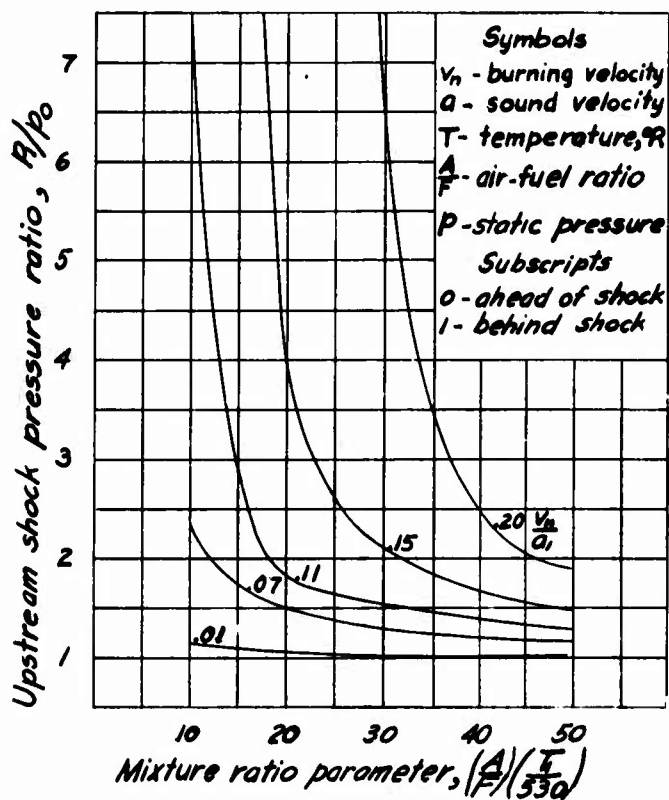


FIGURE 10

Pressure ratio of upstream shock resulting from intermittent combustion.

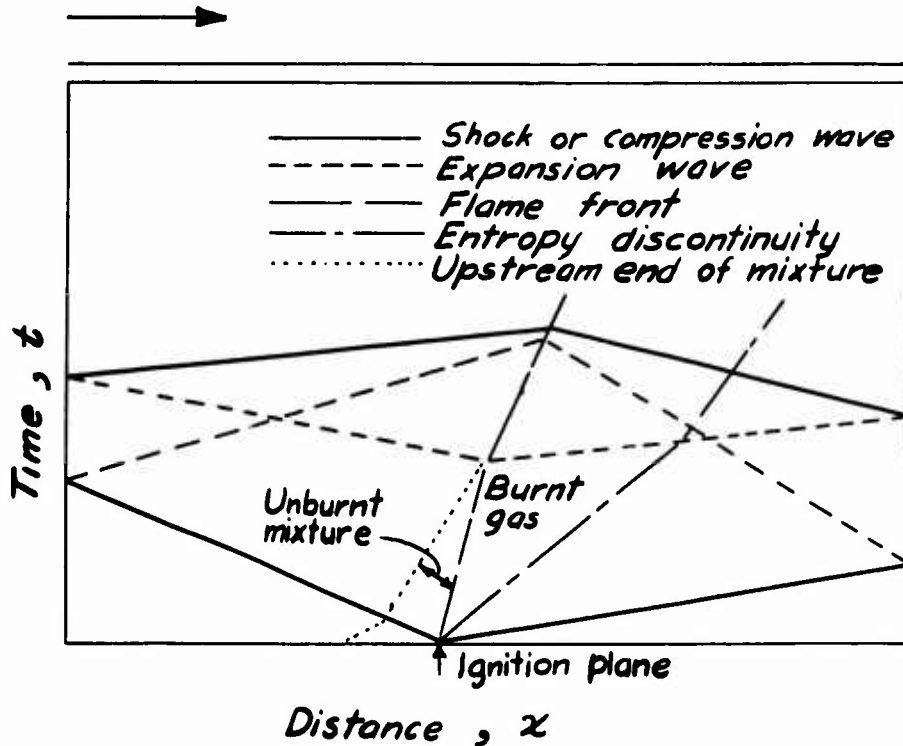


FIGURE 11

Schematic gas dynamic cycle.

Since the upstream moving shock wave will tend to spill air out of the front end of the tube, a requirement for most efficient operation is that the inlet of the tube be shaped so as to prevent this. A diffuser-like entrance will effect a weakening of the compression wave to prevent spillage.

Thermodynamic efficiency. The ideal thermodynamic cycle of the engine is shown on the pressure-specific volume (p - V) plane in Figure 12. The ideal cycle is the well known Brayton cycle. The process a - b is the adiabatic ram compression obtained by virtue of flight speed, and is the same as that experienced by a ram jet at the same flight speed (disregarding diffuser losses). Process b - c is the adiabatic compression of the mixture by the forward moving shock wave. Process c - d is the combustion process through the flame front. A small stagnation pressure loss occurs here, but for simplicity this process will be assumed to be a constant pressure process for the ideal cycle. This is common practice in ram jet and turbo jet work. The adiabatic exhaust of the burnt gases to atmospheric pressure occurs from d to e , and e - a is the constant pressure closure of the cycle. The ideal thermodynamic efficiency η_1 , of the

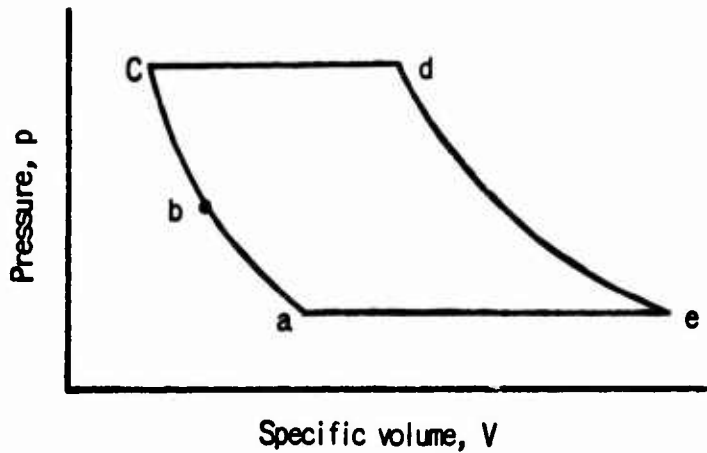


FIGURE 12

Ideal thermodynamic cycle.

cycle is

$$\eta_i = 1 - \frac{1}{\left(\frac{P_b}{P_a} \frac{P_c}{P_b}\right)^{\frac{\gamma-1}{\gamma}}}$$

where γ is the ratio of the specific heats.

The efficiency that can be obtained with this intermittent valveless jet engine at various flight Mach numbers for several values of mixture compression $\frac{P_c}{P_b}$ by the forward moving shock wave is shown in Table I. Shock wave losses are small in these cases and have been ignored. A value of $\gamma = 1.4$ has been used.

The results indicate that remarkable increases of efficiency over that obtained with the ram jet ($\frac{P_b}{P_a} = 1.0$), are made possible by the pressure rise occurring with intermittent combustion. A value of $\frac{P_c}{P_b} = 2$, has already been experimentally obtained.

TABLE I

Flight Mach Number	$\frac{P_b}{P_a}$	Ideal Thermal Efficiency η_i			
		Ram Jet			
		$\frac{P_c}{P_b} = 1.0$	$\frac{P_c}{P_b} = 1.4$	$\frac{P_c}{P_b} = 1.8$	$\frac{P_c}{P_b} = 2.2$
0	1.0	0	.09	.15	.20
.3	1.065	.02	.11	.17	.22
.6	1.28	.07	.15	.21	.26
.9	1.69	.13	.21	.27	.31
1.2	2.32	.21	.29	.34	.37
1.5	3.66	.31	.37	.42	.45
1.8	5.75	.39	.45	.49	.52

TEST PROGRAM

TEST EQUIPMENT.

