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UNITED STATES NAVY

PROJECT SQUID

ANNUAL

PROGRAM REPORT

1 JANUARY 1948

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ANNUAL PROGRAM REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT

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NEW YORK, NEW YORK
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PHASE I

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

Outline of Motivation and Objectives

Parts (1), (2), and (3) of this phase were initiated because high-speed motion pictures taken through a transparent-walled pulse jet indicate that flame propagation in such jet tubes differs markedly from that in bunsen burners and other devices which have been used extensively in laboratory studies of non-turbulent combustion. The differences between the two types of propagation have been attributed (*Bulletin of Meetings on Fundamentals of Combustion Applied Physics Lab.*, Johns Hopkins University, Silver Spring, Md., March 17-18, 1947, pp. 1-5) to the large scale turbulent flow structure in the jet tubes, as contrasted with almost laminar flow in the burners. In the burners the flame takes the form of a mildly curved thin shell which advances into the unburned gas with a relative velocity of only a few feet per second. In pulse jets, on the other hand, the flame appears to advance very rapidly in the form of a billowing cloud which may extend over several feet of the jet tube, and which may continue to glow for several milliseconds.

Since the operation of pulse jets depends on this little understood turbulent combustion, and since questions of scientific as well as of practical interest are involved, it was decided to investigate relevant combustion and flow processes. Since factors governing combustion in actual jet motors are not readily controlled, it appeared that fundamental information might best be obtained by use of special types of flame tubes in which combustion simulating that in pulse jets could be produced under laboratory conditions. For this purpose two different types of flame tubes were designed, one for moving and one for stationary flames. The first type which has provided considerable data on flame propagation, is described below; and the second type of tube will be put into operation at our Rye Lake test site when current tests of a modified Merlin supercharger blower have been completed. (See Project SQUID *Semi-Annual Report*, January 1, 1947, and *Quarterly Report*, July 1, 1947, for details).

In order to interpret the flame tube results in a form which should be useful in the analysis of pulse jets, a one-dimensionalized theory for wave and flame propagation in tubes was developed. A *Technical Report* on this theory is now being printed for general distribution and will be followed shortly by a report on the experimental results. An outline of the theoretical and experimental results is given in the next section.

Part (4) of Phase I was introduced because it was thought initially that the effectively high flame speeds observed in pulse jets probably involve more violent chemical reaction than those in non-turbulent combustion. On this assumption, and because of the possible existence of shock waves in pulse jets, the effects of strong gradients in velocity, pressure, temperature, and concentrations of active molecules might be important. Since hydrodynamical treatments of viscosity, heat conduction, and diffusion assume that these gradients are small, it was thought that a more general statistical mechanics approach to the processes would be of interest. Although some progress was made in formulating these problems, lack of sufficient personnel with suitable training hindered the development of a general treatment.

Objectives and Results for Flames Moving in Tubes

As has been indicated in previous *Quarterly Reports*, it is possible to produce high speed turbulent flames in a pyrex tube containing an igniter at a closed end and a grid or multiple nozzle structure between the igniter and the open end. The tube is usually 4 to 8 feet long and about 5 to 10 square inches in cross section (circular or rectangular). The grid is either a disc of fly screen or a multiple nozzle structure made of sheet metal in a form resembling a can with no top and with one or more holes (about one cm.²) in the bottom. Each hole is usually rimmed by a sharp edged "fence" about 1 cm. high (see Figure 1).

The high speed flames are produced as follows: The tube is initially filled with a combustible mixture at rest, the igniter is turned on and a normal non-turbulent flame starts to propagate between the igniter and the grid. Expansion of the gas due to the temperature rise

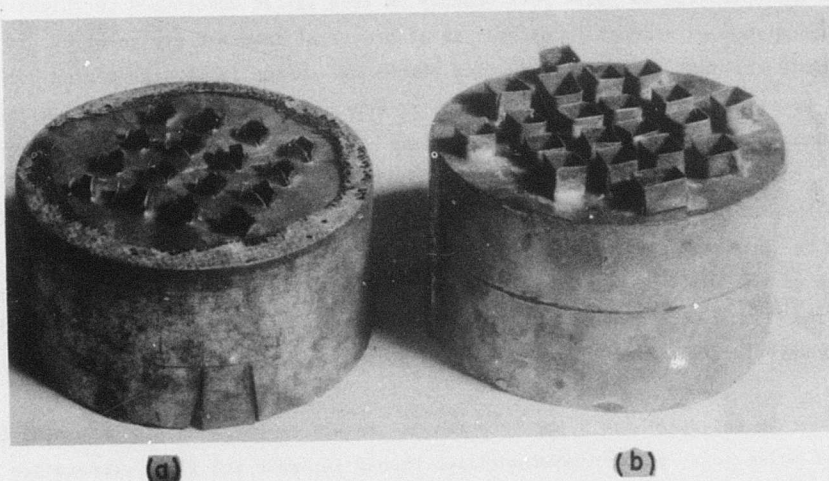


Figure 1.
Turbulence Making Grids.

produced by this combustion causes gas to flow through the holes in the grid, thereby establishing a turbulent flow structure (probably of multiple jet type) into which the flame propagates after passing through the grid. High speed photographic recording shows that the flame "cloud front" then advances into the turbulent gas with an effective velocity of several hundred feet per second relative to the tube. Typical streak camera records showing the flame front positions versus time are reproduced in Figure 2. Similar records were obtained under a variety of conditions in order to obtain clues concerning the nature of the turbulent flame propagation, with particular emphasis on correlation with geometric parameters and with normal flame propagation. The following characteristics were varied: (i) tube length, (ii) tube cross-sectional shape and area, (iii) grid shape and position, (iv) fuel-air mixture ratio, and type of fuel, (v) type of igniter. Considerable care was taken to obtain reproducible results. Accurate pre-mixing of the gases and careful scavenging of the flame tube before each experiment were found to be necessary. Special timing and relay devices were developed

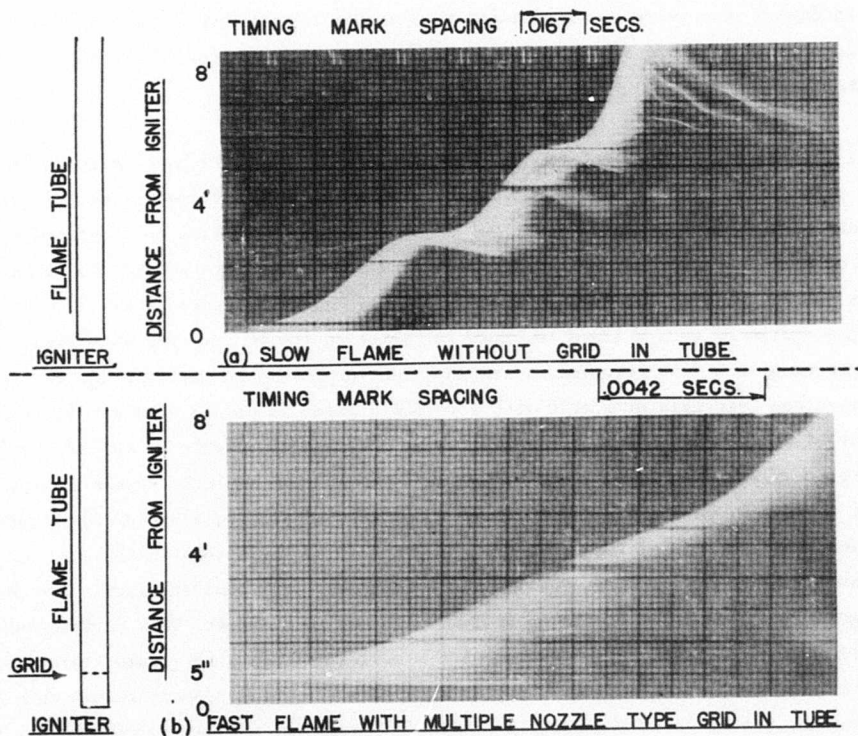


Figure 2.
 Streak Photographs-Flame Motions-8' Tube.

for the photographic recording. It was possible to obtain some oscillograms of pressures and Schlieren movies indicating flow structure at the open end of the tube, but these require further verification.

Briefly, the results thus far are as follows:

(i) The length of the tube does not affect flame propagation until pressure waves, produced by the early combustion near the igniter, have had time to travel to the open end of the tube and back to the flame front. Subsequent reflections of the waves from the closed and open ends of the tube appear to affect the flame velocity in a manner predicted by the one-dimensionalized theory, on the assumption that the oscillations in the cross-sectional average stream velocity do not affect the intrinsic flame speed or reaction rate.

(ii) The flame speeds are not detectably affected by the size or shape of the cross section of the tube for the range considered. Therefore the usual concept of Reynolds number for flow through a pipe plays no significant part in the type of turbulent combustion involved here, in conformity with the idea of a multiple jet type of turbulent flow structure suggested in the preceding section.

(iii) The shape of the grid and its distance from the igniter have marked effects on the flame propagation. Without any grid whatever in the tube the flame speeds relative to the tube are normally less than 100 feet per second, in agreement with observations made elsewhere on non-turbulent flames. These relatively slow flames are subject to rather erratic variations which are largely unexplained but which may be due to sporadic development of eddies. A streak photograph of such a flame is shown in Figure 2a (to be compared with Figure 2b which corresponds to a fast turbulent flame in a tube containing a multiple-nozzle-type grid). When a fly-screen type grid or a grid with very few nozzles is placed within a few inches of the igniter, flame speeds somewhat less than those indicated in Figure 2b are obtained. Furthermore the flame speeds appear to be somewhat slower when a single nozzle is placed at the center instead of at the edge of the grid. Somewhat erratic results for flame speeds are obtained near the open end of the tube, probably because of variations in the fuel-air ratio due to convection and diffusion in that region. Even less reproducible results are obtained when the grid is placed a few feet away from the igniter in the tube; this erratic behavior is probably related to that mentioned above for slow flames, since the flame travels slowly until it reaches the grid. Similarly, rather unreproducible flame speeds result when the "fences" forming the walls of the nozzles (shown in Figure 1b) are partly removed (as indicated in Figure 1a) or are entirely removed to form an orifice-type grid. Speculative explanations, based on ideas related to the development and persistence of single or multiple jets, which may account for the above effects, are described in a forthcoming *Technical Report*. Schlieren movies and other techniques are being applied to the study of these phenomena.

(iv) The dependence of fast flame speed on fuel-air ratio and on type of fuel (propane or n-butane) shows marked qualitative correlation with that for normal non-turbulent flames. This correlation implies that the turbulent flow structure, produced by the initial non-turbulent combustion forcing gas through the grid, affects the flame propagation to a degree correlated with the speed of that non-turbulent combustion. A slowing down of the flame shortly after penetrating the grid appears to be explained by a rarefaction wave developed when the combustion is completed near the grid. A fuller discussion of these features will be presented in the *Technical Report* mentioned above.

(v) Although no very systematic investigation of effects due to different igniters has been undertaken, it appears probable that the fast flame speeds are independent of the type of igniter. Electrically heated metal sheets and wire, electrically exploded wires, and electric sparks were used at various times, but sparks were used in most of the work because it simplified timing procedures. The intensity of an igniter may be an important factor in connection with the ignition lag and ignition limits of concentration, but normally would not be expected to affect the moving flame once it is established.

The one-dimensionalized aero-thermodynamic theory of wave and flame propagation referred to above is described in detail in a *Technical Report* which is now being printed. Here it suffices to mention that the theory is a generalization of that developed in a previous report (*AMG Report 151*, N.Y.U. Inst. for Math. and Mech., 45 4th Ave., New York, June, 1946), and that explicit analytical solutions of linear differential equations are shown to provide good approximations for numerical solutions of the complete non-linear equations involved.

Merlin Engine Blower Unit

During 1947 from April through December, the members of Project SQUID designed and constructed a blower unit to supply high velocity air in large quantity for the proposed stationary flame tests to be performed in connection with Phase 1 of our contract. This blower unit is to deliver air to a diverging duct in which flame holders and turbulence-producing grids are installed. The diverging section is intended to produce continually decreasing stream velocities in the hope that the flame front will stabilize at some definite position in the tube and its velocity of propagation and other characteristics determined by inspection through the glass walls of the test section. The blower unit to produce this air stream has been under construction since April due to the fact that other phases of Project SQUID were considered more important from the overall point of view.

It was considered highly desirable to have a unit simple to construct and capable of movement to various test sites without great expense. Various sources of air supply in use at other universities were considered. Commercially produced blowers were considered first

and it was found that the blower alone would cost over \$6,000 and could not be delivered for six to eight months; furthermore, no power source could be found to drive the blower. The second installation that was investigated was one in use at Massachusetts Institute of Technology, which consisted of an Allison engine driving the two stage supercharger from a Pratt and Whitney engine. This installation seemed to be of reasonable cost and fairly simple construction.

Before construction was started on a blower of this type, however, information was received through Marquardt Aircraft Corporation, Venice, California, that the Power Plant Laboratory at Wright Field had developed a considerably simpler and more compact installation. This installation was the one finally chosen for construction and consisted simply of a Rolls Royce Merlin engine (V-1650-7) on which the modifications required were of a minor nature. The only problems faced by the builders of this type of unit were getting and installing the necessary accessories for control, cooling, and lubrication.

The completed unit consists of a small trailer 8 feet wide and 12 feet long on which is mounted athwartships the Merlin engine with the control panel at the forward end of the trailer and the cooling and lubrication system installed aft of the engine. Inside the trailer itself is installed a fuel tank for the engine. This unit has been run, but due to pressure of other work, has not been completely tested.

On the basis of the results obtained at Wright Field, it seems possible to obtain maximum air flow of 18,000 pounds per hour at 65 pounds gauge. The unit is almost completely self-contained; the only outside connection required is to a fire hydrant through a 2½-inch canvas hose to supply cooling water.

It is expected that as soon as construction work on the JB-2 thrust stand is completed, final running tests on the blower unit will be made and construction of the diverging duct will be undertaken. It is expected that this work will be completed by June 1948, and the only further expense involved in these tests will be for the services of personnel to operate the equipment.

Some Future Plans. During 1948 it is planned to make a careful experimental and theoretical analysis of the flow structure and its interaction with the fast flames in flame tubes and in special types of laboratory burners. Gas pressure, temperature, and radiation oscillograms as well as Schlieren movies will be made at various positions in the flames, and effects produced by pressure pulses and other disturbances will be studied.

PHASE 2

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

Outline of Motivation and Objectives

This Phase is concerned mainly with the determination of experimental and theoretical information concerning heat transfer and temperature distributions in rapidly heated thin walls such as are used in rockets. In such walls stresses due to temperature gradients are superimposed on stresses due to gas pressure inside the motor. To calculate the thermal stresses and the effective strengths of the walls during the heating it is necessary to know the temperature distributions as functions of position and time; this requires a knowledge of the dependence of thermal conductivity and heat capacity on temperature (and on the rate of rise of temperature if there are lag effects in the absorption of heats of transformation). On the other hand, in order to determine experimentally the distribution of temperature in a rapidly heated wall it is important to know how much disturbance in the temperature is produced by the insertion of the thermocouple or other measuring device. These theoretical and experimental problems, together with the determination ultimately of functions for heat transfer between turbulently flowing hot gases and walls, provide the basis for this phase.

Outline of Theoretical Results

A numerical solution of the equations for heat conduction through a wall containing a thermocouple wire in a "well" has confirmed some earlier analytical approximations which indicated that 30% perturbations in the temperature readings could be produced by the presence of even a very narrow thermocouple and well. Convenient analytical expressions have been obtained for the modifications in temperature distributions due to thin layers of paints or foils in rapidly heated walls or due to thermocouples attached to the external face of a rocket wall. Furthermore, exact analytical solutions for temperature perturbations due to the presence of wedge shaped thermocouple structures in the walls have been obtained. All of these analytical results strictly refer to walls with thermal diffusivity independent of the temperature. In a continuation of work on non-linear heat conduction described in the *Semi-Annual Report*, January 1, 1947, particular solutions of the heat conduction equation with temperature dependent diffusivity have been obtained. All of the above theoretical matters will be treated in detail in a forthcoming *Technical Report*.

Outline of Experimental Results

In the first half of 1947 some oscillograms were obtained for temperature in a steel rod which was rapidly heated by current from a storage battery. Four six-volt storage batteries in series-parallel arrangement were shorted through a steel (AISI-C 1040) rod 3 mm. in diameter and 20 cm. long. Reproducible rates of rise of temperature as high as $1000^{\circ}\text{C}/\text{sec.}$ were obtained and inflections corresponding to absorptions of heats of transformation at critical temperatures were noted. Since calculations indicated that radiation losses from the surface of the rod were probably large enough to interfere with quantitative measurements, the major part of subsequent work was devoted to the design, construction, and preliminary testing of radiation shields around vacuum chambers, and of precision electronic equipment for amplifying and recording the temperature, current, and potential drop in the rod. This work has been retarded because of lack of sufficient personnel.

A quartz wedge-shaped thermocouple was designed and the wedges and metal sputtering equipment were procured. When completed, the wedge thermocouple will be sent to Inyokern for tests in rocket walls. This type of thermocouple produces little disturbance in the temperature in a rapidly heated wall, and the disturbances can be calculated theoretically.

Future Plans. Theoretical work on non-linear conduction of heat and on heat transfer between turbulently flowing hot gases will be continued and extended. Supporting experiments will be performed. The experimental determination of effects of high rates of heating on the thermal parameters of steel rods will, it is hoped, be completed in 1948.

PHASE 3

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

Statement of Objectives and Motivations

It is clear from the foregoing statement of the phase assignment that while the numerous problems suggested by it are definite ones to formulate and carry out, they are all interdependent and are pointed up toward one main objective. This objective is to obtain fundamental information and basic data concerning the operation of pulse jets and other jet devices

for purposes of comparison with, check of, and use in a gas-dynamical formulation of a theory of pulse jets. This theory, developed in *AMG-NYU Report No. 151*, is based on the idealization of the equations of aero-thermodynamics to one-dimensionalized gas flow, but with a non-uniform cross section. It is necessary, for the application of this theory to any particular type of pulse jet device, to have such basic data as flame speeds in a highly turbulent burning mixture, pressure and flow conditions at the valve and exhaust end of the device, as well as information concerning the state of flow and combustion at some particular instant inside the engine. There follows in this introduction a list of the problems on which work has been done toward obtaining some of this information, together with an indication of the motivation of each investigation. Details of the observations and some of the methods of attack on the problems are given in subsequent sections.

Numerous observations have been made on small pulse jets of the dynajet type, as well as on full scale pulse jet engines. One reason for studying pulse jets of small size is that they constitute an extremely convenient laboratory tool with which many experimental techniques of value in the study of large scale pulse jet performance can be developed and tested. Furthermore, some fundamental data can be obtained from the small jet engines and a comparison can be made with similar observations on the large pulse jets in order to determine scale effects. The first series of tests on the large pulse jets were run during the summer at a test site near Lake Denmark, New Jersey. The purpose of these tests was to obtain observations on flame and valve motions in order to provide checks on the aforementioned general theory of pulse jets and to help fix the boundary conditions in it. After a considerable delay necessitated by termination of the lease at Lake Denmark, the tests are now continuing at a new site, and it is planned to study ultimately the effect of modifications in the basic construction of the engine suggested by theory and experiment.

Experiments involving actual pulse jet engines, even the small ones, are never entirely under the control of the experimenter, especially as regards the combustion process and the boundary conditions at the intake and exhaust ends of the engine. Moreover, some characteristics of the phenomena which occur are frequently blanketed by other effects so that observation is difficult. To surmount these obstacles in part, a study of various analogues of pulsating and other jet devices is under way. Such analogues are often of value as instructional and illustrative aids, as well as in furnishing quantitative information. In one class are the water and electromechanical analogues, which in effect serve as integrating machines for solving the non-linear aero-thermodynamic equations in the pulse jet theory. In a slightly different category are two types of simulating mechanisms under study. One such mechanism is designed to simulate the flow conditions at the intake or valve end of a pulse jet. This might be called the "cold pulse" valve simulator. The other mechanism consists of a vibrating piston driving the air column in a cylinder at resonances with large amplitude vibrations. This simulator permits a controlled study of the flow conditions at the exhaust end of a pulse jet.

Observations and Results

Pulse Jet Observations. One problem of primary importance is to find a method which makes possible the visual observation of flames and particle motions in the tail pipe and combustion chamber of small pulse jets. This has been solved by constructing a pulse jet similar to a Dynajet but with tail pipe and combustion chamber rectangular in cross section so that the side walls can be made of sheets of transparent pyrex glass or quartz. A final model of such a transparent-walled pulse jet shown in Figure 3 has been constructed and is being used for the observation and measurement of flame motions relative to the jet tube. A large quantity of such observations have been made, primarily using streak photographic techniques, and the techniques are continually being improved. By means of a make-break contact on the valves, which lights a neon light when the intake valves are open, it has also been possible to observe the phase relations between the valve states and the flame positions. Figure 4a shows a typical streak photograph of the flames in a transparent walled Dynajet.

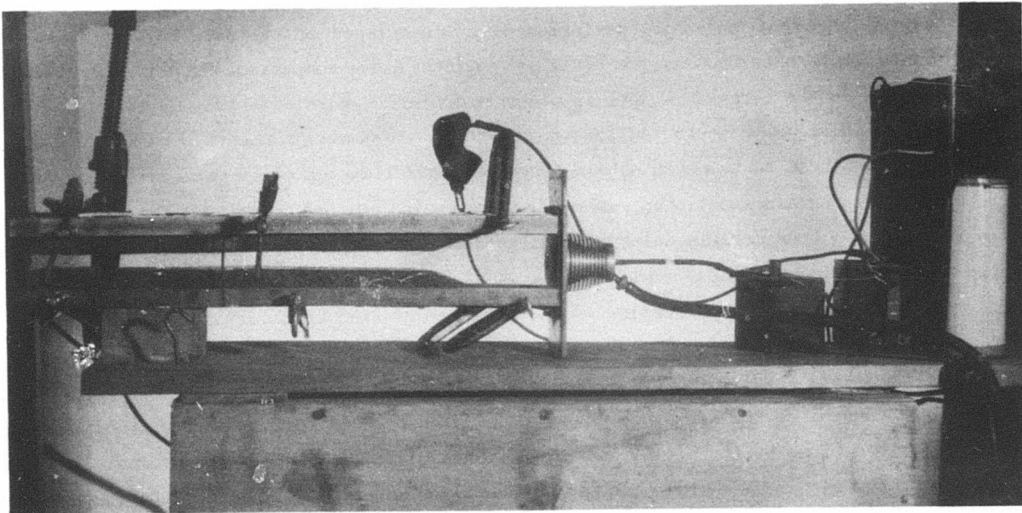


Figure 3.

The transparent-walled dynajet ready for operation.

Another group of problems, some of them similar to the preceding ones, arose in connection with tests on the full scale PJ-31 pulse jet engine, mounted on a JB-2 pilotless aircraft. The problem of observing the flame motions was solved by viewing the flames directly through a series of holes drilled along the engine, and the valve state was observed by viewing the light transmitted through the valves when open. The flame patterns and valve phase relations are similar, qualitatively, to those obtained with the small scale pulse jets,

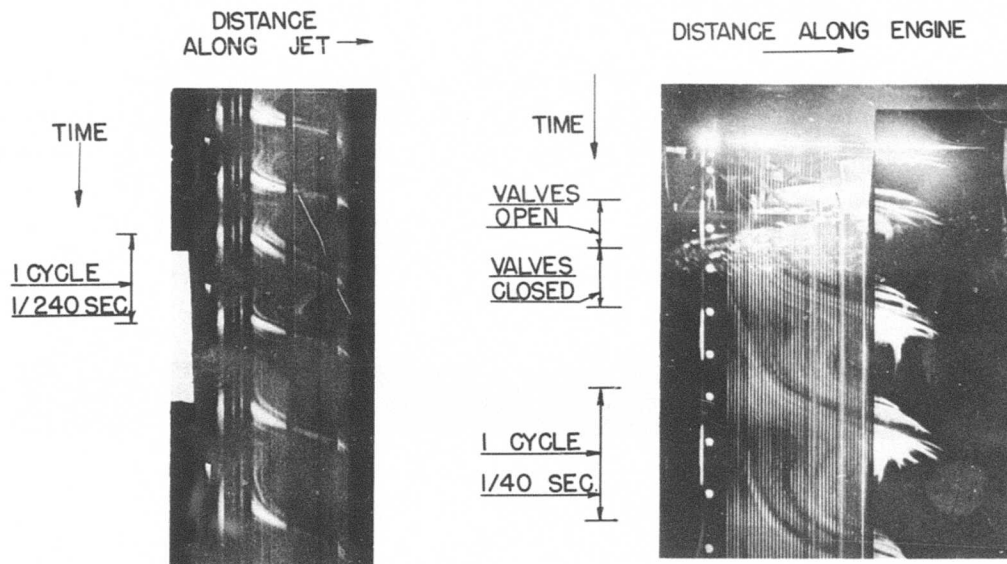


Figure 4a. Streak photograph of flames in a transparent-walled Dynajet in operation. Compare with Figure 4b.

Figure 4b. Streak photograph of flames in a PJ-31 pulse jet engine in operation. The series of white vertical dashes on the left indicate the intermittent opening of the intake valves. The dots forming a vertical row on the left are timing marks. The shaded vertical lines are traces of the windows drilled in the side of the engine, shown at the top of the photograph. Thus the hooked curves are traces of regions of flame as they travel in the combustion chamber and tail pipe. A slit to the right of the photograph delineates the flame emerging from the tailpipe, which appears as the vertical sequence of bright regions on the right.

as may be seen by comparing Figure 4b, in which the flame motions and relative valve positions for the PJ-31 engine are shown, with Figure 4a. From such photographs it can be seen that the flame accelerates along the tailpipe when the valve closes, and then part of it reverses its motion near the end of the tailpipe, doubtless as the result of a return flow of air into the rear end of the tailpipe. This takes place at about the time the valves open. A fresh combustible mixture, indicated by the dark region on the photograph, is then introduced through the valves and compressed by the return flow. After reignition of the gas the valves close again and the cycle is repeated. It can be seen that at all times there is a flame somewhere in the engine. But this may be an effect due to leakage through the windows, since according to some early observations the flame may be extinguished throughout the entire tube for part of the cycle. The answer to this question is still uncertain, for inferences cannot safely be made from observations on the small jets for which the duration of burning is probably a larger percentage

of the period than for the full scale engine.

During these experiments a fair idea of the main characteristics of the valve action in the PJ-31 engine was obtained by photographing the valves directly with a high speed motion picture camera. A typical cycle of operation is shown in Figure 5. Study of these pictures

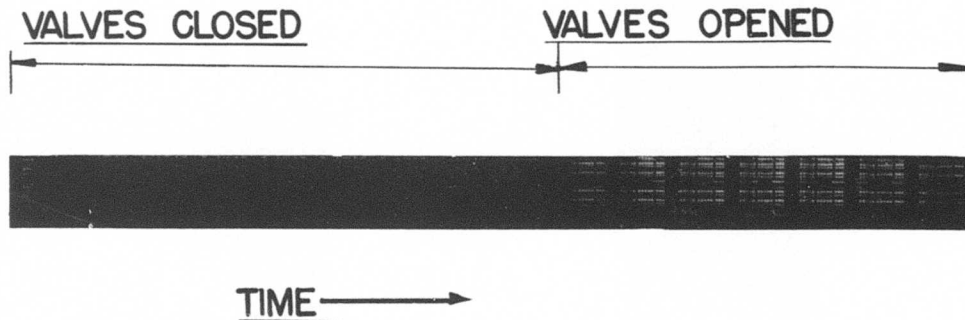


Figure 5.

A typical cycle of operation of part of the valve grille in the PJ-31 engine. Note that all the valves snap open or snap shut almost simultaneously.

reveals that the valves all snap open almost simultaneously and in a very short time compared to the period of the cycle. They also snap shut in a similar rapid manner. This means that in the one-dimensionalized pulse jet theory the statement of the boundary conditions at the valve end is probably much simpler than if the valves opened and closed slowly, necessitating a detailed treatment of mechanical-aerodynamical interactions.

Large Scale Pulse Jet Test Facilities. The necessity for moving the equipment from Lake Denmark to another site resulted in a considerable curtailment of the tests, and much effort was expended on obtaining and clearing a new site. In addition it turned out that the new site lacked most of the material conveniences obtainable at the old site, necessitating a large amount of time and effort to be devoted to the setting up of mobile units of equipment to furnish electric power, air supply, and shop facilities. It was decided that it would be advisable to construct a mobile thrust stand for the JB-2 fuselage and pulse jet engine on top of a trailer, for ease of transport from the laboratory to the test site. The acquisition and adaption of mobile facilities of these types and the actual construction of the new test site near the Westchester County Airport near Rye Lake, N. Y., have just been completed. In the meantime, the fuel supply and starting system of the PJ-31 engine have been completely overhauled and modified so that much better control over the operation of the engine is possible. Schematic

diagrams of the test site and the pulse jet and trailer may be seen in the October *Quarterly Report*.

Analogues.

(a) Water Analogy Theory. As indicated in the phase assignment, a series of problems involving hydraulic and other analogues of pulsating and other jet devices has been studied. It is possible under certain reasonable assumptions, if we restrict ourselves to compressible gas flow in one dimension or at most in a channel of slowly varying cross section, to circumvent the classical limitation of hydraulic analogues to gas flows for which the "ratio of specific heats" is exactly equal to 2.0. For instance, water flow along a V-shaped channel turns out to correspond to compressible gas flow in one dimension with a specific heat ratio equal to 1.5. Furthermore, it is possible in principle to include non-isentropic processes, by utilizing an additional pressure applied in some way to the water surface, as another parameter, provided the slope of the water surface is not too large.

To see how the above analogue has been worked out, consider a volume of water contained in a channel whose cross section is of some such shape as indicated in Figure 6. As shown, the distance of a point on the channel wall from the vertical center-line is taken to be proportional to some power, β , of the height of the point from the bottom of the channel. The factor of proportionality may depend on the x -coordinate of the cross section under consideration, thereby introducing the analogue of the desired non-uniformity in the cross section of the gas stream. The water pressure is assumed to be entirely due to the static gravitational head and an additional pressure p_A exerted on the surface, whose amount and variation with position are under the control of the experimenter. Thus we assume that we can neglect all dynamical pressures arising from accelerations. The force F_w of the water on one side of a vertical section exerted against the water on the other side is then computed to be proportional to the product of area of the section and an average pressure on it. The average pressure turns out to be proportional to the sum of the water depth h and a quantity f , proportional to the additional pressure head p_A . The negative gradient of this force is the accelerating influence, provided we take into account the fact that the x -variation of the cross-sectional area in the gradient and the x -variation of h in the terms in the gradient involving p_A introduce terms which are balanced out by the reaction of the wall and the horizontal component of the force on the slant height of the water surface, respectively. However, to obtain the desired analogy of the pressure gradient term appearing in the momentum equation for compressible gas flow, it is necessary to assume that this latter force component may be omitted. This is a reasonable enough assumption if the slope of the surface is small. It is further necessary to assume that in flow along the channel the material cross sections remain plane, and that inertial effects associated with flow at right angles to the axis of the channel are small and can be neglected.

With these assumptions in mind we can liken the system comprised of the water and the device for controlling pressure on its surface, to an ideal compressible gas flowing in a non-uniform tube and obeying the equation of state of an ideal gas. This follows from a correspondence which is set up between the basic physical parameters of length (and area), density, and force associated with the gas on the one hand and quantities associated with the water analogue on the other. First, choose distances measured along the channel to be numerically the same as

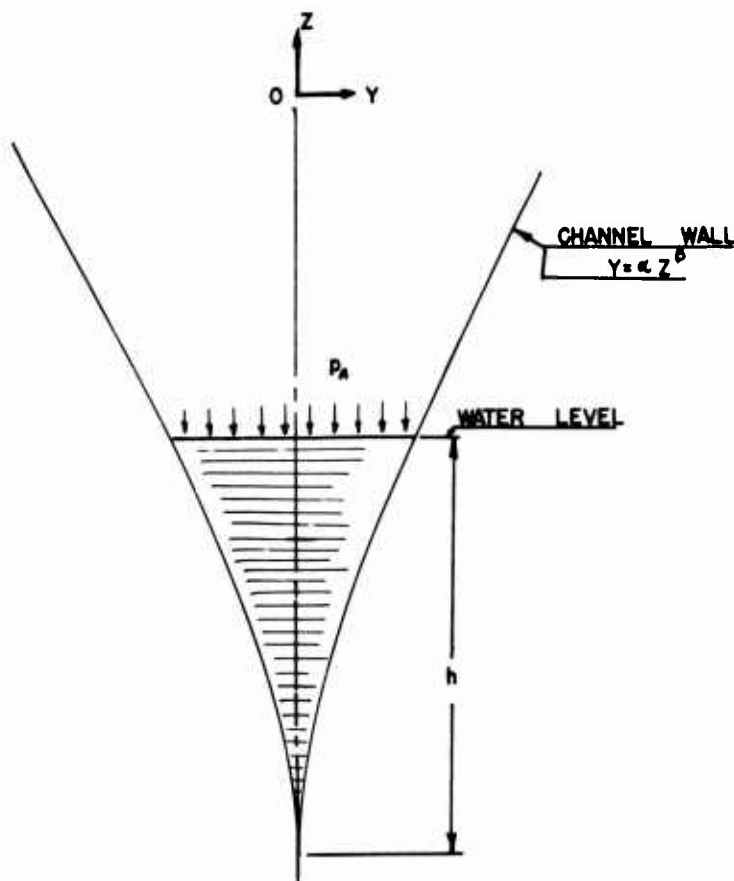


Figure 6.

Diagram of a cross section of a water channel used in an analogue of a perfect gas in which compressibility and non-isentropic processes are considered.

distances in the direction of the gas flow. Let A , ρ , and F be the area of the gas cross section, the gas density, and the force on a cross section at the gas, respectively. Then we may identify A with a water analogue quantity proportional to the parameter describing the non-uniformity of the water channel, ρ with one proportional to the weight of a vertical slice of the water normal to the channel axis, and F with one proportional to F_W (defined above). The last factor turns out to be inversely proportional to $(h_0 + f_0)$, the value of

$(h + f)$ when the water is in some standard reference state. Then the analogue of the gas pressure p turns out to be a quantity proportional to the product of the gas density and $(h + f)$. Consequently the formal analogue of the gas temperature is proportional to the "total head," $(h + f)$. Since the gas may be presumed to be a perfect one, it follows that in a reversible adiabatic process the pressure is proportional to the density raised to a power equal to γ , "the ratio of the specific heats." In order to simulate such processes in the analogue, the exponent β must be related to γ by

$$\beta = \frac{2 - \gamma}{\gamma - 1} .$$

Furthermore, it follows that during such a process, the pressure p_A above the water surface must be so adjusted that the total local pressure head $(h + f)$ is proportional to the local depth h .¹ The propagation of sound waves in a gas involves such processes, and hence, with this in mind, one easily calculates the velocity of propagation of small gravity waves in the channel to be

$$a_w = \sqrt{(\gamma - 1) g(h_0 + f_0)} .$$

The velocity of such waves (with $f_0 = 0$) is being measured experimentally at present, for $\gamma = 1.5$.

It is easily seen, by treating the first law of thermodynamics as a definition of what is meant by quantity of heat for the analogue, that variations in f , not proportional to h , lead to processes which can be interpreted as involving heat contributions, as in combustion or other irreversible processes.

Hence it is possible in principle to construct water analogues of gas flows in one dimension involving combustion. Because of the difficulty of "following a particle" in this kind of analogue, this system appears useful at present only for steady compressible gas flow, such as occurs in a ram jet in operation. A device for simulating a ram jet, with combustion, is being designed.

(b) Electromechanical Analogues. To get around some of the difficulties encountered with the water analogues, possibilities of several electrical and electromechanical types of analogues have been explored. In these the analogy is obtained by replacing the partial differential equations of aero-thermodynamics by difference-integral equations describing the action

* * * * *

¹If one wished to consider a water analogy of isentropic processes only, it is not necessary to have such an adjustment of $(h + f)$. For by redefining the pressure p in terms of the analogue quantities, so as not to involve f_0 , and by keeping the pressure p_A uniform over the surface, we arrive at the usual water analogy of adiabatic gas flows.

of a one-dimensional array of masses or circuit elements, with "spring" elements between them with stiffnesses that are controllable in space and time in order to simulate combustion and a non-uniform cross section of the "jet tube." Such systems of course are essentially integrating machines designed, for one thing, to avoid the tedious numerical integrations which are encountered in solving the non-linear aero-thermodynamic equations for pulse jets. The necessary mathematical equations describing these analogues have been formulated.

(c) Boundary Conditions Simulators. It is necessary to know the boundary conditions which one must impose at the valve end and at the exhaust end of a pulse jet. In addition to studying these conditions for an actual pulse jet, it is possible to get an idea of them by considering two other types of simulating mechanisms. One such is a "cold pulse" system in which simulated valve banks in an air stream are closed and opened periodically by raising and lowering the pressure downstream. Thus the type of flow and pressure drop through the valve grille can be determined. Another type is a piston and cylinder system, in which the air column in the cylinder is driven at resonance and the flow pattern at the end of the cylinder is observed. A piston and cylinder for obtaining large amplitude oscillations is under construction, while some calculations have been made on the pulsing mechanism for the cold pulse study.

Theory of Pulse Jets. In the previously mentioned *AMG-NYU Report 151* a general one-dimensionalized theory for pulse jets was developed. Furthermore, for purposes of computation in a special idealized case, the non-linear differential equations were approximated by certain linear differential equations which could be solved explicitly. Recently a numerical integration of the non-linear equations has been started, using methods based on characteristic curves; the preliminary results of this calculation indicate that a good approximation for the true solution is provided by the explicitly approximate solution mentioned above. If further calculations confirm this result, it will be possible to develop general formulas for a refined analysis of pulse jet cycles. Results obtained in Phase 1 coupled with experimental studies of boundary conditions are expected to contribute to this analysis.

PHASE 4

In connection with liquid rockets and pulsating jet engines, to develop instruments for recording (i) transient thrust, (ii) pressure, temperatures, and densities of hot oscillating gases, and (iii) gas velocities.

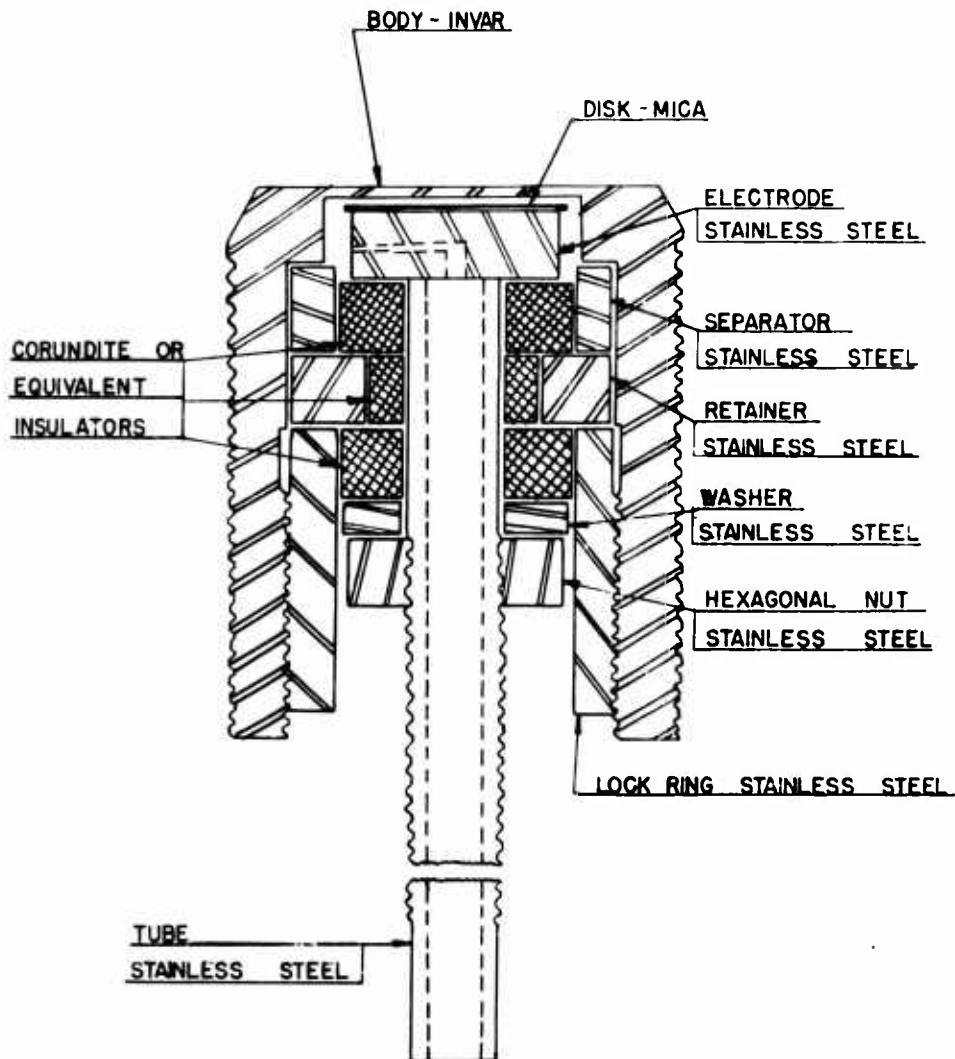


Figure 7.
Vertical section of the condenser gauge pickup element.

