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PROJECT SQUID

QUARTERLY PROGRESS REPORT

1 April, 1950

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QUARTERLY PROGRESS REPORT

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

A Cooperative Program
Of Fundamental Research in Jet Propulsion
For The
Office of Naval Research, Department of the Navy
And The
Office of Air Research, Department of the Air Force

Contracts and NR Numbers:

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1 April 1950



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I. J E T P R O P U L S I O N E N G I N E S

A. EXPERIMENTAL INVESTIGATION OF THE EFFECT OF COMBUSTION CHAMBER PRESSURE UPON ROCKET MOTOR PERFORMANCE AND HEAT TRANSFER. (PRF-7R8 and PRF-7R9).

Submitted by: C.F. Warner and C.M. Beighley, Purdue University.

The object of problems PRF-7R8 and PRF-7R9 is to determine experimentally the influence of combustion chamber pressure upon the performance of, and heat transfer in, rocket motors. Studies are to be based upon a motor using approximately 98 per cent concentrated nitric acid as the oxidizer and commercial AN-F-58 as the fuel.

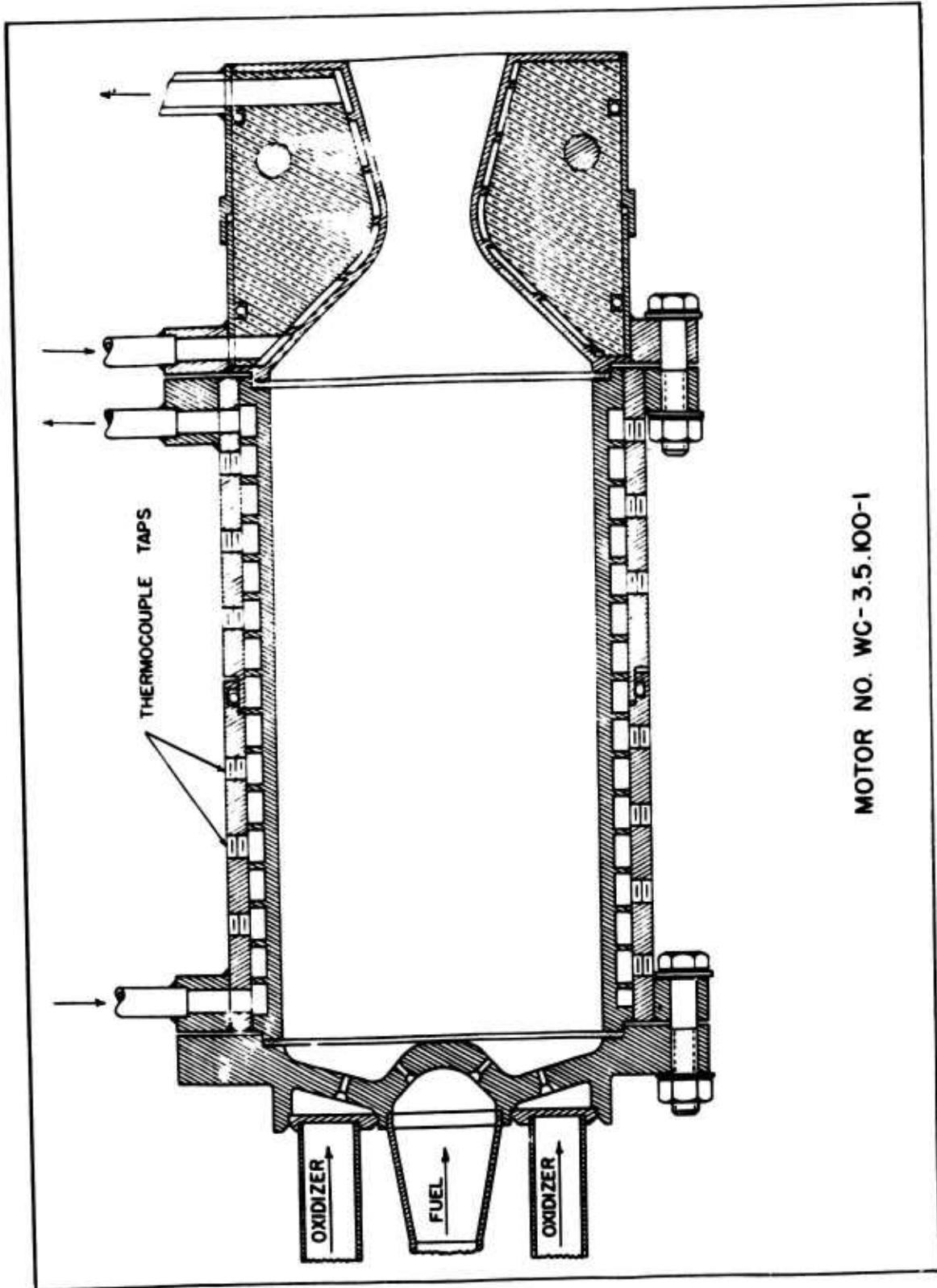
Tests have been conducted on a 500-lb thrust rocket motor (No. WC-5.3.100-1), shown in Fig. 1, designed for 300 psi combustion chamber pressure. This motor has an L^* of 100 inches and a 1 to 1 impingement injector with six impingement points. Combustion is initiated by injecting furfuryl alcohol ahead of the AN-F-58 fuel. The combustion chamber and nozzle are water cooled with thermocouple outlets located at various positions along the chamber. Fifteen runs have been made at chamber pressures varying from 222 to 375 psi and with oxidizer-fuel mixture ratios varying from 3.2 to 7.2. The average performance and heat transfer data are given in Table I.