Injection Equipment. The purpose of the initial test program was to determine as rapidly as possible whether intermittent combustion could be produced at all in a flowing gas, and whether appreciable pressure rise could be obtained from such combustion. Since the combustion process depends in a large part upon injecting fuel and forming a fuel-air mixture in as short a time as possible, it was necessary either to develop or to procure commercially available injection equipment of a suitable nature. The former course of action was naturally out of the question from the point of view of the money and time involved. A diesel type injection pump manufactured by the Fiedler-Sellers Corp. of Philadelphia, which injects fuel in the extremely short duration of 10 degrees of pump crank angle was used. The shortest injection duration of other diesel pumps is about 35 degrees of crank angle. The Fiedler type injection equipment is described in U. S. Patents 2,250,364 and 2,244,874. Two pumps have been used. The first pump had a single plunger of 16 mm diameter, and it injects a maximum of about 0.0006 pounds of fuel per stroke. The second pump is a double plunger pump of 1 inch plunger diameter with injection from each cylinder 180 degrees of crank angle out of phase with the other. Maximum fuel injection per stroke is about 0.0015 pounds. Both pumps have a speed range up to about 2400 rpm, the maximum injection frequency of the single cylinder pump therefore being 40 cycles per second, whereas that of the two-cylinder pump is 80 cycles per second.

Air Supply. Two 25HP electrically driven blowers were secured from the War Assets Administration through JANMAT. In the initial exploratory tests only one blower was used; it delivered velocities as high as 400 feet per second in a 5 inch diameter free jet. The second blower was added in series in December 1948 providing a maximum velocity of 550 feet per second ($M = .50$) in a 4" diameter free jet.

Jet Tube. The initial combustion studies were made using a 4" square tube which was 8 feet long. Details of the tube are shown in Figure 13. The combustion chamber was provided with glass side windows of two foot length. Since the jet area and tube entrance area were about equal, it was recognized that the tests could not duplicate external flow conditions as obtained in flight, but it is expected that the internal flow would be fairly well simulated.

Pump Drive. The injection pump was driven, in the exploratory setup, by a 2HP intermittent type DC motor. A 24 Volt DC gasoline generator was used to provide the electric power. Directly connected to the pump drive was a tachometer generator and a stroboscopic contactor. This drive system, which is shown in Figure 14, was not satisfactory since the motor speed would tend to wander and would also change radically with throttle setting.

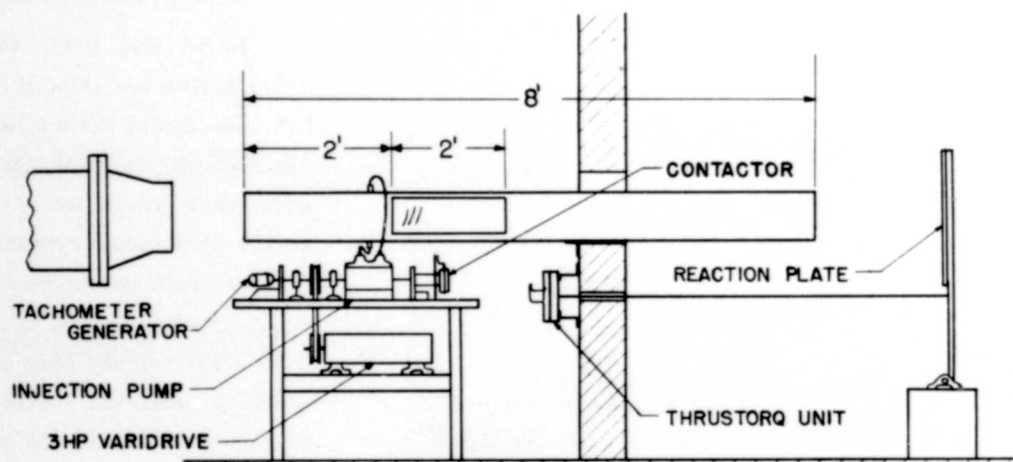


FIGURE 13

Jet tube equipment layout.

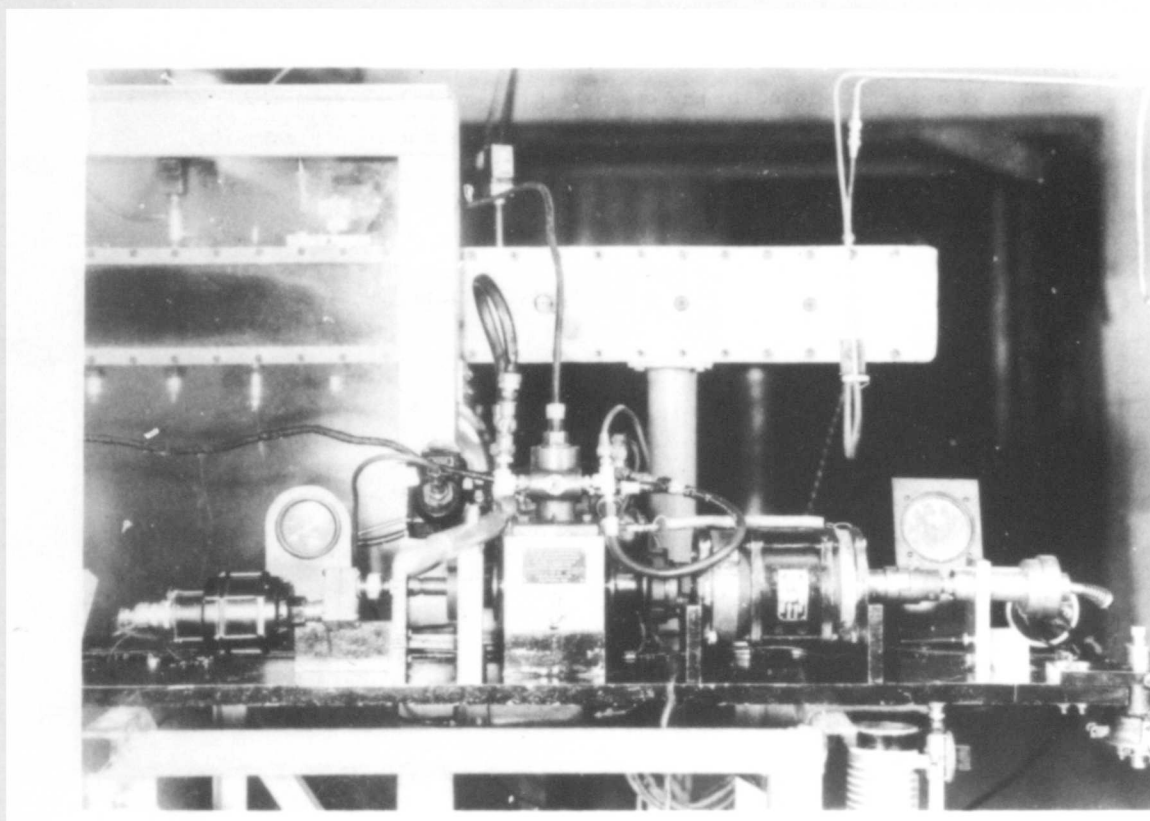


FIGURE 14

View of original single cylinder pump drive.