Statement of Objectives and Results

The experimentation on pulsating jet engines and liquid fuel rockets carried on at N.Y.U. is of two types. One type is a semi-qualitative one of observing or producing effects and estimating their orders of magnitude in order that plausible physical assumptions may be made in setting up idealized theoretical models for the analysis of pulse jet cycles. The second kind of experimentation has to do with the accurate measurement of physical quantities involved in the phenomena, in order to furnish basic data for use in the general one-dimensionalized aero-thermodynamical theory, and to check rigorously the results predicted by it. In conjunc-

tion with the latter type of experiments it is necessary to develop many special measuring instruments and calibration devices. Because of the extreme conditions involved in most of this work, e.g. mechanical and thermal oscillations of large amplitude, and high frequency harmonics, and because of the difficulty of measuring some of the quantities without perturbing them, the instrumentation for the most part has been novel in design and conception. There follows a summary list of the accomplishments in this direction to date.

Pressure Gauges

Several types of pressure gauges have been designed and constructed. Of these, a gauge with a condenser type pickup element shown in Figure 7 appears to be the most satisfactory.

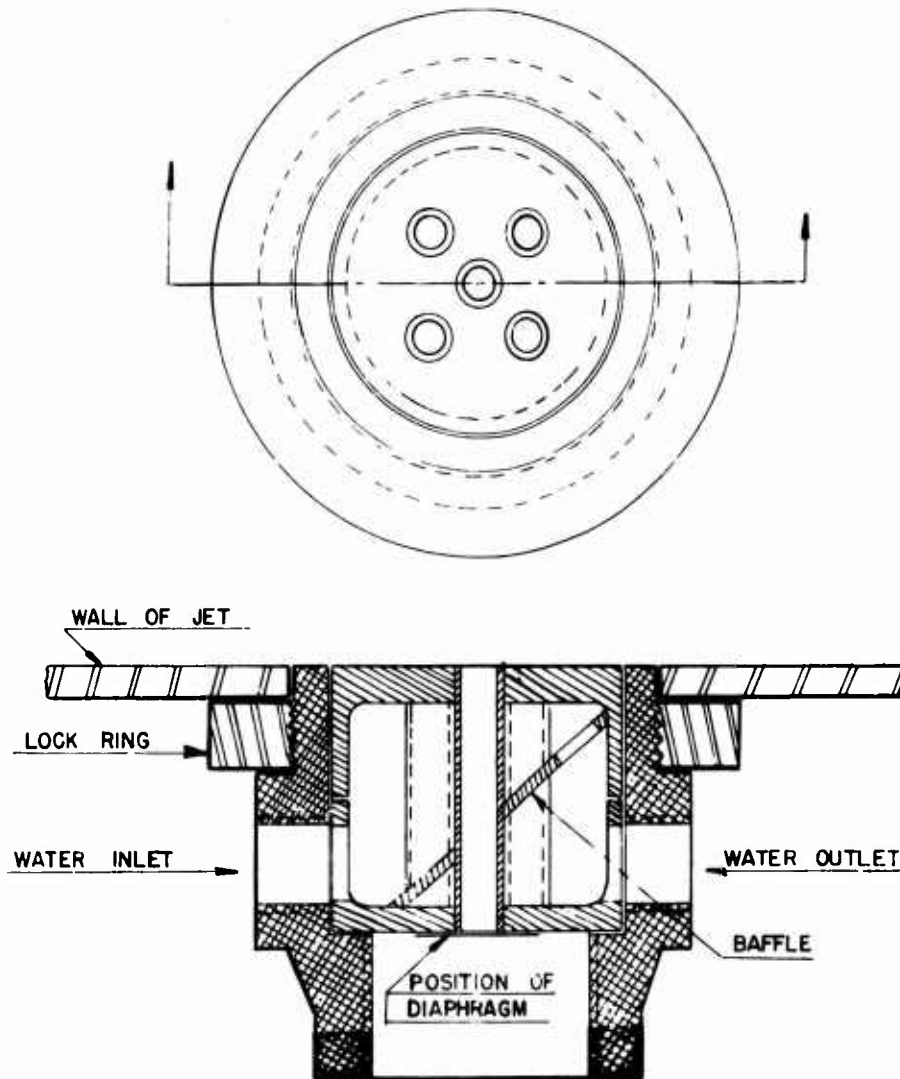


Figure 8.
Plans of the five-hole cooling chamber for pressure gauges.

For the recording of pressure cycles in a pulse jet it was found necessary to develop the cooling chamber shown in Figure 8 for the gauges, in order to minimize signals due to thermal expansion of the pickup elements in the presence of hot swirling gases. Such a cooling chamber has been constructed and tested and shows excellent cooling characteristics. It is now being tested for its effect on the frequency response of the gauge. Reasonably accurate measurements of the pressure cycle of a Dynajet have already been obtained, as well as measurements of the transient pressure wave issuing from the mouth of the flame tube. Figure 9 shows a typical record of pressures obtained with a Dynajet. Another type of pressure gauge which has been constructed is a limit gauge for use in determining individual points on the pressure-time curves for pulse jets, and in particular, in determining the zero level for the other gauges. Magnetostriction type pressure gauges, with an output of about 0.1 volt for 20-pound pressures, have been designed and constructed, but certain difficulties with the integrating circuits have thus far limited their usefulness. Details of the pressure gauges

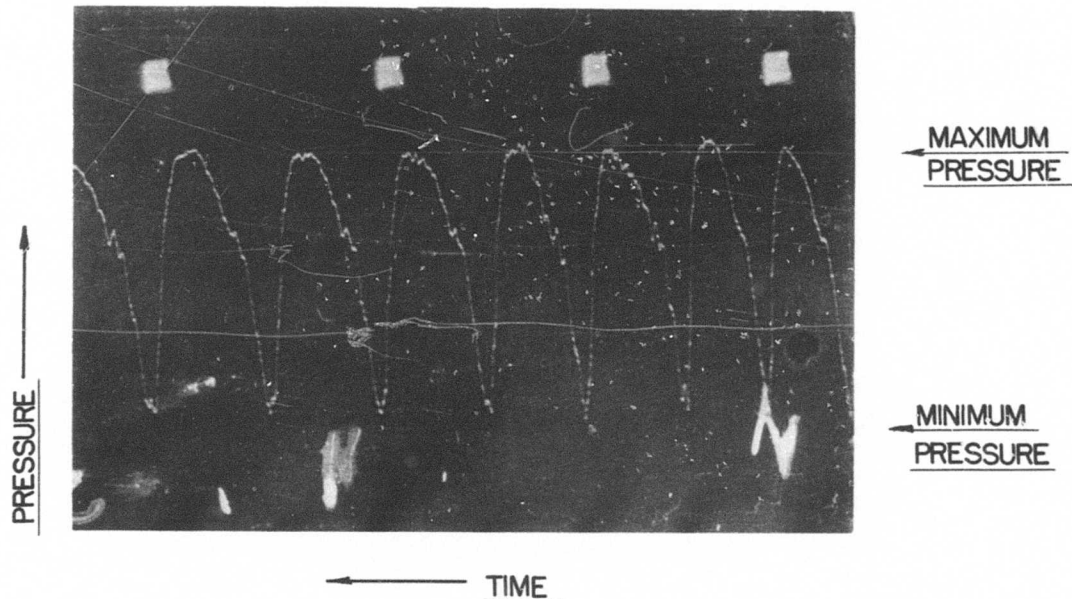


Figure 9.

A typical record of pressure cycles in the combustion chamber of a dynajet obtained with a condenser gauge. The timing marks occur at ten millisecond intervals. The peak to trough pressure is about 35 p.s.i.

and of cooling chamber are given below.

Condenser Gauge System. The FM condenser system described in the *Quarterly Progress Report* for 1 October 1947 has been modified at the receiver end. This modification was undertaken to increase the stability of the system. The diagram of the new circuit is given in Figure 10. This circuit operates as follows:

Mounted directly back of the gauge is a transmitter which consists of a Hartley oscillator electron-coupled to a cathode follower output tube. Both tubes are 6AK5 miniatures. The output impedance is about 50 ohms. The carrier frequency is 2 m.c.p.s. The output is fed through a coaxial cable to the receiver which consists of a 6SA7 pentagrid converter tube producing an intermediate frequency of 450 k.c.p.s. A 6SJ7 IF amplifier is coupled to

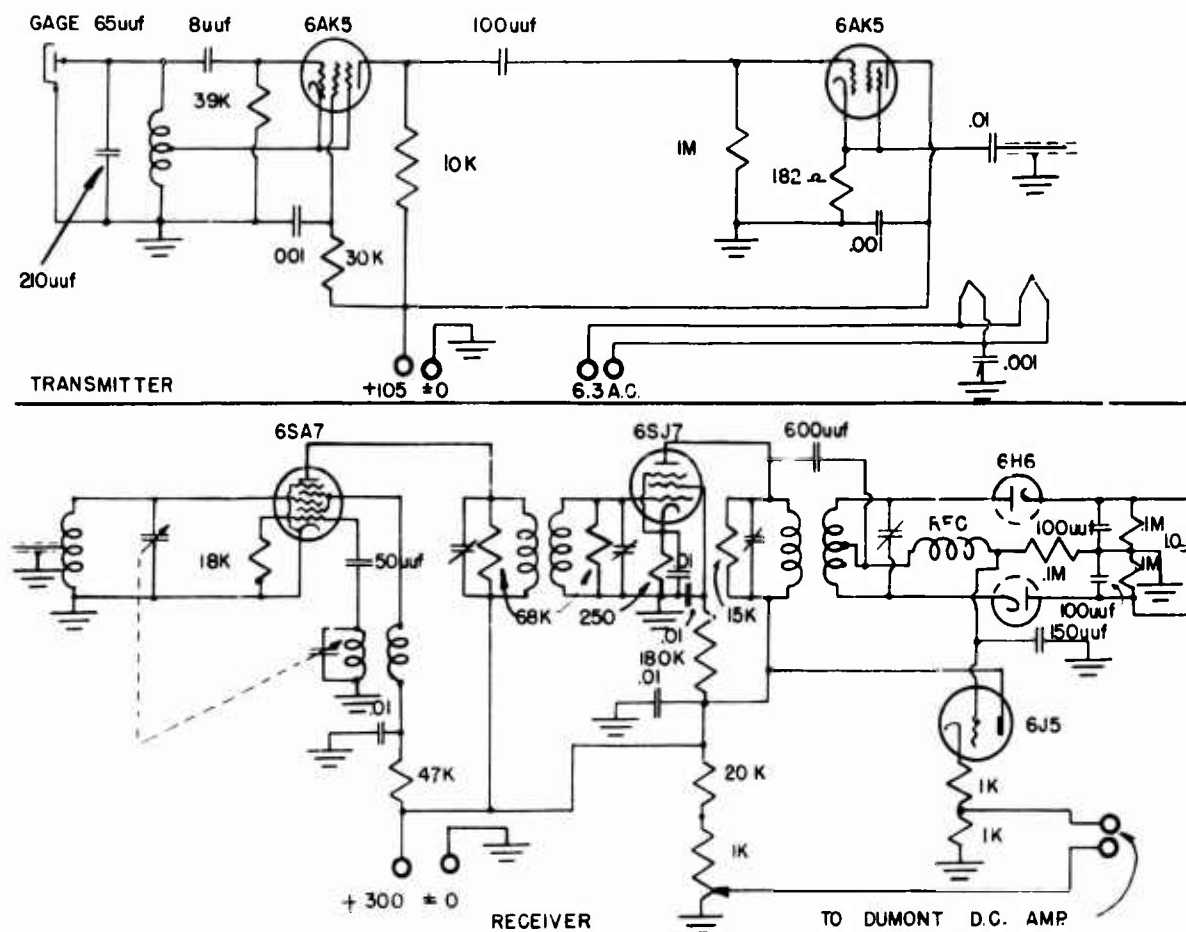


Figure 10.

Diagram of the transmitting and receiving circuits used with the FM condenser gauge.

the converter and feeds the discriminator transformer. The input transformer is double tuned and broad banded by shunting with a resistor. The discriminator transformer drives the ratio detector which is used here because it is relatively insensitive to amplitude variations. It also supplies a d-c voltage proportionately to the IF signal, which might be used as an automatic level control.

The d-c output of the ratio detector feeds the cathode follower and then through the connecting cable to a modified Dumont 208 oscilloscope having d-c response. No gain control has been provided and thus far has proved unnecessary. The gain has been adjusted so that the full linear output from the discriminator, about +3 volts, covers 4 inches on the cathode ray tube screen.

When required, the sensitivity of the system may be reduced by shunting the gauge with a capacity. We have found the distributed capacity of the gauge head to be about 65 $\mu\mu\text{f}$. The diaphragm itself provides a capacity change of 1 $\mu\mu\text{f}$. for 10 p.s.i. applied pressure. The transmitter is practically non-microphonic, although no potting wax or plastic was used.

The gauge system is calibrated before each run by mounting the gauge head in an air chamber and bursting a diaphragm at known pressures.

Possible errors in wave shape of the cycle due to temperature fluctuations have been investigated by chopping at pulse jet frequency a blow torch flame with a toothed wheel placed between the diaphragm and flame. The flame is adjusted so that the rate of heating at the back of the condenser diaphragm was the same as in the operating Dynajet. No change was observed on the oscilloscope.

Cooling Chamber. A 9-hole cooling chamber, similar to the 5-hole device previously described and shown in Figure 8, is now in operation. This cooling chamber, mounted on a Dynajet, will stabilize the back of a stainless steel diaphragm at 85°F in about 7 seconds with water pressure 85 p.s.i. temperature input 55°F. We have observed frequency components up to 14 k.c.p.s. in the Dynajet with this system (see Figure 9). In general, decreasing the number of holes in the cooling chamber decreases the frequency response. We are investigating the effect of spacing between the end of the cooling chamber and the face of the diaphragm.

Limit Gauges. To check possible pressure distortions due to cooling chamber characteristics, a limit gauge has been constructed and tested with a stainless steel diaphragm .004" thick. This diaphragm is normally back-pressured with nitrogen, and contact is made against a hemispherical stainless steel contact. First tests show uncertainty in closing of about 0.25 cm. Hg. Improvements in design are expected to improve this figure considerably.

Magnetostriction Gauge. No work has been done on this gauge since the early part of the year, but interest has been shown in it by designers of guided missiles. The output was about 0.1 volt for 20 lbs. pressure. We plan to test this again with a high amplification before the integrating circuit where most of the loss normally occurs.

Gas Temperature Measurements

Many methods for recording the gas temperature cycles within a pulse jet engine have been investigated. The one which at first showed promise employed a photomultiplier tube, which was to be used to compare the intensity of flames colored with sodium in jet engines with the intensity of steady sodium flames whose temperature had been determined by a D-line reversal method. Difficulties in obtaining effectively infinitely thick pulse jet flames caused the eventual abandonment of this method. Various other methods have been investigated; all those requiring the knowledge of the values of the absorption coefficient, such as the two-color method, have been discarded on the grounds that the absorption coefficient for oscillating gasoline flame is unknown. Determination of such coefficients would demand an extended program of research. We, therefore, limit ourselves to either direct transmission methods using standard lamps, or a multiple path method in the jet. We are setting up a two-thickness method for the PJ-31, with one thickness effectively twice the other as in the sketch of Figure 11.

Using this method, it is possible to derive directly from Planck's law and simple absorption laws the equation:

$$\left[1 - e^{-\frac{C_2}{\lambda} \left(\frac{1}{T_1} - \frac{1}{T} \right)} \right]^2_R = \left[1 - e^{-\frac{C_2}{\lambda} \left(\frac{1}{T_2} - \frac{1}{T} \right)} \right]$$

where T_1 and T_2 are the apparent temperatures in paths 1 and 2, T the true temperature and R the net reflectivity of the mirror system.

For the photocell pickup of such a system, we originally experimented with a photomultiplier and d-c inverter circuit. The frequency response of the inverter was too low. Also, our d-c amplifiers were not well developed at the time. At present we are using a 929 photocell, a cathode follower, and d-c amplifier, available gain 1,500, and a Dumont 241 oscilloscope. The trace without filter is given in Figure 12 for a Dynajet using a single window. Zero level is approximately room temperature. The higher harmonics are, we believe, microphonics not yet eliminated.

It was originally planned to calibrate the pickup system from gas flames whose temperatures had been determined from a standard lamp by the sodium line-reversal method. Much work

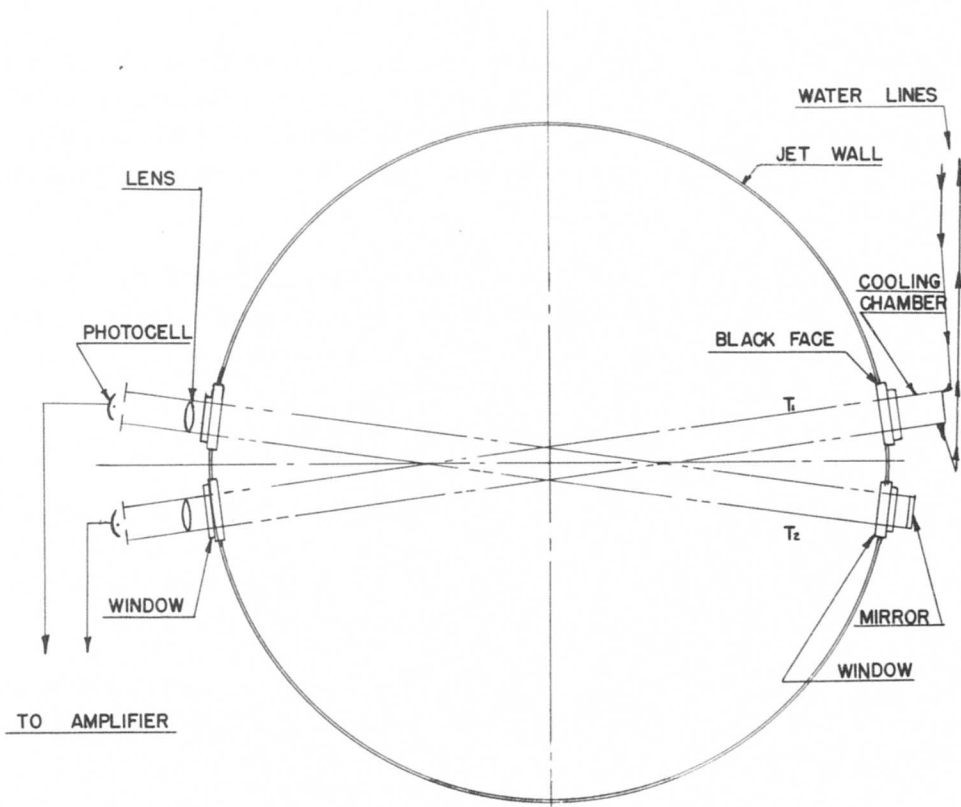


Figure 11.

Cross section of a PJ-31, engine showing the optical paths for temperature measurements.

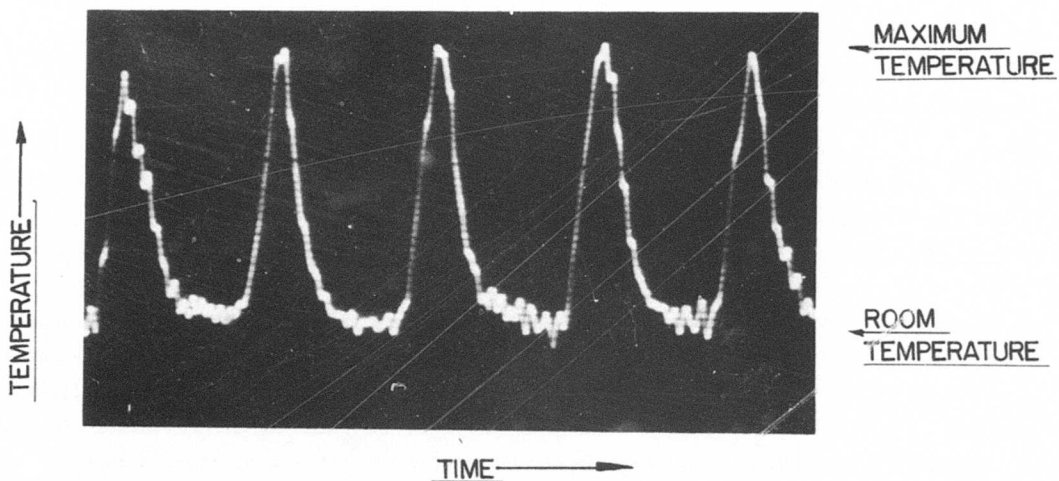


Figure 12.

A typical record of temperature cycles in a dynajet combustion chamber. Peak temperatures are estimated in the neighborhood of 2000°C while the temperature drops nearly to room temperature between peaks.

was done checking concentration of sodium versus temperature, also the quantities of sodium required for flame saturation. Most useful additive was found to be powdered sodium methyrate added to dehydrated gasoline. The calibration can be conveniently done in the laboratory using these flames. However, for field calibration we will attempt to use the standard lamp directly.

The temperatures will be taken at different cross sections of the JB-2. Our setup is such that if necessary we can modify it to determine the absorption coefficient or we can use direct transmission methods.

Flow Velocity Measurements

It is necessary to develop instruments for observing instantaneous local velocities of fluids in non-steady flow in order to get a complete picture of gas flow in and around a jet engine, and fuel flow in the injection system. For the fuel flow several types of thermistors have been studied, particularly the bead and flake types (Western Electric XB-547).

The thermistor is a sintered oxide of semi-conductors such as oxides of manganese, nickel, and cobalt. They are characterized by a high negative temperature coefficient of resistance such as $-4.3\%/C^{\circ}$ at $25^{\circ}C$.

If the time lag is small enough it should be possible to use thermistors analogously to hot wire anemometers with the advantage of higher sensitivity and considerably greater ruggedness.

The thermistor response has been checked according to a method suggested by N.A.C.A. (T.N. 1331), using an impressed audio-signal. The response curve of amplitude versus signal frequency is given in Figure 13.

There is sufficient signal at 1000 cycles to warrant the construction of a compensating circuit. The circuit design is along lines developed by Runyan and Jeffries at N.A.C.A. for hot wire anemometers.

In liquids (water and alcohol are used), the frequency calibration method just described could not be used because, when the liquid touched the thermistor beads or the leads, undesirable pick up of the oscillator signal occurred; but a mechanical method of frequency calibration gave good results. The tuning fork was touched to one of the leads of the thermistor element. The thermistor then vibrated in the liquid and the frequency of the fork appeared on the scope. In this way it was found that the Bead type thermistor responded excellently to a frequency of 500 c.p.s. in water and the flake type went over 1000 c.p.s. The flake type also responded

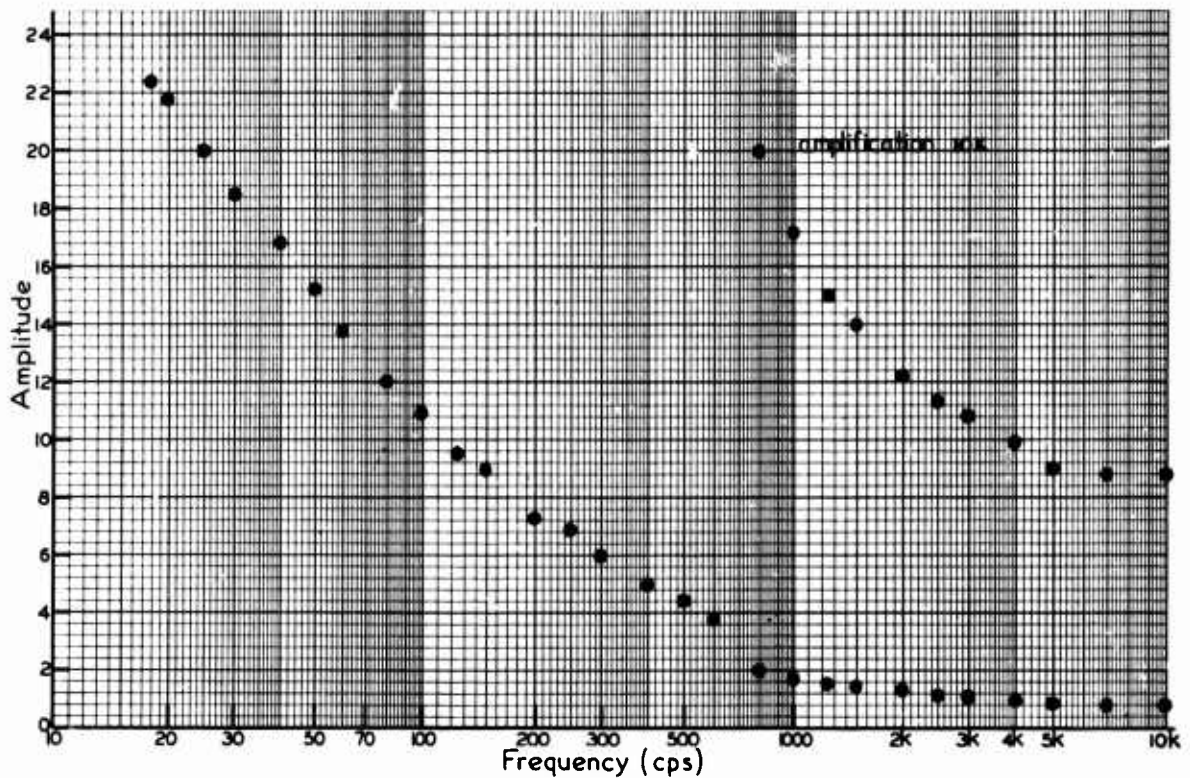


Figure 13.
The frequency response of a thermistor element.

in air to a 1000 c.p.s. tuning fork held near it.

It has been found that operation of the thermistor in liquids causes bubbles to form, especially at higher values of current. It is not expected, however, that these bubbles will cause any trouble in an actual flow line.

We have developed designs for mounting the bead type thermistor in gasoline feed lines. When this work is completed, attention will be given to the use of the flake XB-J47 as an air flow anemometer.

The only methods actually used thus far for measuring instantaneous gas velocities have either employed high speed photography of smoke tracers or of DDT spray illuminated in a schlieren setup. A smoke generator for use with the small scale pulse jet flow studies has been constructed and is now in use. A photograph of this setup is shown in Figure 14.

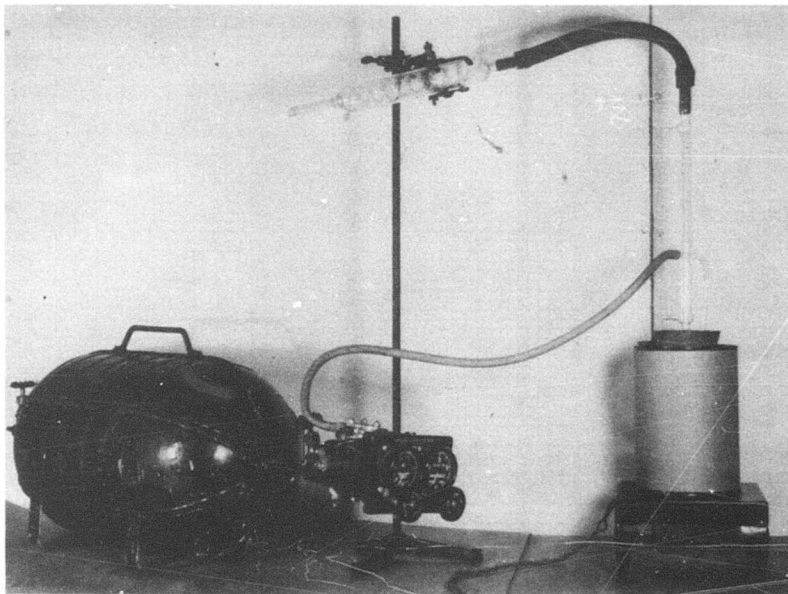


Figure 14.

The tobacco smoke generator for tracing air flow around small jet engines. Ground up cigars are placed in the metal container mounted on the electric heater shown at the lower right in the figure. The pressure tank to the left provides compressed air which forces smoke out through the glass condenser which removes most of the rather considerable amount of tar and other unidentified materials.

Thrust Measurements

Several thrust stands for the small jet work have been constructed, and a large pendulum-type thrust stand for the full scale pulse jet tests has been built and is now being assembled; it will measure the average thrust of the PJ-31 engine. A schematic diagram of it may be seen in the October *Quarterly Report*.

PHASE 5

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

Outline of Motivation and Objectives

As was mentioned in the *Semi-Annual Report*, January 1, 1947, the division of the forces acting on a pulse jet motor into gross thrust and drag is largely a matter of convention. The difference between these two is the net thrust and may be uniquely defined as the integral of the forces over the surface of the motor. Frictional drag at the sharp intake valves and non-uniform pressure distribution over the surfaces of the motor doubtless provide the main terms in the net thrust. This non-uniform pressure distribution depends on the forms of the internal and external flows. Experiments indicate that the form of the flow is rather sensitively dependent on the geometry of the motor near the intake and, probably more importantly, near the end of the tailpipe. This indication has motivated the experimental and the theoretical work in Phase 5 during 1947. This work is mainly directed toward the determination of the flow pattern near the ends of a tube which acts as a source for pulsations in the flow.

Experiments

Using a schlieren optical system and a light-scattering sheet of DDT spray as described in the *Quarterly Report* dated 1 October 1947, high speed movies were taken of the pulsating flow near the ends of a Dynajet motor. The most successful pictures were taken at a speed of about 3,300 frames per second, corresponding to about 13 frames per cycle of the Dynajet. Pictures of the jet pattern may be seen in the above mentioned *Quarterly Report*. In the schlieren pictures of the flow near the end of the tailpipe of a Dynajet, the following characteristics are observed: (1) A rather well-defined pulsing jet of varying shape issues from the tailpipe. (2) The jet aspirates a relatively steady flow from the region surrounding the jet tube, this aspirated flow being more or less directed towards the end of the tailpipe except in the region adjacent to the jet, where the aspirated flow is directed roughly parallel to the jet. (3) Vortex rings are formed at the rim of the tailpipe, with directions of circulation controlled by the directions of the relative velocities of the internal and external flows. (4) A marked necking of the jet is observed somewhat before as well as during a phase, when an *inflow* surrounding a central core of continuing *outflow* through the end of the tailpipe, is developed. Then the flow is decidedly non-uniform through the cross section of the tube. The necking lasts for about one quarter of the cycle and disappears gradually as the outflow decreases. The vortex rings appear to be considerably weaker when there is a flaring end on the tailpipe.

To treat the pulsing flow theoretically with due regard to the development of vortex rings and vortex sheets around the hot jet is a very difficult problem. Even for steady jet flow in a homogeneous incompressible fluid, mathematical expressions for the flow are not readily obtained. Possibly a good idealization is represented by an incompressible potential flow in a jet of fluid with a certain density, surrounded by an incompressible "external"

potential flow of a fluid with another density, the interface being regarded as a non-uniform vortex sheet which moves in space and time but which remains attached to the sharp edge of the tailpipe. Numerous angles of attack on the problem have been explored, but thus far extensive calculations have been restricted to variable potential flow patterns generated by various distributions of vortex sheets and basic flows. The strengths of the vortex sheets were assumed to vary in a manner controlled by the relative magnitudes of external and internal flows. Patterns resembling those actually observed were obtained in this manner, but a more complete and consistent theory must be developed before really satisfactory results can be obtained.

Future Plans

In 1948 considerable extensions to the observational and theoretical work on non-steady flows around jet tubes are planned. Laboratory models for developing two-dimensional pulsing jet flow are being constructed and are expected to provide helpful hints for theoretical developments. In particular the jet flow associated with the very promising Bodine type motors will be studied experimentally and theoretically.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-98, TASK ORDER II

POLYTECHNIC INSTITUTE OF BROOKLYN
BROOKLYN, NEW YORK
1 JANUARY 1948

INTRODUCTION

The research work on Project SQUID at the Polytechnic Institute of Brooklyn has been extended considerably during the year 1947, both as to the scope of the program and to the number of research personnel. In January there were two phase assignments dealing with flow of air through valve systems of pulse jets and with the development of high temperature alloys. In July the former assignment was expanded to include the development of a unified theory for pulse jet propulsion units.

In January a new phase assignment was begun which dealt with the flow of fluids in boundary layers over porous surfaces through which a fluid was being injected into the boundary layer. The application of this work, of course, lies in the field of sweat-cooling of rocket and jet combustion chamber liners. The analytical work on this phase progressed to the extent that a report entitled "A Theoretical Investigation of the Temperature Field in the Laminar Boundary Layer on a Porous Flat Plate with Fluid Injection" by Dr. S.W. Yuan was submitted in early September and has been published recently. Plans for the experimental work on this topic were started in the latter half of the year and have progressed to the extent that tests are about ready to begin in the turbulence channel at P.I.B.A.L.

Similarly, a fourth phase dealing with the analytical study of the microstructure of shock waves was tentatively approved in January and has progressed to the point where a report entitled "On the Structure of Shock Waves in Laminar Flow" by Professor H.J. Reissner and Mr. Leonard Meyerhoff has been completed and is ready for submission for publication. This latter phase, however, has been transferred recently from the cognizance of the Bureau of Aeronautics to the Fluid Mechanics Section of the Office of Naval Research under a current contract.

For the testing of pulse jets on Phase 1, a Naval test facility located near Williamsport, Pennsylvania, has been loaned by the Bureau of Aeronautics. Actual occupancy was taken over in December. Two pulse jet valve systems incorporating the use of rotating valves have been designed and were constructed by I.T.E. Circuit Breaker Company, Philadelphia. The first model is to be run without combustion in the wind tunnel at P.I.B.A.L., the second will be run with combustion at the Williamsport facility. Tests on the former are about to get underway.

The various problems associated with the development of high temperature alloys were carried to the point where specific items of greater promise became evident and were concentrated upon. These will be enumerated in this report under Phase 2.

The number of full and part-time professors, instructors, and research fellows and assistants who are working on various phases has increased as follows from January to December: Phase 1 from 10 to 16; Phase 2 from 4 to 5 although during the mid-year there were 8 at one

time; Phase 3 from 1 to 5; Phase 4 from 2 to 4.

In addition to the reports mentioned above the following reports and memoranda are in progress and will be completed in the near future:

"Compressible Flow through Reed Valves for Pulsejet Engines."

I. "Reed Valves Hinged." Paul Torda.

II. "Reed Valves Clamped." Paul Torda.

"On Turbulent Compressible Flow through Ducts of Varying Cross-Section at High Velocities."

H. Reissner and L. Meyerhoff.

In addition three reports on the Martensitic indication of temperature, the high-temperature extensometer, and on the dilatometer will also be prepared.

Members of the staff had been invited to visit and participate in discussions at technical meetings and symposia at the N.A.C.A. laboratories at Langley Field and Cleveland as well as at the Sweat-Cooling Conference at Wright Field and the symposium dealing with the present status of the application of free flight aerodynamic data to high speed missile design at G.A.L.C.I.T.

The work of the instrumentation group, which began after the middle of the year, will be described in this general introduction inasmuch as some of the instrumentation projects apply to more than one phase assignment.

Equipment for Strain Gage Instruments

The proposed use of strain gages for various fluctuating measurements requires the development of a carrier-type amplifier and phase-sensitive detector to drive the recording oscillograph. To obtain a high degree of stability and constancy of calibration, large amounts of negative feedback are used in the amplifiers. The phase-sensitive detector is of the balanced-modulator type, as is common in commercial practice.

Ultrasonic Pressure Waves

A method is being investigated for the instantaneous measurement of temperature in both steady and non-steady gas flow utilizing the variation of the velocity of ultrasonic waves with temperature. Because of the high frequency of the fluctuation of the gas temperature in pulse jets, and because it is desired to have many measurements per combustion period, ultrasonic waves must be used. This method will also produce a sharply defined pulse wave front, thus increasing the accuracy of the transit time measurements.

Since the temperatures involved approximate, and in many cases exceed, the Curie point of quartz and other piezoelectric crystals, magnetostriction transmitters and receivers will be used. Transit time will be measured as the distance between two pips on the screen of a cathode ray oscillograph. A four-gun cathode ray tube will be used together with a recording camera; three guns for three points of measurement and the fourth as a timing axis.

The necessary electronic equipment to be used with this type of instrument is, in part, commercially available and will be ordered after the characteristics of the transducers have been determined. The remaining components will be built at P.I.B.A.L.

X-Ray Temperature Measurements

The application of x-ray techniques to the measurement of temperature of crystalline substances has been done experimentally.

The macroscopic thermal expansion of solids reflects the more fundamental expansion of the crystal lattice. Back reflection x-ray scattering is very sensitive to change of lattice constants and can, therefore, be correlated to temperature. It was estimated that within the temperature range at which materials give reasonably sharp diffraction lines (upper limit not known for most materials), temperatures can be measured to less than 20°F. Three developments are underway:

- (1) The determination of the upper temperatures at which the method ceases to be useful.
- (2) The development of Geiger counter recording for the measurement of the x-ray scattering and consequent temperature measurement over short time intervals.
- (3) The incorporation of more refractory crystalline materials in walls to aid in the temperature determination.

Experiments have been conducted using a back reflection flat cassette camera on a specimen of stainless steel which was heated from the rear with an oxy-acetylene torch. Unfiltered chromium radiation was used and the specimen was located about 2½ cm. from the camera. The temperature change at the surface of the material was indicated by a change in the diameter of the resulting rings on the film. Since the diameter of the rings can easily be measured to a tenth of a millimeter, temperature indications of less than 20°F can be detected. The sensitivity appears to increase slightly with increase in temperature up to the maximum temperature (900°F) so far investigated. It is expected that the accuracy can be further increased by using other x-ray targets.

It appears that the method can be applied to the measurement of surface temperatures inside combustion chambers by directing the x-ray beam through a metallic window whose characteristics are such that the least possible absorption of the x-ray radiation used takes place. It is expected to employ a Geiger counter to determine the position of the rings, rather than the photographic method, so that more rapid readings can be taken. As intermediate steps, it is proposed: (1) to duplicate the measurements on a sample of the specific material used in the pulse jet model to determine the most efficient x-ray source; and (2) to apply this information to measurements on a cylinder of similar dimension in order to work out mechanical details.

X-Ray Density Measurements

Because of the small thickness of shock waves (on the order of magnitude of the mean free path) short wave radiation such as x-rays must be used to determine quantitatively the density distribution in the neighborhood of the shock waves. This technique was used in Germany with some success. It is felt that by using improved x-ray and Geiger counter equipment and techniques more satisfactory results may be obtained.

Preliminary investigations will be carried out under static conditions. When facilities are available, the work will be extended to supersonic flow.

Hot-Wire Anemometry

The construction of the hot-wire anemometer as developed at P.I.B.A.L. has been modified and improved. New fabrication techniques are being used. Some progress has been made on the development of a two-wire instrument for simultaneous measurements of temperature and velocity in a compressible flow in the transonic and supersonic regions.

Future plans call for further work on the development of a unified pulse jet theory; on a continuation of the tests on the rotating pulse jet valve systems with the adaptation of refinements, where necessary; on the development of high temperature carbide materials for rocket chamber liners; and on experimental work on both cold and hot installations of sweat-cooling adaptations. Analytical work on the latter project will also be carried into the field of compressible laminar and incompressible turbulent boundary layer phenomena with fluid injection. Some experimental equipment has been obtained with the view of expanding this aspect of the entire program. Although the work was predominantly analytical during 1947, it provided a relatively inexpensive means of determining the specific experimental problems which were later found desirable to carry through.

The specific assignments and the work done to present, as well as future plans are presented as follows:

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

A survey of the available literature on various pulse jet engines revealed some of the disadvantages of the reed type intake valves, such as restricted intake area, short reed life, etc. Attempts have been made in Germany to increase the effective air intake area by introducing conical valve banks. For the operation of these units air scoops of necessarily high drag characteristics had to be installed. To increase the life of the valves, both neo-prene-coated and laminated reeds were tried by American investigators, improving the shock resistance but still having high bending stresses.

In order to increase the air intake for each period without creating additional drag and in order to prolong the life of the reeds, two lines of research are being carried out at P.I.B.A.L.

Reed Valves. It was felt that the efficiency of the valves could be increased by adapting the shape and elastic properties of the reeds to a variable stream line pattern of the inflow which would be desirable from the viewpoint of the aero-thermodynamical processes of the engine. In addition, the valve life would be lengthened if the bending stresses in the reeds as well as the high constraint at the support could be reduced. It was decided, therefore, to investigate hinged as well as clamped reed valves.

Rotating Valves. To increase the mass of air taken in during each period and to overcome the disadvantages of the reciprocating motion of the valves, a new design of the intake mechanism was thought desirable. In all previous designs approximately sixty per cent of the cross sectional area of the combustion chamber could open for air intake. In the new P.I.B.A.L. design the intake slots are placed around the circumference of the combustion chamber. Sleeve valves, coaxially rotating across these slots, are used to eliminate reciprocating motion. It

is hoped that by proper design of the intake slots, intake of any desired mass flow may be achieved. The drag increase due to the necessity of an air scoop can be reduced to a minimum by a properly designed air intake configuration and should be more than balanced by the greater thrust of the unit. It is thought that this thrust increase will be achieved by the greater mass of air handled in each period and the augmentation produced by the heating of the ducted cooling airstream. In any case intake ducting is necessary for jet engines operating at supersonic speeds.

Progress

Air Inflow Analysis. The basic lines of the analysis can be summarized as follows: Two methods have been developed for the study of the inflow through periodically moving reed valves. Both are based on the theory of non-steady compressible flows with isentropic change of state of the gas. The one method assumed a two-dimensional and the other a quasi-one-dimensional flow.

Different boundary conditions have to be satisfied for the hinged and the clamped reed valves at the support.

The elastic and inertia properties of the reeds have to be adapted to the time variable streamline pattern of the flow.

To find the functions for the flow between the reed valves in the two-dimensional analysis, a "basic" flow, anticipating observed and theoretically expected phenomena, was assumed.