Additional runs will be made at 300 psi chamber pressure with various mixture ratios to check the instrumentation calibrations and to obtain data to be used as a basis for reporting the performance and heat transfer results at the higher chamber pressures.

Two water-cooled nozzles designed for operation at 500 psi and 700 psi combustion chamber pressure with 500-lb thrust are being fabricated to fit the combustion chamber of the (No. WC-5.3-100-1) motor. These nozzles consist of a stainless steel shell wrapped with 3/8-inch copper tubing silver-soldered to the shell. This motor will be operated at 500 and 700 psi chamber pressure in order to obtain preliminary heat transfer and performance data which will be used in the design of the higher chamber pressure motors.

The design of a 500-lb thrust, 500 psi combustion chamber pressure, 60-inch L^* motor has been completed. Both the chamber and the nozzle sections will be water cooled in order to obtain heat transfer rates. The nozzle, chamber, and injector shells will be fabricated from Type 347 stainless steel.

The preliminary design of a 500-lb thrust, 700 psi chamber pressure motor has been initiated. The design of motors to operate at combustion



MOTOR NO. WC-3.5.100-1

FIG. 1

Table I. Average Performance Data for Rocket Motor. (Motor No. WC-5.3.100 - 1)

Run No.	Thrust T (lb)	Chamber Pressure P _c (psi)	Mixture Ratio R (O/F)	Specific Impulse I _{sp} (sec)	Characteristics Velocity C* (ft/sec)	Nozzle Heat Trans. q _n (Btu/sq in/ sec)	Chamber Heat Trans. q _c (Btu/sq in/ sec)	Comments
9	417	222	7.21	153	3163	.33	.16	Temps. doubtful
10	535	295	3.23	166	3530	.352	.268	
11	Explosion in injector							
12	555		5.9	165				
13	578	340	5.9	162	3840	2.06	.155	
14	515	310	6.4	156	3660	2.53	.527	
15	556	305	3.48	180	4150	1.01	.407	
16	452		6.05	154		1.52	.54	P _c clogged
17	560		2.97	190		.91	.49	" "
18	580		3.03	196		.91	.49	" "
19	550	300	4.36	187	3950	1.04	.30	" "
20	660		3.70	183				Leak in acid line.
21	670	360	3.84	192	4060	1.53	.475	" "
22	645	365	4.10	197	4150			Leak in injector on acid side
23	625	375	4.56	179	4040	1.96	.592	
24	600	360	5.38	173	3880	2.15	.583	Leak in flexible hose in acid line
25	600	345	4.16	185	4110	1.32	.43	
26	570	345	4.89	169	3955	1.48	.44	
27	610	320	7.05	170	3460	2.0	.66	
28	655	345	6.62	187	3810			

chamber pressures of 1000 psi and above will be postponed until more performance and heat transfer data are available.