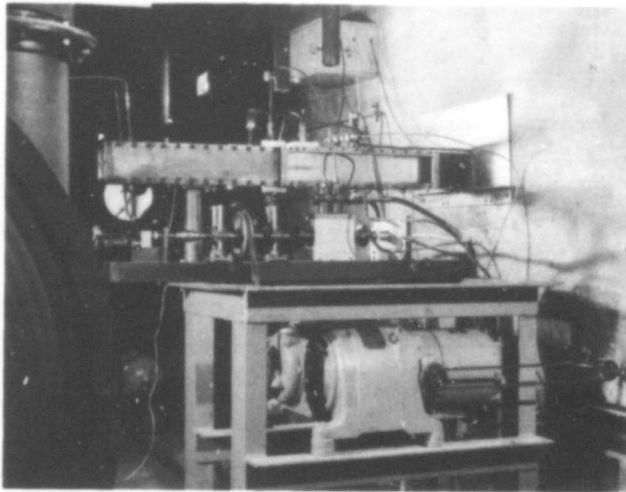


FIGURE 15

Revised pump drive setup with two cylinder injection pump.

ed it was evident that this would no longer be advisable, and a test room about 12 feet from the tube, was built. A photograph of the test room layout is shown in Figure 16.

Thrust Balance. A pendulum type reaction plate type thrust balance was built in mid-December 1948. A Hagan Thrustorq unit is used with a mercury manometer. The balance layout is indicated in Figure 13.

Instrumentation. Statham pressure pickups are being used to record transient pressures. The system consists of an amplifier, oscillator, power supply, and a Hathaway recording oscillograph. Three pressure pickups can be used simultaneously in a variety of positions in the jet tube. The nature of the dynamic

In November 1948, the pump drive system was rebuilt. A 3HP U.S. Electrical Motors Vari-Drive was used to power the pump. In addition a protractor was added to the stroboscope contactor so that accurate measurements of the duration of injection could be made. The revised pump drive which is indicated in the sketch of Figure 13 and in the photograph Figure 15, operates very satisfactorily.

Test Room. During the initial exploratory tests the engine was operated from a position close to the jet tube. When the larger capacity pump was add-

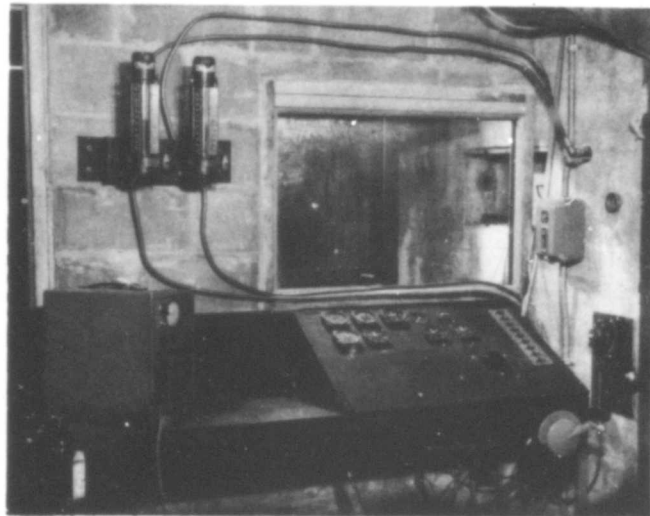


FIGURE 16

Test house layout.

response of the Statham pickups was determined by bursting a diaphragm within a 20' shock tube, causing a shock wave (a step in pressure) to be propagated past the gage position. The tests indicated that the response of the gages was satisfactory.

A schlieren system, utilizing two 12 1/2 inch parabolic mirrors has been constructed. An 8 mm Western Electric Fastax high speed camera (up to 8000 frames per second) can be used with the schlieren system for photographic investigation of the nature of the combustion process.

A strobotac and strobolux are used to 'stop' the fuel spray pattern for visual and photographic observation, and to determine the injection duration. Rotameters are used to measure the fuel flow rate.

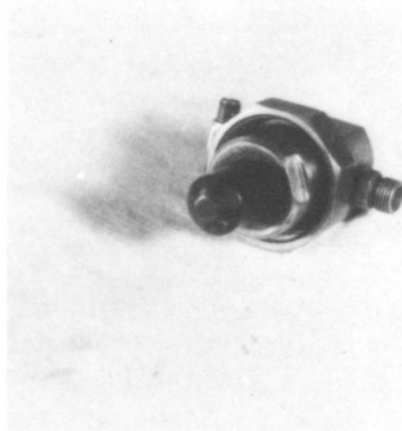


FIGURE 17

Nozzle No. 1

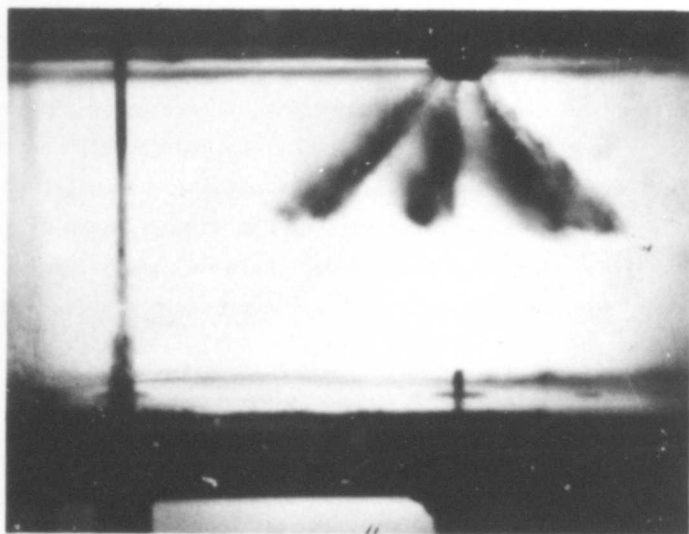


FIGURE 18

Stroboscopic photograph of spray of nozzle No. 1

TESTS

Injection. The first nozzle used was a standard Fiedler-Sellers diesel nozzle mounted flush with the inner wall of the jet tube. This nozzle (designated nozzle No. 1 and shown in Figure 17) had 8 orifices, the spray being conically emitted in 8 jets with a cone angle of 80 degrees. A typical stroboscopic photograph of the spray of this nozzle is shown in Figure 18. The injection with this nozzle was considered unsat-

isfactory since a good deal of the fuel impinged upon the side walls.

To avoid impingement several nozzles similar to nozzle No. 1, with varying numbers of holes and cone angles, were modified by plugging up the side holes. The holes injecting towards the tube rear were also plugged to avoid a large region along the spray cone axis from which mixture was absent. The best nozzle of this series was designated nozzle No. 2. All but two forward holes of this nozzle were plugged; the cone angle was 140 degrees. The injection with this series of nozzles was considered unsatisfactory because of the non-uniform mixture distribution obtained.

To obtain more uniform mixture distribution, nozzle No. 3 was built. The nozzle (shown in Figure 19) was simply a ring of 2" diameter fashioned from approximately $\frac{1}{8}$ " I.D. tubing. Eight .8 mm holes were drilled in the tube in uniform positions around the ring, the spray, therefore, consisting of 8 jets parallel to the tube axis in the upstream direction. The injection was cut off by a Fiedler-Seller fuel flow valve mounted on the wall of the tube. This valve is also shown in Figure 19. Two of these nozzles could be used simultaneously with the two cylinder pump with the arrangement of Figure 20, the spray of each being 180 degrees out of phase with the other. A typical stroboscopic photograph of the spray of nozzle No. 3 is shown in Figure 21.

The spray duration with this nozzle was 20 degrees because of the distance between the nozzle holes and the flow valve. The nozzle would also drip somewhat between injections because of this.

Ignition. In the initial combustion tests, attempts to ignite the mixture with spark plugs placed at various positions in the tube proved fruitless except at zero velocity. Various types of flame holders were then tried. Combustion could be maintained in this manner up to velocities of about 180 feet per second, but the pressure rise obtained was extremely small. The first method of ignition that proved successful was the use of a standard oxy-acetylene welding torch in the center of the tube as a continuously burning pilot flame. This type of pilot flame, however, would blow out when the combustion pressure rise exceeded about 6 psi.