This flow, however, required, in order to satisfy the non-linear Eulerian dynamic equations, a correction which was achieved by superimposing a "correction" flow upon the "basic" flow. Both of these flows had to be symmetrical about the centerplane between a pair of reeds. Thus only the force distribution at the bounding streamlines of the reed valves remained to be determined. It was found that the results of this two-dimensional method led to cumbersome numerical calculations and therefore the second method, described below, was developed.

In the second method, using the quasi-one-dimensional approach, the appropriate boundary conditions had to be satisfied for the inflow through hinged and clamped reed valves, together with the condition that the mass distribution of the reeds must be a constant, or a space variable only.

It has been mentioned in the introduction to this phase that the inflow between hinged as well as clamped reed valves is being analysed. At first particular solutions of the resulting non-linear partial differential equations were treated and numerical examples worked. Later a

method was found to integrate the equations in a closed form and again numerical examples were calculated. It was intended to submit a technical report containing the numerical results of the particular cases, but in view of the changed situation of the availability of funds it is thought to be more expedient to finish the general case and submit a technical report to include the conclusions reached on the theoretical analysis so far. This report will be a useful basis for working numerical examples if designers wish to do so, or, if at a later date funds become available within Project SQUID, this group could continue the numerical evaluation.

The cases of the hinged reed valves and of the clamped reed valves are treated separately, and the first technical report (to be submitted) will treat the case of hinged reed valves only.

Gas-dynamical Analysis

An analysis of the aero-thermodynamical process of the pulse jet engine has been started. For a first approximation the problem has been simplified in the following manner: The equations of a quasi-one-dimensional compressible gas flow with heat input and turbulent friction in the duct of constant or variable cross section have been formulated. A periodic density function was chosen, variable both in time and space. From this function and from the variation of the cross section, the pressure function and the space and time characteristics of the corresponding heat input process were derived. Some freedom was allowed by means of arbitrary integration functions for the adaptation of the results to the conditions of operation. Though the treatment is idealized, it is exact and contains the essential features of the process. The results will serve as a basis for comparison with experiments and for a refinement of the theory. A numerical comparison with experimental data shows good qualitative agreement for this simplified case. The governing feature is the realization of the theoretically resulting heat input function.

Experimental Program

As mentioned before, a coaxially rotating sleeve valve mechanism has been designed. The air enters through a scoop and, in passing the single row of blades, drives the valve cylinder in a rotary motion. The alternately covered and uncovered slots in the combustion chamber wall serve as the air intake openings. When the combustion chamber intake slots are covered, the air passes through openings in the scoop into the cooling duct surrounding the combustion chamber and the tail pipe. Besides cooling, the intermittently admitted air can be utilized for thrust augmentation due to heat addition and to friction on the hot jet wall. The test model has been designed and two engines ordered from I.T.E. Circuit Breaker Company, Philadelphia.

One engine will serve for experiments without combustion and the other for experiments with combustion. The first test model arrived on December 16, 1947, and is being mounted in our wind tunnel. The second engine is in a rough machined state at I.T.E., Philadelphia, and will be machined to final dimensions after the optimum air intake slot configuration has been determined by the results of the cold test.

Rotary Valves

The model of the P.I.B.A.L. rotary valve mechanism will be tested without combustion in the wind tunnel (working section 32" x 42", maximum speed 135 m.p.h.) to determine the flow phenomena through such valves for varying intake slot areas and shapes and also to determine the scale of the resulting turbulence in the combustion chamber. The hot-wire anemometer method, which has been developed and successfully used at P.I.B.A.L. for qualitative and quantitative turbulence measurements, will be used to measure velocities and turbulence on the down stream side of the valves.

Experiments with combustion will be conducted at the Navy Experimental Station near Williamsport, Pennsylvania. It is intended to measure pressure and temperature at various points along the combustion chamber and tail pipe in order to determine data for the analysis of the aero-thermodynamical mechanism of the combustion process in such a device. Apart from the relatively well-established pressure measurements, others of a novel type are planned. These new types of measurements are noted below under the heading "Instrumentation." As a departure from the conventional thrust measurements, the instantaneous and average values of thrust of the pulse jet will be measured simultaneously. A pendulum type of suspension of the unit is planned. This type of suspension will reduce the friction and inertia effects of the support to a minimum in contrast to the parallelogram support at present employed by most investigators.

Reed Valves

At present no experiments are planned with reed valve mechanisms, since it is felt that other experimenters have collected sufficient material for a comparison of the analytical results with actual engine data. Should it be necessary to extend the measurements already made by others, a program will be worked out to collect additional information.

Instrumentation

Thrust. Dynamic strain gauges on a thrust rod will be employed for thrust measurements using an oscilloscope for both instantaneous and average readings. The former type of gauge has an instantaneous response and can be balanced against the influence of temperature changes.

Pressure on the Walls of the Combustion Chamber and Tail Pipe. It is proposed to use dynamic strain pressure gauges, utilizing the strain gauge principle, as manufactured by the Statham Laboratories, California, for the continuous measurement of pressure in the combustion chamber and tail pipe. Equipment is under construction to enable calibration of these gauges by sinusoidal and square wave pressure variation at frequencies up to 200 c.p.s. and also for temperature variations up to approximately 1000^oF.

Gas Temperature. Ultrasonic waves will be employed to measure the temperature over a cross section in the pulse jet. The method described in the general introduction to this report will be used.

Wall Temperature

The average wall temperature will be measured by built-in thermocouples at various points of the unit. The temperature of the wall surface inside the unit will be measured by the x-ray scattering method as described under instrumentation in the general introduction.

Fuel Flow

The rate of fuel flow will be measured by commercially available rotameters and at least one other type of metering unit as a check. These instruments are already available at Williamsport, Pennsylvania.

Air Flow

To determine the fuel-air ratio in the combustion process, the air will be ducted from a compressor into the unit. The amount of air taken in is determined by an orifice at the surge tank. Once the thrust developed with exclusion of ambient air flow is determined as a function of fuel-air ratio, measurements will be made under simulated flight conditions to determine the net thrust, i.e. the difference between thrust and drag.

Recording Instruments

Bifilar reflecting galvanometers or multi-gun cathode ray tubes will be used for simultaneous recording of the electric impulses received from the pressure and temperature indicators discussed above. In the latter case the measurements will be recorded on a continuously moving film.

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

The first quarter of 1947 brought to a close the initial period of Phase 2. Preliminary library research was completed on several research ideas that had been discussed and formulated within the original phase outline.

It may here be stressed that the topics were planned as long-term fundamental yet practical research that would require more and more funds and personnel as the topics developed.

It was believed that this approach was the most rational and likely to yield materials and data necessary for the advancement of rocket and jet motors.

The end of April brought approval by the Metallurgical Advisory Committee of some of the topics proposed by Professor O.H. Henry and Mr. M. Stoll, Research Associate. Thus a formal program was crystallized and this permitted the commencement of concentrated research early in May 1947.

The approved program comprised four main topics:

1. Study of Carbides and Nitrides
2. System Beryllium—Chromium
3. Temperature Distribution Studies
4. Modified Creep Tests

Recently the four topics were sub-divided and codified. The connection between the original topics and the new code numbers is indicated in the following tabulated summary. This summary contains a brief description of progress made on each topic and suggestions as to the subsequent development.

Tabulated Summary of Work Done in 1947 on Phase 2

Original Topic	Code Number	Official Title	Achievements in 1947	Proposals for Future
Modified Creep Tests	PIB 2R1	Construction of a dilatometer	Essentially completed	To be suspended until funds and personnel are made available.
	PIB 2R2	Development of high temperature extensometers	Completed	
	PIB 2R3	Variable Temp. Creep Machine	Nearing completion	
	PIB 2R4	Constant strain rate variable temperature testing	Started. Awaiting completion of PIB 2R3	
	PIB 2R5	Modified Creep Tests	Dormant. Awaiting completion of PIB 2R3 & 2R4	
Temperature distribution studies	PIB 2R6	Changes in Martensitic Structure as a record of temperature	Method developed and calibration completed	Merits continuation by performance of simulated rocket test and actual rocket tests
Beryllium Chromium System	PIB 2R7	Study of Alloy System: Be-Cr	Extensive experiments so far failed to produce satisfactory melts due to exceptional difficulties	Temporarily suspended until refractories, funds and personnel are available
Carbides and Nitrides	PIB 2R8	Study of Carbides and Nitrides	Method developed. Tests in progress	Merits continuation on much larger scale due to importance for jet and rocket motors

A detailed account of achievements and some of the technical difficulties encountered in the development of each of these topics may be found on the subsequent pages.

Originally, it was intended that 1947 be devoted to the preliminary probing of potentialities, difficulties and the development of experimental methods, and above all to instrumentation. The latter involves assembling and modifying existing equipment, and developing instruments that are not commercially available and which are essential to implement the program. It follows from the tabulated summary and the detailed account presented on the following pages that this program has been closely followed.

From the work done it is now clear that some topics, as originally anticipated, merit a much larger outlay of energy and funds than provided for in the present reduced budget. This and the recent warning of possible termination of Phase 2 by July 1948 is disturbing because the program, as approved by the Metallurgical Advisory Committee, is felt to be of importance to rocket and jet development.

With the available personnel and present funds, it seems advisable during the next six months to consolidate the effort on two topics of immediate importance, namely, Study of Carbides and Nitrides, and Changes in Martensitic Structure as a Record of Temperature.

Judging from the facts reported on these pages one may deduce that the 1947 goal has been achieved in great measure in spite of the many unexpected obstacles.

P.I.B. 2R1-Construction of Dilatometer

A review of the literature disclosed many types of dilatometers which for various technical reasons were deemed unsuitable for the work contemplated in connection with the modified creep tests. Space, however, does not allow even a brief review of the existing types of dilatometers and reasons for their unsuitability.

To outline the system developed it is sufficient to say that it is composed of a dilatation indicator actuating a selsyn motor which drives another selsyn in the recording mechanism. Certain difficulties of applying the original scheme were encountered. This necessitated a development of a modified solution which had to be tested experimentally. As for the difficulties encountered, problems of torque at the dial indicator and of lag between the selsyns which occurs under load may be quoted as examples of what had to be overcome. The selsyns had to be used as controllers with the torque supplied by a motor at the pickup end and another at the recorder end.

At present this design is being written up in its entirety and will be published as a technical memorandum.

P.I.B. 2R2-Development of High Temperature Extensometers

This instrumentation problem deals with the design of an automatic recording, high temperature extensometer applicable for use in creep and modified creep tests, which also may be easily adapted for use in tension tests.

The requirements of this instrument specified that it must provide for the measurement of 100 per cent elongation of a two-inch specimen, and it must be reversible to provide for the measurement of negative elongation which may occur.

In principle the operation of this instrument is as follows:

A beam which may be rigidly constrained at one or both ends, to which electrical strain gauges have been attached, is the actuating element. In either case, as the beam bends, the longitudinal fibers either lengthen or shorten depending upon their positions with respect to the neutral axis and the direction of bending. If, therefore, the beam is rigidly connected to the test specimen mounted in the furnace, the strain in the specimen is reflected by a definite fiber stress. As a result of the induced fiber stress, the above-mentioned lengthening and shortening takes place. If an electrical strain gauge is attached to either the upper or lower faces of the beam, or to both surfaces, a change in the electrical resistance of the gauge or gauges occurs. The gauges are connected as arms of a Wheatstone Bridge, and owing to their resistance changes a difference in potential is produced across the bridge. This voltage may be measured and recorded by a potentiometric recorder, and a voltage-vs.-time trace is therefore available for immediate conversion to a strain-vs.-time-trace.

In the development of this extensometer, two separate designs were considered. The first had a cantilever beam as the actuating member, and the second used the principle of a doubly constrained beam. In each case, Baldwin-Southwark SR-4 strain gauges were attached to the beam surfaces, and inconel rods acted as the rigid connection running from the piece under test to the extensometer beam.

In the cantilever type design, a working stress of 50,000 p.s.i. was used in the beam fibers, and a heat-treated spring steel was used. Calculations showed that with a beam 1/16 inch thick and one inch wide, a length of 10.6 inches was necessary for a maximum deflection of two inches.

This particular design had a clamping effect due to the attachment of the rods to the beam not provided for in the calculations. Constraint of this type substantially reduced the bending stress at the gauges, and consequently only about one-half of the expected electrical result was forthcoming when the instrument was tested.

In the extensometer based upon the principle of the doubly restrained beam, aluminum plates were used to produce the constraints. As in the previous setup, inconel rods were used as the connecting members. The design calculations of each beam shown allows for a deflection of 1 inch, thus providing for a movement equal to 2 inches of the connecting rods, and consequently an elongation of 2 inches by the specimen. Upon testing, it was found that this type of extensometer was far more satisfactory than the cantilever type, since its behavior closely conformed to calculated results.

Calibration of the instrument produced a linear relationship between strain and the unbalanced potential across the bridge. The instrument sensitivity depends upon the slide-wire present in the Micromax. In this type of extensometer it is obvious that minute sensitivity must be sacrificed in favor of the measurement of lengths of the order of magnitude of two inches. Average sensitivity may be reduced to 0.01 inches with a proper choice of slide-wire. Below this value further sensitizing is unnecessary. This extensometer is being described fully in the form of a report.

P.I.B. 2R3-Variable Temperature Creep Testing Machine

The need for a modified creep testing machine to obtain information about the various heat resistant alloys leads to the adoption of a suitable design. A primary requirement was that this design be simple in operation and one that could easily be constructed with limited shop facilities. A further effort was made to make use of equipment and materials that were available in the laboratory. A motor and speed reduced was found that offered a possible source of power so the preliminary design was built up around this unit.

Design Requirements. Plans for the testing of new alloys up to a maximum stress of 60,000 p.s.i. using a standard 0.505-inch diameter test bar require a loading system capable of exerting 12,000 lbs. To increase the utility of the machine should higher stresses be desired, the machine is scheduled to develop a maximum load of 18,000 lbs.

Since the creep tests are expected to extend over a period of at least several hours, a machine fully automatic in operation is necessary. It must have a control system which will maintain a constant load on the specimen regardless of the deformation of the material, and also, an automatic recorder to plot a continuous elongation-time curve.

Design. The proposed design is shown in Figure 1 and the work completed at present shown in the photographs Figures 2 and 3.

Structure. It may be seen in these figures that the structure of the machine consists of upper and lower stress plates supported by two upright columns. The plates carry the specimen loading rod and are heavily gusseted to insure adequate strength. Each of the supporting columns is a box section built up by joining the flange edges of two 4-inch structural channels and butt welding the entire length. This form of construction provides a rigid yet extremely light member. A base plate and supporting angles are welded to the foot of the columns to provide a stand.

The entire power unit is mounted above the machine on a heavy plate which is bolted to the upper stress plate. Since no equipment was available for line boring the holes for the loading rods in the two plates, the power unit plate was drilled with slightly over-size holes to allow axial adjustment on assembly.

Loading System. The adopted loading system consists of a power screw in series with the loading rods and test specimen. The screw is elevated by means of a steel bevel gear having an internal thread cut into the gear hub. Power is supplied to this gear by a mating

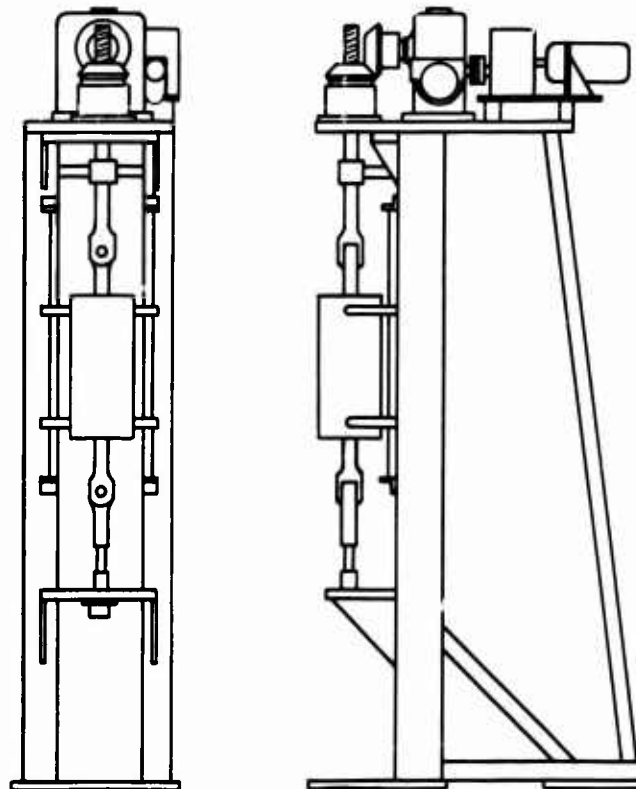
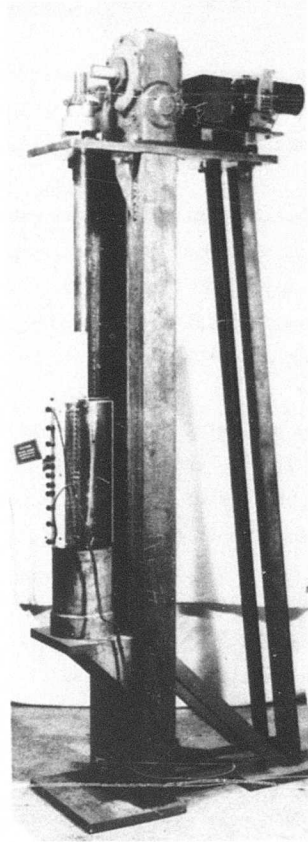
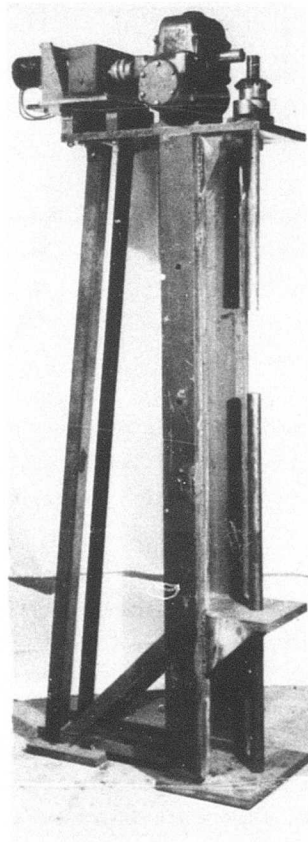


Figure 1.

Proposed design for modified creep test machine.



Figures 2 and 3.

Figure 2. Partially completed creep-rupture machine.

Figure 3. View showing furnace location.

bevel gear and two speed reducers driven by a fractional horsepower motor.

The high thrust load imposed on the threaded bevel gear is supported by a heavy duty roller thrust bearing mounted on a collar type pedestal. Radial thrust on the bevel gear is absorbed in the bearing support by means of a hardened steel ring pressed onto the gear hub. To prevent rotation of the power screw under load, a keyway is cut into the screw shaft to receive a key secured in the thrust bearing support. The loading screw is held rigidly fixed in position by the upper bearing support and by a lower sleeve bearing mount which is welded to the machine frame.

Axial loading of the test specimen is insured by providing roller bearing equipped universal joints between the ends of the loading rods and the test bar. The final design of these joints has not been completed as yet, but it is hoped that they will prove more

satisfactory than the usual spherical seat.

The commercial-type electric resistance furnace is shown in Figure 3. It is mounted on a sliding bracket to permit easy positioning over the test specimen. A controller will be used to maintain constant temperature within $\pm 5^{\circ}\text{F}$ during the test.

Power System. The entire power system is mounted on the upper plate of the machine to provide a compact unit. It consists of two speed reducers coupled together and driven by a 1/4 h.p. 7500 r.p.m. reversible motor. The two speed reducers provide a large reduction and reduce the high motor speed to 1/3 r.p.m. at the level gear shaft. With an overall efficiency of 30% the unit is capable of developing a torque of 600 lb.-ft.

The smaller reducer shown in the photographs is a spur gear train having an overall ratio of 120:1. This reducer and the motor were used as the basic unit in the preliminary design. The larger reducer is a double worm 180:1 unit and was installed to provide the low power-screw speed and high torque required.

Control System. Several methods of automatically maintaining a known constant load by motor control are being investigated at the present time. One method that offers interesting possibilities makes use of the Baldwin-Southwark SR-4 strain gauge to operate the motor start, stop, and reversing contacts. In this system a gauge is mounted on a short bar which is inserted in the loading system and subjected to the same load as the test specimen. The bar deforms elastically at a given load and the resulting strain gauge resistance is used to balance a relay switch. This relay switch controls the motor which drives the screw to keep the load constant.

A mechanical system, by which the relative motion between the power screw and the machine frame is used to operate the motor control, is also being studied. This is to be accomplished by making use of a dial gauge to which electrical contacts have been added.

Conclusion. A well advanced machine design, as well as the progress made in building it, has been described. The machine, when completed, should yield the desired information about the creep phenomena. It should be noted that this machine is being developed not by the regular staff but by thesis students who can only devote to this task a limited amount of time. This considerably slows the progress.

P.I.B. 2R4-Constant Strain Rate, Variable Temperature Creep Testing Machine

The basic structure of a constant strain, variable temperature creep testing machine is expected to be the same as that of the constant load machine nearly completed under PIB 2R3. It is considered that this latter machine should be completed and tested before further work on PIB 2R4, in order that any suggested improvements may be incorporated therein. The framework and a few basic parts not likely to be modified have been completed with similar parts for PIB 2R3.

P.I.B. 2R5-Modified Creep Tests

Early in the planning of the research program it was decided to attempt an experimental study of the combined effect of important variables in creep and creep-rupture phenomena. At the root of the program was the feeling that the conventional tests do not result in data that are truly comparable to service facts observed in rockets and jet engines. A preliminary consideration of the aspects led to the proposal of two new types of tests. These, by a proper variation of test conditions, should better simulate the actual service conditions than do the conventional creep tests. The proposed tests are:

1. Constant stress, variable temperature tensile test. This may be called "variable-temperature-creep" in its initial phase.
2. Constant strain rate, variable temperature tensile-type test. These tests constitute a new approach and it is expected that they should yield data directly useful for designers of machine elements which have to perform at very high temperatures.

The problems PIB 2R1, 2, 3, and 4 are the instrumentation phases of these two tensile-type tests, and completion of these will, of necessity, precede the actual attack on this problem. Some of the topics concerning the instrumentation are being written up and an outline of the expected results and implications of these tests is included as an introduction to these technical reports.

P.I.B. 2R6 - Changes in Martensitic Structure as a Record of Temperature

A method was proposed for determining the temperature in rocket bodies by constructing the part or chamber in question of a temperature responsive material. The structural changes

that occur with temperature and time in martensitic steel were used in the initial program.

A laboratory check was made to determine whether the temperature attained could be determined by the use of simple metallographic and hardness measurements. It is well known that changes in microstructure and hardness can be correlated with the temperature and time of soaking at that temperature. Hence it follows that comparison of the microstructure and hardness of section of a fired rocket with a set of standards of the same steel heat treated under known conditions, will indicate the temperature of the rocket body.

An alloy steel quenched from above its upper critical temperature to ice water temperature will form metastable martensite which has a tetragonal body-centered lattice. A fast quench of an alloy steel may retain some austenite in a matrix of martensite at room temperature. To reduce the amount of retained austenite after quenching, a sub-zero treatment is recommended. Cycling the steel between ice water temperature and sub-zero temperature will tend to stabilize any remaining austenite. This is advantageous since it reduces one more variable to a minimum in the tempering process. On tempering, the untempered martensite will transform to tempered martensite which has a body-centered cubic lattice. Retained austenite will decompose and form bainites. Bainites are similar to martensite, as they both appear as needles that have formed directly from austenite. Increasing the tempering temperature changes the microstructure and lowers the hardness of the martensite in a characteristic manner. Both these changes are indicative of the amount of transformation. Conversely, from the amount of transformation, the maximum temperature may be estimated. This forms the basis for the present method of determining temperature metallographically. The rate, as well as the temperature range, of transformation is a function of the composition of the steel. Standards will have to be made for each particular steel that is used in the construction of a rocket chamber. The steel chosen for this experiment analyzed as follows:

Carbon	1.07%
Manganese	.48%
Silicon	.41%
Nickel	4.96%

Its temperature range is 400°F to 1300°F.

The steel was received as hot rolled plates, 1/8" × 12" random length. Metallographically, the structure was typical of one with a full spheroidized anneal. Strips 1/2" wide were cut and wet-surface ground to remove any decarburized surfaces. These samples were then austenitized at 1750°F for fifteen minutes, quenched in ice water, held at sub-zero temperature in dry ice for one hour, raised to ice water temperature for fifteen minutes, requenched to dry ice temperature for another hour, and

then tempered to the predetermined condition. Tempering was done at 100°F increments from 400°F to 1300°F. The tempering was accomplished by immersing the standard in a temperature controlled neutral salt bath for soaking times of five and ten minutes. The standards were hardness tested and prepared for metallographic examination. Microscopic examination of the standards was made on a Bausch and Lomb metalloscope at 500×. The resulting photomicrographs show that temperature may be readily differentiated by changes in structure. Metallographic examination also showed that small variations of time at the tempering temperature had little effect on the structure once the martensite was tempered. Hardness versus tempering temperature curves did not reveal any substantial difference between the five and ten minute tempering series; however, they are of great use in determining the actual temperature attained. Results indicate that tempering time is a small factor in this experiment.

The heat treating equipment consisted of a Hoskins electric resistance furnace and a Leeds & Northrup potentiometric controlling recorder. The salt pot for tempering was controlled by a Brown electric pyrometer controlling indicator.

The next step along these lines will be the construction of a small rocket chamber from this particular steel-heat treated under the prescribed condition, fired by means of an oxy-acetylene torch, and sectioned for temperature determination.

A technical report covering the exact procedure, accompanied by photomicrographs, hardness, and other data, is now substantially completed and will be published shortly.

P.I.B. 2R7 - Study of the Alloy System of Beryllium and Chromium

After completing a literature survey on the characteristic properties of metals, the possibility of the beryllium-chromium system looked interesting because of the refractory nature of their oxides. Further library research revealed that the phase diagram of this alloy system had not been produced. The only experimental work on the system was that of two Russian scientists, P. I. Dalnov and M. I. Zakharova, who made two melts of beryllium-chromium for x-ray analysis. The description of their melting was very brief and information from a metallographic viewpoint was virtually non-existent.

Actual experimentation on the system started at the Polytechnic Institute of Brooklyn in February 1947.

The difficulties encountered in the preparation of an alloy of these two metals are numerous.

The first problem concerned the selection of crucibles. Refractory crucibles such as alundum, magnesia, silica, zirconia, thorium oxide, and carbon are unsuitable. Beryllium will react with these materials and form beryllium oxide or carbide. It was found that the best crucible for melting beryllium is one made of beryllium oxide.

The second difficulty encountered was that of atmospheres. Chromium and beryllium are good oxidizers at elevated temperatures. The conventional atmospheres of carbon monoxide or dioxide, nitrogen, and hydrogen are of little use. Beryllium will react with carbon monoxide and nitrogen, and the literature mentions the existence of beryllium hydride. After consultation with the Brush Beryllium Company, it was decided to use argon. Another alternative would be to use a vacuum furnace.

The third difficulty to be met was that of impurities. Premium grade beryllium was obtainable, analyzing 99.03% beryllium for a 325 MXD powder and 99.87% beryllium for 1/4" lumps. The purest chromium commercially available contained one-half per cent of oxygen, the very element most detrimental to the production of a clean melt. Up to the present time purer chromium has not been available.

Melting was first attempted in a vacuum induction furnace utilizing an Ajax Northrup driving unit. Powders of beryllium and chromium of 325 MXD were used. Because of the fine particle size, melting was attempted with a non-conducting crucible. Melting was then tried when a carbon ring was placed around the non-conducting crucible to provide an external source of heat. This also failed to produce results. Examination revealed that the crucible had become contaminated with carbon from the rings. Had melting occurred, the melt would have been a three component system. Another source of trouble was that the vacuum pump could not provide a sufficient vacuum.

To make use of the fine metal powders available and because of the inability of the pump to provide a good vacuum it was decided to construct a muffle tube furnace using argon gas as an atmosphere and an oxy-acetylene torch as a source of heat. The first tube furnace was unable to withstand the heat. Two more tube furnaces were built of different design. In both cases the tubes burned out. Combustion tubes were used which withstood temperatures up to 3000° F. These tube furnaces required special crucibles to fit into the tubes. This approach to melting was abandoned because of the difficulty in finding special crucibles and higher temperature combustion tubes.

The next attempt to produce a melt was made in an Ajax Northrup induction melting furnace using an argon atmosphere. In this experiment one crucible was placed inside a larger one and lump metal was used. Because of the small mass of metal involved, enough

heat could not be generated to produce melting. To induce more heat the crucible was floated in a bath of molten iron. Melting occurred but the melt was contaminated with oxide stringers and the mass had little strength though it was hard enough to scratch glass. The latter properties were later found to be characteristic of all of the 150 melts produced.

At this time a smaller induction furnace was purchased which allowed higher temperatures to be reached in shorter times. With this new furnace many more melts were attempted using argon atmospheres, fluxes, and different types of crucibles. The results were always the same—some fusion with much oxide present. This could be the result of the 0.5% of free oxygen in the chromium.

Melts have been made of pure chromium from which a diffusion sample was prepared. Diffusion was accomplished by holding the temperature above the melting point of beryllium (2345°F) and below the melting point of chromium (2900°F) for six hours, under an argon atmosphere.

A metallographic examination showed the presence of a structure similar to an eutectic or eutectoid and possibly of an intermetallic compound. Hardness measurements were made across the face of the diffusion zone. The high beryllium region gave a Rockwell hardness reading of C34 which increased to a maximum of C52 and decreased to less than C20 in the chromium region.

To date a satisfactory alloy of beryllium and chromium has not been produced. All melts have had oxide stringers running through their mass.

Work halted about September 1st, awaiting the arrival of new beryllium oxide crucibles from the Norton Company. As production has been stopped on all special beryllia shapes due to the new occupational disease associated with their production, this phase is now held in abeyance.

P.I.B.2R8 - Study of Carbides and Nitrides

The program on carbides, nitrides, and borides bonded with a refractory metal is designed to indicate quickly which areas of this interesting field are most likely to yield alloys which would supersede existing high temperature structural metals. A general survey of the possible alloys will be followed by detailed investigations of the more promising systems.

Library research furnished only data on the properties of the individual carbides, nitrides, borides, and binder metals. Very little in the literature concerned the high temperature properties of these materials and almost nothing was given on their combinations for refractory purposes. Thus a field of great interest for high temperature parts is entirely unexplored.

The system tungsten carbide-cobalt, or Carboloy, as it is known commercially, has been most widely investigated, though not from the point of view now under consideration. One point of importance is revealed in the literature on this system, namely that the function of the cobalt binder is one not only of cementing mechanically the carbide particles, but also of producing a structure of interlocked and reformed carbide crystals. This it does by precipitating the carbide which it dissolves at high temperature. Although the sintering temperature for the production of Carboloy is below the melting point of cobalt, evidently the cobalt dissolves by diffusing sufficient carbide to render it molten.

Experimental work at the Polytechnic was started on the carbides, using tungsten, titanium, and tantalum carbides in commercially available powder forms. Early work, of necessity exploratory, was aimed at the determination of the wetting characteristics of various refractory metal binders on these carbides. In order to obtain samples for this metallographic examination, a carbon arc was used to form beads of the mixed binder and carbide powders contained in a graphite block. Despite the carburizing conditions in the arc and the absence of temperature control, structures of several types were revealed. Titanium carbide was encountered in matrices of cobalt and chromium; the tungsten carbide and cobalt alloy showed the typical Carboloy structure; the tungsten carbide and chromium or molybdenum alloys exhibited a Widmanstätten structure, indicating reaction between the binder and the carbide.

Because measurements of the properties of the alloys at room temperature are not necessarily informative of their value as high temperature structural materials, a method had to be adopted which would supplement the metallographic and hardness data to give an indication of their high temperature load-carrying properties. It was decided to produce specimens in the form of cones with cylindrical bases. The conical portion serves for the determination of the temperature of softening, which is the ultimate working temperature of the compact, while the cylindrical base affords material for microscopic and other examinations. By comparing the softening temperature of such a cone made of a conventional heat-resistant alloy with the known maximum operating temperature of that alloy, and by applying the ratio of these temperatures to the observed softening temperatures of the carbide alloys, one should be able to predict roughly what might be expected of the latter at operating temperatures. This method is a simple one, and is designed for the first

survey of the vast field of possible combinations in the shortest possible time.

Cold compacting the intimately mixed powders was first done, before fritting the compact. This was time-consuming, and it was found that filling the mold cavity and tamping the powder was sufficient to produce test pieces of good density. The effect of prepressing has been set aside for future study.

To secure temperature control, a special carbon resistance furnace was designed and built. High current passing through the walls of the carbon crucible heats the charge. This may be surrounded with a protective or inert atmosphere. Temperature is conveniently measured with an optical pyrometer, sighting through the cap of the furnace. This furnace heats rapidly and the temperature can be maintained quite well, but the transformer capacity presently available limits the temperature range.

The fritting was also tried in the high frequency induction furnace, using as a crucible a carbon block drilled to form the conical-bottomed cavity. In this, it was possible to heat as many as twelve samples at one time. Heating in this large block, however, was not as rapid as was desired, and it was necessary to revert to the use of single-cavity crucibles in a smaller high frequency furnace. With these crucibles it is possible to bring the charge to 3000°F in about two minutes, temperature being measured with the optical pyrometer.

Many of the potential binder metals form carbides rather freely, and reaction with the graphite mold wall has been encountered. As a preventative, oxide mold washes were tried, but these did not hold up under firing. Finally, a means of producing shaped cavities in refractory oxides was devised.

Chromium is very active at its melting temperature and will pick up carbon from both the graphite wall of the crucible and the atmosphere, if that is carbonaceous. Alloys of titanium carbide and chromium have been prepared in the oxide lined crucible. These did not pick up carbon from the crucible, but the microscope revealed that they were somewhat contaminated by the carbon monoxide atmosphere of the furnace.

Alloys of titanium carbide with cobalt as a binder have been made. This binder does not react with the graphite crucible wall, and the experimental work on this system is being continued in plain carbon crucibles.

It is proposed to prepare the carbide alloys without attempting to eliminate all contamination by carbon from the furnace atmosphere, in order to obtain quickly some information about the possibilities of the alloys as they might be produced in commercial forms. Such alloys, which are somewhat carburized in production, may or may not be suitable for high

temperature work. The effect of the influence of the atmosphere will be determined later.

Further work in this investigation is planned using vacuum techniques, protective and inert atmospheres, and protective fluxes.

PHASE 3

(a) To investigate the metallurgical, fabrication, and design problems involved in cooling rocket and intermittent jet motors by the diffusion of fluids through porous metal combustion chamber liners. (b) To study analytically and experimentally (1) the diffusion of fluids through porous media under high pressures and temperatures and (2) the effects (of this diffusion) on the internal aerodynamics. (c) To study problems in the field of physical-chemistry pertinent to (a) and (b) with consideration given to the clogging of pores, the use of catalysts imbedded in the linear walls, and endothermic diffusion processes.

Summary

A theoretical investigation of the laminar boundary layer of an incompressible fluid flowing along a porous flat plate with fluid injected through the porous cells of the plate was presented in Technical Report No. 4. Further investigation of this problem with consideration of the compressible effect is in the numerical calculation stage. An experimental program to investigate the stability of the laminar boundary layer along the surface of a porous flat plate with injection is in progress.

Progress

Technical Report No. 4 entitled *A Theoretical Investigation of the Temperature Field in the Laminar Boundary on a Porous Flat Plate with Fluid Injection* has been published. This work, which started in January 1947, is described briefly as follows:

Studies of the problem of cooling rocket and intermittent jet motors by the diffusion of fluids through porous metal combustion chamber liners were made by means of an investigation of the boundary layer behavior along the porous walls. 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 the same flow condition. It is believed that this approximation will yield some indication of the actual case.

The theoretical study of the aero-thermodynamic problems involved began with the investigation of the flow of a hot fluid over a porous flat plate under the condition of uniform fluid injection from the bottom of the plate. The assumptions made in this investigation were (1) the fluid was incompressible, i.e. the mass density and the viscosity of the fluid were assumed to be constant, and (2) the flow was assumed to be laminar. It is evident that this analysis gives an unconservative answer in comparison with the actual problem, but the qualitative results are rather interesting in this first approximation.

In the solution of the laminar boundary layer equation, the momentum and energy equations were reduced to the integral relation form similar to the Karman integral relation of the Prandtl equation. The velocity and temperature profiles were assumed as a polynomial of the fourth degree and also as exponential functions. Solution of the above equations gave the relationship of length in the direction of flow to the boundary layer thickness and to the temperature layer thickness in the boundary layer. The velocity profiles and the temperature profiles for different Prandtl numbers were then calculated. The solution was also extended to the case where the coolant injection begins at some distance from the leading edge of the plate.

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 was established. It may be noted that a linear relation exists between the wall temperature and the square of the injection coolant velocity. For a presumed wall temperature the amount of coolant required per unit can be determined provided the temperatures of the outer edge of the boundary layer and of the coolant are known. The comparison of the above theoretical results with some available experimental data shows good qualitative agreement.

The analysis for a compressible fluid under the same flow conditions was carried out. In this analysis the inverse proportion between mass density and temperature was used, and the viscosity was assumed to be proportional to the square root of the temperature.

In the solution of the laminar boundary layer equations, Prandtl's number was assumed to be equal to unity; then the temperature T could be expressed by a certain parabolic function of the velocity only, which satisfied both the equation of motion and the energy equation. The velocity profile was assumed as a polynomial of the fourth degree. A numerical solution of the final differential equation in boundary layer thickness and flow direction is underway.

Experimental verification of the above-mentioned theoretical investigations is being carried out at present for the case of the laminar boundary layer with no temperature gradient.

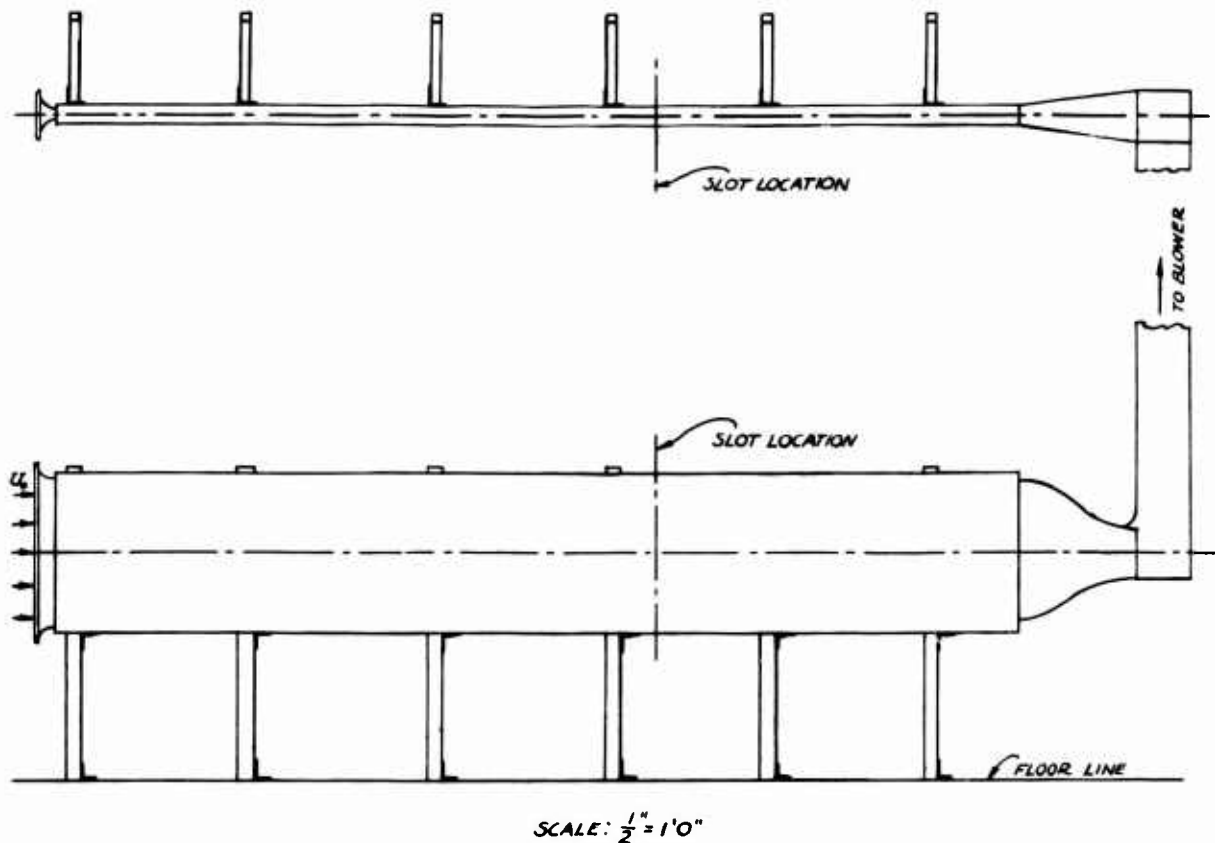


Figure 4.
Turbulence channel.

The apparatus to be used for the experimental investigation is the P.I.B.A.L. turbulence channel (Figure 4). This channel is a rectangular duct of 17 ft. length with a width of 2 in. and a depth of 30 in. With such a ratio of width to depth, a two-dimensional velocity distribution is obtained. Some modifications of the original channel are being made for this particular application. Three important factors have been considered. First, a laminar boundary layer has to be established at the leading edge of the porous wall plate over which the tests are performed. Second, a means of fluid injection with a uniform velocity through the wall has to be supplied. Third, a method of making velocity and direction measurements in the boundary layer is necessary.