The simple torch was then replaced by a low pressure gas rocket which consisted simply of a 2 inch long piece of stainless steel tubing fitted onto a welding torch. The fuel used was acetylene, the oxidant being a mixture of compressed air and gaseous oxygen. The gas pressures were roughly; acetylene, 12 psig.; air, 25 psig.; oxygen, 50 psig. The gas rocket has proved fairly satisfactory for the needs of the investigation, only occasionally blowing out during extremely high pressure bursts.



FIGURE 19

Nozzle No. 3 and fuel flow valve.

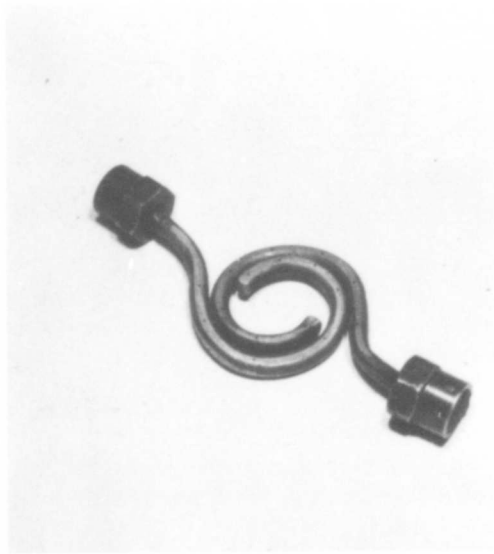


FIGURE 20

Double nozzle No. 3.



FIGURE 21

Stroboscopic photograph of spray of nozzle No. 3.

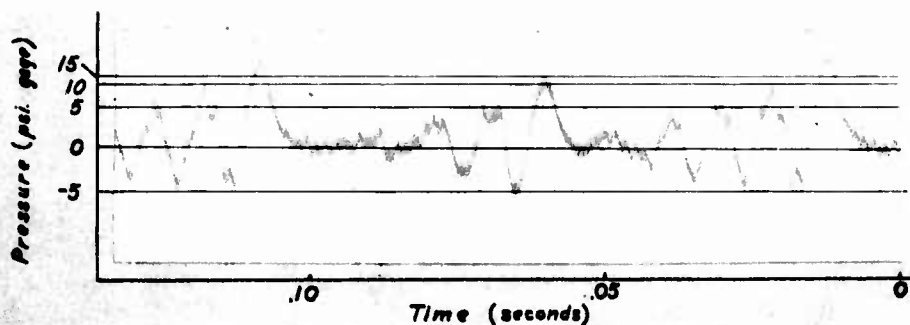


FIGURE 22

Transient pressures with nozzle No. 3. Fuel 75 octane gasoline. Blower jet speed 500 ft-sec. Fuel flow 110 lb-hr. Injection frequency 19.2 cycles-sec.

Combustion Tests. Both fuel oil No.2 and 75 octane gasoline were used as fuel. It was found that higher pressures were obtained with gasoline; the pressure values quoted below are therefore from the tests using gasoline. Pressure measurements with the diesel type nozzles No.1 and No.2 using the single cylinder pump indicated peak pressures during combustion of 4 and 6 psig respectively. The peak pressure obtained with the ring type nozzle No.3 using the two cylinder pump, exceeded 15 psig. A typical pressure record with nozzle No.3 is shown in Figure 22. It may be noted that the negative pressure peaks are of the order of -5 psig. In these tests the pilot flame was located along the tube center line 8 inches downstream of the nozzle. The nozzle was placed 29 inches from the inlet to the tube. The pressure gage was located in the combustion chamber. The blower jet speed was 500 feet per second, the average velocity at the tube inlet being 410 feet per second.

An interesting conclusion as to the order and magnitude of the burning velocity may be reached using the above data and the theoretical results of Figure 10. If we assume that the air-fuel ratio is about stoichimetric $A/F = 15$ (no exact method of determining the air-fuel ratio has been devised as yet), and using the observed combustion pressure ratio $\frac{P_1}{P_0} = 2$, from Figure 10 it may be determined that the burning velocity is $V_n = .08a_1$. Since a_1 was the order of 1200 feet per second, the burning velocity V_n is approximately 100 feet per second. This result is approximate in as much as the theory is applicable to plane flame fronts, whereas with ignition at a point, the flame front is initially a spherical one which may or may not become plane depending upon the length of the mixture zone.

Thrusts of the order of 1.3 pounds per square inch of combustion chamber area have been measured. This value has little meaning since the constant area tube used is far from the optimum tube shape.

Preliminary Conclusions. A combustion pressure rise $\frac{P_C}{P_0}$ (using the symbols of Figure 13 and Table I) of the order of 2 has been obtained. A glance at Table I indicates that with this combustion pressure rise the ideal thermal efficiency of the proposed intermittent valveless jet engine exceeds that of the ram jet by from 17 to 11 percent depending on flight Mach number. It is also apparent that at low flight Mach numbers the thermal efficiency of the proposed engine is many times that of the ram jet; e.g. ten times as great at $M = 0.3$, 3.5 times as great at $M = .6$. At values of Mach number greater than unity, exceedingly high thermal efficiencies relative to existing prime movers are possible e.g. an efficiency of 50% at $M = 1.8$. It is therefore concluded, that from the standpoint of thermal efficiency the proposed engine competes favorably with the ram jet, especially at low speeds, and has possibilities of being a highly efficient thrust device at high Mach numbers.

It remains to be seen, however, whether the increased energy available due to higher thermal efficiencies can be converted into thrust. This problem which is essentially a gas dynamic one, concerns the shaping of the tube, and will be under investigation shortly.

Plans

Immediate plans include continuing experimental studies of the combustion process in a constant area tube to determine effects of tube length, cycle frequency, combustion chamber position in tube, average velocity in tube, and many ignition centers, on the combustion pressure rise. The theoretical studies of the gas dynamic cycle will also be carried out. In addition, schlieren motion pictures of the combustion process will be taken. Theoretical and experimental determination of the optimum cross-section and length distribution shape of the engine will then be made. The operating characteristics of the engine as well as the specific thrust and fuel consumption will be determined.

PROJECT SQUID

Administration and Technical Direction

Project SQUID is sponsored by the United States Navy through the Office of Naval Research. The Navy has requested that Princeton University assume the functional responsibility of controlling, supervising, and coordinating this basic research program in jet propulsion. A Policy Committee consisting of six academic and industrial scientists has been appointed by the member universities and is responsible to Princeton and to oversee and direct the activities of the overall programs.

The assignment of assisting the Policy Committee in the formulation of its recommendations to the Navy and in the execution of its supervisory technical duties has been delegated to the Project Organizer and his technical and administrative staff located at Princeton University. It is the function of this group to work closely with the scientists at the member universities, to remain continually cognizant of related activities outside Project SQUID; and to be informed of military requirements and developments so that the program may best benefit the aims of the Military Establishment.

Assisting the Project Organizer with the technical functions are five panels composed of technical personnel from the participating SQUID groups. These panels are selected in fields to cover all scientific aspects of jet propulsion research, i.e., Fluid Mechanics and Heat Transfer, Combustion, Materials, Instrumentation, and Applied Research. Meeting several times a year to consider in detail all aspects of Project SQUID research, these panels serve in a technical advisory capacity in the program planning. These panels have sponsored in the past year a number of scientific conferences to consider specific technical topics. At such meetings, technical personnel from a number of outside industries and agencies have been invited to participate.

In addition, a Metallurgical Advisory Committee with members from leading industrial metallurgical laboratories parallels the function of the Materials Panel in order that the industrial aspects of the materials research can be fully appreciated.

The following scientific conferences were held within the past year:

April 28 and 29, Washington, D. C. - Instrumentation Panel

Measurement of Temperatures and Pulsating Burning Gases

May 6, Washington, D. C. - Combustion Panel

The Problem of Flame Holding.

May 24 and 25, Princeton, New Jersey - Fluid Mechanics and Heat Transfer Panel
The Status of Pulse Jet Theory

July 22 and 23, Washington, D. C. - Applied Research Panel
Ducted Propulsive Devices

November 17 and 18, Washington, D. C. - Materials Panel
Sheet Materials for Jet Propulsion Engines

Project SQUID joined with the Jet Propulsion Laboratory, California Institute of Technology in the sponsorship of a symposium held at Pasadena, considering as a topic *Heat Transfer Problems in Jet Propulsion*. This symposium was a part of a larger meeting held in cooperation with the Heat Transfer and Fluid Mechanics Institute and the Fluid Mechanics Division of the American Physical Society in Los Angeles and Pasadena, June 21 to June 24, 1948.

The Office of the Project Organizer assumes the responsibility for the duplication, printing, and distribution of all Squid reports and memoranda. A technical lending library and abstracting service is maintained for the use of the member universities.

In the past year, thirty-six different memoranda and reports were distributed by Project SQUID Headquarters and have been added to the list of SQUID publications printed in the appendix of this Annual Report.

Until June of the past year, Engineering Research Associates, Inc., under contract with Princeton, assisted the Project Organizer with staff duties. This group cooperated in the formulation of the SQUID Program Report, and assisted with the coordination of the various activities. Publication of the Instrumentation Bulletin was undertaken by the Engineering Research Associates, Inc., group.

As a further function, the immediate staff of the Project Organizer with the aid of scientific personnel from the member universities has assisted the Navy with several specific technical problems outside the activities of the Project and of immediate importance to the Navy. Several engineering studies of particular propulsive devices have also been undertaken at the request of the Navy.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N8-ONR-74000 and 74001

University of Delaware
Newark, Delaware
1 January 1949

PHASE I

Work under this phase is divided into two parts both of which deal with *Heat Transfer in Passages with Free Convection and Counter Flow*. The problem is stated as follows: (1) The visual study is to be carried out using a vertical rectangular duct having two opposed glass walls with provision to heat the middle portion. Free convection will be upward but arrangement will be made to force air downward at a controllable velocity. By means of spark photography the resulting gas can be studied; (2) The quantitative study is to be carried out with emphasis on the cooling effect of liquid under conditions of free convection with forced counterflow. Various liquids will be chosen so as to give a wide variation in the Grashof number

Summary

As the Navy contract authorizing this work was drawn up in November, 1948, work is just getting under way as of 1 January 1949. Information with regard to progress and plans will be forthcoming in later Project SQUID Progress reports.

APPENDIX

Technical Memoranda, Reports and other Publications

During the two year period 1 January 1947 to 31 December 1948, the member universities of Project SQUID submitted to the headquarters organization at Princeton 58 informal technical memoranda covering the technical progress at the respective universities. These memoranda received either internal distribution (within Project SQUID) or general distribution which includes internal as well as Army-Navy-Air Force Guided Missiles list distribution. The mode of distribution depends upon the importance attached to the memorandum by the originating organization. A complete list of the memoranda by universities follows; the distribution of each memorandum is indicated.

NEW YORK UNIVERSITY.

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
The Application of Schlieren High Speed Moving Picture Techniques to Investigation of High Speed Turbulent Flames.--M. W. Evans, M. D. Scheer, L. J. Schoen.	May 1, 1948	NYU No. 1	Internal
Report of Conference on Measurement of Temperatures of Pulsating Burning Gases,--J. H. Hett	April 28, 1948	NYU No. 2	General
Wedge Thermocouples.--J. H. Hett	Aug. 1, 1948	NYU No. 3	Internal
Second Part of One-Dimensionalized Aero-Thermodynamic Theory of Turbulent Flame Propagation in Flame Tubes.--J.K.L. MacDonald, J. L. Neuringer.	July 1, 1948	NYU No. 4	Internal
A Mobile High Capacity Blower Unit.-- D. Kasner, M. W. Woody.	Nov. 1, 1948	NYU No. 5	Not yet distributed. (General)

POLYTECHNIC INSTITUTE OF BROOKLYN

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
Problems Encountered in a Study of the Beryllium-Chromium System.--G. H. Schippereit.	May 20, 1948	PIB No. 1	Internal
Changes in Martensite Structures as a Record of Temperatures, Part I.-- M. Stoll, G. H. Schippereit.	June 1, 1948	PIB No. 2	Internal
An Automatic Recording Extensometer System.--R. J. Flynn, M. Stoll.	June 2, 1948	PIB No. 3	Internal
Changes in Martensite Structure as a Record of Temperatures, Part II.-- G. H. Schippereit, O. H. Henry	June 1, 1948	PIB No. 4	Internal
Surface Temperature Determination by X-Ray Diffraction Technique.--A. Bender, I. Fankuchen.	June 22, 1948	PIB No. 5	Internal
Application of Statham Pressure Transducers to the Continuous Recording of Instantaneous Pressures.-- W. I. Weiss.	July 1, 1948	PIB No. 6	Internal
Measurement of Rapid Temperature Fluctuations in Pulsating Gas Flow.-- R. G. Lefeber.	July 30, 1948	PIB No. 7	Internal
Calibration Method and Equipment for Dynamic Pressure Detectors.--P. Torda, and W. I. Weiss.	Sept. 1, 1948	PIB No. 8	Internal
Application of Dynamic Strain Gages to the Measurement of Continuous and Average Thrust of Pulse Jet Engines.-- P. Torda, W. I. Weiss, E. Shatzki, J. Lovingham.	Sept. 1, 1948	PIB No. 9	Internal

PURDUE UNIVERSITY AND PURDUE RESEARCH FOUNDATION

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
The Measurement of Gas Temperature, II,--M. Carbon, R. J. Albert, G. A. Hawkins.	July 1, 1947	PUR No. 1	Internal
The Measurement of Gas Temperature,-- M. Carbon, R. J. Albert, G. A. Hawkins.	May 1, 1947	PUR No. 2	Internal
Heats of Combustion of Nitrogen Containing Compounds.--M. V. Sullivan, G. M. Kibler, H. Hunt.	July 1, 1948	PUR No. 3	Internal
Experimental Heat Release Determination for Flame Holding in Gaseous Mixtures.--H. J. Buttner, W. W. Floyd, N. E. Parshall.	Sept. 15, 1948	PUR No. 4	Internal

CORNELL AERONAUTICAL LABORATORY

Frequency Response of Pressure Pick-ups Required for Measurements on a Pulse Jet.--G. Rudinger.	June 16, 1947	CAL No. 1	Internal
On the Possibility of Representing One Dimensional Gas Motion by Means of an Electrical Analog.-- J. Logan.	June 23, 1947	CAL No. 2	Internal
Phenomena in Electrically and Acoustically Disturbed Bunsen Burner Flames.--M. L. Polanyi, G. H. Markstein.	Sept. 15, 1947	CAL No. 3	Internal
Study of Gas Oscillations in Half-Open Pipes of Various Shapes.-- G. Rudinger.	June 30, 1947	CAL No. 4	Internal