It was decided to produce a laminar boundary layer by inserting a vertical slot in the channel wall at the leading edge of the porous plate. This slot is 12 in. long, which is slightly more than twice the width of the plate. By applying suction to this slot one can remove the boundary layer previously established within the channel at this point. As shown in Figure 5, the slot width can be varied from 0" to 1/2". The optimum slot width for complete removal of the boundary layer will be determined experimentally. A supercharger will supply the suction to a suction bell, Figure 6, which will be fitted over the slot.

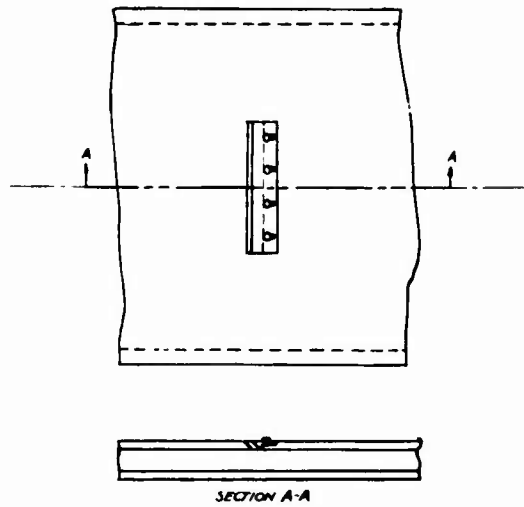


Figure 5.
Slot.

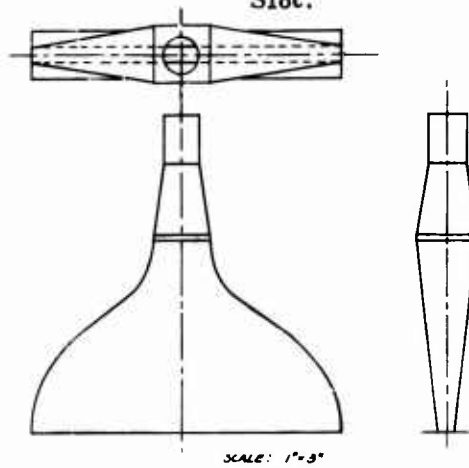
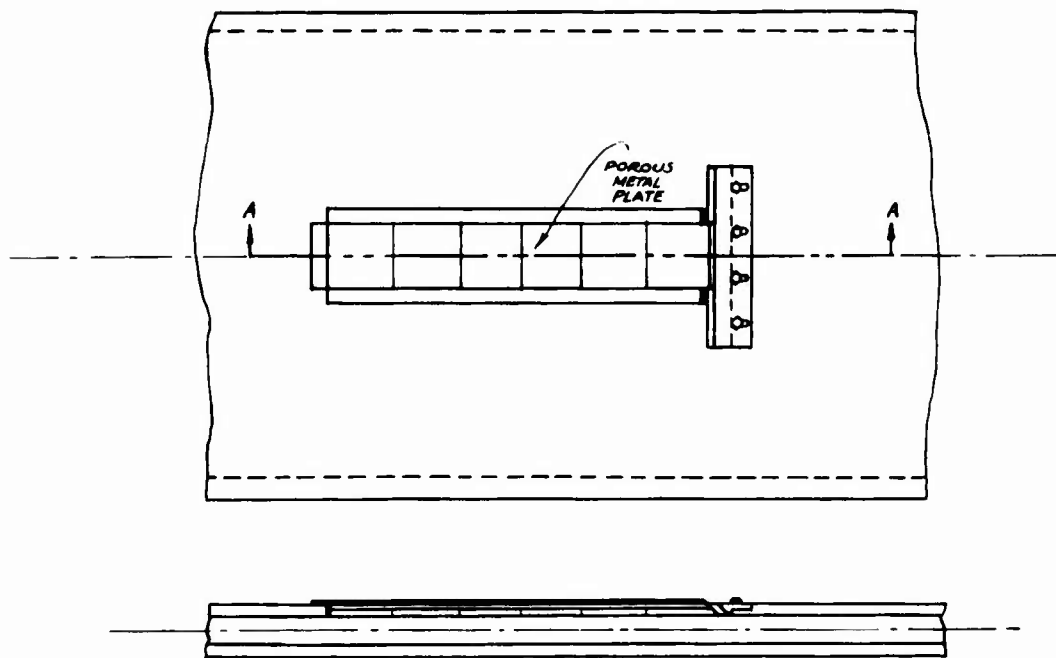


Figure 6.
Suction Bell.

To obtain a uniform injection velocity, a porous metal plate made up of 6 plates ($4\text{-}5/16'' \times 4\text{-}7/16'' \times 17/32''$ thick) supplied by the Jet Propulsion Laboratory of the California Institute of Technology will be used. The resultant plate ($26'' \times 4\text{-}5/16'' \times 17/32''$) will be mounted in relation to the slot as shown in Figure 7. Over this plate will be placed an injection chamber similar to the one depicted in Figure 8. Since this injection chamber requires air at a pressure of 20.5 p.s.i. and 23 cu. ft./min. of free air supplied to it to give an injection velocity of 0.5 ft./sec., a suitable system is being devised to give these conditions.



SECTION A-A
SCALE: $\frac{1}{2}'' = 1'0''$

Figure 7.

Porous metal plate as mounted with respect to slot.

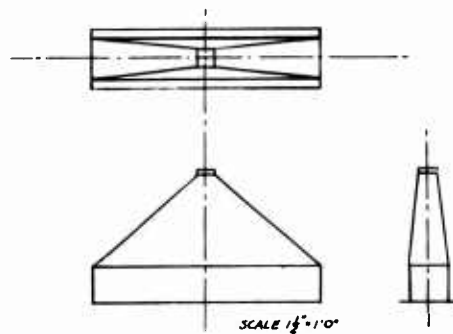


Figure 8.

Injection chamber.

Velocity and direction measurements within the boundary layer will be made with a P.I.B.A.L. two-wire hot-wire anemometer.

Proposed Work

Future theoretical work on the investigation of a turbulent boundary layer of a fluid on a porous flat plate with fluid injection is planned. The problems connected with the flow of the fluid through porous metal will also be studied.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-104, TASK ORDER I

PURDUE UNIVERSITY
and
PURDUE RESEARCH FOUNDATION
WEST LAFAYETTE, INDIANA
1 JANUARY 1948

INTRODUCTION

A review of the research activities on Project SQUID at Purdue University reveals steady progress. Inasmuch as many of the studies are fundamental in nature, and many of the conclusions can only be classed as tentative until they are subject to further test and evaluation, the results accumulate slowly. Hence, only two *Technical Memoranda* have been submitted, and both of these reports covered the investigation on the general subject of the measurement of gas temperature. Several additional *Technical Memoranda* will be forthcoming within the next several months.

PHASE I

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

Project Leader: G. A. Hawkins, Westinghouse Research Professor of Heat Transfer.

Summary

Data and information have been collected in an investigation of measurement of gas temperatures by means of thermocouples and have been presented in two technical memoranda dated May 1947 and July 1947. The investigators recognized that many of the problems in the use of thermocouples for measuring the temperatures of gases under transient conditions may be unsolvable. But for engineering use the advantages of a system of temperature measurement based on a thermocouple are many. Although a system of thermoelements may not measure the actual temperature, such a system can, with suitable correction factors, indicate the temperatures within ten per cent of the actual value.

Apparatus has been designed and tested for detecting, amplifying, observing, and recording the electrical impulses from the thermocouples. Special welding techniques have been developed for fabricating small-wire thermocouples.

Progress

For several years the problems associated with the measurement of the temperature of gases flowing at high velocities have received considerable attention by engineers and scientists. The need for such measurement is felt in the fields of heat transfer, thermodynamics, jet propulsion, and others.

Besides the usual considerations in measuring the temperature of a moving gas stream, the heating of the measuring element must be taken into account. At very high velocities the gas layers adjacent to the measuring element are slowed down by friction, and a rise in temperature results. Serious errors may be introduced in the measurement of temperature of high velocity gases if the so-called friction effect is not considered.

The temperature T' of a high velocity gas stream as measured by the usual laboratory apparatus is higher than the true temperature T , which would be indicated by a measuring element moving with the gas stream and at the same velocity. Temperature T' would be higher than T because of the heating of the gas layers adjacent to the measuring element by the so-called damming and surface friction effects. The temperature T' lies between the true static gas temperature T and the so-called total temperature T_T . The total temperature is defined as the temperature which would result if the velocity of the gas were reduced to zero at the measuring element. A relationship may be obtained from the steady flow energy equation for the total temperature. The kinetic energy of the gas plus the enthalpy at an upstream position is equal to the enthalpy at the measuring element, if an adiabatic process is considered. Hence

$$(1) \quad \frac{V^2}{2gJ} + h = h_T$$

For a perfect gas the change of enthalpy is equal to the product of the temperature change and the specific heat at constant pressure.

$$(2) \quad h_T - h = c_p (T_T - T) = \frac{V^2}{2gJ}$$

or

$$(3) \quad T_T - T = \frac{V^2}{2gJc_p}$$

By thermodynamic analysis it is demonstrated that

$$(4) \quad c_p - c_v = \frac{R}{J}$$

Designating the ratio of the specific heat C_p / C_v by the symbol k , it follows that

$$(5) \quad c_p = \frac{Rk}{J(k-1)}$$

Hence

$$(6) \quad T_T - T = \frac{V^2}{2g \frac{(k)}{(k-1)} R}$$

For air, this relation becomes

$$(7) \quad T_T - T = \frac{V^2}{11,930}$$

if the velocity and temperature are expressed in ft./sec. and F units.

Since the temperature (T') indicated by the measuring element lies between the true or static temperature T and the total temperature T_T , the following relations may be written:

$$(8) \quad T' = T + \beta (T_T - T)$$

when $1 \geq \beta \geq 0$ and $T = T' - \beta \frac{V^2}{11,930}$

The factor β may be determined by experiment.

Indicating the temperature difference, $T - T'$, by ΔT , the relationship becomes:

$$(9) \quad \Delta T = -\beta \frac{V^2}{11,930}$$

Equation 9 may be used to show the difference between T and T' for various velocity and β values, as shown in Figures 1 and 2. From Figure 2 it is apparent that with certain conditions found in research work, the ΔT value will have to be considered.

A survey of the literature on the measurement of gas temperature for high velocity flow available to the research group at Purdue has been made and was fully reported in the *Technical Memorandum* of May 1947 from Purdue University.

Design studies and construction of apparatus capable of detecting, amplifying, and recording the voltage generated by a thermocouple in contact with a gas, the temperature of which fluctuates rapidly, have been made. Since temperature changes of 120 times per second are encountered, the ordinary methods of thermocouple voltage recording are much too slow for use in this research program. Thus it was decided to use an oscilloscope and a rotating drum camera to record the voltage fluctuations. A schematic diagram of the apparatus is

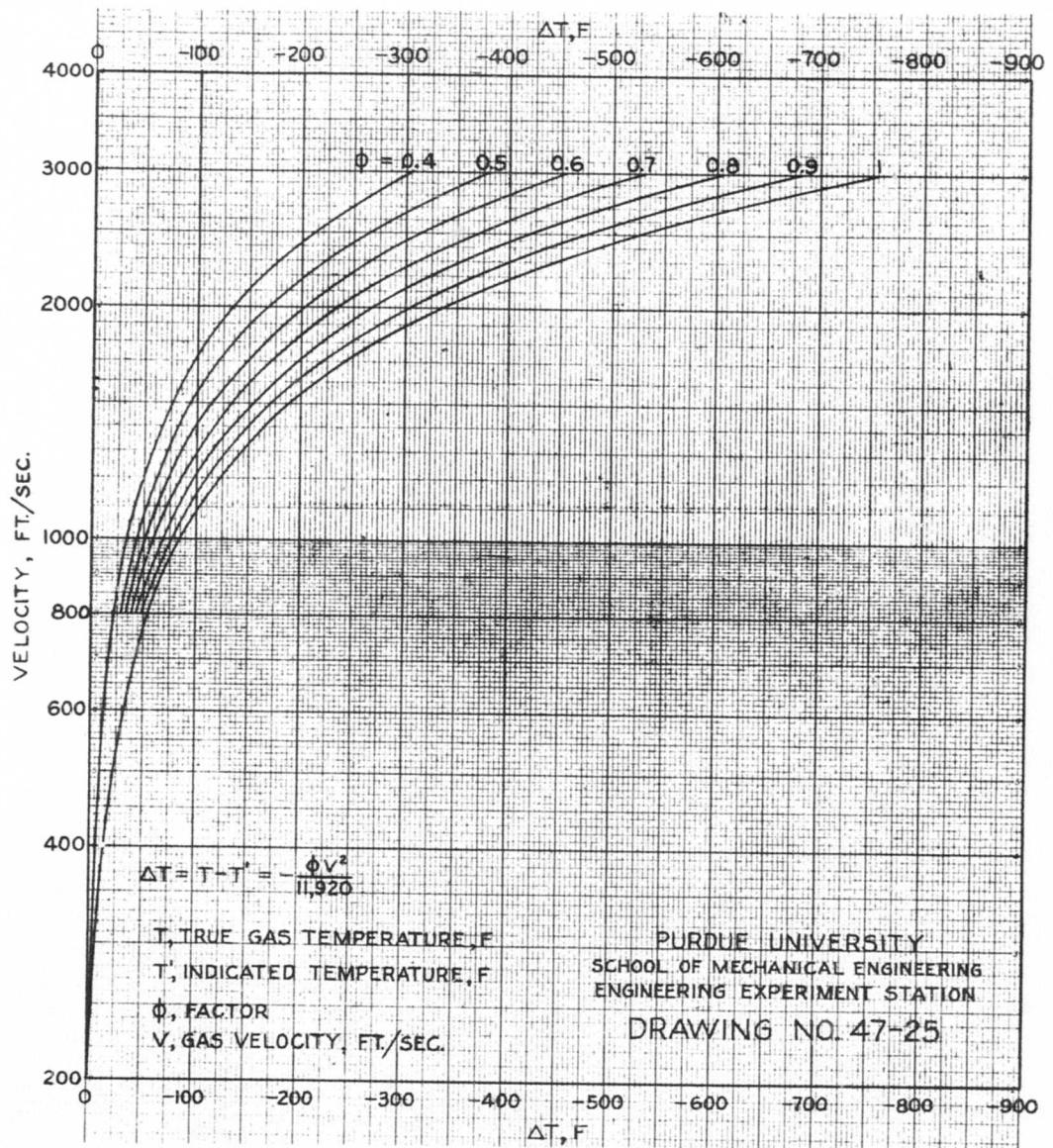


Figure 1.
 ΔT Values for Gas Temperature Measurement.

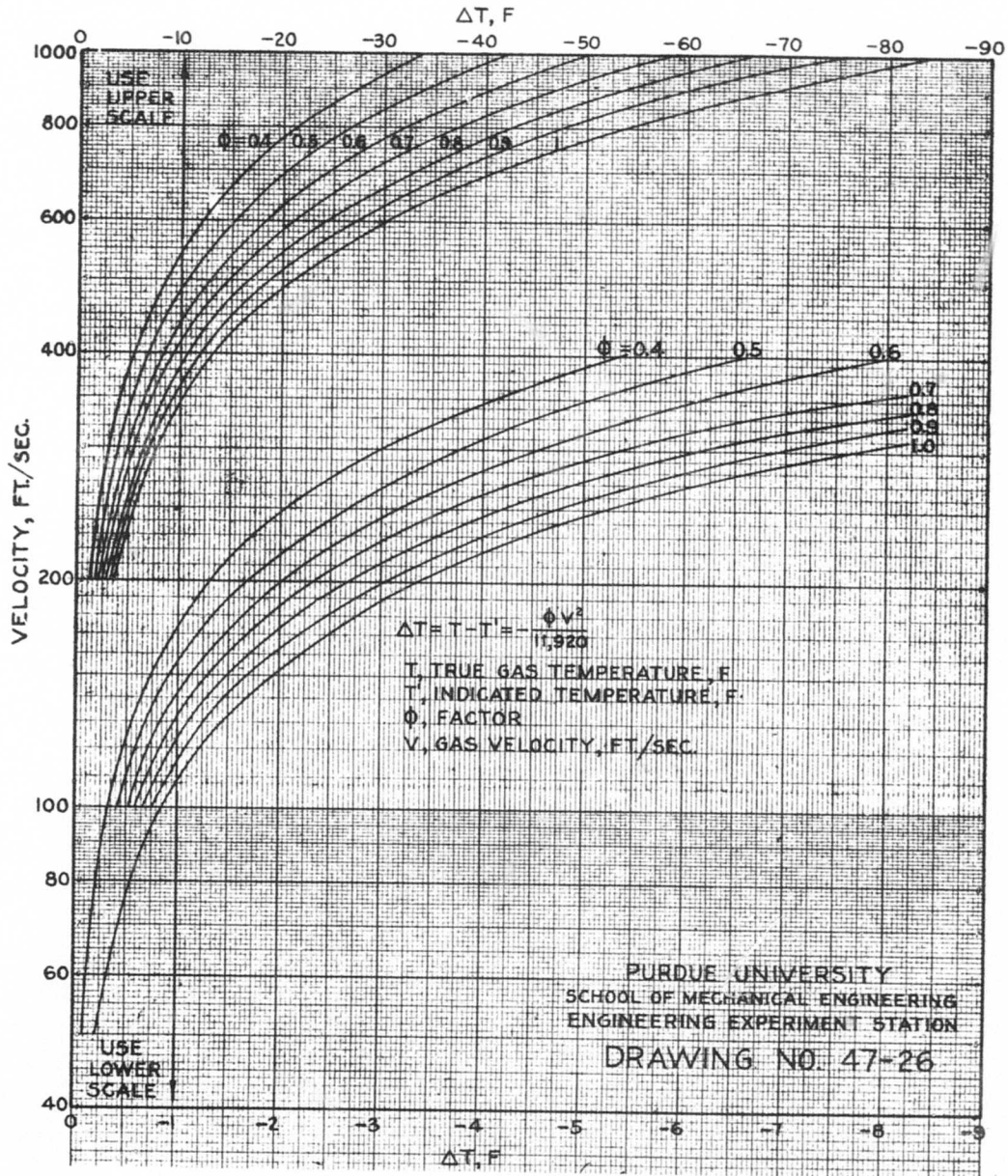


Figure 2.
 ΔT Values for Gas Temperature Measurement.

shown in Figure 3.

The use of an oscilloscope necessitates the use of an instrument to amplify the thermocouple voltage. Inasmuch as direct current amplifiers are often unstable, it was decided to "chop-up" the voltage and use an alternating current amplifier. A rotary switch was designed to do the chopping, although such a switch has definite disadvantages.

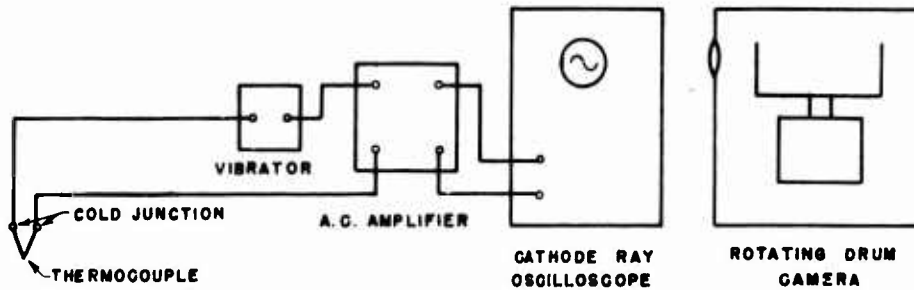


Figure 3.
Schematic Diagram of Test Apparatus.

For timing the voltage fluctuations, it was decided to use a modulator tube operating at 60 cycles per second. By proper focusing, it was hoped to obtain timing marks on the recording paper from which it would be possible to interpret the results.

Figure 4 is a copy of an actual test record. The thermocouple used was a 0.001 inch diameter Pt-Pt/Rh couple with a bead diameter slightly greater than the size of the wire.

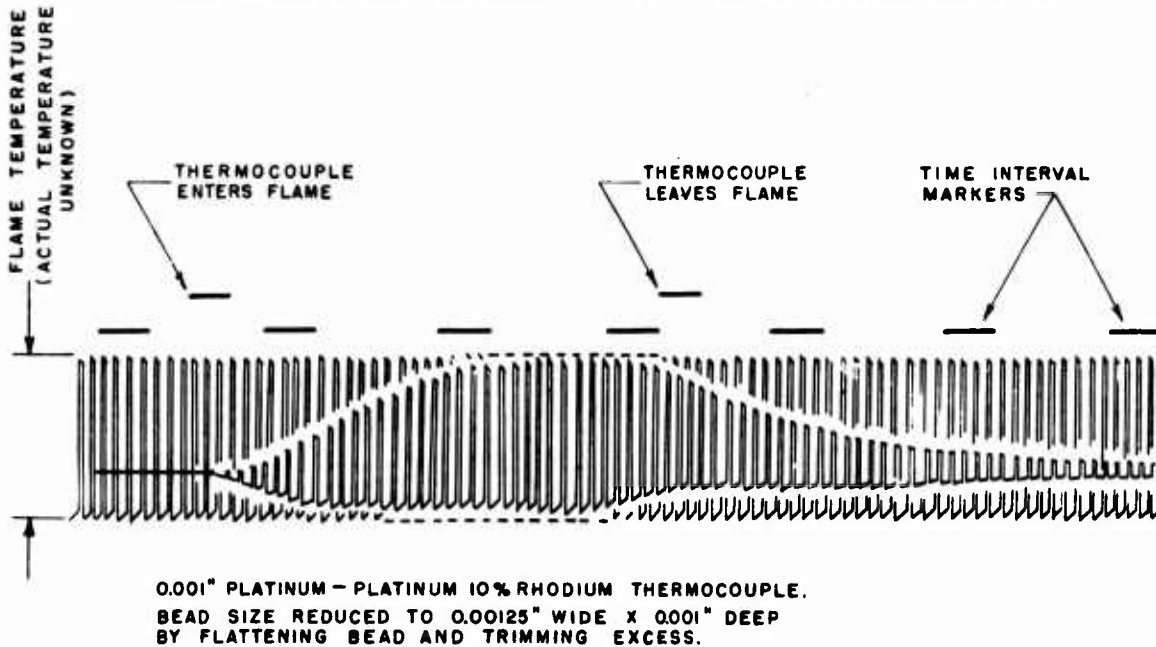


Figure 4.
Record of Test.

An insufficient number of experiments have been conducted to properly estimate the experimental error. The greatest error will probably be introduced in interpreting the height of the trace on the photographic paper. However, the error should be within 3 per cent.

Plans: The researches of Phase 1 have been inactive since 1 July 1947.

PHASE 2

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

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

Summary

The research efforts of the combined staff have been directed almost entirely to the study of the effects of turbulence as covered in the statement of the problem. This study has been partially subdivided into two closely related main categories: (1) the fundamentals of turbulence and its effect on rates of flame propagation, (although most hydrocarbon fuels burn slowly in quiescent air, with large scale turbulence they burn much faster), and (2) the fundamentals of flame holders, required where the local mixture velocity rate exceeds the flame propagation velocity.

PROGRESS

A. Effect of Turbulence on Flame Propagation

Literature Survey: This survey has disclosed that there are basically five different methods for determining flame speeds—the so-called Guoy method,¹ the constant pressure method, the constant volume method, the static method, and analytical methods. In the majority of cases the Guoy method seems to be recognized as the basic method of flame speed determination in Punsen-type burners. Lewis and von Elbe² compute the flame velocity at any point on the flame front by use of the equation of the conservation of mass. Von Elbe and Mentser³ also have presented an analytical equation for point flame speed determinations based upon the pressure difference across the flame front. Both of these analytical determinations refer to the Guoy method for substantiation. Damkohler⁴ (in the only experimentation found concerning the effect of turbulence on flame speeds), Carside, Forsythe, and Townend⁵ (prominent

English combustion investigators) Jost⁶ (a German investigator), and many others use Guoy's method of flame speed determinations.

The effects of variables on space between the base of flame cone and burner tip, flame tip shape, blow-off, flash-back, etc. were also investigated for Lunsen burner combustion. In general, investigators agree on the reasons for the various phenomena but do not agree on the effect of certain variables such as the diffusion of the ambient atmosphere into the combustion zone and the consequent effect on combustion.

The limited work on turbulence in connection with flames has in general been based upon Prandtl's equation for turbulent exchange. To use Prandtl's equation, the degree and scale of turbulence must be known.⁴ These values are best found by use of a hot wire anemometer in connection with an oscilloscope.

As mentioned previously, the only published results of experimental work concerning the effect of turbulence on flame speed were reported by Damkohler.⁴ In this work, the turbulence factors were taken from previous data reported by Nikuradse⁸ on turbulent flow in identical tubes. In Damkohler's final analysis, however, even when using fine body turbulence, he admits errors of some 30% in flame speed calculations. He explains this discrepancy by the fact that the Prandtl's turbulent exchange quantity, $E = l\bar{u}$ is only partially effective (where l = mixing length and \bar{u} = average velocity due to turbulence).

Various experimental setups for non-turbulent flame study have been advocated. These include Schlieren method,⁹ direct⁵ photography of flames, and photographing light reflecting particles which are introduced into the gas stream.² Turbulence is introduced generally by grids or by increasing the velocity in the burner to obtain a Reynolds number⁴ that will result in turbulent flow.

Experimentation: An experimental setup as shown in Figure 5 was constructed for studying the effect of turbulence on combustion. The apparatus was arranged to give control of variables such as mixture strength, mixture velocity, and turbulence, with particular precaution to obtain stability of conditions. Multiple pressure reducing valves and surge tanks in the fuel and air supply systems, as well as a surge tank in the mixture supply line, were required to maintain the stability necessary for this investigation.

Figure 6 indicates the burner and device for creating turbulence. The high speed motor is capable of rotating the rod up to 18,000 r.p.m. so that a reasonable range of intensity and scale of turbulence is available. A hot wire anemometer for measuring the turbulent effects is under construction.

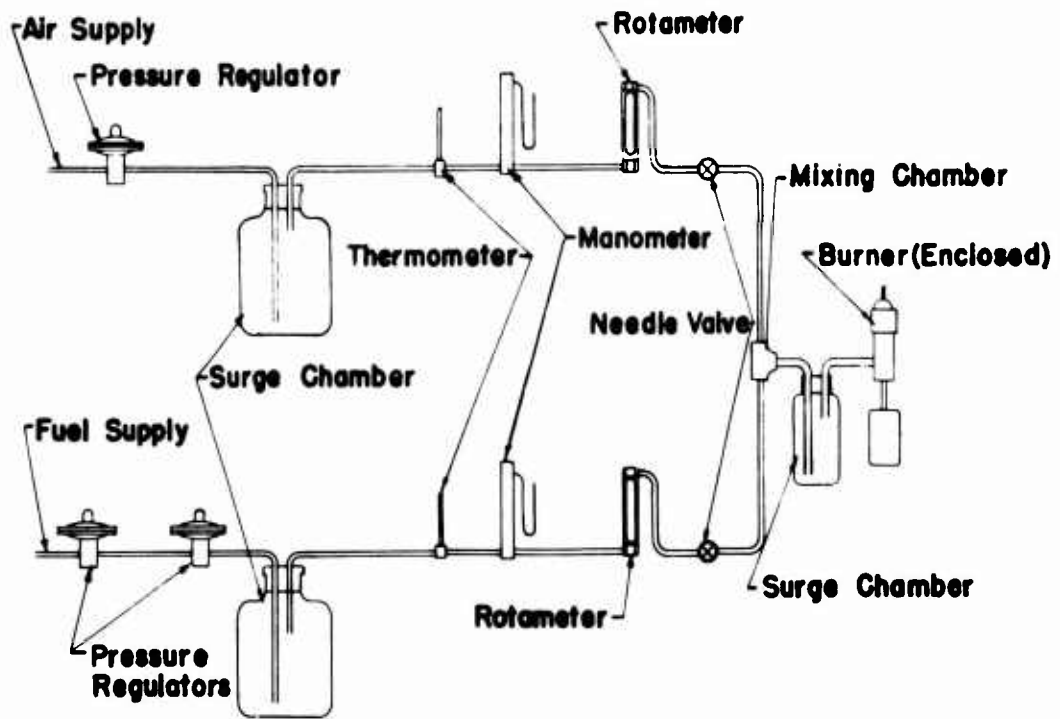


Figure 5.

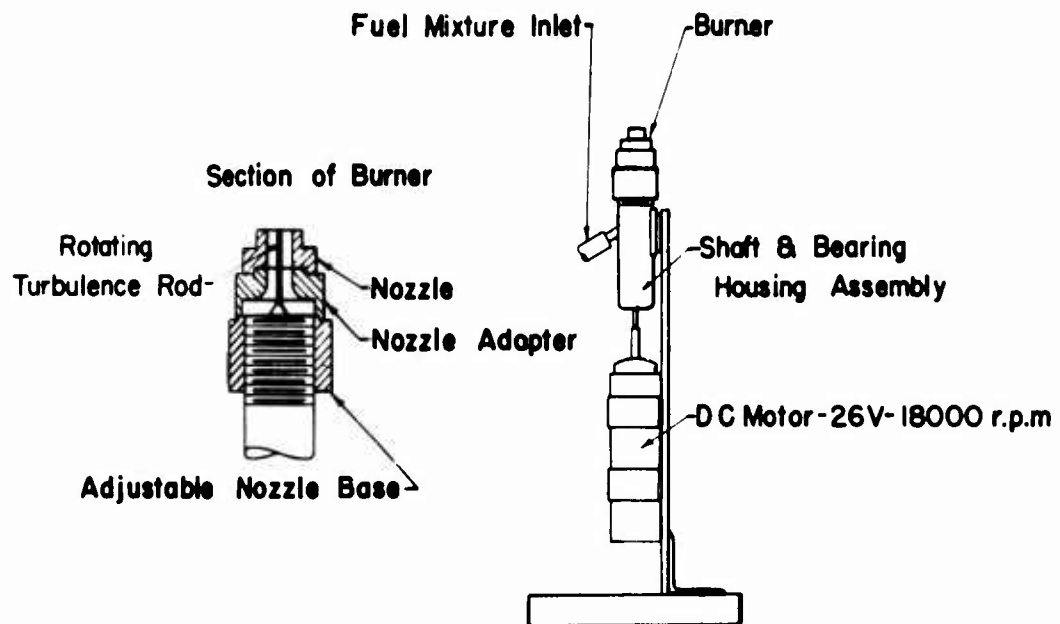


Figure 6.

In order to obtain flame cone areas for determining flame speeds, straight magnification of the flame was tried as outlined by Carside, Forsythe, and Townend.⁵ This method, which consisted of the projection of a magnified inverted image of the flame on a ground glass screen, was not considered because a darkroom was not available. Next, a Schlieren system was set up as advocated by van de Poll and Westerdyk,⁹ using one f3.5 aircraft camera lens having a focal length of 13.5 inches and another considerably inferior lens substituted for a second aircraft camera lens being recoated. Flame pictures obtained by this method were barely discernible, mainly because of the inferior lens. Finally, direct flame pictures were attempted with an Agfa Compur f4.5 camera. By using Agfa Isopan film and developing in Eastman D-11 developer, flame photographs as in Figure 7 were obtained. The negatives showed that the sharpness of the flame front decreased as the amount of turbulence (as indicated by the rotational speed of the turbulence creating rod) was increased. As shown in Figure 8 there was a 30% decrease in flame cone area for an increase in rod speed from 0 to 7280 revolutions per minute. Motion pictures were obtained, but because of insufficient luminosity of the flame this type of photography was not successful.

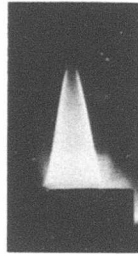
During the first stages of experimentation a hot wire anemometer was obtained on loan for a very brief time. The results obtained with this instrument as presented in Figure 8, seem to indicate a substantial amount of turbulence and variation in intensity across the burner. Figure 7 indicates the same thing, since it is believed that an increase in turbulence means an increase in flame speed.

Pending completion of a hot wire anemometer, non-turbulent flame velocities are being determined to assure further that the method of flame velocity determination now used will give results substantiated by previous investigators.

B. Flame Holding

The flame holders developed to date have in general resulted in rather indiscriminate turbulent conditions, with possible large variation of intensity and scale of turbulence. It was desired, therefore, to determine what parameters are necessary for the most efficient use of that portion of the total supplied mixture entering into the flame-holding function. Knowledge of these parameters should permit the establishment of design criteria for combustion chambers utilizing continuous process combustion.

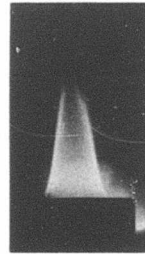
Based on the premise that the local mixture velocity must be maintained equal to or below the flame propagation rate in quiescent gases, in order that stable burning will be possible without flame blow-off, combustion chambers were fabricated to maintain a stable



0 R.P.M.



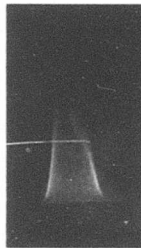
1320 R.P.M.



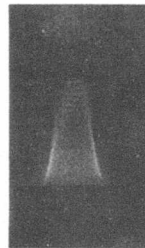
3200 R.P.M.



5940 R.P.M.



6750 R.P.M.



7280 R.P.M.

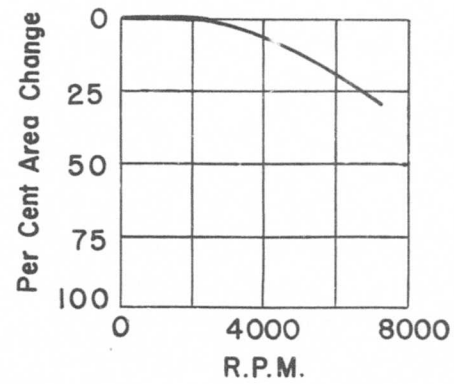


Figure 7.

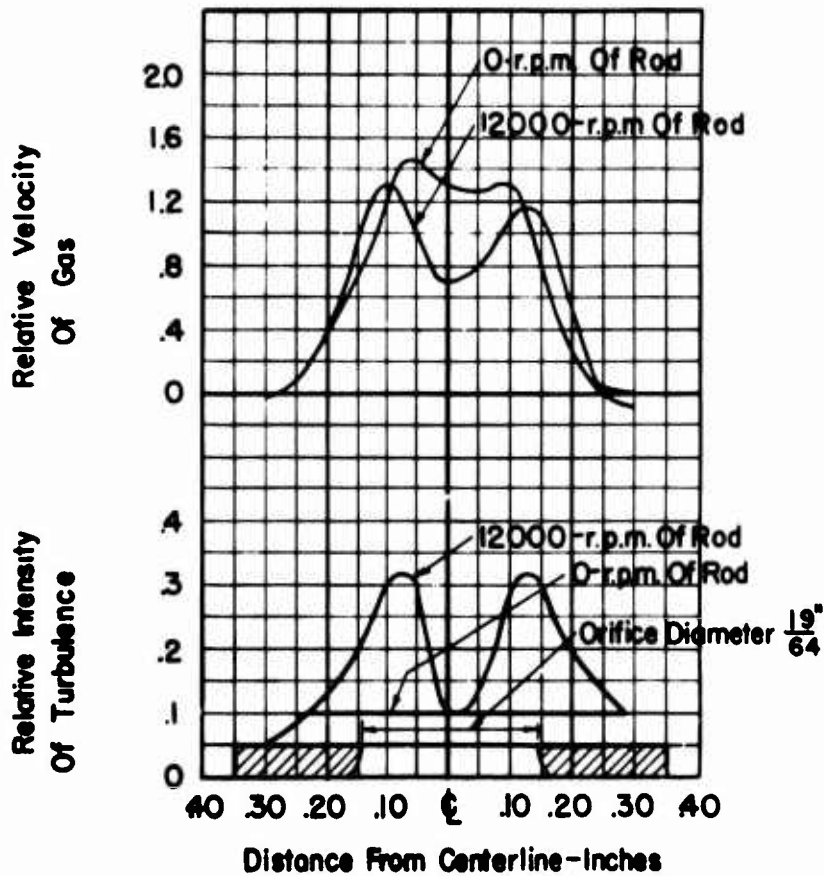


Figure 8.

Effect of Rotating Turbulence Rod

On Gas Velocity & Turbulence Intensity in a Contracting-Jet Type Burner

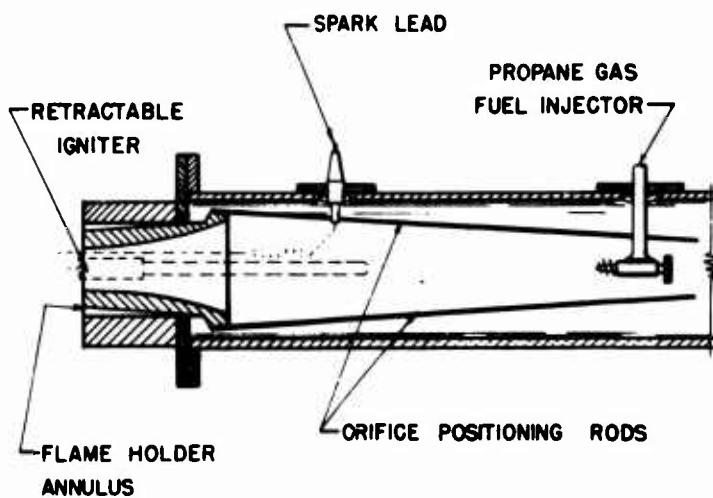


Figure 9.

flame front in the pilot flame or flame holder independent of conditions in the main stream or jet. Also it was desired to retain this pilot flame front regardless of the velocity or pressure supplying the mixture to it. In all designs employed an expansion zone was provided to permit automatic positioning of the flame within reasonable limits.

The first burner tested that gave any indications of satisfactory performance is illustrated in Figure 9. Surrounding the main jet was an annulus or passage in which the mixture velocity was reduced until a stable flame could be maintained within the annulus. This flame served as an igniter for the main jet passing through the main orifice. The rate of flow through the annulus could be controlled by varying the position of the orifice within the outer section and throttling the mixture supplied. It was possible by means of a hydraulic positioner to vary the orifice during operation.

This burner served effectively to indicate the possibilities of this type of flame holder. Maximum mixture velocities through the main jet of approximately 700 feet per second were obtained while it was being used. The main disadvantages of this particular burner were the difficulties (1) in positioning the inner member with respect to the outer so that uniform flow was obtained in all sections of the annulus and (2) in determining the exact percentage of flow through the annulus section.

After several modifications, the burner shown in Figure 10 was developed. This burner made it possible to control and measure the rates of fuel and air to both the annulus section and the main jet. A diagram of the complete testing apparatus is shown in Figure 11.

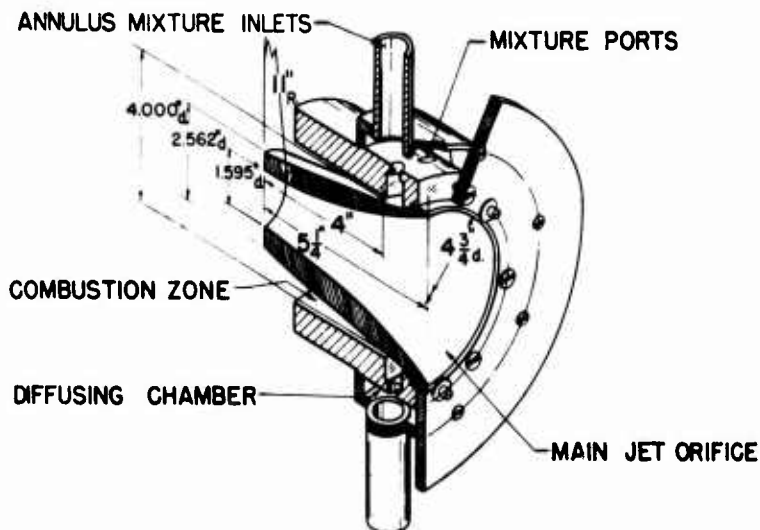


Figure 10.

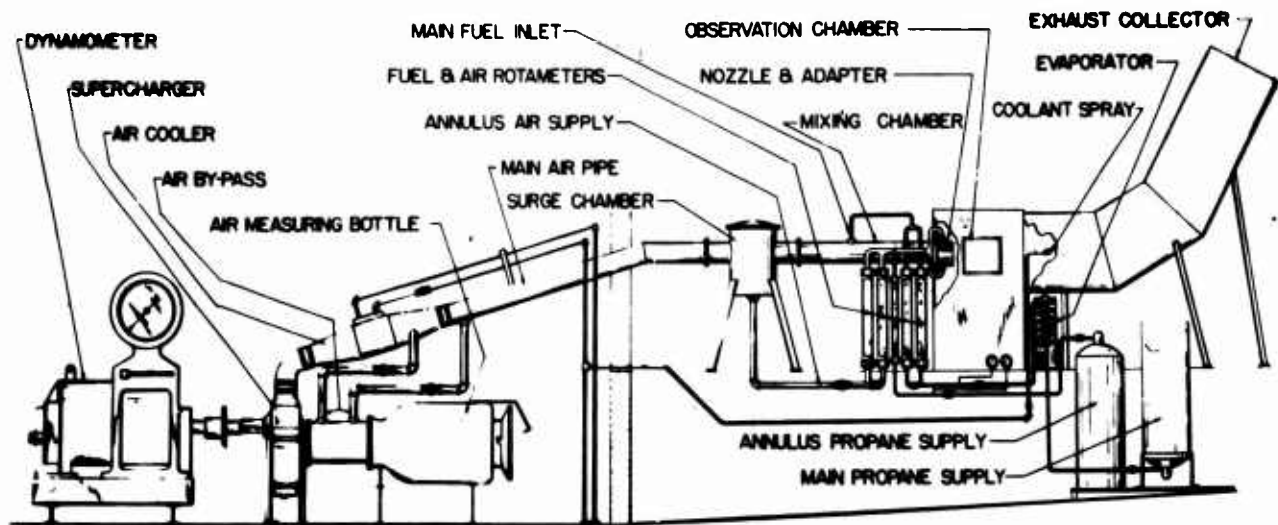


Figure 11.