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
Two-Dimensional Supersonic Wind Tunnel Simulation of the Flow over the External Surface of Ducted Bodies with and without Spillover.-- M. Kamrass.	June 30, 1947	CAL No. 5	Internal
Preliminary Experimentation on the CAL 6" x 4" Pulse Jet.-- J. G. Wilder, Jr.	June 30, 1947	CAL No. 6	Internal
Two-Dimensional Supersonic Wind Tunnel Investigations of Flow in a Duct with Fluctuating Exit Pressure.--M. Kamrass.	June 30, 1947	CAL No. 7	Internal
Study of the Use of a Cooled Probe for Sampling Hot Combustion Gas as a Means for Determining Heat Release.-- P. E. Erbe, J. T. Grey, J. L. Beal.	Sept. 1, 1948	CAL No. 8	Internal
Preliminary Study of a Supersonic Induction-type Wind Tunnel for Cornell Aeronautical Laboratory.--J. L. Moore, O. B. Finamore, J. G. Wilder.	Sept. 22, 1947	CAL No. 9	Internal
Pneumatic Vibrator for Determination of High Temperature Fatigue Properties of Sheet Materials.--F. J. Gillig, L. W. Smith.	Dec. 17, 1947	CAL No. 10	Internal
Influence of Strain Rate on High Temperature Tensile Properties of Sheet Material.--G. J. Guarnieri, J. Miller.	Jan. 16, 1948	CAL No. 11	Internal
Investigation of Acoustic Jets, Part I.--G. Rudinger, J. Logan, W. Dashifsky.	Feb. 10, 1948	CAL No. 13	Internal

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
The Construction of Wave Diagrams for the Study of One-Dimensional Non-Steady Gas Flow.--G. Rudinger, L. D. Rinaldi.	Mar. 10, 1948	CAL No. 14	Internal
Suggested Forms of Air Duct Motors Utilizing Intermittent Combustion: Part I - Intermittent Jet Engines, Part II - Intermittent Combustion Turbines.-J.G. Logan, Jr.	Feb. 25, 1948	CAL No. 15	Internal
Suggested Forms of Air Duct Motors Utilizing Intermittent Combustion: Part III - Modification of Combustion Cycle to Obtain Wave Reinforcement.--J. G. Logan, Jr.	Mar. 10, 1948	CAL No. 16	Internal
High Temperature Deformation Characteristics of Several Sheet Alloys.- J. Miller, G. U. Guarnieri.	April 20, 1948	CAL No. 17	Internal
Investigation of Acoustic Jets, Part II.--G. Rudinger, J. Logan, O. B. Finamore.	April 20, 1948	CAL No. 18	Internal
Preliminary Investigation of an Underwater Jet.--G. Rudinger, J. Logan, O. B. Finamore.	April 20, 1948	CAL No. 19	Internal
Suggested Forms for Air Duct Motors Utilizing Intermittent Combustion.-- J. Logan, O. B. Finamore.	April 28, 1948	CAL No. 20	Internal
Short-Time High Temperature Tensile Properties of Six Sheet Alloys.-- J. Miller, G. J. Guarnieri.	Aug. 1, 1948	CAL No. 21	Internal

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
The Application of Spectrography to the Study of Reaction Mechanisms in Low Pressure Flames.--G. H. Rothgery, J. T. Grey.	Nov. 1, 1948	CAL No. 22	Internal
The Construction of Wave Diagrams to Study the Propagation of Flame Fronts in Ducts.--George Rudinger, L. D. Rinaldi.	Nov. 1, 1948	CAL No. 23	Internal
PRINCETON UNIVERSITY			
The Evolution of the Pulsating Jet Engine and Its Future Prospects.--L. B. Edelman.	Oct. 3, 1946	Special Paper No. 1	Internal
Effect of Temperature on the Low-Pressure Ignition Limits of n-Butane in Air and Oxygen.--J. H. Davidson, E. J. Badin.	July 1, 1947	Tech. Paper No.28	Internal
Burning Velocities of Nitrogen-Oxygen-Butadiene-1,3 and Helium-Oxygen-Butadiene-1,3 at reduced Pressures.	July 1, 1947	Tech. Paper No. 29	Internal
Ionization Flame Detector.--H. F. Calcote.	July 1, 1947	Tech. Paper No. 30	Internal
The Reaction Between Atomic Hydrogen and Molecular Oxygen.--E. J. Badin.	July 1, 1947	Tech. Paper No. 31	Internal
Blow-off Limits for Open, Bunsen type Flames in the Turbulent Region.--Hartwell F. Calcote.	Aug. 15, 1947	Tech. Paper No. 32	Internal

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
The Combustion of Butene-1 Induced by Aluminum Borohydride,--R. S. Brokaw, E. J. Badin.	Oct. 20, 1947	Tech. Paper No. 33	Internal
Critical Considerations of Burning Velocity Measurements at Reduced Pressures.--A. T. Whatley, J. A. Faucher, E. J. Badin.	Nov. 1, 1947	Tech. Paper No. 34	Internal
The Reaction Between Atomic Hydrogen and Molecular Oxygen at Low Pressures.II.--E. J. Badin.	Dec. 20, 1947	Tech. Paper No. 35	Internal
Remarks on the Interaction Between Shock Waves and Boundary Layer in Transonic and Supersonic Flow.--L. Lees.	Nov. 1, 1947	PR No. 1	General
Unsteady One-Dimensional Flows with Heat Addition or Entropy Gradients.--A. Kahane, L. Lees.	Nov. 27, 1947	PR No. 2	General
Flow in Ejectors Driven by Supersonic Jets.--K. D. Miller.	May 14, 1948	PR No. 3	Internal
The Development of the Aeroresonator of the V-1 Flying Bomb.--Dr. I. G. Diedrich (translation).	Dec. 1, 1946	PR No. 4	General
The Reaction Between Atomic Hydrogen and Molecular Oxygen at Low Pressures, III.--E. J. Badin.	June 1, 1948	PR No. 5	Internal
Electrical Properties of Flames: Part I. Literature Study Part II. Burner Flames in Longitudinal Electric Fields Part III. Burner Flames in Transverse	June 15, 1948	PR No. 6	Internal

<i>Title and Author</i>	<i>Date</i>	<i>Memorandum No.</i>	<i>Distribution</i>
Electrical Properties of Flame: (cont'd) Part III. Electric Fields. Part IV. Explosions in Longitudi- nal Electric Fields.-- H. F. Calcote.	June 15, 1948	PR No. 6	Internal
The Formation of Nitric Oxide in Flames Calculations for Methane- Oxygen Nitrogen Mixtures.--R. S. Brokaw.	July 1, 1948	PR No. 7	Internal
The Princeton Pilot Variable Density Supersonic Wind Tunnel.--S. M. Bogdon- off.	May 29, 1948	PR No. 8	General
The Kinetics of the Reaction of Alu- minum Borohydride Vapor with Olefins.-- R. S. Brokaw.	Dec. 15, 1948	PR No. 9	Internal
The Thermal Oxidation of Ammonia with Oxygen.--E. R. Stephens.	Dec. 15, 1948	PR No. 10	Internal

In addition to the informal technical memoranda listed above, formal technical reports have been issued during the period. These reports contain information which was considered sufficiently significant to warrant formal printing and general distribution. A list of these technical reports, presented by university, follows:

NEW YORK UNIVERSITY

<i>Title and Author</i>	<i>Date</i>	<i>Tech. Report No.</i>	<i>Distribution</i>
One-Dimensionalized Aerothermo- dynamic Theory of Turbulent Flame Propagation in Flame Tubes.--J.K.L. MacDonald.	Nov. 15, 1947	Tech. Report No. 6	General

<i>Title and Author</i>	<i>Date</i>	<i>Tech. Report No.</i>	<i>Distribution</i>
A Preliminary Study of Flames in Tubes Containing Grids.-- M. W. Evans, M. D. Scheer, L. J. Schoen.	Dec. 1, 1947	Tech. Report No. 7	General
A Water Analogue of the Isentropic Flow of Compressible Gases Which Have Arbitrary Ratios of Specific Heats.--R. F. Probstein and G. E. Hudson.	Aug. 1, 1948	Tech. Report No. 15	Not yet published