All tests to date have been upon an unconfined flame, which permitted visual flame observation and much higher mixture velocities than are possible with confined flames. It has been of primary interest to develop a burner which could maintain stable combustion over a wide range of velocities and fuel-air ratios within the main jet. Although not completely tested, the results to date indicate that it is possible with this burner to obtain suitable stability to permit studying variables entering into flame holding.

The highest mean velocity obtained in the main jet is 935 feet per second. Higher velocities were impossible because of the limited speed of the dynamometer used to drive the supercharger. Relatively wide variations in fuel-air ratios were possible within the main jet and also in the annulus with no appreciable effect upon stability. Also the rate of air flow through the annulus was not critical at these conditions.

A series of tests has been started to determine the stability and blow-off limits of the burner for various rates of flow and fuel-air ratios within the main jet. The curve in Figure 12 shows the per cent of total supplied mixture flowing through the annulus plotted against the fuel-air ratio in the annulus for conditions of instability and rich and lean blow-off limits. For these tests the velocity in the main jet was approximately 630 feet per second and the fuel-air ratios were varied as indicated.

The results indicate that the blow-off point and flame stability are entirely dependent upon the conditions within the annulus and are not affected appreciably by variations in the fuel-air ratios in the main jet, within combustible limits. This will probably hold true for higher

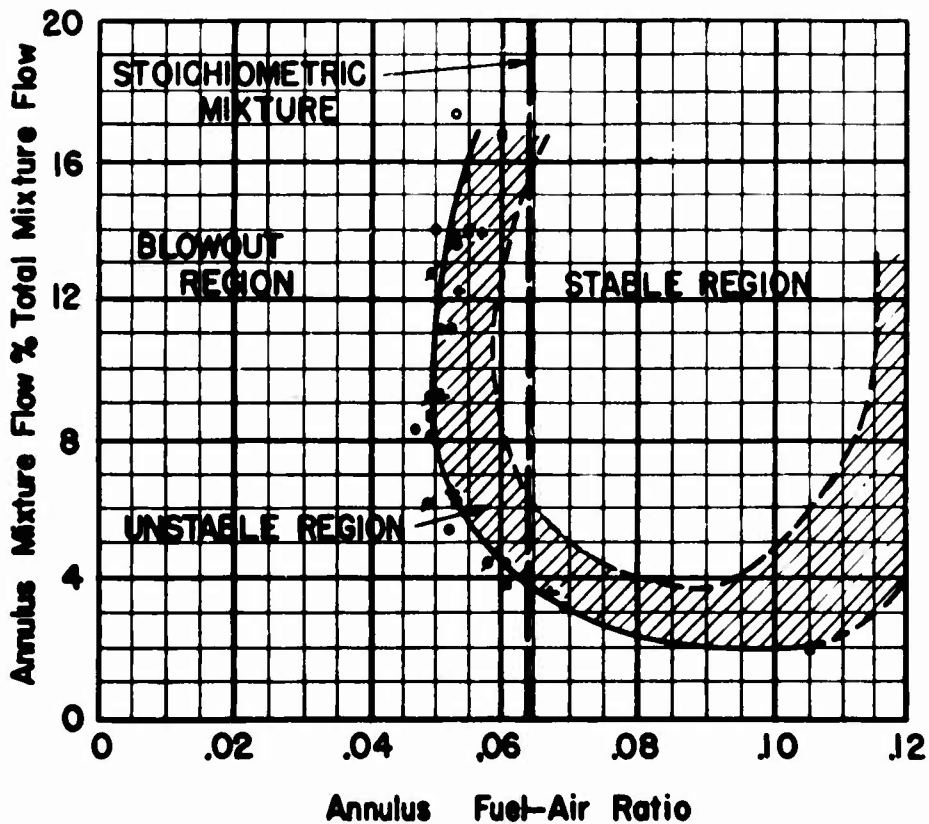


Figure 12.

Blow-Off & Stability Limits For Variations In Rates of Fuel & Air Flow Through Annulus
 Mixture Velocity In Main Jet = 630 ft./sec., Mixing Chamber Pressure = 7"Hg.,
 Mixing Chamber Temperature = 85°F., Main Jet Fuel/Air Ratios (.000 =)
 (.042 = o)(.049 = +)(.0565 =)(0.079 =).

velocities within the main jet, but present data are insufficient to substantiate this conclusion.

Unsuccessful attempts have been made to determine the rich limit blow-off points. At high rates of mixture flow through the annulus, the capacity of the fuel system is insufficient to cause blow-off. At lower rates of flow where the blow-off point can be measured, repeated tests have given widely-varying results.

In determining the lean limit fuel-air ratio in the annulus necessary for stable burning, some difficulty has been encountered in determining the exact point of instability. Considering the stable limit as the point where burning in the main jet is accompanied by a frequent loud popping or a visible raggedness, certain general characteristics pertinent

to the lean stable limit have been noted. The stable limit is very close to the blow-off point when the mixture flow rates through the annulus are greater than 7 or 8 per cent of the total flow. For smaller flow-rates through the annulus, the stable limit varies with the fuel-air ratio in the main jet, and slightly richer fuel-air ratios are necessary in the annulus for decreased fuel-air ratios in the main jet.

According to Morgan,¹⁰ a definite quantity or volume of mixture must be heated to its ignition temperature before it will burn. The volume of gas originally burned must release sufficient heat to ignite the gases that surround it in order that the combustion process may continue.

A flame holder may be considered as a constant igniter which must have a definite rate of heat release to maintain a stable flame in the main jet. This rate of heat release would depend upon the time available for the transfer of heat to the main stream, the ignition temperature of the main mixture, and the specific heats and conductivities of the gases.

Sufficient tests have not been conducted to determine whether the unstable limits for the burner are due to the reduced rate of heat release or the instability of the annulus flame itself. The blow-off points of the annulus flame with no fuel supplied to the main jet fall on the same general curve obtained when burning is occurring in the main jet. Further tests will be necessary to determine which is actually the controlling factor.

C. Facilities

The facilities in operation in January 1947 consisted of a 100 horse-power electric dynamometer driving an Allison auxiliary stage supercharger, air flow and fuel flow measuring equipment, a temporary duct for the air supply leading from the supercharger to the burner, and a low pressure fuel supply system together with a simple spray tube for introduction of fuel oil into the mixing chamber ahead of a 3-inch contracting jet burner.

Subsequent modifications were made, including substitution of a high pressure fuel system and improved nozzles to obtain better distribution and vaporization of the fuel oil. Since the distribution of fuel is a variable that should be handled as a separate investigation, it was deemed desirable to eliminate it in all work in progress at this time. Thus propane was selected as a substitute for fuel oil since it is extremely volatile and is available in sufficient quantities for immediate use. At this time the system has been developed to supply 400 pounds of propane per hour drawn from pressure cylinders as a liquid and passed through a vaporizer before being measured and introduced as a gas into the mixing

chamber. The fuel system can be seen in Figure 11, which shows the complete testing setup in the Mechanical Engineering Laboratory.

The original intent had been to conduct all work in a combustion laboratory to be constructed to house the project. Numerous delays in obtaining authorization for construction and in completing construction necessitated starting operation in the Mechanical Engineering Laboratory. Although the amount of work was limited because of noise and associated hazards, many problems were solved during this interval of time, that would otherwise have had to be investigated after moving into the new quarters. Initial occupation of the laboratory was started with the installation of the engines in October 1947. The laboratory was completed in December 1947 and is scheduled for complete occupation by January 1, 1948.

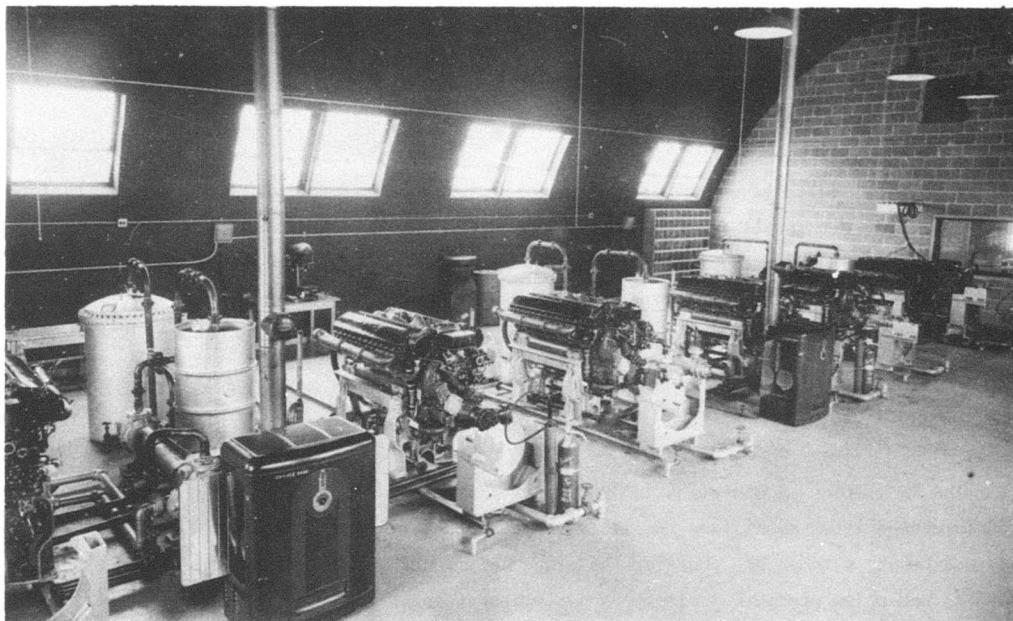


Figure 13.

Figure 13 shows the arrangement of the six Allison V-1710-23 aircraft engines with two of the auxiliary stage superchargers in position. The remaining ten superchargers are not shown in the photograph. The nearly completed systems required for the operation of the engines and superchargers can be seen. A more detailed view of one engine and two superchargers is shown in Figure 14. These have been in operation and are ready for connection to the air supply ducts. The superchargers connected in parallel will supply 240,000 pounds of air per hour at an absolute discharge pressure of 42 pounds per square

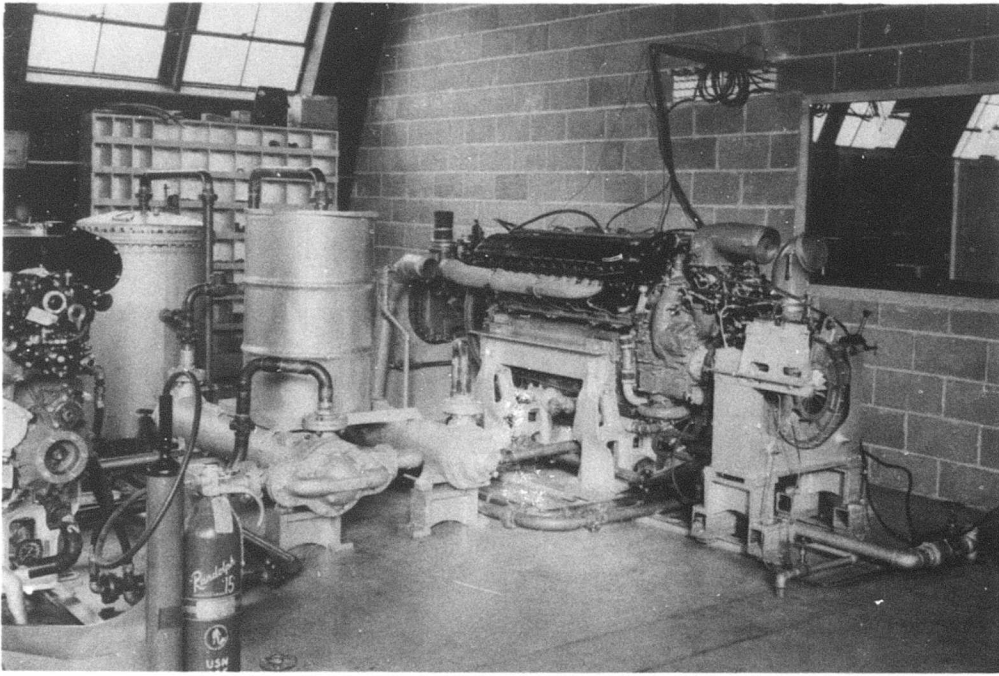


Figure 14.

inch, and when two-staged will supply approximately 100,000 pounds per hour at a discharge pressure of 60 pounds per square inch.

The 24-inch diameter low pressure air duct, which also serves as a structural member carrying the monorail for the chain fall trolley, has been released for fabrication. The setup shown in Figure 11 will be utilized in the new laboratory until completion of the new duct system.

Figure 15 shows the control panel for the engines and superchargers. This panel can also be used for additional instrumentation required for the combustion chambers to be installed in the same room.

Two 2,000-gallon storage tanks for the engine fuel system have been installed, and the system is otherwise nearly completed except for selector valves and supply pumps. The supply system for the propane is pending bids of vendors.

The combustion laboratory will provide 3,200 square feet of area and will house all of the activities of Phase 2, Project SQUID.

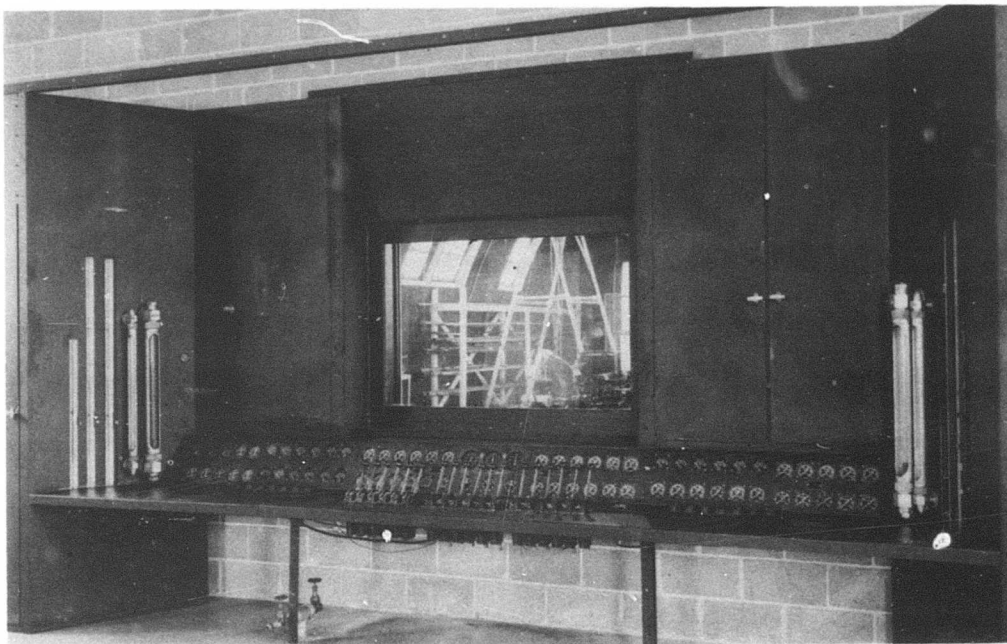


Figure 15.

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PHASE 3

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

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

Summary

The high temperature gaseous oxidation of high-chromium steel has been studied by several methods. The crystalline structure of the oxide layer has been investigated by electron and by x-ray diffraction; the physical arrangement of the oxide studied by means of x-ray absorption and by optical and electron microscopy.

Progress

In view of the general aims of Project SQUID, this research is confined to high temperature gaseous corrosion, with the chief emphasis on oxidation.

The steps which may be considered as basic to an understanding of high temperature corrosion phenomena are: identification of the corrosion products, determination of their physical arrangement, rate of growth, electrical properties, rates of diffusion of components, etc. In order to simplify such measurements, work to date has been confined to the iron-chromium system.

The primary identification method used in this research is the observation of the diffraction patterns obtained with x-rays and electrons. An additional x-ray diffraction unit has been built for use with Lebye-Scherer, back reflection, and Wyland precision cameras when representative samples can be obtained by abrasion or stripping techniques. There are many problems where the products must be investigated *in situ*. A Phillips focusing spectrometer, which uses a flat sample, has been purchased for making such measurements. Since this instrument is limited to Cu and Fe characteristic radiations, neither of which is suitable for investigation of some materials, a Fragg ionization spectrometer has been rebuilt to do similar work with Mo radiation.

For the identification of very thin layers and of the surface of thicker layers, the electron diffraction technique is used. Most of this has to be done in reflection, which

gives limited accuracy. An apparatus has been built for the electrolytic removal of very thin oxide layers to permit their examination in transmission and with the electron microscope.

Since electron diffraction methods are sensitive to very small surface effects, there is some danger that changes may occur between oxidation and examination. To obviate this possibility, a furnace attachment to the electron diffraction camera has been built so that the specimen may be oxidized while in the camera and the surface examined (in reflection) without an intervening cooling cycle. Using this equipment, a routine investigation of the early stages of oxidation as related to time and temperature of exposure was begun with a series of chromium-iron alloy.

The oxides which might be expected to form on a chromium-iron alloy are very complex, and some of their diffraction patterns may be indistinguishable with the accuracy available in electron diffraction. Thus in Table I, O may correspond to γ Fe_2O_3 , one of the spinels Fe_3O_4 , FeCr_2O_4 , or their solid solutions, and X may correspond to α Fe_2O_3 , Cr_2O_3 , or their solid solutions. The first entry is the structure found after the initial heating period (approximately five minutes) in the residual gas of the camera (5×10^{-5} mm. Hg).

In contrast with the oxidation of pure iron, no FeO is found. This may be the chief function of chromium in producing a heat resistance material. The sequence of the structures formed at the oxide surface is α Fe, Fe_3O_4 , α Fe_2O_3 ; this is an understandable sequence in view of the decreasing rate of diffusion of metal ions to the surface associated with a thickening film. The non-regular progress of the time at which the higher oxide is first formed is probably the result of different rates of variation with temperature of the film thickness, ion diffusion, and equilibrium constants. At 700°C , X is unstable relative to O. The coexistence of both structures over a considerable time was difficult to understand and has been studied further. Both structures are maintained for at least an additional hour of oxidation and are retained on fast cooling to room temperature in a vacuum. The X structure disappears within thirty minutes of heating at 600°C in a vacuum of 5×10^{-5} mm. Hg and is formed again in less than seven minutes of oxidation.

The electron diffraction technique is extremely sensitive to thin layers but lacks the precision to distinguish with certainty between iron-rich and chromium-rich oxides. X-ray diffraction is much more precise but requires several tenths of a milligram of oxide for each square centimeter of surface for good patterns. To bridge this gap, an x-ray absorption method of analysis has been devised for Fe-Cr alloys; this is sensitive to a few hundredths of a milligram per cm^2 of surface and also gives the amount of iron and chromium in the oxide. This method is capable of extension to include the Cr-Ni-Fe alloys. In this method the weakening of a base metal diffraction line by absorption

Table I

Structures Formed on an 11% Chromium-Iron Alloy Oxidized by Dry Oxygen at One Millimeter Pressure (Hg).

Legend: I = α Fe; 0 = Fe_3O_4 (or other spinel); X = $3Fe_2C_3$ (Cr_2O_3)

Oxidation Time	Polish	4/0	4/0	4/0	4/0	4/0	electro-lytic
	Oxidation Temperature	400°C	500°C	600°C	600°C	600°C	600°C
0 min.		I,0	I,0	I (?)	0	0	0
1 min.		0	0	0	0	0	0
5 min.		0	0	X	X	0,X	0
30 min.		X	0	X	X	0,X	0
60 min.		X	0,X	X	X	0,X	0

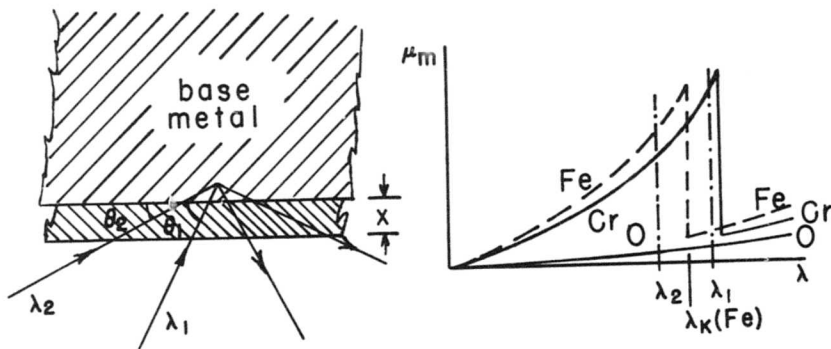


Figure 16.

Absorption curves of oxide components and geometry of absorption by the oxide layer of x-rays diffracted from the base metal. I_0 and I , intensity diffracted without and with oxide respectively. μ_m , $\bar{\mu}_m$, mass absorption coefficient of a component and of the total oxide, respectively. Absorption in the oxide will weaken the intensity by the ratio $I/I_0 = \exp. (-\bar{\mu}_m 2DX/\sin \theta)$. When this fraction is measured for each radiation, λ_1 and λ_2 , the ratio $R = \bar{\mu}_{m1}/\bar{\mu}_{m2} = \ln(I/I_0)_1/\ln(I/I_0)_2 \cdot (\sin \theta_1/\sin \theta_2)$, may be calculated.

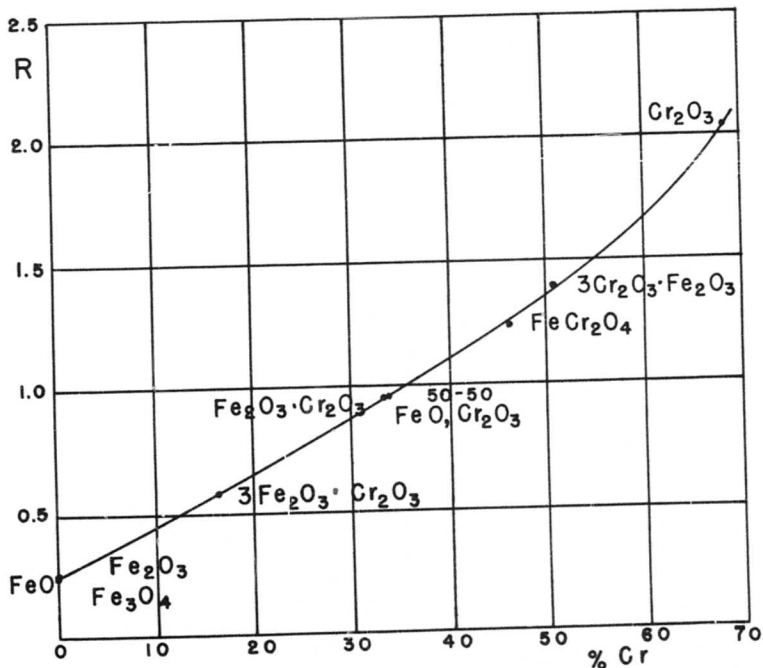


Figure 17.

Dependence of $R = \bar{\mu}_{m1}/\bar{\mu}_{m2}$ on the composition of the oxide layer.

in the superposed oxide layer is compared for two radiations $\text{FeK}\alpha$ and $\text{CuK}\alpha$ (λ_1 and λ_2 , Fig. 16), which lie at wavelengths on either side of the characteristic absorption discontinuity of iron, λ_K . The ratio of the two absorption coefficients so found is a calculable function of the percentage of chromium in the layer and nearly independent of the state of oxidation (Fig. 17). Having determined the percentage of chromium present, the percentages of iron and oxygen which will give agreement simultaneously with the two observed absorptions may easily be found. The total weight of oxide and weight of each constituent can then be computed. A second method of reducing the observed data gives the amount of iron in the oxide layer without the use of trial calculations or assumptions concerning the nature of the layer. The X-ray absorption coefficients of all elements are known to vary (between characteristic discontinuities) proportionally with the cube of the wavelength of the radiation. Hence it is possible to compute from the measured weakening of the two radiations used, what intensities would be found for the two wavelengths, λ_a and λ_b , on either side of the iron characteristic discontinuity and adjacent to it. The ratio of these intensities depends only on the amount of iron in the layer; the absorption due to any other element cancels out. The values obtained by this interpolation method are shown in parentheses in Tables II and III.

Table II lists the results obtained with a commercial 18 Cr-steel at two temperatures. At the higher temperature a loose scale was formed in addition to an adherent scale. This loose scale was removed and analyzed separately. In this case the absolute values given (marked *) depend upon an estimate of the ratio of the area of collection of sample to the area of the specimen prepared for measurement and are not as reliable as their relative values.

It is evident that at both temperatures the initial oxide is rich in chromium, with the percentage decreasing with increasing time. Over the range of times shown, the actual amount of chromium in the adherent layer approaches a constant value, and the increase in total adherent oxide is due to the addition of iron oxides. This implies that a protective layer of a fairly definite composition is built up and that iron diffuses outward through it at a greater rate than chromium does. The chromium which does penetrate goes into the loose scale, while part of the iron forms adherent scales. It will be noted that the initial percentage, and also the absolute amount, of chromium involved in this layer is considerably larger at the high temperature than at the low. Since the initial chromium enrichment of the oxide must be at the expense of local chromium impoverishment at the alloy surface, the diffusion rate of chromium in the alloy must increase more rapidly with temperature than does the rate for iron.

The measurements on small homogenized cast ingots of an 11% Cr-Fe binary alloy have been hampered by the formation of a non-uniform layer, the thickness of which increases near the edges of the specimen. As oxidation proceeds, this layer encroaches upon the region of measure-

Table II

Oxidation of 18% Chromium-Iron Alloy by Oxygen at One-Atmosphere Pressure							
Sample	Temp., °C.	Time, hrs.	Nature of Oxide	Cr, %	milligrams/cm ²		
					Total Oxide	Cr	Fe
2..	775	10	yellow-brown, adherent	26	0.38	0.10	0.167 (0.178)
2..	775	20	yellow-brown, adherent	24	0.69	0.165	0.317 (0.316)
2..	775	30	yellow-brown, adherent	19	0.78	0.151	0.397 (0.393)
16..	900	1	gray-brown, adherent	42	0.744	0.312	0.208 (0.194)
16..	900	5	gray-brown, adherent (some loss of loose scale)	21	0.765	0.101	0.375 (0.35)
1c..	900	1	gray-brown adherent and loose gray scale	45	0.53	0.238	0.13 (0.08)
			above, after removing loose scale	45	0.434	0.195	0.108 (0.10)
1c..	900	5	gray-brown adherent and loose gray scale. After removing loose scale	27	0.87	0.235	0.373 (0.34)
			removed scale	20	*0.94	*0.189	*0.470*(0.465)
	900	10	gray-brown adherent and loose removed scale	17.8	1.30	0.232	0.678 (0.665)
			removed scale	18	*1.46	*0.263	*0.76 *(0.763)

Table III

Oxidation at 11% Chromium-Iron by Oxygen at One-Atmosphere Pressure

Sample	Temp., °C	Time, Minutes	Nature of Oxide	Cr, %	milligrams/cm ²		
					Total Oxide	Cr	Fe
11E ₁ A ...	640	10	gray, rough	26	0.33	0.087	0.15 (0.15)
	640	30	gray, rough	9.6	0.74	0.071	0.44 (0.46)
11E ₁ R ...	640	15	yellow-green	8.4	0.14	0.012	0.088 (0.095)
	640	35	gray, rough	8.0	0.41	0.033	0.26 (0.25)
	640	55	gray, rough	19.5	1.01	0.20	0.51 (0.51)
11E ₂ A ...	640	10	yellow-smooth	10.8	0.36	0.039	0.21 (0.21)
	640	30	yellow, smooth	13.2	0.48	0.064	0.27 (0.27)
	640	120	brown, smooth	30.0	0.63	0.19	0.25 (0.24)
	640	240	brown-gray	26.0	0.72	0.19	0.31 (0.32)

ment. Careful rounding and polishing of the specimen edges have reduced this difficulty but have not eliminated it. The data presented in Table III are thought to be free from such effects, but they must be considered as tentative only.

The samples named in Table III show widely different degrees of oxidation resistance. As previously found, the more resistant layers are the semi-transparent ones showing a yellow to brown color. The gray of similar thickness is less protective. Even the third sample shows as high a rate of attack as did the 18% Cr-steel at 900°C. There is some indication of approach to a constant amount of chromium in the oxide layer.

Larger samples of these materials made by rolling or forging are much more reproducible and resistant than the original ingots. They frequently show only a few tenths of a milligram per square centimeter of surface after twenty to forty hours of oxidation at 670°C. The details of the oxide growth are obscured, however, by an experimental difficulty. After the first short period of oxidation (30 min.), the diffraction of Fe K α x-rays from the base metal, which is used as a reference in the absorption measurement, is stronger than before oxidation in spite of the absorption by the oxide formed. A similar effect has been found on surfaces polished through 4/0 paper, on surfaces polished and etched, and on surfaces polished electrolytically. It was first thought that this was due to recrystallization and stress relief of the polish layer, but similar effects are found after hydrogen annealing. It is now believed that the effect must be due to a change in the composition of the metal near the oxide-metal interface. A local depletion of chromium would produce the observed increase in diffracted intensity, since the absorption coefficient of the metal would be decreased. If one assumes that the enhanced intensity is representative of the base metal diffraction for the later oxidations, one finds chromium percentages of more than 50%, which seem improbable in view of the diffraction patterns obtained. An undetectable continuance of this trend during the longer oxidations would give measured values of final chromium percentages in the oxide which would be too low rather than too high. If, on the other hand, one assumes that the postulated chromium depletion is only temporary and uses the original base metal diffraction data, the calculated chromium percentages are reduced to more reasonable values of approximately 30%. Wrought samples of commercial 13 Cr-steel (13.72 Cr, 0.077C, 0.23 Si, 0.018 P, 0.029S, 0.40 Mn) do not show the initial increase of intensity, and give chromium percentages of 40% to 50%. Investigation of this anomaly will continue at higher temperatures where the relative diffusion rates of chromium and iron in the metal and oxides may be expected to be changed.

Weak x-ray diffraction patterns have been obtained on the Phillips spectrometer from the thicker oxide coatings of the above specimens. In general two phases are found of the structures

types Fe_3O_4 and $\alpha\text{Fe}_2\text{O}_3$, in agreement with the electron diffraction data. There are no indications of pure chromium oxides. In some cases there are definite indications of deviations toward chromium-rich solid solutions, but the accuracy of this instrument is not sufficient to make useful quantitative estimates. The percentages found by the absorption method require up to approximately 50% replacement of iron by chromium. Since 100% replacement corresponds to less than one per cent change in the diffraction patterns, precision parameter measurements are necessary. This work is in progress by the conventional Debye-Scherrer and back reflection techniques, but because of the small amounts of sample available a modification of the Wyland focussing method probably will be required.

The principal method of determining the physical arrangement of the oxides in the protective layer is the use of the optical microscope, supplemented, especially for the thinner layer, by the electron microscope. This requires embedding the oxidized specimen and polishing a cross section through the oxide layer. The preparation of such a section through a hard alloy, a brittle oxide, and a soft mounting material is a difficult task. A completely satisfactory technique has not yet been found for the thin layers formed on high chromium alloys. On low chrome alloys a definite layering structure is found similar to that on pure iron, but on higher chrome materials the structure is much more nearly homogeneous.

The Fe-Cr-O system is very complex, and the various phases are not easily distinguishable by microscopic techniques. Two additional methods are being tried for differentiation of chrome-rich and iron-rich regions. If a technique can be found to polish sufficiently thin plates of the oxide section, x-ray microradiography can be employed. Also under investigation is the possibility of using a low power electron microscope to photograph separate images of the section with photoelectrons which are released with characteristically different velocities from the iron and chromium atoms by the absorption of x-rays (Fig. 18). This instrument is now in the vacuum testing stage.

An electron microscope investigation, using the Formvar replica and shadow casting technique, is in progress to study the oxide formation relative to grain boundary precipitation of carbides and/or nitrides in high chrome-steels. There are definite indications of the formation of oxide crystallites on the matrix material which decrease in size as the boundary is approached. The precipitates show no obvious growth of oxide. Either the oxidation is very slow or the coating is extremely smooth and continuous.

Plans

The electron and x-ray diffraction and the x-ray absorption work will be continued to higher temperatures on alloys of higher chromium content. The cause of the anomaly in the

absorption measurements will be investigated by measuring the intensity as the oxide is removed and by working at higher temperatures.

The precision x-ray lattice parameter measurements, leading to oxide identification, will be intensified and extended to certain commercial alloys. These will include selected specimens (supplied by Mr. Howard S. Avery, American Brake Shoe Company) from the series of Cr-Ni-Fe alloys, for which extensive data on mechanical and high temperature corrosion properties have been published (Howard S. Avery and A. Matthews, *Transaction of the A.S.M.*, 38, 957, 1947; Anton deS. Brasunas, James T. Gow, and Oscar E. Harder, *Proceedings A.S.T.M.*, 46, 129, 1946).

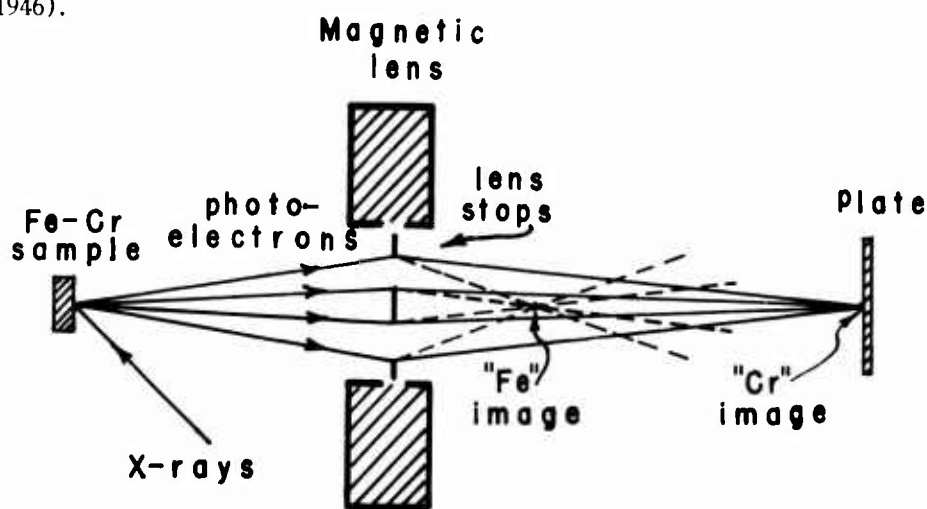


Figure 18.

Electron image formation of the photoelectrons released from a chromium-iron sample by x-rays adjusted to give the "Chromium" image in focus on the plate. Lens stops screen the plate from out-of-focus electrons and x-rays. A different adjustment of the lens will bring the "iron" image into focus.

Attempts to determine the distribution of chromium and iron in sections through the oxide layer will be continued by the x-ray microradiography and photoelectric image formation methods. Further electron microscope studies of oxide formation will be made.

It is planned to institute experiments on the resistance and other electrical properties of the oxide films as a function of composition and temperature.

PHASE 4

Statement of Problem: The purpose of this research is to study, by means of bomb or continuous flow experiments, temperatures, pressures, and concentration of reactants for various oxidation reactions of materials which may be of value as fuel for a rocket or jet engine.

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

Summary

The equipment needed for the planned program of research has been assembled. Minor adjustments are about complete so that experimental investigation of the effect of surface on the rate of combustion of hydrazine monohydrate will be begun. Later, a study will be conducted on the thermal oxidation of hydrazine in the vapor phase at about 100°C.

Progress

During the first three months of 1947 the work done was concerned with qualitative tests on the nature of explosive combustion maintained within a small combustion chamber. The purpose was to determine the practicability of studying the explosive region of combustion of a fuel by a dynamic method. An attempt will be made to carry out a continuous explosive combustion reaction in a small combustion chamber and to sample the reaction products at various time intervals by quenching the combustion gases with an impinging stream of inert gas. Qualitative tests showed that a uniform combustion zone could not be maintained in a tube and that the flame front was so thin that it could not be sufficiently elongated at velocities possible in the combustion tube to allow the partial quenching of it by an inert gas.

The remainder of the year was devoted to the design and construction of equipment for the study of the slow combustion of hydrazine. The equipment as designed consists of a reactor surrounded by a jacket through which oil is circulated from a thermostatically controlled heating tank. The reactor is equipped with a manometric system which allows direct pressure reading and which also maintains constant volume within the reactor. The apparatus has charging vessels and various other auxiliaries. The construction of the parts that could be made at Purdue has proceeded continuously. Slow delivery of essential parts, especially a relay and a vacuum pump, has delayed the construction program. Almost all of the equipment needed for the initial and exploratory experiments has now been received and assembled. The elimination of leaks and the cleaning of apparatus are in progress preparatory to the initial runs.

The experiments are so planned that the effect of surface upon the overall rate of reaction can be ascertained. These researches are to be carried out in the constant volume reactor; the surface to volume ratio will be varied by packing the reactor with glass tubes, and the reaction will be followed by measuring the rate of pressure rise.

To supplement the data obtained from the planned surface-effect experiments, equipment is being assembled to carry out the thermal oxidation of hydrazine in the vapor phase at 100°C and to collect and prepare the reaction products for chemical analyses. This is to be done during the same period as the surface effect experiments in order to supplement the data obtained by them.

Plans

The planned experiments are to be carried out in constant-volume vessel and the reaction products are to chemically analyzed. The data thereby obtained will be useful in the interpretation of the rate of reaction of the selected material.

PHASE 5

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

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

Summary

During 1947 the apparatus ordered for this project was received and installed. As a result of trial runs it was deemed necessary to redesign the electrical heaters so that a maximum temperature of 2000°F might be approached. New materials were ordered, and the reconstruction is rapidly nearing completion.

Progress

To separate the radiation heat transfer rate from the total heat transfer rate for a radiating gas, the object of this research, will necessitate accurate data concerning the convection heat transfer rate. Hence it will be necessary to determine convection coefficients

for non-radiating gases such as air. The experimental apparatus has been constructed as shown in the diagram. Such an arrangement may be used with few modifications for the measurement of heat transfer coefficients for radiating gases.

Since air is to be used as the first test gas, an oil trap, a soda-lime absorber, and a silica gel absorber were constructed to remove oil, carbon dioxide, and water vapor respectively. Since the latter two are radiating gases, their removal is obligatory. A pressure regulator was also provided to control pressure fluctuations in the air supply. For measuring the flow rate, a test-accuracy rotameter was installed. With this instrument errors in heat transfer coefficients due to errors in the flow rate will be reduced to a minimum (Fig. 19).

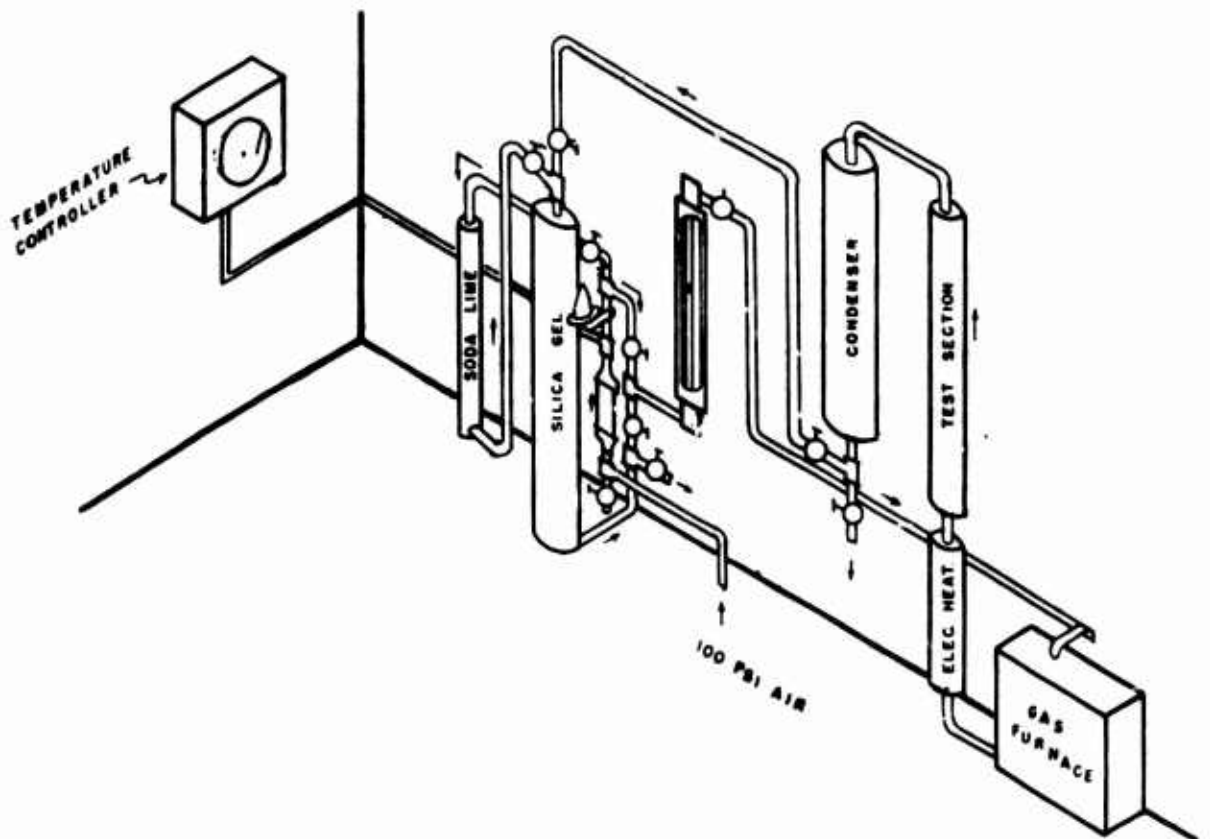


Figure 19.
Schematic diagram of equipment.

The initial air heater is a gas-fired furnace consisting of a nichrome pipe coil packed with nichrome turnings and suitably baffled for protection from the impinging flame. Initial tests indicate that this furnace will heat 110 pounds of air per hour from room temperature to 1600°F.

The air leaving the gas furnace enters a 2-inch nichrome tube packed with nichrome turnings and electrically heated by nichrome resistance coils. The electric heaters proved incapable of raising the gas stream temperature up to 2000°F (the maximum temperature set for this project). On the basis of trial runs the electric heaters were redesigned and new resistance wire was ordered. The new heaters have now been installed.

The test section also consists of a two-inch nichrome tube approximately three feet long. It is also electrically heated so that variations in the temperature drop in the tube may be obtained. Due to the above mentioned trial runs these electrical heaters are being remade so that the total capacity may be increased. Altogether it is estimated that 3.4 kilowatts will be available in the heater section and that 1.3 kilowatts will be available in the test section. Both the test and heater sections will be lagged with two inches of diatomaceous earth and two inches of magnesia.

A condenser-cooler of the coil-in-box type was constructed so that the heated air may be vented to the room. Preliminary tests show that at an entrance temperature of 1500°F the exit temperature is in the neighborhood of 70°F. This cooler may also be used as a condenser for steam when this material is used as a radiating gas in later experimentation.

Also during this year significant progress was made on the temperature measurement problem despite material shortages. A series of thermocouple shields was designed and constructed for the purpose of eliminating the radiation error in readings from pyrometers placed in the high temperature gas stream in the test section. A small platinum tube was clamped over the end of the thermocouple and insulated from the couple by a thin mica sheet. This assembly was then inserted radially through two concentric tubes. The inner shield is a one-half inch O. D. platinum tube. The outer shield is a one inch O. D. Inconel tube. The entire shield assembly, four inches in length, will be suspended in the test section. One such arrangement will be used for the entrance temperature and one for the exit temperature. During the reconstruction of the test and heater sections mentioned above, several modifications were made in the piping to facilitate introduction and maintenance of these shields. On the basis of similar apparatus tested by Hock at the Bureau of Standards, such shielding arrangements should eliminate the radiation error.

Platinum-platinum rhodium thermocouples will be used for measuring gas stream temperatures. Chromel-alumel thermocouples will be used to obtain the test section wall temperatures. Wire for these couples was obtained and the couples were made up. Each couple was annealed for 3.5 hours at 2045°F and then was calibrated against a Bureau of Standards calibrated couple from 500°F to 2000°F.

An instrument panel was constructed and wired so that regulation of the voltage input to the electrical heaters and measurement of thermocouple e.m.f.'s might be facilitated. A potentiometer with an accuracy of ± 0.001 millivolt was purchased.

The input to the electrical heaters is controlled by variacs. In order that a steady temperature might be maintained in the gas stream leaving the heater section, an automatic temperature controller-recorder was installed and connected to the variac controlling the heater nearest the exit of the test section.

Plans

During the next period it is hoped that trial runs on the apparatus may be completed. This work is to be followed by an extensive investigation of the convective heat transfer from air over the range 500-2000°F. Following this, the apparatus will be redesigned so that tests may be made on radiating gases such as steam and carbon dioxide.

PHASE 6F

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

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

Summary

The apparatus for the adiabatic determination of heat of combustion of selected compounds containing the nitro group and of interest to Project SQUID has been assembled and placed in operating condition. The data obtained will not only be used in the calculation of the heats of combustion but also in ascertaining the relationship between chemical structure and the heat of formation of the lower molecular weight nitroparaffins.

Progress

A calorimeter assembly of the adiabatic type has been constructed and is now being calibrated prior to tests to determine the heats of combustion of certain of the lower

nitroparaffins. The assembly consists of a modified Emerson adiabatic jacket with a standard Parr double-valve, self-sealing, stainless steel bomb. Control of the temperature difference between the outer jacket and the inner calorimeter can is maintained by electrically heating the water in the outer jacket. A thirty junction, copper-constantan thermel, wired through a spotlight galvanometer, is used to detect temperature differences between the inner and outer baths.

Values for the heats of combustion of nitro-methane, tetranitro-methane, nitroethane, 1-nitropropane, and 2,2,4,4-tetranitrobutane are available in the literature. The present investigation will involve the experimental determinations of the values for the heats of combustion of trinitro-methane, hexanitroethane, 2-nitropropane, and the four dinitropropanes. Five of these substances are now available in a purified form, and the remaining samples will be procured when necessary.

Heat of combustion data for the above samples will enable calculations to be made of

- (a) the heat of isomerization of mononitropropane
- (b) the heat of isomerization of dinitropropane
- (c) heats of formation of the compounds studied, and
- (d) relationships between chemical structure and the heat of formation of the lower nitroparaffins.

Plans

The experimental determination of the heat of combustion of selected substances of particular interest to Project SQUID will be initiated during the next few months.

PHASE 6G

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

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

Summary

Although equipment for the measurement of heats of combustion by the non-adiabatic method was at hand during the period covered by this report, extensive modifications to this existing equipment were made in an effort to increase the accuracy and precision of the

measurements. The calorimeter was calibrated using benzoic acid, standard sample 39f from The National Bureau of Standards, and the heats of combustion, at constant volume, of 8-hydroxyquinoline, 5-nitro-o-toluidine, 3-nitro-p-toluidine, p-aminoacetophenone, ethyl-p-aminobenzoate, and methyl nitroacetate were determined.

Progress

During the past year the work accomplished under this phase of Project SQUID may be divided into two classes: (1) modifications of existing equipment, and (2) experimental measurement of heats of combustion.

Certain modifications of the equipment which had previously been used here were made for the purpose of increasing the accuracy and precision of measurements. Additional modifications are contemplated and will be made as soon as the ordered equipment arrives. Orders have been placed for a White Double Potentiometer and a galvanometer for use therewith, a Mueller G-2 bridge, and two platinum resistance thermometers.

Some of the more important changes which have been completed are: a new galvanometer support to reduce vibrations; a new galvanometer housing which provides for circulating air from the thermostated calorimeter chamber to prevent "drift" due to temperature changes; electrical shielding of the potentiometer and its accessories; an electronic temperature control for the constant temperature chamber; and a device consisting of a stop watch and photoelectric relay to provide an audible time signal at one minute intervals with an accuracy of 0.2 sec.

The heat of combustion has been determined for each of the following compounds. These data were obtained by the nonadiabatic method using a Parr double valve oxygen bomb of 358 ml. capacity, using an oxygen pressure of 30 atmospheres at 25°C. The value of the heat of combustion at constant volume, together with the standard deviation of each, were calculated in accordance with the recommendations of Rossini (1).

8-Hydroxyquinoline	1064.9±0.2	Kg-cal/mole
5-Nitro-o-toluidine	910.44±0.30	"
3-Nitro-p-toluidine	915.12±0.12	"
p-Aminoacetophenone	1129.7±0.2	"
Ethyl-p-aminobenzoate	1122.1±0.2	"
Methyl nitroacetate	342.21±0.08	"

Plans

Future work will consist in a continuation of the measurement of heats of combustion of selected compounds. These will include hydrazine derivatives and other substances which are believed to be potential fuels or oxidizers of interest to Project SQUID.

Reference: 1. F. D. Rossini, *J. Wash. Acad. Sci.*, 29, 416 (1939).

PHASE 7

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

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

Summary

The preliminary plans and specifications for the rocket test pit have been completed. One contractor has submitted an estimate, but bids will not be solicited until a building site has been obtained. Favorable action on this matter should be forthcoming within the next two weeks.

Equipment design and instrument purchases are virtually completed.

An accurate and less timeconsuming method for determining the theoretical performance of rocket propellants is being investigated.

Progress

The researches of Phase 7 are still in the development stage. The preliminary plans and specifications for the rocket motor test pit have been completed for some time. One contractor has submitted an estimate on the construction of the facilities, but before final plans can be completed and actual bids obtained, the building site must be obtained.

At present, negotiations are in process for the purchase or lease of a section of the gravel pit adjoining the Purdue University Airport. This location is considered ideal for rocket motor testing, but another location directly north of the Aircraft Engine Laboratory is also being considered.

The decision by the University Purchasing Department concerning the securing of machine shop equipment from JANMAT is pending action on the building site.

Three part-time craftsmen are now engaged in the making of detailed drawings of units to be fabricated by manufacturers or to be assembled by the University Machine Shop. Design studies and specifications for the various instruments have been completed, and virtually all have been on order for several weeks.

The rocket motor test pit is to consist of two test cells on opposite sides of a common control room. Office space, a small chemical laboratory, and a small machine shop are to be located behind the test chambers and control room. An instrument panel has been designed and located around the observation windows of each test cell. Each instrument panel will consist of two sections, one for the control of the very high chamber pressure rocket motors to be tested, and the other for indicating and recording performance data. Data will be recorded by strip chart instruments and by photographs of a bank of precision gages. Two high speed potentiometers and a recording oscillograph will be available to each of the two test cells, and also to the chemical laboratory. A complete description of the design of the rocket motor test pit and its instrumentation is being prepared by Mr. W. J. Hesse, Research Fellow.

An evaluation of the available methods for determining the theoretical performance of a rocket propellant is in progress. It is hoped that a general method can be developed which is sufficiently accurate but less time-consuming than the present methods.

Plans

The SQUID Coordinator's Office and Phase 7 activities are to move to new quarters in two or three months. Approximately 1400 square feet of office space has been set aside for the above activities in a new addition to the airport facilities. The space has been divided into offices, drafting rooms, library, and conference room.

Design studies of experimental rocket motors for use in Phase 7 will commence as soon as the equipment designs and the securing of instruments have been completed.

As soon as laboratory space becomes available, the experimental work in connection with the measurement of the ignition lag of rocket propellants will be started. The apparatus for measuring ignition lag is being assembled.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-119, TASK ORDER I

CORNELL AERONAUTICAL LABORATORY
BUFFALO, NEW YORK
1 JANUARY 1948



PHASE I

In connection with pulsating jet engines: to undertake theoretical and wind tunnel investigations on flows and losses in diffuser inlet, diffusers, intake valves, exhaust nozzles, and thrust-augmenting ducts for subsonic and supersonic pulsating jets.

Summary

The work carried out under Phase I at Cornell Aeronautical Laboratory may essentially be divided into three parts: (1) study of non-steady gas flow in ducts of various shapes; (2) investigation of the free-piston pulse jet (Bodine jet); and (3) supersonic wind tunnel experiments.

1. In the study of non-steady gas flow, a simplified theoretical treatment by Lewy was extended, and for experimental verification, analogy experiments were investigated. An attempt to develop an electrical analogy was unsuccessful but the analogy of surface-gravity waves in open water channels appears very promising. A preliminary water table was built and the required instrumentation for the recording of instantaneous water depth was completed. Work is still in progress to develop a method of recording flow velocities. Another experimental approach to check theoretical conclusions is direct verification by measuring some property of the gas. Some preliminary studies to measure gas density were undertaken but the work has been temporarily discontinued because of lack of space and personnel. A more accurate theoretical treatment of unsteady one-dimensional gas flow was afforded by the method of characteristics. The method was studied and is now being applied to actual problems. Comparison of results obtained by this method, the simplified theory, and experiments is now under way.

2. The free-piston pulse jet was first investigated on a very small scale by using a loudspeaker, fitted to a tube, as the power source. It was found that when the exit of the tube was partly closed by an aperture plate, the thrust obtained was very large compared with the power required. Experiments on a larger scale used a mechanically driven piston and, although the developed thrust per unit power input remained approximately the same, maximum thrust was obtained without an aperture plate. The mechanism of jet formation is not clear yet and various models for underwater operation were built to facilitate study of the flow patterns.

3. Experiments in the supersonic wind tunnel were carried out to find the effect of spillover on the external wave drag of ducted bodies, and to study the motion in a diffuser of a shock wave under the influence of pulsating back pressure. The latter problem was also approached theoretically.

The preparatory work for the first issue of an Instrumentation Bulletin was carried out with the cooperation of the Instrumentation Panel. A number of reports were issued on various programs and several more are in preparation.

Progress

1. A theoretical treatment of gas flow in half-open pipes by Lewy was studied.¹ The method deals with the outflow of gas, initially under pressure, from a pipe when one end is suddenly opened. The flow depends on the initial pressure and on the shape of the pipe, and it has been found possible to derive analytical relations for the corresponding two parameters. In view of the very simplifying assumptions made by the theory, this work was interrupted pending experimental verification of the results obtained up to that stage. A report on this phase was issued.²

The problem of experimental verification was approached by various methods. An attempt was made to treat gas waves of large amplitude by means of an analogy with an electrical transmission line. All efforts, however, failed to develop a satisfactory electrical equivalent circuit, and unless a new approach should become apparent, no further work is planned. A report was issued on this work.³

An investigation of non-steady gas flow problems by means of the analogy between gas-pressure waves in pipes and surface-gravity waves in open water channels is being undertaken. A preliminary survey showed that this method should be useful in studying the effect of shape on non-steady flow and should also permit finding the optimum operation of inlet valves for pulse jets and the optimum timing for the combustion process.

A simple water table was built to develop the necessary instrumentation and to gain sufficient experience for a final setup. The test channel is 2 feet long and 6 inches wide leading into a large basin about 4 feet square. A gate at the channel outlet may be kept closed by means of electromagnets; this permits different water levels to be set up inside and outside of the channel. Sudden opening of the gate produces surface waves which are analogous to gas-pressure waves in a tube which are set up when the gas, initially under pressure, is suddenly released to the atmosphere at one end of the tube.

Measurements of instantaneous values of water depth and flow velocity are required. Various methods of depth measurement were tried. The one finally adopted utilizes the change of electrical resistance with the level of the water between two electrodes formed by parallel graphite rods dipping into the water. An electronic circuit was developed to record measurement by means of a cathode ray oscillograph and to obtain timing from the same record. An

extended series has been started to compare these records with theoretical results obtained by Lewy's method and with the results obtained by the characteristics method.

Various attempts were made to measure instantaneous flow velocity. Because of the small values—less than about 1 foot per second—difficulties were experienced. It seems now that a hot-wire method might solve the problem. Promising results have already been obtained.

Another method to obtain experimental verification for theoretical conclusions is direct measurement of gas flow in a pipe. It was planned to measure instantaneous gas density by means of light absorption when smoke was added to the gas. It was found that uniform initial distribution of the smoke particles could probably not be achieved and the method would, therefore, be restricted to regions very near a closed end so that uniformity of smoke distribution would not be required. Because of lack of space and personnel, this experiment was temporarily discontinued.

An extensive study was made of the method of characteristics to solve problems of non-steady one-dimensional gas flow. Information was collected from a number of publications, and in some cases it was found desirable to develop additional procedures. The theoretical basis of the method and graphical and numerical procedures as far as required are being assembled and will be issued as a report in the near future. While studying the application of the characteristics method to pulse jets it has become apparent that interception of some of the waves at the proper place and instant should result in an improvement of performance. This would also offer an experimental means of checking conclusions derived by the method. A simple pulse jet model was built where the inlet and an interceptor valve consisted of discs with suitably shaped holes. The discs were driven by an electric motor. It was intended to use natural gas as fuel, but burning was found to be too slow. Other fuels will be tried.

2. An investigation of the free-piston pulse-jet (Podine) was started. This mechanism consists of a tube closed at one end by a piston which is mechanically driven forward and backward at resonance frequency. For the first experiments, the piston was replaced by the membrane of a small loud speaker, and the latter fitted to the end of a tube 1 foot long. The whole system was suspended to measure thrust, at first by the deflection produced and later by means of a strain gauge mounted on the suspending rod. At the resonance frequencies some thrust could be detected but the values were too small for measurement. It was found, however, that an aperture plate at the open end of the tube produced very definite jets. Thrusts developed by this system were of the order of 1 gram per watt input to the loud-speaker. This is considerably more than is obtained from other jets. The mechanism of jet formation is not clear yet. At certain frequencies the jet shows a peculiar instability which also cannot be explained. Injection of fine powder and stroboscopic observation revealed that the jet consisted of individual vortex rings being emitted from the aperture at the rate of the exciting frequency. A report on these experiments is being prepared.

For the next step, a piston driven by an eccentric mechanism was used. The tube had to be made much longer (5 feet) to produce the jet at lower frequencies. Thrust was determined by measuring the force of impact of the jet on a suspended plate. It was found that the beneficial effect of the aperture end plate disappeared if the amplitude of oscillations was increased beyond a certain limit. The maximum thrust measured with this unit was about 200 grams and the specific power consumption was again of the order of 1 gram per watt, but the power measurements are not satisfactory yet. No instability of the jet was observed with this setup. In order better to visualize the jet formation, small-scale models for underwater operation were built. It was found that appreciable jets were only formed when an aperture plate was used. Thrusts were of the order of 3 grams per watt. However, the frequency at which the jet was formed was very much lower than would be expected from the speed of sound in water and the length of the tube. There is a definite effect of the tube length on the resonance frequency, but the question concerning the factors that determine the resonance frequency has not been answered yet. Flow patterns could be visualized by means of aluminum powder suspended in the water, but no motion pictures have been taken. The characteristics method was used in an attempt to explain the phenomena, but it could only be shown that at resonance frequency the building up of gas-pressure waves could lead to flow velocities larger than the piston velocities. The phenomena are possibly too complex to be explained by a one-dimensional theory.

3. Experiments were carried out in the supersonic wind tunnel to study the effect of spillover on the external wave drag of ducted bodies, and the results have been issued as a technical report.⁴ In another group of experiments, the shock motion inside a diffuser under the influence of fluctuating back pressure was investigated. High-speed schlieren motion pictures at 3000 frames per second were taken. A preliminary report describing the experimental techniques has been issued.⁵

Professor Kantrowitz developed a theoretical treatment of the shock motion. Analytical formulas were derived for the effect of small fluctuations of back pressure and Mach numbers near one. A preliminary report was supplied to the Laboratory and was later returned for final editing. At present the experimental work is temporarily discontinued.

A technical memorandum was issued on the frequency response of pressure pickups required for measurements on pulse jets.⁶ The investigation itself, however, had been completed during the preceding year.

In cooperation with the Instrumentation Panel, material was collected for the first sample issue of an *Instrumentation Bulletin*. The manuscript was submitted to the SQUID Organizing Office where the necessary steps will be taken to have a final manuscript prepared and published.

Plans

1. It is hoped that all instrumentation problems for the analogy experiments with surface-gravity waves on water will be solved soon. Theoretical and experimental results will then be compared over a wide range; and once the methods are properly established, the ultimate program of studying the effect of duct shape on the pulse jet cycle will be investigated. It will also be possible to study a number of problems connected with the optimum design of inlet valves and instant of combustion. The experiments with the pulse jet with mechanically operated inlet and interceptor valves will be continued.

2. Work on the free-piston pulse jet will be continued, particularly with the objective of finding an explanation for the various puzzling phenomena noted.

3. It is planned to resume the study of shock motion in a supersonic diffuser and to complete this study.

PHASE 2

In connection with pulsating-jet engines: to study the theory of combustion, effect of turbulence on flame propagation and cooling, and to verify and augment existing theories by means of experimental investigation of ignition, combustion, flame holding, flame propagation and cooling.

Summary

During the year 1947 the work carried out under Phase 2 at Cornell Aeronautical Laboratory may be classified under the following problems: (1) combustion chamber experiments; (2) flame-tube experiments; (3) burner experiments; (4) theoretical study of the catalytic influence of combustion-chamber-wall materials; (5) theoretical study of and determination of heat release during combustion; (6) theoretical study of the mechanism of combustion.

1. For the combustion chamber experiments, an investigation is being made of stationary combustion in a duct, simulated by means of an ignition source moving with predetermined speed through a combustion chamber. The purpose is to study flame propagation under controlled conditions of gas pressure, temperature, composition, and flow. A spark between parallel-wire electrodes driven along the chamber by the field of a permanent magnet serve as ignition source. Because of a delay in the delivery of the magnet, work has not yet progressed to the performance of actual combustion tests.

2. An investigation has been started to measure the velocity of flame propagation in a steel tube of 2½-inch internal diameter and 12-foot overall length by means of an electronic timing device connected with a number of ionization gaps along the tube. The tube is made up of sections 2 feet long to permit insertion of constrictions or other obstacles, in order to study their influence on flame propagation.

3. By means of stroboscopic observation, a study is being made of the distortion of flame fronts under the influence of periodical disturbances. The effects of electrical, acoustical, and other disturbances have been investigated and found to be essentially identical. The observed shapes have been interpreted in terms of flow disturbances. An effect of electrical fields on the blow-off limits of burner flames has been discovered.

4. To study the possible catalytic influence of combustion chamber wall material, a special burner and its attendant instrumentation were designed and built. Among the tubes tested were Inconel, stainless steel, iron, and quartz. The data indicate that a quartz tube has a higher combustion capacity than the metal tubes which were examined.

5. Further proving tests to establish the efficiency of a refrigerated probe for sampling combustion gases have been conducted and have been complicated by delays in delivery of equipment and by the difficulties encountered in obtaining a satisfactory equilibrium mixture for sampling purposes. The results to date look encouraging.

6. In the absorption studies of combustion, a low-pressure mantled burner and its attendant control instrumentation have been completed.

Progress

1. Work on this project was suspended until the magnet was obtained during the third quarter of the year. Thereafter, tests of several electrode systems were performed. Successful operation of the moving-spark device was achieved with two stainless-steel wire electrodes of 1/16-inch diameter, stretched parallel in the air gap of the magnet about 1/16 inch apart. An induction coil spark between an auxiliary electrode and the main system starts the discharge at one end of the device. Subsequently, the spark is maintained by a high-voltage supply; it moves along the electrode system with a speed which depends on the magnetic field strength and the spark current. The latter depends on series resistance and voltage in the spark circuit.

In order to measure the velocity of spark movement, a number of auxiliary electrodes were placed along the device, which transmitted a short voltage pulse to an oscilloscope

whenever the spark passed one of them. These pulses were recorded on a single-sweep trace started simultaneously with the spark. Timing was achieved by modulating the beam intensity at a known frequency. These tests have shown that the velocity remains fairly constant during the movement, and can be reproduced accurately. The average velocity over the length of 2 feet could be varied between about 21 and 37 feet per second by adjusting resistance and voltage in the spark circuit.

The combustion chamber in which the spark device will be incorporated has been designed, and construction is almost finished. The chamber has a rectangular cross-section with plane glass plates as side walls, through which the shape and movement of the flame front will be observed. Shadowgraph and striae methods will be employed, utilizing either a 100-watt Zirconium arc lamp or condensed sparks as light sources.

2. Preliminary tests in which the ionization gaps used for the timing of flame travel were connected directly to the oscilloscope gave unsatisfactory results, owing to the persistence of ionization in the hot gas after the flame had passed the gap. An electronic timing device was therefore designed, which utilizes one thyatron circuit for each ionization gap; the tubes are triggered by voltage pulses received from the ionization gaps at the moment when the flame front reaches them. A unit operating on this principle was built which utilized ten thyatron circuits. Each time a tube fired, the single sweep of the oscilloscope was triggered and at the same time the trace was displaced vertically, so that a record of a run consisted of nine parallel traces, the length of which indicated the time intervals.

Apart from minor defects it was found that this unit functioned satisfactorily. In a final version now under construction, modifications are being incorporated that will permit the sensitivity of each circuit to be adjustable separately, thus compensating for unavoidable differences in tube and circuit parameter characteristics. Only one single sweep combined with an auxiliary recurrent vertical sweep will be used, in order to accommodate a sufficiently long total time interval with high resolution.

This work has progressed rather slowly owing to lack of space and personnel.

3. This study constitutes a novel approach to the problem of flame propagation under turbulent conditions. Application of the statistical theory of turbulence to this problem has been largely unsuccessful in the past, chiefly because of the lack of information on the relation between flow disturbances and combustion. The present investigation is an attempt to obtain such information by observing the effects of simple periodical disturbances on flame propagation.

A report has been issued on the work carried out through August 1947.² During that period the effects of alternating electrical fields and of sound waves on Bunsen burner flames were studied. Stroboscopic direct flame photographs and shadowgraphs were taken which show that the disturbances create a wave-shaped distortion of the flame front, which travels upwards from the nozzle tip with the flow velocity of the unburnt gas. For moderate intensities of the disturbance, the amplitude of the distortion increases continuously during this travel, while for stronger intensities it decreases after an initial increase.

Computations of the surface areas of distorted flames were performed which showed them to be independent of amplitude and phase angle of the disturbance. From this result the conclusion was drawn that the burning velocity is constant and independent of the distortion of the flame surface. It was further concluded that the gradual increase of the distortion must be due to flow disturbances which appear when an initially small disturbance is introduced into a flame front.

In later work, attempts have been made to visualize and measure these flow disturbances by the method of intermittently illuminated particles injected into the gas stream. These attempts, as well as an attempt to apply the principle of the induction flow meter to this problem, have not yet been successful. During the latter tests it was found, however, that alternating voltages of the order of 10 millivolts could be picked up by a pair of electrodes inserted into a disturbed flame, if at least one electrode was located close to the flame front. This effect might be useful for the determination, at least in a qualitative way, of the state of turbulence in a flame.

The application of electrical and acoustical disturbances did not allow a measurement of the initial amplitude of the distortion introduced into a flame. It was found later that a vibrating wire inserted into the flame front caused the same type of distortion. Since the amplitude of vibration of the wire can be measured accurately, this method is now used in tests, in which the relation between amplitude and frequency of the initial disturbance and the observed distortion of flame front will be determined.

During the earlier work, it was found that the blow-off limit of a Bunsen flame could be increased by a factor of roughly two by applying an electrical field between the metallic nozzle and an electrode placed close to the outer cone of the flame.

4. Combustion can take place very readily on certain solid surfaces and this principle has been used in furnaces in which the combustion occurs on a porous surface, usually a refractory. The use of a catalytic surface in the combustion chamber of a pulse jet is of interest where space, weight and time are at a premium. A favorable catalytic influence

might enable a small combustion unit to produce more energy than a much larger unit without the catalytic lining.

At first glance it would appear that catalytic walls could have but a small effect on the combustion in a large burner, because of the low surface-to-volume ratio and the high gas velocity. Furthermore, at the ultimate temperatures in a propulsion unit, the rates of reaction are sufficiently high that catalysis offers small hope of increasing them further. In refuting these *a priori* conclusions, several points must be considered. Before the entering fuel can burn, it must acquire additional energy. This energy can be imparted by the purely thermal process of heat transfer by radiation or through the introduction of excited particles in the mixture, which serve to initiate the combustion mechanism. The definite possibility exists that this energy can be supplied more rapidly from certain types of surfaces than from others: thermally through a highly radiative surface, such as a Welsbach mantle, or through a surface which produces or regenerates active centers. Since the rate of diffusion of the active centers can be substantial when compared to the gas velocity, particularly during this preheating stage, this mechanism cannot be discarded. Further, during the initial stages of the preheating, the rate of reaction in the gas stream is low because the temperature is low, and therefore it is susceptible to catalytic action. Thus, a surface which can supply energy more efficiently in the initial phases of combustion should be useful in propulsive devices.

To investigate these considerations, a combustion chamber of small internal diameter was supplied with a gaseous hydrocarbon fuel premixed with air. The tube was heavily insulated and for each rate of flow sufficient time of combustion was allowed for equilibrium to be established. The temperature attained over the length of the tube was measured at regular intervals by thermocouples affixed to its external surface. When thermal equilibrium was attained, it was assumed that there was little or no difference in temperature between the wall and the gas adjacent to it. In this regard it can be shown by heat transfer considerations that in a tube of small internal diameter a thermocouple inserted as a probe would read essentially the wall temperature rather than the true gas temperature. This, coupled with the difficulty of obtaining a shielded thermocouple with which to probe the combustion tube without disturbing the combustion, led to the decision to employ thermocouples on the external surface.

It was expected that, if the surface of the combustion tube acted catalytically, the position of maximum temperature should move downstream more slowly with increasing fuel input than for the case in which a non-catalytic wall was present. The distance from the flame arrestor, and thereby the time to reach a maximum temperature, was used as a measure of the combustion capacity of the tube. Completeness of the reaction was also determined in certain

cases by inserting a refrigerated probe into the combustion tube and sampling the flue gases.

Numerous tests were run in an Inconel tube. The wall temperatures were recorded and plotted against the tube length by thermocouple position. Plotting the temperature in this manner produced a graph which rose sharply to a maximum and then gradually receded. As the input velocity increased, the position of maximum temperatures moved downstream and eventually was blown out of the combustion tube. In these tests it was necessary to increase the air/fuel ratio as the input rate was increased, in order to prevent the maximum temperature attained in the tube from exceeding the melting point of the tube.

A series of tests was then conducted in which the air/fuel ratio was maintained as nearly constant as possible and the input was gradually increased. A similar family of curves was obtained in which the initial slope of each member of the family was nearly the same. The position of the maximum temperature moved downstream. Similar results were obtained in other metallic tubes.

When a quartz tube was installed, similar results were obtained, with the exception that the position of maximum temperature moved downstream more slowly with the increased input and that the slope of the curve downstream from the maximum was less pronounced.

The data taken from several series of runs were plotted so that the distance to the point of maximum temperature for various rates of fuel input in stainless steel and in quartz is compared. It was observed that in a quartz tube 12 inches long approximately twice the amount of fuel could be burned than could be burned in the stainless steel tube. Additional experiments have substantiated this observation and gas analyses are being conducted on trials under these conditions.

5. In determining the heat release in combustion and the total time and variation with time of such heat release, a water-cooled gas-sampling probe has been developed, as a practical approach, for use in any type of burner. From the analysis of the flue gases, pertinent thermodynamic data can be calculated for the combustion which was under observation, provided the sample obtained thereby was representative of the equilibrium existing in the flue gases. The criterion of usefulness of the probe is then its ability to "freeze" the dissociation reactions of carbon dioxide and water vapor.

A number of experiments have been devised in which the chief difficulty has been the establishment of an adequate equilibrium with the dissociation products present in such magnitude that they could be detected analytically. The experimental trials can be roughly divided into two classes. The first includes those experiments in which a flowing carbon dioxide system was used, and the second includes those in which flames were used as a source of equilibrium products. It is necessary to obtain a temperature in excess of 3000°F in

order to obtain substantial quantities of oxygen and carbon monoxide from the dissociation of carbon dioxide.

Using a Zircofrax tube or an Alundum tube sealed with sodium silicate, a slow current of carbon dioxide was heated with an oxy-gas flame. The temperatures were determined with an optical pyrometer. Samples were collected by inserting the sampling probe at a point of close proximity to the region of maximum temperature. With the Zircofrax tube, no decomposition was observed. In the Alundum tubes, which were of smaller diameter, a higher rate of flow existed and the amounts of oxygen and carbon monoxide were in the order of magnitude predicted for the dissociation calculated at the observed wall temperature of the tube. However, small discrepancies indicated that leakage may have occurred through the walls of the tube.

To eliminate the possibility of leakage, a platinum tube was substituted and heated to temperatures just below its softening point by a 60-cycle alternating current. A series of tests was conducted but no dissociation of the carbon dioxide was observed. This may have been due to reassociation of the gases in the portion of the platinum tube which was cooled by its contact with the sampling probe.

One other attempt was made to establish an equilibrium mixture in a special ceramic U-tube. The U-tube was to be immersed in a molten-copper bath at temperatures above 3000°F. A slow current of carbon dioxide was admitted through the arm and the sampling probe was inserted into the heated zone through the other arm. Unfortunately, the ceramic tube failed due to thermal shock before the apparatus could be put to use.

Tests were conducted in which samples of gases were withdrawn through the probe from flames produced by various types of burners. The analysis of the samples withdrawn from the natural gas-producer gas flame showed amounts of carbon monoxide, hydrogen, and oxygen which corresponded to an equilibrium at a high temperature, but not at as high a temperature as the theoretically calculated flame temperatures. The amount of dissociation of carbon dioxide and water vapor individually corresponded to exactly the same temperature. The excellent agreement indicates that the sampling probe affects the two reactions in the same manner.

To simplify the reaction, a metered mixture of methane and air was supplied under pressure to a Meker-type burner. The probe was inserted just above the inner cones. It was possible to calculate the hydrogen/carbon balance, the air/fuel ratio, the flame temperature, and the extent of dissociation from the gas analysis. It was found in one trial that agreement of the results was extremely good, but when the method of analyzing for carbon monoxide was changed and the previous experiments repeated, very poor agreement was obtained. The flame temperature calculated from the apparent dissociation of carbon dioxide was much too

high and indicated that the combustion was incomplete. As a check on this point, increased air/fuel ratios were used, but incomplete combustions were still obtained. These tests are therefore inconclusive, since a true equilibrium was not established in the flame.

One final effort to establish the efficiency of the sampling probe is in progress. Instead of sampling an equilibrium at an extremely high temperature, it has been decided to eliminate the difficulties encountered in that procedure by sampling an equilibrium at a much lower temperature. This approach requires the removal of a much larger sample of gas, and in order to accomplish this a major portion of the undissociated carbon dioxide is being absorbed chemically and the residual amount, together with the carbon monoxide and oxygen, is being collected for subsequent analysis.

6. Any approach to the mechanism of combustion or heat release from the theoretical side through a literature survey on spectroscopic means reveals a degree of uncertainty pervading the subject. A report has been issued summarizing the status of research on the mechanism of combustion.⁷ In this report it was concluded that "much more extensive studies, possibly supplemented by new techniques, are required of the oxidation of specific hydrocarbons before an approach can be made to a quantitative understanding of the processes involved."

One of the chief weaknesses of many previous investigations has been the lack of adequate control. Recent developments in technique of low-pressure combustion have provided for adequate control over a greater number of these factors. The results are better spectrographic data.

In this laboratory a low-pressure burner and the necessary instrumentation for careful control of the experimental parameters have been constructed. Assembly of the equipment has just been completed and the recording of data will be started about the first of the year. A description and a diagrammatic sketch of the apparatus has been prepared.⁸

Plans

1. Upon completion of the combustion chamber, actual combustion experiments will be started. The effects of various disturbances on flame propagation under controlled conditions of temperature, pressure, and mixture composition will be studied.

2. As soon as the timing device is completed, flame propagation tests in the tube will be performed and the effect of constrictions on flame speed will be studied. In particular, an investigation will be made of the possibility of producing very high flame speeds and of

maintaining these speeds after the flame has passed the constrictions. It is also planned to compare other flame detection devices, such as those proposed by Calcote, with the ionization gaps. Insertion of pyrex sections for simultaneous photographic registration of flame travel is contemplated.

3. Studies of periodically disturbed flames will be continued. Gas mixture composition will be varied, and other fuels besides propane, which has been used until now, will be tested in order to determine the influence of burning velocity and amount of heat release on the effects. The attempts of direct observation of the postulated flow disturbances will be resumed. In addition to strictly periodical disturbances, the study of transient phenomena in flames, particularly in those burning freely in a gas jet or on a flame holder, is contemplated.

4. As soon as sufficient data is obtained, a report will be issued covering details of the catalytic influence of combustion-chamber-wall materials.

5. The water-cooled gas sampling probe will continue to be tested by sampling an equilibrium at low temperatures until it is possible to accurately evaluate its measure of usefulness.

6. Using the low-pressure burner it is planned to investigate the effect of pressure, oxygen/fuel ratio, fuel-input rate, and extraneous gases on the spectrographic data obtained from the combustion of simple hydrocarbons or other desirable fuels.

PHASE 3

In connection with pulsating jet engines: to undertake experimental investigation of temperature and fatigue resistant materials for intake valves and coatings, and of fabrication methods and techniques to cover these materials.

Summary

Work under Phase 3 has centered upon an investigation at high temperatures of bending-fatigue, short-time-creep, and tensile properties of various valve materials for pulse jets. A study of tensile fatigue and repeated shock or impact properties has been started. The investigation is limited to heat-resistant alloys available in sheet stock. Type 310 + 2 silicon stainless steel (25-20-2), regular Inconel and S-816 are being tested. Additional materials will be considered as the program progresses.

Data are being correlated to further the understanding of high temperature failure and to provide sound bases for development of better high temperature materials. To aid in accomplishing this purpose, a high temperature metaloscope is being developed.

1. A pneumatic fatigue machine has been developed and bending-fatigue tests have been run at temperatures of 1200°F, 1400°F, and 1600°F.

2. A high temperature tensile study has been undertaken to obtain tensile properties which can be used for design purposes. Instrumentation has been developed for controlling and recording stress, strain, temperature, and time.

3. Short-time-creep tests have been started, but no summary data is yet available. The tests provide limiting stress data over a temperature range of 1200°F to 1800°F for deformations up to 5 per cent and for time periods up to 2 hours.

4. A satisfactory optical system has been procured for the high temperature metaloscope. Two types of furnaces, electrical resistance and electrical induction, with suitable vacuum chambers have been designed and built. The initial assembly of the metaloscope has been accomplished.

Progress

1. The auxiliary instrumentation has arrived and the pneumatic fatigue machine has been assembled into a usable unit. A report has been issued which gives design and operating characteristics of the machine.⁹

2. This high temperature tensile study has been undertaken not only to obtain tensile properties which can be used for design purposes but also to discover why metals deform and fail at high temperatures. Accordingly, instrumentation has been developed for controlling and recording stress, strain, temperature, and time.

For these tests, a standard sheet-stock specimen with a two-inch gage length is loaded in a hydraulic-type tensile machine with a variable head-speed control. Heating is accomplished with a resistance-wound furnace and a control system capable of maintaining a uniform temperature over the specimen gage length with a maximum spread of 3°F and a constant test temperature within $\pm 3^\circ\text{F}$ of the nominal value. Strain measurements are made using a CAL extensometer system and a cantilever pickup device capable of detecting 0.00010-inch strain with a minimum accuracy of 2 per cent.

Because tensile properties are highly sensitive to the rate of strain at elevated temperatures, this variable has been carefully examined and controlled in the course of testing. To this end, the actual gauge-length strain is automatically recorded as a function of time as well as of load, and a record of these three variables is obtained on the same data sheet. One report has been issued describing this test assembly in detail¹⁰ and another report on the same subject is now being written.¹¹

Tensile data providing values of elastic modulus, proportional limit, yield stress, ultimate strength, and per cent elongation at temperatures up to 1800°F have been obtained for 25-20-2 Silicon stainless steel, regular Inconel, and S-816 sheet alloys over a range of strain rates varying from approximately 0.01 to 10 per cent per minute.¹¹

Principally through consideration of strain rate, or the influence of time upon high temperature tensile properties, it has been shown¹¹ that an insight may be gained concerning the manner of high temperature deformation. These data provide a measure of the activation energy required to cause deformation. The concept of activation energy for deformation satisfactorily explains the dependence of elastic limit on strain rate at elevated temperatures. This explanation is also in agreement with the data obtained from creep tests.

3. Testing is in progress, but no summary of data has yet been reported. The tests provide limiting stress data over the temperature range of 1200°F to 1800°F for deformations up to 5 per cent and for time periods up to 2 hours. These data are more directly concerned with the design of combustion chambers, pressure housings, and turbine wheels, but they are expected to correlate with the results from the bending-fatigue and the tensile tests. Development and instrumentation of the creep-testing apparatus have been completed.

4. A high temperature metaloscope was conceived as a tool for studying the micro-structure of metals at the temperatures to which they are subjected in service. A literature search was completed during the early part of the year and correspondence was carried on with several optical companies in an effort to work out a suitable high temperature optical system. Pausch and Lomb have supplied an optical system with a relay lens which allows a working distance of 2½ inches from the heated specimen to the first lens and thereby keeps the optical system from being overheated. The image from the relay lens is picked up by a standard 16 millimeter objective and passed through a 3× projection lens. The light is then split by a prism which allows 90 per cent to pass to a 16 millimeter moving picture camera and 10 per cent to be deflected to the eyepiece. The magnification with this system is rather low, but the resolution is sufficient so that projection of the moving picture film at 200× will give a resolved image. The prism allows simultaneous visual observation and photographing of the image.

Two approaches have been made to the problem of designing a suitable hot stage with means for heating the specimen and for maintaining a vacuum or an inert gas atmosphere. Several resistance-heated furnaces were designed and built. The first model could be heated to 1800°F successfully, but due to the large amount of refractory in the furnace it was impossible to obtain a high vacuum. This was circumvented by another furnace design in which the refractory is outside of the chamber. This furnace may prove to be satisfactory.

The second line of attack has been to use induction heating so that only the specimen is heated, thereby cutting down the amount of heat in the furnace. The Ohio Crankshaft Company has delivered a portable heat gun which attaches to a standard loco converter. Experiments with this heat gun and a pyrex-glass furnace chamber indicate that this arrangement may also be usable. Arrival of the vacuum diffusion pump and Pirani gauge will complete the equipment necessary for the assembly of the vacuum system. Figure 1 shows the high temperature metaloscope in its present state of development. A 16 millimeter camera is available for setting on the top of the projection lens.