POLYTECHNIC INSTITUTE OF BROOKLYN

A Theoretical Investigation of the Temperature Field in the Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection.-- Dr. Shao-Wen Yuan.	Sept. 5, 1947	Tech. Report No. 4	General
Compressible Flow Through Reed Valves for Pulse Jet Engines, I. Hinged Reed Valves.--P. Torda, I. P. Villalba, J. H. Brick.	June 14, 1948	Tech. Report No. 9	Not yet published
Compressible Flow Through Reed Valves for Pulse Jet Engines, II. Clamped Reed Valves.--P. Torda.	July 22, 1948	Tech. Report No. 10	Not yet published
Approximate Theory of Compressible Air Inflow Through Reed Valves for Pulse Jet Engines.--P. Torda.	Sept. 15, 1948	Tech. Report No. 12	Not yet published
On Time and Space Functions of Heat Input Necessary to Produce in a Tube, Waves of Density, Velocity, Pressure, Temperature, Momentum and Periodic Thrust of Required Character.--H. J. Reissner.	July 1, 1948	Tech. Report No. 13	Not yet published

<i>Title and Author</i>	<i>Date</i>	<i>Tech. Report No.</i>	<i>Distribution</i>
On the Structure of Shockwaves in a Viscous, Heat Conducting, Compressible Fluid, Part I. Shockwaves in a One Dimensional Flow with Constant Coefficients of Viscosity and Conductivity.--H. Reissner and L. Meyerhoff.	Feb. 1, 1948	Tech. Report No. 14	Not yet published

CORNELL AERONAUTICAL LABORATORY

(Reissue of CAL-1)	June 16, 1947	Tech. Report No. 1	General
(Reissue of CAL-2)	June 23, 1947	Tech. Report No. 2	General
(Reissue of CAL-3)	Sept. 15, 1947	Tech. Report No. 5	General
(Reissue of CAL-4)	June 30, 1947	Tech. Report No. 3	General

PRINCETON UNIVERSITY

William C. House, and Harold S. Bell, Jr.	May 15, 1948	CONFIDENTIAL Tech. Report No. 8	General (except for 8 copies)
William C. House and Harold S. Bell, Jr.	July 1, 1948	CONFIDENTIAL Supplement to Tech. Report No. 8	Special Distribution
Stability of the Laminar Boundary Layer with Injection of Cool Gas at the Wall.	May 20 1948	Tech. Report No. 11	General

Other publications have been prepared and distributed during the period through 31 December 1948. These are indicated below.

<i>Title</i>	<i>Date</i>	<i>Distribution</i>
Annual Program Report	January 1, 1948	General
Semi-Annual Progress Report	January 1, 1947	General
Quarterly Progress Reports	April 1, 1947	General
	July 1, 1947	General
	October 1, 1947	General
	April 1, 1948	General
	July 1, 1948	General
	October 1, 1948	General
Monthly Progress Reports	September 1, 1946 to date	Internal
Project SQUID Handbook, 1947	December 31, 1947	Special
Project SQUID Handbook, 1948	October 1, 1948	Special

Special reports prepared prior to June 30, 1948, either by Engineering Research Associates or by Engineering Research Associates in conjunction with the Project SQUID staff are as follows:

Introductory Report on Project SQUID	December 31, 1946	General
Field Survey Report (Classified)	June 30, 1947	Restricted
Bulletin of the Instrumentation Panel No. 1	January 1, 1948	General
Bulletin of the Instrumentation Panel No. 2	May 1, 1948	General.

DISTRIBUTION

1. Joint Army-Navy-Air Force Guided Missiles Mailing List Number 7 and Change Sheet Number 1, dated 15 February 1949. Parts A, B, C, DP.
2. Chief of Office of Naval Research, Power Branch, Washington, D. C., Attn: Comdr. J. L. Schoenhair. (11 copies)
3. Bureau of Aeronautics, Power Plant Division, Experimental Engines Branch, Washington, D.C., Attn: Lt. Comdr. C. Hoffman. (2 copies)
4. Commanding Officer, Office of Naval Research, New York.
5. Commanding Officer, Office of Naval Research, Chicago.
6. Guided Missiles Branch, Bureau of Ordnance, Navy Department, Washington, D.C., Attn: Comdr. H. M. Mott-Smith. (2 copies)
7. Mr. A. G. Leigh, Office of Naval Research Representative, University of Rochester, Rochester, N. Y.
8. U. S. Navy Office of Naval Research, Branch Office, San Francisco, California.
9. Naval Ordnance Test Station, Pasadena, California.
10. Policy Committee, Project SQUID. (6 copies)
11. Technical Representatives of Project SQUID at member universities. (6 copies)
12. Contract Administrators of Project SQUID at member universities. (6 copies)
13. Technical Panel Members, Project SQUID. (12 copies)
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15. Metallurgical Advisory Committee of Project SQUID. (3 copies)
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21. Prof. Clark Millikan, California Institute of Technology.
22. Prof. R. Folsam, University of California.
23. Mr. William Tenney, Aeromarine Company, Vandalia, Ohio.

24. New York University, New York, N. Y., Attn: Mr. M. W. Woody. (18 copies)
25. Committee on Undersea Warfare, National Research Council, Washington, D.C., Attn: Mr. J. S. Coleman.
26. The Director, U. S. Navy Electronics Laboratory, San Diego 52, California, Attn: Library Ref. 617-206.
27. Graduate School of Aeronautical Engineering, Cornell University, Ithaca, New York, Attn: Prof. A. R. Kantrowitz.
28. Chief of Naval Research, c/o Science and Technology Project, Library of Congress, Washington, D. C. (2 copies)
29. Chief, Exchange and Gift Division, Library of Congress, Washington, D. C., Attn: Mr. Lewis C. Coffin.
30. Mr. P. Kratz, Office of Naval Research Representative, University of Pennsylvania, Philadelphia, Pa.

End
Filmed
12-83

TITLE: Annual Program Report - Dnd Appendix - 1 January 1949

ATI- 59022

AUTHOR(S) : (Not known)

DIVISION

(None)

ORIG. AGENCY : New York Univ., Polytechnic Inst. of Brooklyn, Purdue Univ., & Others

ORIG. AGENCY NO.

(None)

PUBLISHED BY : (Same) for USN Project Squid

PUBLISHING NO.

(None)

DATE	U. S. CLASS	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan '49	Unclass.	U.S.	English	193	photos, tables, diagrs, graphs

ABSTRACT:

Progress made during a period of a year is reported for Project Squid. Several phases of a cooperative program of fundamental research in jet propulsion especially with liquid rocket and pulse jet engines are reported by the Universities of New York, Purdue, Princeton and Delaware, as well as Polytechnic Institute of Brooklyn and Cornell Aeronautical Laboratory. Photographs of some of the equipment used in testing these engines as well as special apparatus for studying various phases of combustion are included and the results of the tests are shown in tables and graphs.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)

SECTION: General (0)

SUBJECT HEADINGS: Jet propulsion - Research

Project squid

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AIR TECHNICAL INDEX

USN Contr. No. N6-ori-11; 98; 104;
and Others

TITLE: Project Squid - Annual Program Report - A Cooperative Program of Fundamental Research in Jet Propulsion - and Appendix - 1 Jan. 1949

AUTHOR(S) : (Not known)
ORIG. AGENCY : Office of Naval Research, Washington, D. C.
PUBLISHED BY : (Same) for Project Squid

ATI-65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	193	photos, tables, diags, graphs

ABSTRACT:

The status of work as of 1 January 1949, in various phases of the "Project Squid" for the development of pulse jet and rocket engines is described. Individual reports are submitted by New York University, the Polytechnic Institute of Brooklyn, Purdue University, Cornell Aeronautical Laboratory, Princeton University, and University of Delaware covering the technical progress at the respective universities.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Combustion (4)