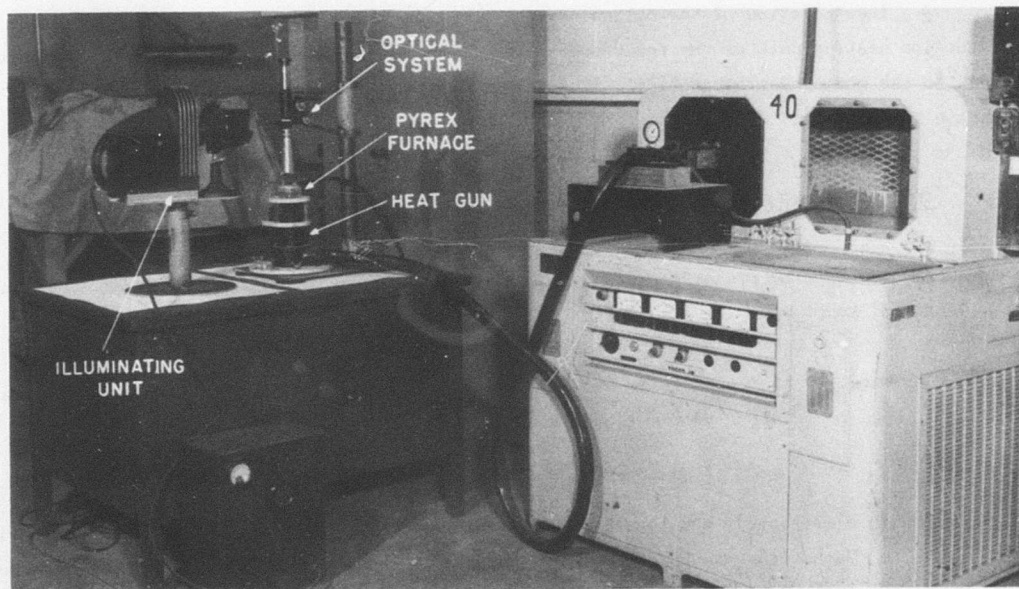


Figure 1.
High temperature metaloscope.

Plans

1. Amplitude of deflection will be evaluated in terms of strain so that the data will be more useful for design purposes. This will be attempted by means of high tempera-

ture strain gages. Inasmuch as most of the test deflections used produce stresses in excess of the elastic limit, it is felt that both from a practical design standpoint, and as a means of comparing different alloys, a plot of initial strain versus the number of cycles will be more useful than a plot of stress versus the number of cycles.

Experiments using frequency other than the natural frequency of the metal specimen are being planned, and a pneumatic valve is being made for these tests.

2. High temperature tensile tests at various strain rates will be continued and data obtained for additional materials.

3. Tests will be completed for 25-20-2 Silicon stainless steel, regular Inconel, and S-816. The effect of fluctuating load (tensile fatigue) on the creep characteristics of these materials will be examined.

4. Incorporation of the optical system with its 16 millimeter camera, the hot-stage induction heating unit or the resistance furnace, and the vacuum system into a working unit will be the coming year's problem. It is expected that initial pictures will be available within three months.

SQUID Technical Reports and Memoranda Issued During 1947

Frequency response of pressure pickups required for measurements on a pulse jet by G. Rudinger. Technical Memorandum CAL-1, June 16, 1947. Reissued as Technical Report No. 1.

On the possibility of representing one-dimensional gas motion by means of an electrical analogy, by J. Logan. Technical Memorandum CAL-2, June 23, 1947. Reissued as Technical Report No. 2.

Phenomena in electrically and acoustically disturbed bunsen burner flames, by M. L. Polanyi and G. H. Markstein. Technical Memorandum CAL-3, September 15, 1947. Being reissued as Technical Report No. 5.

Study of gas oscillations in half-open pipes of various shapes, by G. Rudinger and J. Logan. Technical Memorandum CAL-4, June 30, 1947. Reissued as Technical Report No. 3.

Two-dimensional supersonic wind tunnel simulation of the flow over the external surface of ducted bodies with and without spillover, by M. Kamrass. Technical Memorandum CAL-5, June 30, 1947.

Preliminary experimentation on the CAL 6" x 4" pulse jet, by J. G. Wilder. Technical Memorandum CAL-6, June 30, 1947.

Two-dimensional supersonic wind tunnel investigations of flow in a duct with fluctuating exit pressure, by M. Kamrass. Technical Memorandum CAL-7, June 30, 1947.

Preliminary study of a supersonic induction-type wind tunnel for Cornell Aeronautical Laboratory, by J. L. Moore, O. B. Finamore, and J. G. Wilder. Technical Memorandum CAL-9, September 22, 1947.

Pneumatic vibration for determination of high temperature fatigue properties of sheet materials, by F. J. Gillig and L. W. Smith. Technical Memorandum CAL-10, December 17, 1947.

Influence of strain rate on high temperature tensile properties of sheet materials, by L. W. Smith and G. J. Guarnieri. Technical Memorandum CAL-11, being issued.

References

1. Motion of gas in half-open pipes, by H. Lewy. AMG-NYU Report No. 73, October 17, 1944.
2. Phenomena in electrically and acoustically disturbed Bunsen burner flames, by M. L. Polanyi and G. H. Markstein. Technical Memorandum CAL-3, September 15, 1947. Being issued as Technical Report No. 5.
3. On the possibility of representing one-dimensional gas motion by means of an electrical analogy, by J. Logan. Technical Memorandum CAL-2, June 23, 1947. Reissued as Technical Report No. 2.
4. Two-dimensional supersonic wind-tunnel simulation of the flow over the external surface of ducted bodies with and without spillover, by M. Kamrass. Technical Memorandum CAL-5, June 30, 1947.
5. Two-dimensional supersonic wind tunnel investigations of flow in a duct with fluctuating exit pressure, by M. Kamrass. Technical Memorandum CAL-7, June 30, 1947.
6. Frequency response of pressure pickups required for measurements on a pulse jet, by G. Rudinger. Technical Memorandum CAL-1, June 16, 1947.

7. A summary of the status of research on the mechanism of combustion, prepared by Arthur D. Little Inc. Bumblebee Report No. 47, October 1946.
8. CAL Quarterly Progress Report, Project SQUID, October 1, 1947, p. 42.
9. Pneumatic vibrator for determination of high temperature fatigue properties of sheet materials, by F. Gillig and L. W. Smith. Technical Memorandum CAL-10, December 17, 1947.
10. Termination report on Combustion Chamber Design Improvements, by V. Pingel and F. Dietrich. CF-710, June 30, 1947.
11. Influence of strain rate on high temperature tensile properties of sheet materials, by L. W. Smith and G. Guarnieri. Technical Memorandum CAL-11, being issued.

ANNUAL PROGRAM REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-105, TASK ORDER III

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY
1 JANUARY 1948

THE OFFICE OF THE PROJECT ORGANIZER

This office has the responsibility under the Policy Committee for the overall coordination and management of Project SQUID. In addition, the Technical Survey Group under this office has been undertaking certain technical work and technical liaison duties.

Field Survey Report. The preparation of the Field Survey Report was conducted by Engineering Research Associates with the assistance of two persons from the office of the Project Organizer. The report was essentially completed in the first half of 1947. It contained a detailed review in nine separate reports of all existing work sponsored by Government agencies in the fields of liquid rockets and pulse jets, in addition to related work in the fields of combustion, fluid mechanics, materials, heat transfer and cooling, fuels, and instrumentation.

Progress Reports. This office has been responsible for the editing, printing, and distribution of three Quarterly Progress Reports containing descriptions of the research work at the five member universities. In addition, twelve sets of Monthly Progress Memoranda have been assembled and distributed.

Semiannual Program Report

During the last quarter of 1947, visits were made from the Project Organizer's office to the member universities to obtain detailed data for the Semi-Annual Program Report. This report, known as the Project SQUID Handbook, contains a breakdown of phase assignments within the project, showing specifically all the problems being investigated under each general phase assignment. In addition to phase breakdowns, the Project SQUID Handbook contains information on the personnel, administration, budget, and organization of the project. The first issue of the Project SQUID Handbook was issued as of 31 December 1947, and will be revised every six months thereafter.

The Handbook receives distribution within Project SQUID only and is intended to acquaint research workers within the project with the work being carried on at the various member universities.

Instrumentation Bulletin

The Instrumentation Panel of Project SQUID is sponsoring a *Bulletin* devoted to instrumentation problems within the field of jet propulsion. The *Bulletin* will contain

contributions from laboratories throughout the country and will be issued by Engineering Research Associates of Washington, D.C. as often as sufficient material is available.

The contributions to the *Bulletin* will cover new developments in instrumentation, particularly devices and methods for measuring the physical and chemical quantities encountered in jet propulsion research. The *Bulletin* will also contain brief descriptions of ingenious solutions to specific problems which have helped investigators and which may be useful to other research groups.

Through the *Bulletin* it is hoped to effect a closer association between groups working on similar problems within the jet propulsion field and to help resolve special difficulties by the establishment of a medium through which research workers may exchange ideas affecting their particular problems.

The first issue of the *Instrumentation Bulletin* has been prepared and will be published in January 1948. It is planned to give the *Bulletin* the widest possible distribution.

Technical Library

The Technical Library of Project SQUID was established for the purpose of loaning pertinent reports to the member universities. Two librarians are engaged in cataloging, abstracting, and filing of the reports. Reports are received from Government agencies and contractors engaged in jet propulsion and guided missile work. Three copies each of approximately 2,000 reports are now contained in the library. Abstracts of all reports received are sent out weekly to the members of Project SQUID.

Engineering Studies

Members of the office of the Project Organizer have acted as consultants on certain of the technical phase assignments and to the Bureau of Aeronautics. In particular, the design for a gaseous propellant rocket motor and system was prepared for Princeton University Phase 3, and an engineering analysis of a regenerative cycle pumping system for a liquid propellant rocket motor was prepared at the request of the Navy through the Applied Research Panel.

Committees and Panels

During 1947, there were a total of 27 meetings of the various committees and panels of Project SQUID. Prior to June 30, 1947, the following committees and panels were operating:

Policy Committee	6 members
Technical Committee	11 members and 5 alternates
Rocket Panel	5 members
Pulse Jet Panel	5 members
Instrumentation Panel	5 members
Metallurgical Advisory Panel	4 members

On June 30, 1947, the Rocket, Pulse Jet, and Instrumentation Panels were dissolved in favor of five new panels to be constituted of four members each who were the most highly qualified people within Project SQUID in the field of the respective panels. These new panels are:

Fluid Mechanics
 Combustion
 Materials
 Instrumentation
 Applied Research

The panels were formed primarily as discussion groups to keep members informed of the detailed work and to act as a clearing house for proposed problems for Project SQUID research.

The Technical Committee as constituted above was dissolved on September 30, 1947, and a new committee formed. This new committee is composed of one member from each of the five member universities with the Project Organizer as chairman.

The office of the Project Organizer has prepared agenda and minutes for the Policy and Technical Committees and is also responsible for the duplication and distribution of panel meeting notices and minutes. In addition, personnel of this office and of Engineering Research Associates serve as non-voting members of the panels.

PHASE I

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

Summary

At its inception the supersonics research group at Princeton selected for investigation the general problem of viscous effects in supersonic flow, including boundary layer-shock wave interaction at the rear of airfoils and bodies of revolution, shock waves in channels and diffusers and the effects of the boundary layer on such flows, etc. A thorough study of these problems requires the production of a uniform supersonic gas "jet" over a range of Reynolds numbers far beyond the reach of any existing or contemplated continuous flow or vacuum-operated supersonic wind tunnel. It was therefore decided to build a supersonic "blow-down" or pressure-operated tunnel of a new type, powered by a supply of stored air that could be delivered at any pressure from approximately 30 to 500 p.s.i. absolute. These supply pressures correspond to a range of Reynolds numbers of from two to forty million, based on a three-inch-chord model, or an altitude range of from sea level to 100,000 feet.

The work of the last year has been mainly occupied with the design, assembly, construction and installation of the equipment and apparatus for the main supersonic tunnel, and with the "pilot" supersonic "blow-down" tunnel in which problems of operation and also some supersonic viscous flow problems are to be investigated. Concurrently, theoretical studies have been carried out on boundary layer-shock wave interaction, triple shock interaction, unsteady one-dimensional flows with heat addition and a number of other theoretical problems.

Status of Project

After more than a year of preparation and effort, substantial progress has been made in recent weeks. It is expected that the experimental phase of the research program will get under way in two to three weeks when the "pilot" tunnel is placed in operation. The main supersonic tunnel is installed and will be in operation early in 1948, depending largely on the delivery of the regulator valve and control system.

Personnel

The personnel now engaged on this project are as follows: Research Associates S. Bogdonoff (in charge of tunnel design and operation), H. J. Shafer (instrumentation and optical apparatus) and A. Kahane (theoretical problems); Research Assistant A. Solarski. The research staff is assisted by two mechanics, two machinists (one full time and one part time), and two computers. The project is under the direction of Prof. L. Lees.

I. Main Supersonic Tunnel

1. *Air Supply System.* After a thorough overhauling, the two Worthington compressors complete with cooling water supply system have been installed and operating satisfactorily. Except for certain minor tasks the compressor room is virtually completed (Figure 1).

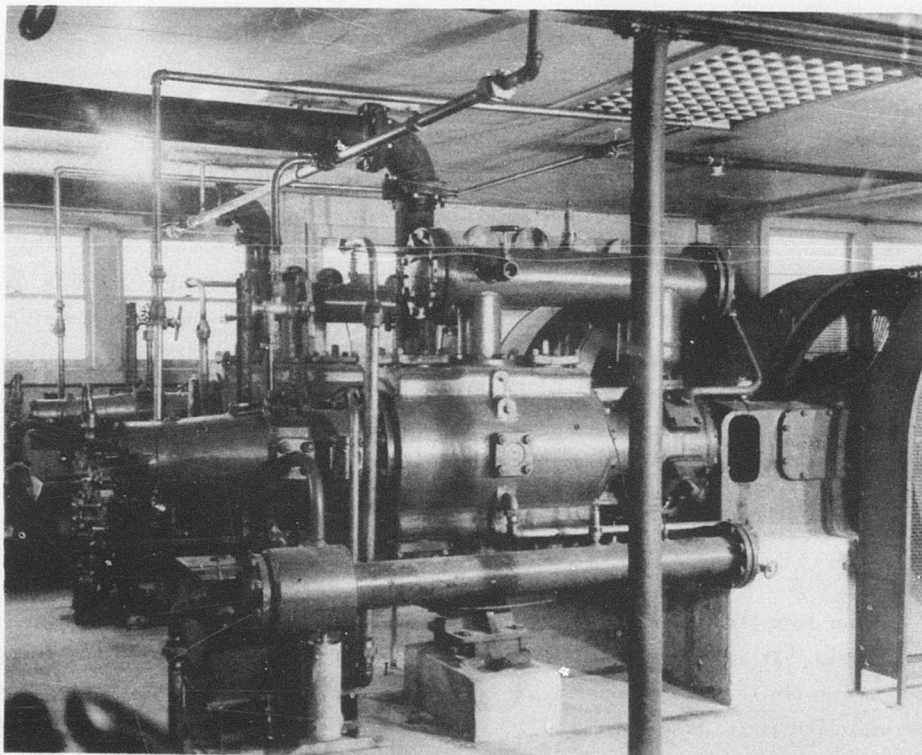


Figure 1.
Compressor Room.

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The aftercooler and surge tank are on hand and the installation of the piping for the air supply system is in progress. It is expected that the piping up to the control valve will be completed in the next few weeks. The main component that has not yet been delivered is the regulator valve and control system. Because of the large casting required for the valve, the contractor has experienced several delays and delivery is now anticipated early in 1948. The date for the initial operation of the main supersonic tunnel will be determined largely by the delivery of this component.

2. *Wind Tunnel and Jet Room.* The wind tunnel proper from settling chamber to last diffuser section was constructed by a nearby machine shop from our blueprints and installed recently (Figures 2, 3, and 4). A considerable amount of work remains to be done before the tunnel is in operating condition, including fabrication of the nozzle blocks complete with pressure orifices, fabrication of metal window-inserts for initial runs, sound-proofing of diffuser sections, etc. The overhead crane is installed and the work of sound-proofing the jet room can proceed.

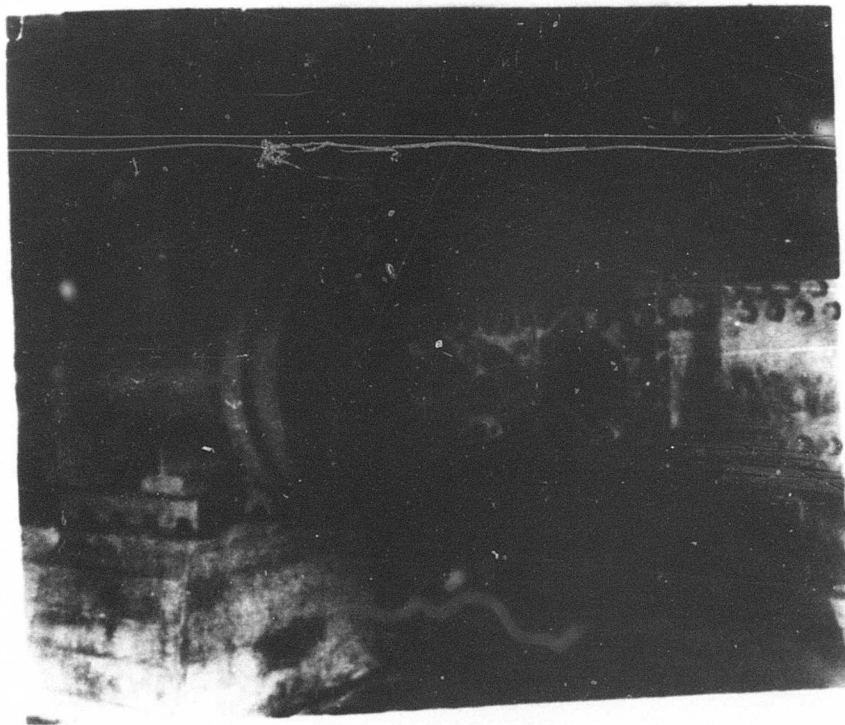


Figure 2.
Test Section.

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II. Pilot Tunnel

The pilot tunnel installation is about 90 per cent completed and the tunnel should be in operation in January. All piping and valves are installed and the wind tunnel proper is complete except for the subsonic diffuser; the diffuser is now being fabricated. The test channel and nozzle blocks for $M = 3.01$ complete with pressure crifices are ready for installation. All necessary instrumentation will be installed in the next few weeks. (The pilot tunnel design is described in detail in a Princeton University Master's Thesis by R. C. Scott entitled "The Design of a Supersonic Blow-down Pilot Wind Tunnel With a Mach No. 3.01 Nozzle," dated 28 October 1947).

The experimental program planned for the pilot tunnel is described in Project SQUID Quarterly Report, Princeton University, dated 1 October 1947. After the initial calibration runs, an experimental study will be made of the possibility of condensation of the components

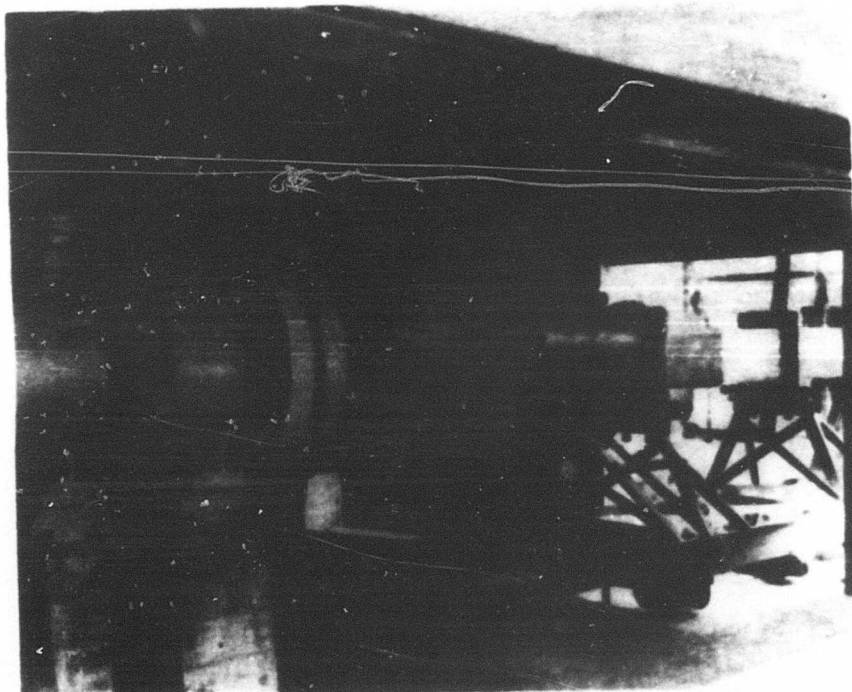


Figure 3.
General View of Wind Tunnel.

of air at high Mach numbers. It is also planned to investigate the triple or Mach-shock intersection between the oblique shocks from two wedges mounted in a supersonic channel and to study the boundary layer shock-wave interaction involved in the reflection of an oblique shock from a plane wall. All of this work is closely correlated with theoretical studies now in progress.

III. Instrumentation and Optical Apparatus

1. *4" Interferometer.* The plates for the 4" interferometer are being finished by the Naval Gun Factory and should be delivered in the next few weeks, the mounts are to be fabricated in our machine shop, where the interferometer will be assembled. The interferometer carriage and lifting-jack are under construction. Two 4" interferometer-quality windows are also to be fabricated by the Naval Gun Factory and it is expected that the interferometer will be available for the pilot-tunnel studies early in 1948.

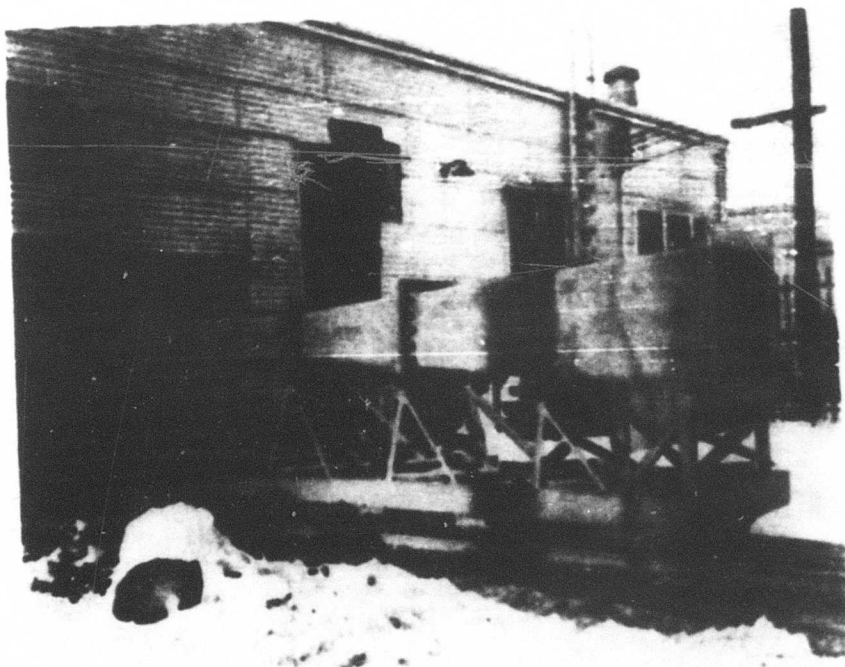


Figure 4.
Exhaust Section.

2. *Schlieren Apparatus.* The 4", 8" and 12" schlieren mirrors are on hand and mounts for the 8" mirrors are being made by our shop. A knife edge adjustable in three dimensions is also to be built here. Scheduled work includes installation of schlieren beams for both the main and pilot tunnels and assembly of optical systems. Light sources for the optical systems are on hand and spark equipment should arrive shortly.

3. *Instrumentation.* All required pressure gauges have been received. These gauges are of the aneroid type and were selected to cover three ranges between zero and 500 p.s.i. absolute. Thermocouples and temperature recorders are on hand. The instrumentation is to be installed first in the pilot tunnel.

IV. Theoretical Studies

In addition to theoretical calculations carried out directly in connection with the supersonic wind tunnel, studies that are in progress or that have been completed include (1) fundamental boundary layer-shock wave interactions, (2) the triple or Mach-shock interaction, (3) flow conditions directly behind the trailing edge of a two-dimensional supersonic airfoil.

As an outgrowth of the interest of the research group in the gas-dynamic aspects of the pulse jet, a study was made of unsteady one-dimensional flows with heat addition, such as the flow arising when heat is suddenly added to an initially isentropic flow in a tube. The results of this study are reported in Project SQUID Technical Memorandum No. Pr-2, "Unsteady One-dimensional Flow With Heat Addition or Entropy Gradients," by A. Kahane and L. Lees, dated 27 November 1947. This work led to an investigation of the possibility of a valveless aeroresonator that would utilize the compression waves generated by combustion, and would possibly be more efficient than either the pulse jet or the ram jet. It is proposed to continue this work as a new phase, the proposed Phase 4 at Princeton University.

1. *Boundary Layer - Shock Wave Interaction.* Some progress has been made in a theoretical study of fundamental interactions such as the reflection of an incident oblique shock at a plane wall. The theoretical work suggests an answer to the question as to why the interaction depends so critically upon whether the boundary layer ahead of the incident shock is laminar or turbulent. The thickness of the boundary layer is also found to be critical. This study is reported in Project SQUID Technical Memorandum No. Pr-1, "Remarks On The Interaction Between Shock Waves and Boundary Layer in Transonic and Supersonic Flow," by L. Lees, dated 1 November 1947. The conclusions reached will be tested by experimental work planned for the pilot tunnel and this study should also furnish a guide for future theoretical work.

2. *Triple or Mach-Shock Intersection.* An analysis is in progress of the triple-shock or Mach-shock intersection for weak incident shocks. This study makes use of recent experimental results obtained by Dr. Ladenburg's group and Dr. Bleakney's group at the Palmer Physical Laboratory, Princeton University, and also involves a reexamination of L. Smith's results in the older shock-tube experiments. The possibility exists that viscous diffusion in the neighborhood of the "triple point" is responsible for the anomaly between theory and experiment for weak shocks. An experimental study of the phenomenon over a wide range of Reynolds numbers is planned for the pilot tunnel.

3. *Flow at the Rear of a Supersonic Airfoil.* An analysis of the flow direction directly behind the trailing edge of a two-dimensional supersonic airfoil has been carried out on the assumption of non-viscous flow. Of course the flow is affected seriously by viscosity, but it is important to know the inviscid flow as a basis for comparison with experiment. The downwash is of interest from the standpoint of airplane stability. For a flat-plate airfoil at an angle of attack α the downwash β is of the order of α^4 , and is negligible for Mach numbers between 1.2 and 5.0. For a symmetrical biconvex airfoil of half vertex angle δ , the flow deflection directly behind the trailing edge is:

$$\left[\left(\frac{\delta}{\alpha} + 1 \right)^4 - \left(\frac{\delta}{\alpha} - 1 \right)^4 \right]$$

times the downwash for the flat-plate airfoil, and may be appreciable. The results of this study are reported in an article entitled, "The Flow at the Rear of a Two-dimensional Supersonic Airfoil," by A. Kahane and L. Lees, to be published shortly in the Journal of the Aeronautical Sciences.

4. *Other Studies.*

(a) *Condensation of Components of Air at High Mach Numbers.* Theoretical calculations of the condensation points for supersaturated oxygen and nitrogen in air have been completed by Dr. J. V. Charyk and L. Lees in connection with another project; the results are of course of great interest for the blow-down supersonic tunnel as well. These calculations are based on Volmer's application of kinetic gas theory to the formation of condensation nuclei or droplets of critical size. Tests are planned for the pilot tunnel to check the theoretical results, and in particular, the maximum Mach number that can be reached without preheating of the supply air.

(b) *Departures of Air from Perfect Gas Law, etc.* Calculations of the behavior of air as a van der Waal's gas in the expansion through a supersonic nozzle were carried out utilizing Tsien's recent work. For the operating stagnation temperatures and pressures the

deviations from previous calculations with air assumed to be a perfect gas were negligible up to $M = 5.0$. For larger Mach numbers the deviations would become significant.

Of greater interest is the variation in γ , the ratio of specific heats, during the expansion from settling chamber to test section. Reliable data is not available in the operating range of pressures and temperatures, but it is planned to utilize the results of theoretical calculations of γ if time permits.

(c) Pressure Distributions and Character of Boundary Layer Over Airfoils To Be Investigated In Main Supersonic Tunnel. Theoretical non-viscous pressure distributions are being calculated over six representative supersonic airfoils selected for tests in the main supersonic tunnel; this work is about two-thirds complete. The six airfoils are a symmetrical double-wedge, an unsymmetrical double-wedge, and the same airfoil reversed, a symmetrical biconvex section, an unsymmetrical biconvex section, and the latter airfoil reversed. The thickness ratios selected are 6% and 10%, the angle of attack range is from zero to the maximum angle for an attached shock, and the Mach numbers are 1.5, 2.0, 3.0, 4.0, and 5.0.

With the pressure distributions at hand the laminar boundary layer on these airfoils is being determined chiefly for the laminar stability calculations. Where the boundary layer is clearly turbulent the development is to be calculated by integration of the von Karman momentum equation following Tetervin's method. The objective is to ascertain the thickness and other properties of the boundary layer at the trailing edge as a basis for a study of the boundary layer-shock wave interaction problem.

PHASE 2

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

This phase is jointly sponsored with U.S. Navy, Bureau of Ordnance, APL-JHU associated contract NOrd-7920, Task PRN-3, beginning April 1, 1947.

Technical Supervisor: Robert N. Pease, Department of Chemistry, Princeton University.

The following Technical Papers have been presented since April 1, 1947:

No. 28. Effect of Temperature on the Low-pressure Ignition Limits of n-Butane in Air and Oxygen. By James H. Davidson and Elmer J. Badin, July 1, 1947.

- No. 29. Burning Velocities of Nitrogen-Oxygen-Butadiene-1,3 and Helium-Oxygen-Butadiene-1,3 at Reduced Pressures. July 1, 1947.
- No. 30. Ionization Flame Detector. By Hartwell F. Calcote, July 1, 1947.
- No. 31. The Reaction Between Atomic Hydrogen and Molecular Oxygen. By Elmer J. Badin, July 1, 1947.
- No. 32. Blow-off Limits for Open, Bunsen-Type Flames in the Turbulent Region. By Hartwell F. Calcote, August 15, 1947.
- No. 33. The Combustion of Butene-1 Induced by Aluminum Borohydride. By Richard S. Brokaw and Elmer J. Badin, October 20, 1947.
- No. 34. Critical Considerations of Burning Velocity Measurements at Reduced Pressures. By Albert T. Whatley, Joseph A. Faucher, and Elmer J. Badin, November 1, 1947.
- No. 35. The Reaction Between Atomic Hydrogen and Molecular Oxygen at Low Pressures. II. By Elmer J. Badin, December 20, 1947.

Of these, No. 29 and No. 34 deal with determinations of normal flame speeds as measured by the mantled Bunsen burner method. It is shown that substitution of helium for the nitrogen of ordinary air leads to a marked increase in flame speed. Decreased pressure also leads to an increase in flame speed within limits. The method of estimating the surface of the inner cone of the flame, from which the burning rate is calculated, leads to uncertainties of several per cent in the absolute values.

In Paper No. 32, blow-off limits for an open Bunsen burner are shown to move toward richer mixtures as feed velocities pass into the turbulent region.

The effect of temperature on ignition limits in a closed tube is discussed in Paper No. 28. A means of registering the passage of the flame in such tubes without the use of internal probes is described in Paper No. 30.

In Papers No. 31 and No. 35 it is shown that atomic hydrogen from a Wood's discharge tube reacts with molecular oxygen at low temperatures to give hydrogen peroxide by a wall reaction. Increase in temperature decreases the yield of both peroxide and water.

The ignition of hydrocarbon-oxygen mixtures by addition of aluminium borohydride is discussed in Paper No. 33. It appears that n-butane is only ignited when water vapor is

present; butene-1 does not require water vapor but does involve a prolonged induction period; butadiene-1,3 ignites at once in the dry state.

In addition to the above, three papers on the burning velocity problem have appeared in the July and December issues of *Journal of Chemical Physics*. These were the outgrowth of work carried on by Dr. C. Tanford as a National Research Council Fellow, and hence do not represent work sponsored by the Navy projects. It is shown that normal flame speeds may be treated by assuming that the important step is the diffusion of equilibrium concentrations of atoms and radicals from the flame front into unburnt gas. An approximate relation is obtained

$$V = k(c_0 D)^{1/2}$$

where

V = burning velocity

c_0 = equilibrium concentrations

D = diffusion coefficient

Among other things, it is shown that the effect of water vapor on the combustion of carbon monoxide may be ascribed to hydrogen atoms and hydroxyl radicals, that the first effect of a decrease in pressure is to increase flame speeds, and that the square-root relation represents approximately the change of burning velocity with composition.

The combustion project in the Department of Chemistry at Princeton University was originally undertaken in the spring of 1945 in order to deal with combustion problems encountered in ram jet development at the Applied Physics Laboratory, The Johns Hopkins University, Project Bumblebee, U.S. Navy, Bureau of Ordnance. Such problems were to be approached from the point of view of the physical chemist interested in reaction kinetics and mechanism, rather than that of the combustion engineer. It was recognized that basic information about combustion was sketchy at best, and that it would be necessary to start with fundamentals if an understanding of the new problems presented by the ram jet and other engines depending primarily on the thrust principle was ultimately to be achieved. Consequently, laboratory work was begun on the study of ignition limits (including low-pressure ignition), flame speeds, and the kinetics of combustion of spontaneously ignitable fuels, such as metal alkyls.

Subsequent contact with organizations active in the development of the turbojet (through the Subcommittee on Combustion, National Advisory Committee for Aeronautics), and of the pulse jet and the liquid rocket (through Project SQUID, Office of Naval Research and U.S. Navy

Bureau of Aeronautics), has emphasized not only the common problems, but the extremely limited information in the combined fields of chemodynamics and aerodynamics available for their solution. Such phenomena as ignition and flame propagation on the one hand, and of turbulent flow on the other (to say nothing of their interactions) still lack wholly satisfactory interpretations. Yet these are essential to an understanding of jet devices. Under these circumstances it may be useful to review the current situation as it presents itself to a physical chemist.

Unit Processes

At least one of the outstanding difficulties in rationalizing the operation of jet propulsive devices is due to the fact that atomization, mixing, ignition, and combustion are occurring simultaneously and in close proximity. This may be granted as an essential prerequisite to any sort of useful combustion engine—certainly it is equally true of the Diesel engine and the gas turbine. Nevertheless, this ought not to argue against studies of the individual processes. Yet the development engineer is inclined to be impatient, or is at least indifferent to such suggestions. Here then is one sort of contribution which the pure scientist may make. Let these "unit-processes" be separately investigated.

There are plenty of leads from the applied fields. For example, in a rocket the ratio of chamber volume to exit area, designated L^* , is often taken as a parameter. Values vary several-fold. In particular, for the mono-fuel, nitromethane, L^* , is said to be 10 times that for an acid-aniline fuel; that is, for a given nozzle the combustion chamber must be 10 times as large. Mixing is ruled out for the mono-fuel. Is this difference one of atomization, or of ignition, or of combustion? Does it hold equally after the combustion chamber has been brought up to temperature, that is, does it depend on starting characteristics?

As another example, in high-altitude flight different fuels have different ceilings. Which of the four unit processes is limiting? There is perhaps some evidence that low volatility is a difficulty; on the other hand "vapor lock" may give trouble at low pressure. But chemical composition produces effects which suggest that combustion itself is the weak link. Certainly it is true that ignition limits narrow as pressure is reduced.

The process of flow itself may properly be regarded as a unit process. At the present time it appears that the ill-defined phenomenon of turbulence is not subject to satisfactory measurement or theoretical analysis at high rates in terms of scale and intensity. A characteristic way for disturbances to propagate is as sound waves. Are these predominant, or is grosser mass motion in the form of eddies and vortices induced by obstructions of one

sort or another the important characteristic? What is really meant by turbulence in a medium which is actually molecular even though it is treated classically as a continuum? What is the theoretical significance of critical Reynolds number in these terms?

It is easy enough to ask questions, but it is also true that many questions like those suggested above may be answered if the problem is isolated. Apparatus on an engineering scale may be required, though it is fervently to be hoped that the experimental and theoretical approach will be that of the pure scientist rather than the development engineer. This is not to imply that there are not plenty of practicing engineers who would gladly adopt an "academic" attitude toward basic problems. The difficulty is rather a dread of risking large expenditures on what may turn out to be unsuccessful experiments. The urge to embark on "short-range" problems of foreseeable though limited scope is very strong as a matter of self-protection. A "program" must be presented; yet for the worth-while and unexpected results the program cannot be written until the work is done. A way must be found to encourage such large-scale experimentation where this is essential. Answers to basic questions cannot be expected to emerge incidental to the development of practical devices.

Ignition and Propagation

This report is primarily concerned with the physico-chemical characteristics of the combustion process in so far as it is understood today. It is proposed first to deal with recent work on ignition and flame propagation. Following this, some considerations about the mechanism of slow combustion are presented.

The spark-ignition problem has been materially advanced by recent work of Lewis and von Elbe (November 1947 issue of the *Journal of Chemical Physics*) on the minimum energies required to fire natural gas under a variety of conditions using a capacitance circuit largely free of inductance. By this means the energy, obtained by discharge of a condenser, is delivered almost instantaneously, 10⁻⁸ seconds as compared to 10⁻³ seconds when inductances are involved. The spark gap consisted of stainless steel tips mounted flush at the center of small glass plates, whose separation could be varied to obtain that corresponding to the minimum energy requirement. The gap was mounted at the center of a 5-inch steel sphere.

These minimum energies were strikingly small and yet divergent. Thus for the stoichiometric natural gas-air mixture at 1 atm., the minimum energy was found to be 4500 ergs for a minimum gap width of 0.22 cm. For the stoichiometric natural gas-oxygen mixture at 1 atm., the energy falls to only 40 ergs for a gap width of 0.035 cm.

Reduction in pressure likewise produces pronounced effects. Thus for the stoichiometric natural gas-air mixture at 0.5 atm., the energy is 15,000 ergs for a gap of 0.40 cm., while at 0.1 atm. the figures are 250,000 ergs and 1.8 cm.

Substitution of helium or argon for the nitrogen of air produces large shifts in opposite directions. For the stoichiometric helium mixture at 1 atm. the energy is 18,000 ergs for a gap of 0.4 cm., while with argon the energy is 800 ergs for a gap of 0.1 cm. These figures compare with 4500 ergs and 0.22 cm. for ordinary air.

As the mixtures are made either leaner or richer, both the minimum energies and minimum gap widths increase rapidly (by powers of ten), though the increase is relatively greater for the energies than for the gap widths. This properly suggests conventional ignition limits as points beyond which no mixture will propagate flame, no matter what the igniting source.

Lewis and von Elbe analyse these data on a purely thermal basis with some success, making use of the Mallard-Le Chatelier formula with its outmoded concept ignition temperature, though they recognize that the production of atoms and radicals must be the ultimate goal. Actually, too little is known of the primary action of the discharge to permit a complete solution, but there are interesting possibilities.

Special attention may be directed to the mixtures containing helium or argon in place of the nitrogen of ordinary air. The minimum energies for ignition bear no direct relation to the speed of propagation of the established flame. For $N_2:A:He$, the speeds are given as 60:180:210 cm. per second [Jones and Coward, *J.A.C.S.* 49, (1927)] whereas the minimum energies are 4500:800:18000 ergs. Higher flame speeds in helium and argon relative to nitrogen may be attributed to higher equilibrium atom and radical concentrations consequent on the higher flame temperatures (lower heat capacities, see below). The ignition energies do not stand in direct relation to ionization energies, which may be taken as 15.58:15.68:24.46 electron volts for $N_2:A:He$ (Herzberg, *Atomic Spectra*, p.290; *Molecular Spectra*, p. 500), though the high value for helium may be significant. With respect to nitrogen and argon, a rate process would seem to be involved, since it is well known that, at low pressures at least, it is far easier to excite a discharge in argon than in nitrogen even though the ionization energies are nearly the same.

Another anomaly in correlation of ignition energies and flame speeds is met with in the pressure effect. Ignition rapidly becomes more difficult as pressure is lowered, yet the first effect on flame speeds is an increase with decreasing pressure. The latter may be associated mainly with increase in mean free path and more efficient diffusion of atoms

and radicals. It is possible that a similar effect is operative with respect to ignition energies. Since the spark is generated in a small enclosure between glass plates, there may be greater loss of atoms and radicals by wall-recombination at lower pressures.

Clearly there are many interesting problems presented. It is to be hoped that further data will be obtained comparing fuels which are thought of as easily ignited, such as ether and carbon disulfide, and those which are difficult to ignite, such as ammonia. A comparison of n-heptane and iso-octane should likewise produce valuable data in connection with the knock problem.

There are other possibilities in modes of ignition which merit further investigation. *Thermal ignition*, with its ignition lags and ignition temperatures, has proved to be something of a blind alley, principally because the very important consideration of propagation by atoms and radicals has usually been ignored. Only for pressure-limited branched chain explosions (e.g. $H_2 + O_2$) have useful data been obtained. If a principal source of uncertainty arises from wall reactions which liberate free radicals, it should be profitable to investigate such catalytic effects more directly. Ignition by a hot body in a cold gas is one method of approach. Interesting anomalies have already turned up. For example, a hot platinum wire, which should be an outstanding oxidation catalyst, is much less effective than tungsten or nichrome. All are surpassed by certain refractories. It would appear that a catalyst can do too good a job in disposing of all reactants at its immediate surface. What is required is a copious release of atoms and radicals into unburned gas, but it is not known under what conditions this occurs. Industrial processes for the oxidation of ammonia, methanol, and sulphur dioxide involve passage through metal gauzes, but it is not certain whether a pure surface reaction, or a reaction chain propagating from the surface is involved. Investigation of "flash-back" from such surfaces or from plugs of catalyst in a reaction tube would give information on this point.

Photochemical ignition is a neglected field. It is well known that very pure hydrogen-chlorine mixtures explode on exposure to sunlight. By disposing the apparatus so that radiation of known wave length and intensity is introduced across one end of a blacked reaction tube, a minimum energy for successful propagation down the tube could be obtained. For the particular case of hydrogen and chlorine, the elementary processes may be very precisely defined, and hence a rational approach to the minimum energy problem developed. Other possibilities may be considered. Thus a hydrogen-chlorine mixture at one end of the tube might be used to fire another combustible mixture. Alternatively, useful results might be obtained with other absorbers of radiation, such as acetone and the like. Another variant might depend on the firing of magnesium powder by a radar beam.

With respect to *normal flame speeds*, what appears to be a useful theoretical approach has recently been developed in the Princeton Laboratory by Tanford (July and December 1947 issues of *Journal of Chemical Physics*). It is assumed that in the Bunsen flame at low flow velocities (Reynolds number less than 2,000) the speed of propagation is determined by the diffusion of atoms and radicals from the flame front into unburned gas. Atom and radical concentrations are assumed to correspond to thermodynamic equilibrium at the adiabatic flame temperature, both concentrations and flame temperatures being arrived at by successive approximations. Calculated equilibrium atom concentrations have been utilized in the past with success in accounting for the kinetics of reaction. In any case, they establish a norm about which deviations should group themselves.

The steady-state concentration gradients of atoms and radicals are evaluated by equating a diffusion term to a term for the mass flow of fuel-air mixture up to the flame front:

$$D \frac{d^2c}{dx^2} = -u \frac{dc}{dx}$$

or

$$\frac{dc}{dt} = 0 = D \frac{d^2c}{dx^2} + u \frac{dc}{dx}$$

where

- c = atom or radical concentration
- x = distance from the flame front
- t = time
- D = diffusion coefficient
- u = linear feed velocity.

In order to arrive at a manageable solution, the temperature gradient from the flame front into unburned gas is ignored. This involves a number of approximations. Thus the expansion of the gas as it warms has the effect of decreasing concentrations, and it increases both the diffusion coefficient and the local linear feed velocity. To some degree these cancel, but a considerable approximation remains. The equation can now be readily solved to give:

$$c = c_0 e^{-\frac{u}{D} x}$$

where C_0 = equilibrium concentration in the flame front ($x = 0$)
 C = concentration at distance, x , from the flame front.

The reaction rate at a point, x , is now expressed in terms of a bimolecular process:

Atom + reactant \longrightarrow product

$$dQ = kCcdt$$

Q = quantity of reaction occurring

k = rate constant

C = concentration of reactant

c = local atom or radical concentration.

Further, since

$$\frac{dx}{dt} = u$$

$$dQ = kCc \frac{dx}{u} = kCc_0 e^{-\frac{u}{D} \frac{dx}{u}} .$$

An additional approximation is now introduced. In order that the reaction shall be complete at the flame front, the concentration of reactant, C , should reduce to zero which would take infinite time. Further, as the temperature rises near the flame front, the rate constant should increase exponentially. The approximation then consists in taking a constant average concentration, C_{ave} , and regarding this and k as constants. Integration then leads to:

$$Q = kC_{ave} c_0 \frac{D}{u^2}$$

$$u = \left(\frac{k C_{ave} c_0 D}{Q} \right)^{1/2}$$

This is the approximate form on which the following discussion is based.

In the published papers this approximation is applied with some success to the combustion of carbon monoxide containing water vapor and hydrogen. It is well known that dry pure carbon monoxide burns with extreme difficulty. The rate rises rapidly when hydrogen or hydrogen-containing substances are added. When flame speeds are plotted against calculated equilibrium hydrogen atom concentrations, very good correlation is obtained, the dependence being not far from

$$u \sim c_0^{1/2}$$

A similar plot against hydroxyl radical concentrations yields nearly as good correlation. However, the plot against oxygen atom concentration is of the "shotgun" variety. It would thus appear that reactions involving oxygen atoms are relatively unimportant. The equivalence of hydrogen and hydroxyl is perhaps to be attributed to the reactions



and



A similar correlation appears to apply in the combustion of hydrogen. In this case, hydrogen and hydroxyl concentrations are substantially higher, and the rates are correspondingly larger.

Further confirmation of the approximation is obtained from experiments in which helium or argon is substituted for the nitrogen of ordinary air. As mentioned in the discussion of ignition energies, rates are substantially increased. Thus for stoichiometric mixtures with methane values of 60:180:210 cm. per sec. are given for N_2 :A:He. The main portion of this increase is due to the fact that the lower heat capacities of argon and helium result in higher flame temperatures and hence higher atom and radical concentrations; the remainder is the contribution of the diffusion coefficient.

In the related case of butadiene-1,3 combustion, studied in the Princeton Laboratory, it was calculated that H-atom concentrations would be 8.8 and 43×10^{-4} atm. in ordinary air and in "helium" (or "argon") air, respectively. The diffusion coefficients for H-atoms into nitrogen and into helium at the flame temperatures were calculated by the Stefan-Maxwell equation to be 62 and 143, respectively. Comparison with observed Bunsen burner flame speeds of 43 and 143 cm. per sec. gave excellent agreement with the approximate equation.

Additional confirmation is afforded by experiments at 1/2 atm., where the burning velocity (ordinary air) is raised to 53 from 43 cm. per sec. at 1 atm. This increase represents the combined effects of a decrease of atom concentration as the square root of the pressure, and an increase in diffusion coefficient (due to increase in mean free path) inversely as the first power of the pressure, as the latter is decreased. The result is that the burning velocity should vary inversely as the fourth root of the pressure, which is approximately the case. Similar examples of the increase of flame speeds with decrease in pressure are scattered through the literature. Ultimately the curve goes through a maximum and falls to zero, apparently because combustion is no longer complete in the flame zone.

This atom diffusion theory obviously cuts a number of corners, especially in the approximation considered. In particular it makes no allowance for gain of atoms and radicals by chain-branching or loss by chain-ending processes. It implies that extraneous sources of atoms and radicals "additives," should not be effective in small amounts, yet such substances are known. Conversely, it ignores the possibility of inhibitors, atom and radical "traps," for which there is evidence. It even ignores the detailed mechanism of the overall combustion reaction. Nevertheless, the theory does provide a standard in terms of which Bunsen-type flame speeds in the laminar region may be judged.

Such flames represent a reasonably stable and reproducible sort of combustion, as the wide use of the Bunsen burner testifies. In addition to such relatively low speed flames, it has been known for a long time that there is another high-speed regime of predictable characteristics, represented by *detonation* in closed tubes. By no means all mixtures which will support Bunsen flames have actually been detonated. Nevertheless, there is sufficient overlap to warrant the statement that two stable ranges of propagation exist.

Detonation corresponds to an understandable upper limit for flame propagation since it proceeds at sonic velocity calculated for the conditions at the flame front, with allowance for mass motion of the charge due to thermal expansion of the portion already burned. Under these circumstances the atom diffusion mechanism seems to be entirely superseded by processes occurring in the adiabatic expansion-compression cycle of the wave front, whereby atoms and radicals in the flame are efficiently mixed with unburned gas. Account need be taken of the chemical reaction only as it affects heat release and the composition of the burned gas. These factors in turn determine the temperature, T , the specific heat ratio, γ , and the average molecular weight, M , which enter into the equation for sonic velocity

$$U_s = \frac{(\gamma RT)^{1/2}}{M}$$

They also determine the expansion ratio for burned gas, which is responsible for the mass motion.

Flame propagation in tubes at other than detonation speeds presents a more complex picture. Observed linear velocities vary over a wide range in a single experiment (the flame halts and accelerates), and often from one experiment to the next, and depend on the diameter and the orientation of the tube. The flame itself has been observed to change shape and size, and to undergo vibration (cf. Coward and Hartwell, *J. Chem. Soc.*, 1932, p. 2676). This appears to be due in part to disturbances arising in the flame

which are reflected back from the end of the tube; but mass motion due to expansion and subsequent contraction of the portions of charge already burned must be taken into account. Noteworthy progress on these and other aspects of flame travel have been made recently by Professor MacDonald's group at New York University, though much still remains to be done.

One particularly interesting and puzzling case which has been studied by Professor MacDonald's group relates to the effect of a wire screen in enhancing flame speed. As already mentioned, the rate at which a flame advances through quiescent gas is not entirely constant, but a value of something like 20 ft./sec. for downward propagation in a 4 inch glass tube might be characteristic of a stoichiometric propane-air mixture. If now a wire screen is fitted into the tube a few inches from the top but below the firing point, this rate is increased to perhaps 200 ft./sec. Moreover, this effect does not die out, but persists at least over an 8 ft. length of tubing. If the gas had been in motion, and a flame had propagated from such a screen, the latter would have been called a flame holder. Capacity for handling fuel-air mixture at an increased rate would have been ascribed to flame stabilization in the wake of the screen wires. The experiment described above seems to indicate that something more is involved since flame propagates at higher rate even in initially quiescent gas.

Such experiments will indicate how little is yet known about flame travel even in quiescent gas. A high-velocity fuel-air stream introduces its own complications in the form of stream turbulence (whatever that may turn out to mean), and of vortices, eddies, ripples, and primitive sound waves set up by encounters with obstacles such as flame holders and auxiliary pilots. Such effects undoubtedly promote vaporization and mixing, and they must influence flame travel, though not necessarily for the better. Too little is known of either aspect of this problem in combined chemodynamics and aerodynamics to be more specific, but it is at least clear that new experimental and theoretical approaches conducted without immediate reference to practical application are urgently needed. It is here that expensive equipment may be essential in basic research, especially on the nature of scale-effects.

Slow Combustion and Elementary Reactions

It may seem a far cry from the types of processes just considered to the sort of slow step-wise oxidation of fuel molecules which has been studied at lower temperatures. Nevertheless, the one involves the other, particularly with respect to conditions for the initiation of flame or explosion. Many examples could be cited, but perhaps it is sufficient to recall only Edgar's classical researches, which first revealed by slow

combustion experiments the great differences in reactivity between straight chain and highly branched chain paraffins [Pope, Dykstra and Edgar, *J.A.C.S.* 51, 1875, 2203, 2213 (1929)].

It is by no means intended to review the whole field of slow combustion. Considerable progress had been made before the war in understanding the kinds of chain processes which are involved, but much remains to be done.

Among potentially important reactions, almost nothing has been published about the behavior of systems containing oxygen and the boranes, or hydrazine, or even ammonia (non-catalytic reaction); of the reactions of fluorine with hydrogen and hydrocarbons; or of the decomposition of nitro-paraffins. Such studies would have a practical bearing as related to safety provisions quite apart from chemical aspects.

Even in hydrocarbon oxidation there are many features which have not been fully investigated. Thus the use of tracers and micro techniques might facilitate detection of the primary products which must be accumulating during the long induction periods. It has been variously assumed that olefines or peroxides or aldehydes were responsible. Formaldehyde has been given a primary role in methane oxidation at least, yet Hinshelwood has recently suggested that in hexane oxidation formaldehyde is an inhibitor (September 1947, *Discussion, Faraday Society*).

Again, there is evidence of two rather distinct mechanisms of homogeneous oxidation of the higher paraffins according as the temperature is somewhat above or below 400°C, with a region of negative temperature coefficient between. Further, if the reaction tube is packed with broken glass, these mechanisms are suppressed, and there is little reaction until temperatures (> 500°C) are reached appropriate to dissociation of the hydrocarbon. More detailed investigations of reaction kinetics in these ranges would be desirable. Complete chemical analyses are also lacking, and might perhaps be facilitated by use of the mass spectrograph.

Relatively little has been done with accelerators and inhibitors in hydrocarbon oxidation. The question of the action of formaldehyde was mentioned above; a few experiments with lead ethyl are available; inorganic alkyls and hydrides have been shown to induce explosion. But there is need for systematic exploration. One possibility would be to utilize more fully the intermediates of the reaction itself. Flow experiments are commonly carried out in cylindrical tubes. An alternative would be to promote mixing of fresh reactants with partially reacted gas by stirring in a spherical vessel, or by some form of feed-back. This is of special interest since the induction period

points to slow accumulation of a moderately stable intermediate. Perhaps much lower reaction temperatures could be arrived at in this way, with consequent stabilization of products.

Finally, a great deal has yet to be understood about the details of the atom and radical reactions involved in oxidation and related chain processes. Once again the mass spectrograph gives promise as an analytical tool (cf. Fltnton, July 1947, *Journal of Chemical Physics*). Starting with quite simple processes such as the thermal decomposition of metal alkyls or the photolysis of suitable compounds, it should be possible to build up a body of quantitative data regarding types of radicals produced and their yields. This would open the way to a quantitative estimate of the functions of radicals in chain processes. One exceptionally interesting possibility is presented by the boron hydrides, where the strength of the B-H bond might be quite low.

In addition to the above, the mass spectrograph can furnish data on bond energies by utilization of appearance potentials. This is a field which promises further rich rewards, especially in relation to chemical kinetics.

Perhaps it is unnecessary to add that studies such as are outlined above bear not only on the understanding of combustion processes, but also on commercial production of useful products of oxidation of hydrocarbons. It has been possible for some time now to proceed from hydrocarbons via water gas to such products as methanol and hence formaldehyde. Preservation of part or all of the hydrocarbon chain by direct oxidation should yield a series of substances not now cheaply obtainable. In this connection, the present availability of low-cost oxygen and high-purity hydrocarbons is an important consideration.

The above remarks will indicate some of the directions in which research on combustion might be pressed. It is not meant to imply that all will be pursued at Princeton in the immediate future, but it may be hoped that by the end of another year many of the questions which have been raised will have received at least tentative answers.

PHASE 3

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

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 operation of propulsive devices of the ducted type. The phase was initiated in July 1947 and is being undertaken by the Department of Aeronautical Engineering under Contract No. N6-ori-105.

From the standpoint of practical application the work has been stimulated by theoretical considerations which indicate that under static conditions a combination rocket-ram jet or "inducer" ram jet can produce a thrust considerably in excess of that of the rocket alone, that is, augmentations of the order of 100% appear to be quite feasible. Such a system also appears to have a desirable constant thrust characteristic with forward speed.

One of the key fundamental problems associated with the operation of devices of this type is that of the mixing of the supersonic actuating stream and the induced secondary stream, which may be subsonic or supersonic. This problem of the mixing of a supersonic and a subsonic stream or two supersonic streams at different Mach numbers is one of considerable interest in the fluid mechanics field at the present time.

The experimental portion of the work under Phase 3 is divided into two stages. The first is to be a fundamental study of the process of mixing of a supersonic stream with a subsonic stream. Apparatus for this study is in the process of construction.

The second stage involves the use of a rocket exhaust jet as the primary stream. A small gaseous rocket utilizing methane and oxygen is being constructed at the present time. Test work will first proceed on the rocket alone, then rocket with duct, and finally rocket with duct and after-burner, thus simulating the entire ducted rocket propulsion system.

Suitable facilities for this work are available at Princeton.

Statement of the Problem

The simplest of all ducted propulsive devices is the rocket thrust augmentor. If a duct or tube is placed around the exhaust jet of a rocket, it is found that air will be entrained in the exhaust jet creating a low pressure area around the jet. Air from the outside then flows into the duct and a steady secondary flow is established. This flow, when mixed with the exhaust gases is expelled to produce a net increase in momentum.

The amount of augmentation of the rocket thrust available varies widely with various parameters involved. The action of the thrust augmentor is based on the same principle as that of the jet pump in common use.

As a propulsive device the simple rocket thrust augmentor has certain basic disadvantages. Although it may add as much as 75% to the rocket thrust, the amount of thrust per unit cross-sectional area of the device is very low and decreases as the augmentation is increased. Furthermore, the amount of augmentation is at a maximum when the device is standing still, and falls off very rapidly with forward motion. These factors limit the use of such a device to cases where the forward motion of the device is small. A possible useful application would be as an assisted takeoff device with a duct which could be discarded when high flight speeds had been obtained.

The thrust augmentor may be greatly improved if fuel is injected downstream in the duct and burned with the secondary air.

A still greater improvement should be possible by slowing down and compressing the mixed gases in a diffuser before injecting the additional fuel. The device becomes thus a "supercharged" ram jet, in which the rocket and duct provide an entrance flow for the afterburner which is essentially a ram jet. Such a device would be able to develop considerable thrust statically and would have the further advantage that the rocket could be shut off after a certain flight speed had been obtained, after which the propulsive unit would act as a pure ram jet.

The crucial point in the development of such a system is the design of the rocket and duct assembly. The air-induction effect of the rocket jet depends directly upon a complete mixing of primary and secondary streams before the gases have left the duct.

To date, experimental efforts have met with little success in achieving satisfactory mixing in ducts of reasonable length. Since, as has been pointed out, the mixing is one of the key processes determining the efficiency of devices of this type, further theoretical and experimental studies appear to be required to obtain a clearer picture of the phenomena involved. This is essential before other problems associated with the development can be accurately attacked.

Specific problems requiring investigation in connection with the development of such a device are:

1. The design of the entrance duct,
2. The design of the ram jet entrance diffuser,

3. The design of the combustion chamber, with special attention to flame holders, ignition systems, and possibly cooling,
4. The design of the exit nozzle, possibly with a variable throat area.

Plan of Research

(a) *Personnel.* The program of research under Phase 3 at Princeton is under the direction of Dr. Joseph V. Charyk of the Department of Aeronautical Engineering, with the assistance of Research Associate K. Dexter Miller, Jr., as Project Engineer, and Research Assistant H. Lawrence Pool. Further personnel will be added when the second stage of research has been reached.

(b) *Experimental Studies.* The first stage of research on this problem will be

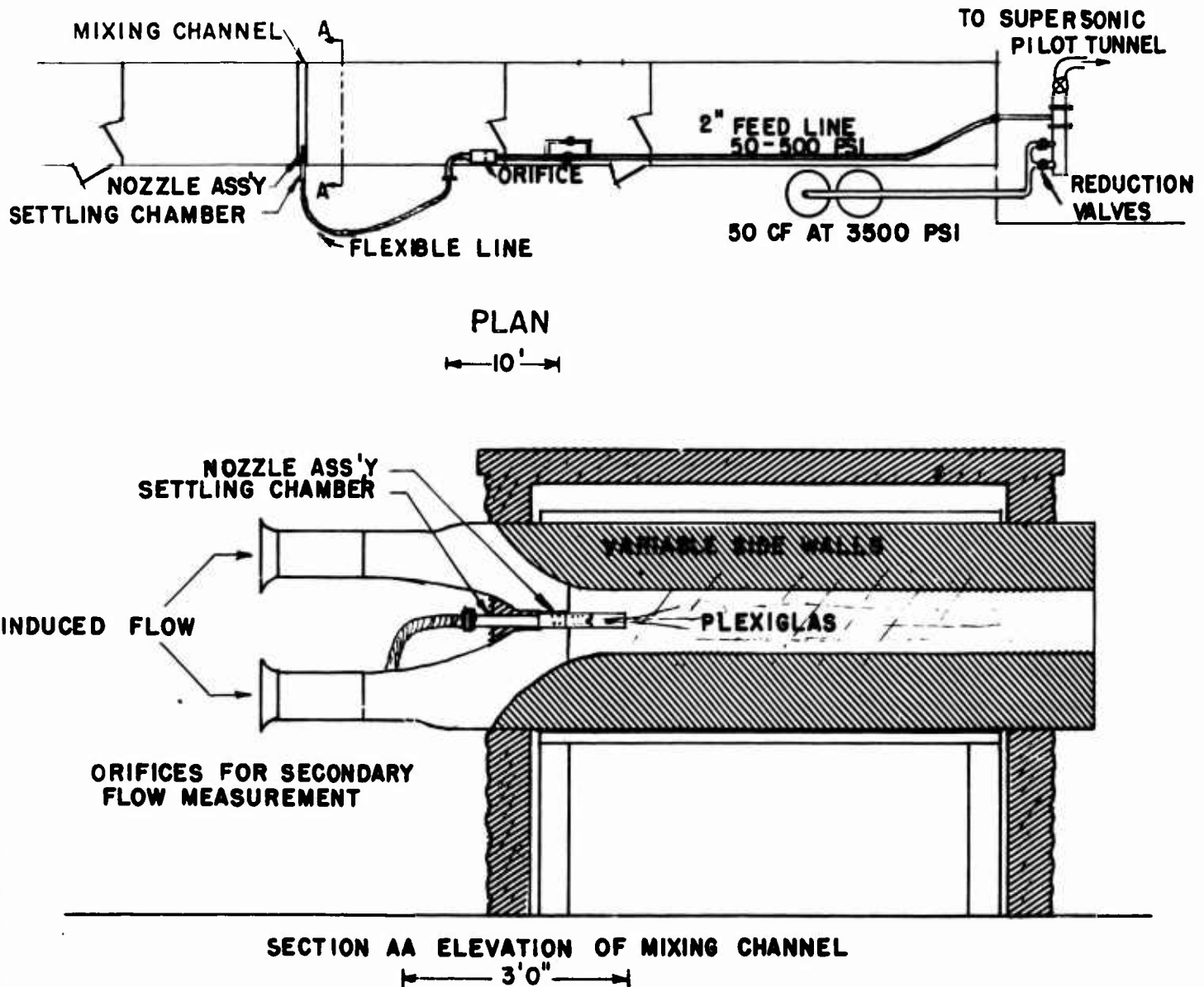


Figure 5.
 Apparatus for mixing studies.

to study the processes involved in mixing primary and secondary streams. The apparatus for studying these effects (see Figure 5) is under construction, and should be in operation by February. Air at 3500 p.s.i. is contained in two 25 cubic foot air bottles which are pumped up by a gasoline engine compressor. In operation, the air passes through a pair of reduction valves which reduce the pressure to a value set between 50 and 500 p.s.i. The air then passes down a 2-inch feed pipe to the installation. A length of flexible piping connects the feed pipe to a settling chamber where the flow is straightened out by a series of screens. The air then enters an adapting block and passes out through a two-dimensional nozzle as a supersonic stream. This stream is two-dimensional in character and stretches from wall to wall in the $1\frac{1}{2}$ -inch channel.

The walls of the channel are mostly of plexiglass except in the vicinity of the nozzle, where they are made of plate glass for purposes of more satisfactory observation. The channel itself is three feet high, ten feet long, and one and one-half inches deep. Secondary air is drawn from the outside through flow-measuring venturis, and the mixed gases are ejected to the outside on the far side of the building. The inside vertical dimension of the mixing channel will be made variable through the use of removable side blocks (see Figure 5).

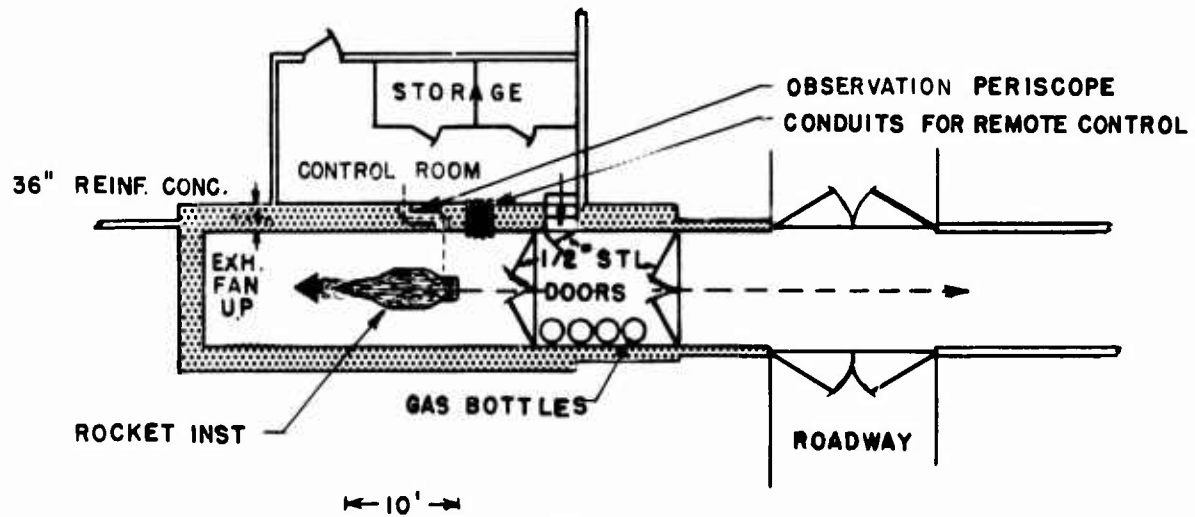
The Schlieren system will use a pair of 12-inch diameter, 96-inch focal length parabolic mirrors mounted on a movable carriage so that observations may be made along the length of the mixing channel. The light source will be a magnesium arc with a flash time on the order of one microsecond.

In addition to shadowgraph and Schlieren photography, mass flow measurements of both primary and secondary streams will be made, and temperature, pressure and total head readings will be made at various points in the channel.

The air jet used in the first stage will be a cold jet and will have a greater induction efficiency than the hot jet of a rocket motor. In order to produce a hot jet similar to that of a production rocket, the second stage of research on this project will be centered about a small rocket. This rocket motor will use gaseous methane as a fuel and gaseous oxygen as the oxidizer. This system was chosen in the interests of simplicity and economy.

This gas rocket will be installed in a concrete test pit shown in outline in Figure 6. This test area has been made available to the Department of Aeronautical Engineering for this work. The test area proper is about 10 feet wide and 20 feet long, surrounded on three sides by 36 inches of concrete and on the fourth by two sets

of ½-inch steel doors. An overhead crane-way is suspended from the ceiling to facilitate the installation of equipment. A large observation and control room is available, equipped with a periscope for safe observation and with conduits through the concrete wall for controls and instrumentation. Exhaust gases will be carried away through an overhead blower at one end of the pit.



← 10' →

Figure 6.

Plan of ducted rocket test pit.

(c) *Theoretical Studies.* Concurrently with the experimental program outlined above, a program of theoretical studies of the operation of a ducted propulsive device will be carried out. Theoretical studies will be made of the air-induction system and of the entire apparatus. These studies will be carefully compared with the experimental data to be obtained in order to develop a design theory for ducted propulsive units.

In addition, a theoretical approach to the mixing problem will be initiated.

Progress, 1 January 1948

Experimental Equipment. The two-dimensional jet mixing channel is under construction and should be completed this month. The steel and concrete foundations are in place, and the major components are nearing completion. All critical components have been arranged for or are on hand.

The gaseous rocket for the second experimental stage of this program is in the preliminary design stage, and consequently no accurate time estimate can be made for the completion of this installation.

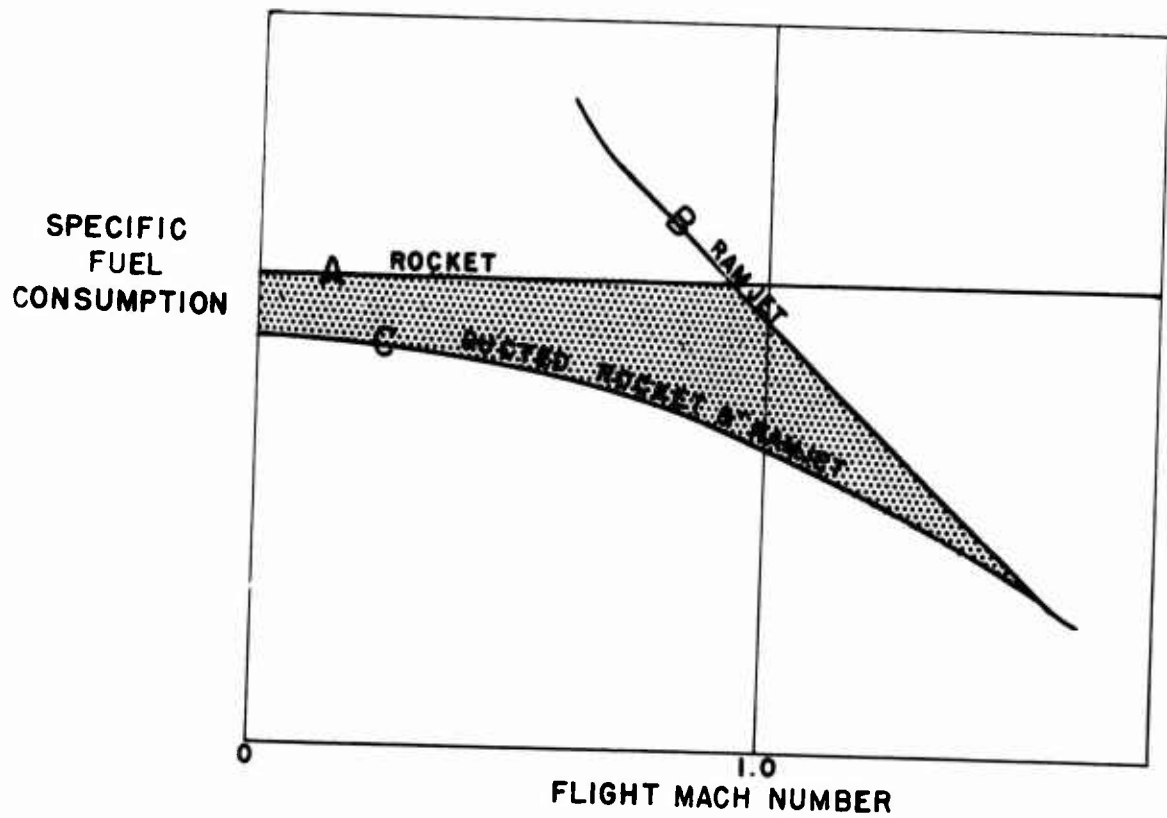
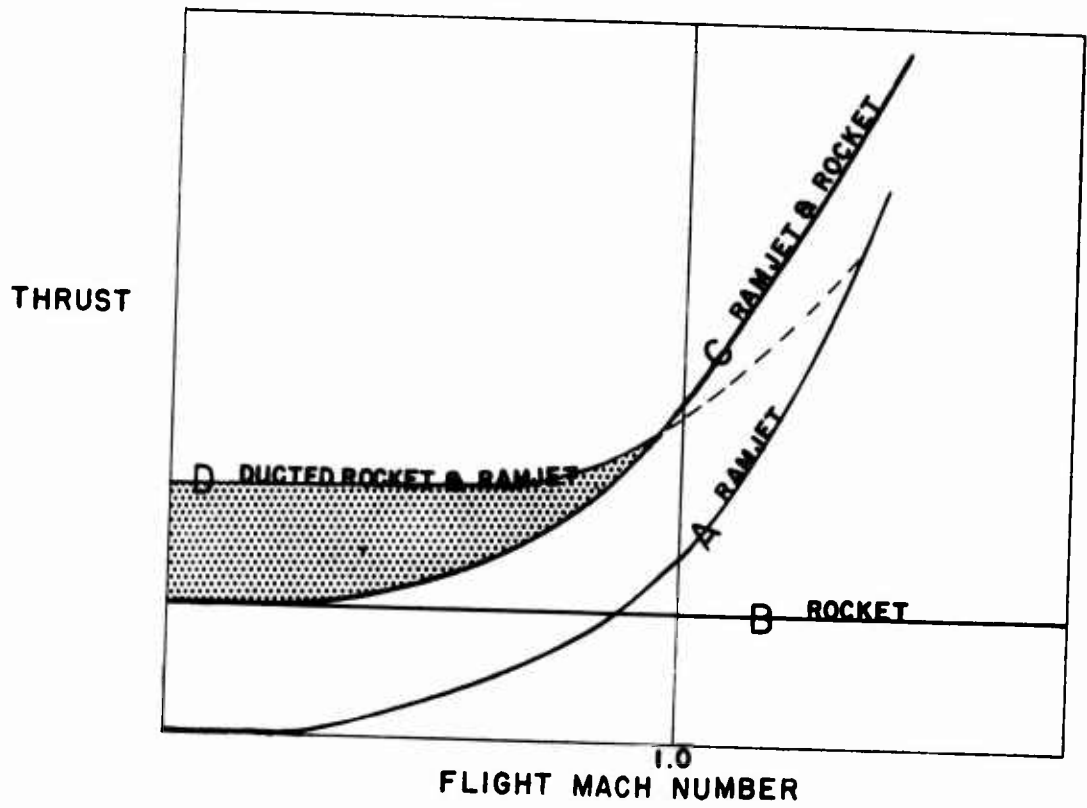


Figure 7.
Performance of ducted rocket system with flight velocity.

Theoretical Studies. A simplified analysis of the flow in a ducted rocket air inducer has been obtained and will be issued shortly as a Technical Report. The development of the solution follows the same general line as that of other investigators of this problem, but the solution is expressed in terms of design parameters which are readily computed for any jet induction system.

A few calculations of the performance of an entire ducted rocket propulsive device, or supercharged ram jet, have been made, and qualitative results of these calculations are shown in Figure 7a. The curve A in this figure represents the thrust of a ram jet at various forward speeds. This unit provides adequate thrust only at high flight velocities. Line B represents the flat thrust curve of a rocket motor. Curve C is the sum of A and B and represents the thrust of a ram jet plus an auxiliary rocket. Curve D is the thrust available from a "supercharged" ram jet whose components are the same as those of A and B. The shaded area represents the excess thrust available by use of the ducted rocket to supercharge the ram jet.

The flat thrust characteristic of the compound unit at low forward speeds seems to be typical of such units. The dotted portion of D after its intersection with C represents a gradual throttling back of the rocket until, at its intersection with A, the rocket is completely shut off and the unit runs thereafter as a pure ram jet.

Preliminary calculations show that the specific fuel consumption of a supercharged ram jet at low forward speeds is superior to that of either component. This is shown qualitatively in Figure 7b.

APPENDIX

Technical Reports and Memoranda

During the period 1 January 1947 to 31 December 1947, the member universities of Project SQUID have submitted to the headquarters organization at Princeton 21 informal technical memoranda covering the technical progress at the respective universities. These memoranda have received general distribution, which includes internal as well as Army-Navy Guided Missiles list distribution, or internal distribution only, depending upon the importance placed on the memorandum by the originating organization. A list of the memoranda by universities, issued during the period indicated above follows. The distribution made is indicated in each case.

Cornell Aeronautical Laboratory

<u>Title and Author</u>	<u>Date</u>	<u>Memorandum No.</u>	<u>Distribution</u>
Frequency Response of Pressure Pickups 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 Analogy.—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
Two Dimensional Supersonic Wind Tunnel Simulation of the Flow Over the External Surface of Ducted Bodies with and without Spillover.—Murray Kamrass.	June 30, 1947	CAL No. 5	Internal

<u>Title and Author</u>	<u>Date</u>	<u>Memorandum No.</u>	<u>Distribution</u>
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
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

Princeton University

<u>Title and Author</u>	<u>Date</u>	<u>Memorandum No.</u>	<u>Distribution</u>
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

<u>Title and Author</u>	<u>Date</u>	<u>Memorandum No.</u>	<u>Distribution</u>
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
The Combustion of Butene-1 Induced by Aluminum Boro- hydride.—R. S. Brokaw, E. J. Badin.	Oct. 20, 1947	Tech.Paper No. 33	Internal
Critical Considerations of Burning Velocity Measure- ments 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 Oxy- gen 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.— Lester Lees.	Nov. 1. 1947	Pr-1	General
Unsteady One-Dimensional Flows with Heat Addition or Entropy Gradients.— A. Kahane, Lester Lees.	Nov. 27, 1947	Pr-2	General

Purdue University

<u>Title and Author</u>	<u>Date</u>	<u>Memorandum No.</u>	<u>Distribution</u>
The Measurement of Gas Temperature.—Max Carbon, R. J. Albert, G. A. Hawkins.	May 1, 1947	No number	Internal
The Measurement of Gas Temperature, II.—Max Carbon, R. J. Albert, G. A. Hawkins.	July 1, 1947	No number	Internal

In addition to the above listed informal technical memoranda, five formal technical reports have been issued during the same period. These reports contain information which was considered of sufficient significance to warrant formal printing and general distribution. A list of the technical reports by universities follows.

Cornell Aeronautical Laboratory

<u>Title and Author</u>	<u>Date</u>	<u>Tech. Report No.</u>	<u>Remarks</u>
Frequency Response of Pressure Pickups Required for Measurements on a Pulse Jet.—G. Rudinger.	June 16, 1947	Tech. Report No. 1	Reissue of Tech.Memo CAL-1
On the Possibility of Representing One Dimensional Gas Motion by Means of an Electrical Analogy.—J. Logan.	June 23, 1947	Tech. Report No. 2	Reissue of Tech.Memo CAL-2
Study of Gas Oscillations in Half-Open Pipes of Various Shapes.—G. Rudinger.	June 30, 1947	Tech. Report No. 3	Reissue of Tech.Memo CAL-4
Phenomena in Electrically and Acoustically Disturbed Bunsen Burner Flames.—M. L. Polanyi, G. H. Markstein	Sept.15, 1947	Tech. Report No. 5	Reissue of Tech.Memo CAL-3

Polytechnic Institute of Brooklyn

<u>Title and Author</u>	<u>Date</u>	<u>Tech. Report No.</u>	<u>Remarks</u>
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	

New York University

<u>Title and Author</u>	<u>Date</u>	<u>Tech. Report No.</u>	<u>Remarks</u>
One Dimensionalized Aero-thermodynamic Theory of Turbulent Flame Propagation in Flame Tubes.—J.K.L. MacDonald.	Nov. 1947	Tech. Report No.6	Not yet printed
A Preliminary Study of Flames in Tubes Containing Grids.—M. W. Evans, M. D. Scheer, L. J. Schoen.	Dec. 1947	Tech. Report No.7	Not yet printed

DISTRIBUTION

1. Army-Navy Guided Missiles List No. 5, Dated February 1948, Parts, A, B, C, DP.
2. Bureau of Aeronautics, Power Plant Division, Experimental Engines Branch, Washington, D. C.,
Attn: Lt. Comdr. C. Hoffman.
3. Chief of Office of Naval Research, Power Branch, Washington, D. C., Attn: Comdr. J. L.
Shoenhair.
4. Commanding Officer, Office of Naval Research, New York.
5. Commanding Officer, Office of Naval Research, Chicago.
6. U. S. Navy Office of Naval Research, Branch Office, San Francisco, California.
7. Naval Ordnance Test Station, Pasadena, California.
8. Policy Committee, Project SQUID.
9. Technical Committee, Project SQUID.
10. Metallurgical Advisory Committee, Project SQUID.
11. Technical Panels, Project SQUID.
12. Contract Administrators of Project SQUID at the member universities.
13. Phase leaders within Project SQUID not covered by above distributions.
14. Columbia University Engineering Library.
15. Purdue University Library.
16. Mr. A. Bodine, Bodine Soundrive Co., Los Angeles, California.
17. Prof. F. Clauser, Johns Hopkins University.
18. Dr. B. L. Crawford, University of Minnesota.
19. Mr. L. B. Edelman, Baton Rouge, Louisiana.
20. Prof. Clark Millikan, California Institute of Technology.
21. Prof. R. Folsom, University of California.
22. Dr. A. W. Sloan, Engineering Research Associates, Inc., Arlington, Va.
23. Mr. William Tenney, Aeromarine Company, Vandalia, Ohio.

TITLE: A Program of Fundamental Research on Liquid Rocket and Pulse Jet Propulsion for the Bureau of Aeronautics and The Office of Naval Research of the Navy Department

AUTHOR(S): New York Univ.

ORIGINATING AGENCY: New York University, N. Y.

ATI- 22103

REVISION none

ORIG. AGENCY NO.
none

DATE
Jan '48

DOC. CLASS.
Unclass.

COUNTRY
U.S.

LANGUAGE
Eng.

PAGES
157

ILLUSTRATIONS
photos, tables, diagr, graphs, drwgs

ABSTRACT:

P21/09,01

A summary is presented of the experimental and theoretical investigations that were carried out on liquid rocket and pulsejet engines. Investigations included the study of flame propagation in jet tubes, characteristics of heat transfer between flowing gases and walls, effects of turbulence in pulsating jet and rocket engines, the development of recording instruments, study of drag characteristics of pulsejet engines and investigation of reciprocating and rotating valve mechanisms. Theoretical and observed results of these studies are included.

U

*A liquid rocket propellants
A guided missiles 257250*

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

DIVISION: Guided Missiles (1) *42*

SECTION: Propulsion (3) *4*

ATI SHEET NO.: R-1-3

SUBJECT HEADINGS: Missiles, Guided - Propulsion (63450);
Engines, Pulse jet - Development (33988.2); Engines, Rocket -
Development (34108.7); Squid (63450);

Air Materiel Command
U. S. Air Force

AIR TECHNICAL INDEX

Wright-Patterson Air Force Base
Dayton, Ohio

TITLE: Project SQUID Annual Program Report

AUTHOR(S): (Not known)

ORIGINATING AGENCY: New York University, New York, N. Y.

PUBLISHED BY: Navy Department Bureau of Aeronautics and Office of Naval Research

ATI- 25803

DIVISION

(None)

ORIG. AGENCY NO.

(None)

PUBLISHING AGENCY NO.

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Jan '48	Unclass.	U.S.	Eng.	180	photos, diagrs, graphs, dwgs

ABSTRACT:

Progress made in the development of project Squid, a research program on liquid rocket and pulse jet propulsion, is discussed. Two flame tubes were designed to study pulse jet turbulent combustion, one for moving and one for stationary flames; and a one-dimensional theory of wave and flame propagation in tubes was developed. Studies were made of the flow of air through valve systems of pulse jets, of the sweat-cooling of combustion chamber liners, and of the microstructure of shock waves. Apparatus has been designed for detecting, amplifying, observing, and recording the electrical impulses from thermocouples. Pulsating jet engine theoretical and wind tunnel investigations were made of non-steady gas flow in ducts of various shapes, of the free-piston pulse jet, of the boundary layer-shock wave interaction, and of triple shock interaction.

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

DIVISION: Engines, Jet and Turbine (5)

SECTION: Design and Description (18)

SUBJECT HEADINGS: Engines, Pulse jet - Development (33988.2); Engines, Rocket - Development (34108.7)

ATI SHEET NO.: R-5-18 -37

Air Documents Division, Intelligence Department
Air Materiel Command

AIR TECHNICAL INDEX

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