SUBJECT HEADINGS: Combustion efficiency - Determination
Jet propulsion - Research
Project Squid

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CADO TECHNICAL INDEX

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

ATI-Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

AUTHOR(S) : (Not known)

ORIG. AGENCY : Univ. of Delaware, Newark

PUBLISHED BY : Office of Naval Research, Washington, D.C. for USN Project Squid

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	1	(None)

ABSTRACT:

Progress made at the University of Delaware on a cooperative program of fundamental research in jet propulsion is discussed. The University was charged with the investigation of heat transfer in passages with free convection and counterflow. The visual study is to be carried out using a vertical rectangular duct having two opposed glass walls with provision to heat the middle portion. Free convection will be upward but arrangements will be made to force air downward at a controllable velocity. By means of spark photography the resulting gas can be studied. The quantitative study is to be carried out with emphasis on the cooling effect of liquid under conditions of free convection with forced counterflow. Various liquids will be chosen so as to give a wide variation in the Grashof number. This work is just getting under way and information in regard to progress and plans will be forthcoming.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Cooling (1)

18
4

SUBJECT HEADINGS: Engines, Jet - Cooling
Jet propulsion - Research
Heat transfer - Measurement
Project Squid

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CADO TECHNICAL INDEX

USN Contr. No. N8onr-74000 and
74001

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

AUTHOR(S) : (Not known)

ORIG. AGENCY : New York Univ. N.Y.

PUBLISHED BY : Office of Naval Research, Washington, D. C. for USN Project Squid

ATI-Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	18	photos, graphs, charts

ABSTRACT:

Jet propulsion research progress made at New York University in investigations of the dependence of flame speeds and combustion rates on highly turbulent-flow structure in combustible gases in tubes, ducts and jets is reviewed. Theoretical methods for calculating transient temperature distributions and thermal stresses in solids in which heat capacities and conductivities are functions of the temperature are developed in connection with rockets and pulse jets. Valve, particle, and flame motions were observed; thrusts and instantaneous pressures, temperatures, and flow speeds were recorded in and near standard or idealized components of pulse jets and related devices. These observations are to be used in theoretical and electromechanical analogue treatment of pulse jets. Development and use of instruments for recording thrust and transient pressures, temperatures, etc. are described.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Combustion (4)

SUBJECT HEADINGS: Project Squid
Combustion efficiency - Determination
Jet propulsion - Research

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CADO TECHNICAL INDEX

USN Contr. No. N6ori-11

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

AUTHOR(S) : (Not known)

ORIG. AGENCY : Princeton Univ., N.J.

PUBLISHED BY : Office of Naval Research, Washington, D.C. for FSN Project Squid

ATI- Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	31	photos, tables, diagrs, graphs

ABSTRACT:

Progress made at Princeton University covers fundamental research in jet propulsion. Investigations directed toward an understanding of the physicochemical aspects of flame propagation and ignition are in progress. Theoretical and experimental investigations of certain fundamental problems associated with the development of ducted propulsive devices were carried out. A valveless intermittent jet engine was investigated which would operate through cyclic injection of fuel. A combustion pressure ratio of about two was obtained with this engine, indicating that high thermodynamic efficiencies are possible from a combustion point of view. Some jet propulsion problems were specifically concerned with the mixing of parallel gas streams, means of improving such mixing, and with combustion chambers.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Combustion (4).

SUBJECT HEADINGS: Engines, Pulse jet - Valveless
Flame propagation
Jet propulsion - Research
Project Squid

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CADO TECHNICAL INDEX

USN Contr. No. N6ori-105

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

ATI- Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

AUTHOR(S) : (Not known)
ORIG. AGENCY : Polytechnic Inst. of Brooklyn, N.Y.
PUBLISHED BY : Office of Naval Research, Washington, D.C. for USN Project Squid

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	34	photos, diags, graphs

ABSTRACT:

Progress at the Polytechnic Institute of Brooklyn in a cooperative program of fundamental research in jet propulsion is reported. The analysis of air inflow through automatically operating reed valves was terminated. Analyses were made of the starting cycle and operating cycle in the problem dealing with the unified theory for pulse jets. In the investigation of the causes of metal failure, temperature distribution studies were made by means of martensitic structure analysis. Studies of carbides, nitrides, and borides bonded with refractory metals were continued. Further investigation of the problem of the laminar boundary layer of a compressible fluid flowing through a porous flat plate with fluid injected through the porous cells of the plate was made with better approximation of the density and viscosity variation inside the boundary layer. In addition, stability investigations were made.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)
SECTION: Performance (16)

2
9

SUBJECT HEADINGS: Flow, Isentropic
Engines, Pulse jet - Air intake valve
Jet propulsion - Research
Project Squid

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CADO TECHNICAL INDEX

USN Contr. No. N6ori-98

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

AUTHOR(S) : (Not known)

ORIG. AGENCY : Cornell Res. Foundation, Aeronautical Lab., Buffalo, N.Y.

PUBLISHED BY : Office of Naval Research, Washington, D. C. for USN Project Squid

ATI- Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclassi	U.S.	English	39	photos, diagrs, graphs

ABSTRACT:

Progress report contains developmental data on fundamental research in jet propulsion conducted at the Cornell Aeronautical Laboratory. The advantages and disadvantages of the analogy between surface gravity waves in shallow water and pressure waves in gases, and the method of characteristics used in the study of nonstationary gas flow are described, and designs for intermittent combustion devices are suggested. Theoretical studies and determinations of heat release during combustion were made, together with an investigation of the possible catalytic influence of combustion-chamber wall material. The effect of combustion conditions on the spectra of hydrocarbon flames was investigated. The physical properties and the mechanism of failure of materials for high-temperature application were studied, and the construction of a high-temperature metalloscope is described.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)

SECTION: Combustion (4)

2
9

SUBJECT HEADINGS: Jet propulsion - Research
Combustion - Thermodynamics
Flow, Non-stationary
Project Squid

Central Air Documents Office
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CADO TECHNICAL INDEX

USN Contr. No. N6ori-119

TITLE: Annual Program Report - Project Squid - A Cooperative Program of Fundamental Research in Jet Propulsion - 1 January 1949

AUTHOR(S) : (Not known)

ORIG. AGENCY : Purdue Univ., Research Foundation, Lafayette, Ind.

PUBLISHED BY : Office of Naval Research, Washington, D.C. for USN Project Squid

ATI- Part of 65987

REVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

(None)

DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan' 49	Unclass.	U.S.	English	53	photos, tables, diagsr, graphs

ABSTRACT:

Progress at Purdue University on a cooperative program covers fundamental research in jet propulsion. Factors involved in continuous-process combustion with emphasis on flame holding were experimentally determined. The investigation of flame stability and blowoff limits with an annular-type flame holder was extended to include mixture supply velocities in a low-turbulence stream of Mach numbers up to unity. Calculations were made of thermodynamic properties of propane-air combustion products. The identification of the oxide formed on several Ni-Cr steels over a limited range of temperatures was completed. Data pertinent to the study of radiation factor and its contribution to heat transfer coefficient inside a pipe with gas flow of low and high temperatures showed various peculiarities in the 1000-2000°F range. An instrument for giving a direct measurement of the ignition delay time for rocket propellants was built.

DISTRIBUTION: Copies of this report obtainable from CADO.

DIVISION: Power Plants, Jet and Turbine (5)

SECTION: Combustion (4)

SUBJECT HEADINGS: Jet propulsion - Research
Combustion - Thermodynamics
Combustion - Blow-off
Project Squid

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CADO TECHNICAL INDEX

USN Contr. No. N6ori-104