B. MIXING AND CHEMICAL REACTION BETWEEN ROCKET EXHAUST JET AND INDUCED AIR STREAM, WITH REFERENCE TO RAM ROCKETS.

Submitted by: J.V. Charyk, Princeton University.

During the past few months, a test program involving certain phases of ducted rocket performance has been underway. Among the aims of this work are the study of instrumentation problems under the conditions of gas velocity and temperature that are encountered in the duct, the study of the direct effect of heat addition during mixing or ejector action and the exploration of static performance possibilities.

The determination of velocity and temperature profiles within the duct is extremely difficult and various techniques are being studied. Water-cooled total head probes appear quite satisfactory for velocity determinations but temperature measurements under the conditions of a high temperature, high velocity, oxidizing gas stream are very uncertain.

Most experimental work has involved a study of constant area mixing with chemical reaction. The heat release as a result of the reaction between the induced air and the rocket exhaust products is varied by changing the ratio of fuel to oxygen in the rocket motor and by using various fuels. These tests have been conducted in an 8-inch diameter duct using a rocket motor whose nominal thrust is 50 lbs.

Figure 2 illustrates typical pressure distribution curves along the duct. Figure 2b depicts the effect of ratio of rocket fuel to oxidizer on pressure distribution. This illustrates clearly the effect of heat addition on induced mass flow since the latter is directly dependent on the magnitude of the negative pressure at the beginning of the mixing section. The magnitude of the heat release can be estimated theoretically by determining under conventional constant area mixing assumptions the heat addition necessary to produce the observed reduction in mass flow. An experimental determination of this heat release is being attempted by exhaust gas analysis. The relative quantities of CO , CO_2 , H_2O , O_2 , and H_2 are determined. Assuming the rocket exhaust gas composition to be known and measuring the mass of air induced, the energy release during mixing is calculated. This also serves as a check on the measured gas temperature at the duct exit. Preliminary estimates of the mean exhaust gas temperature for the cases illustrated in Figure 2B are as follows:

<u>Curve</u>	<u>Temperature ($^{\circ}\text{F}$)</u>
1	1100
2	1250
3	1600
4	2500

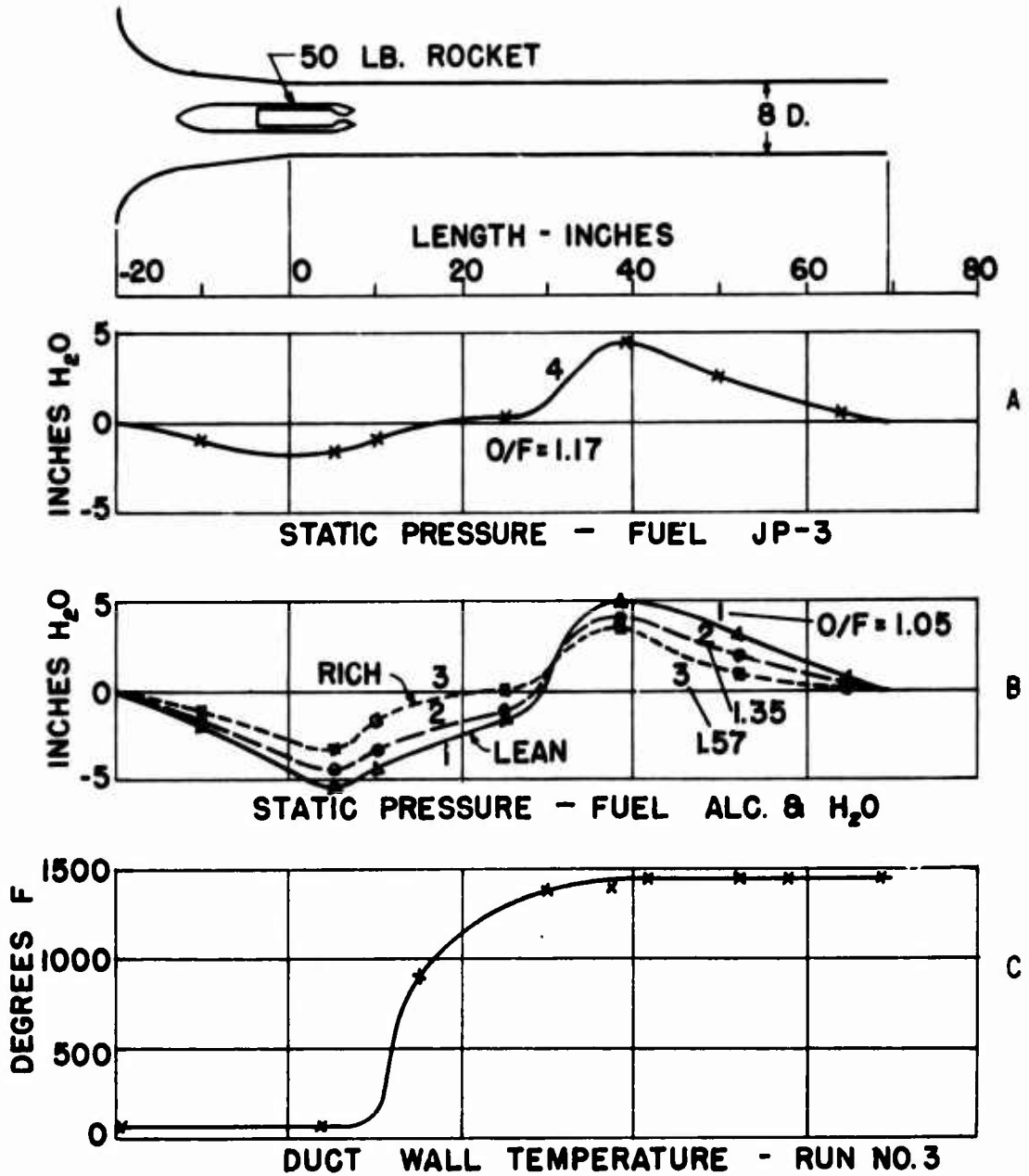


Fig. 2. Static pressure and temperature distributions - ducted rocket.

C. EXPERIMENTAL STUDIES OF AN INTERMITTENT RAMJET ENGINE. (Pr-4R1)
 Submitted by: A. Kahane, Princeton University.

In the earlier investigations of the feasibility of an intermittent ramjet engine, a combustion pressure rise of one atmosphere was obtained in

preliminary experiments. Calculations showed that with a pressure rise of approximately that amount, an intermittent ramjet engine should have a specific impulse superior to that of a steady ramjet at Mach numbers between 0.5 and 2.

The studies that have been carried out previously in this program have been described in Project Squid, Annual Reports, January 1949 and January 1950. The investigation has included exploratory studies of intermittent combustion in a flowing gas, development of a fuel injection nozzle, and specific thrust and fuel consumption measurements of an initial subsonic configuration. All tests have been made in the 0.5 Mach number, 4-inch diameter, air jet.

In the present period the initial subsonic engine configuration (which consists of a 4-inch square combustion chamber and tail pipe and a subsonic diffuser) has been further investigated. The tube was instrumented with static pressure wall orifices along its entire length and on the inlet cowl lip. These orifices are connected to manometers and provide a measure of the average static pressure distribution. Transient pressures were measured simultaneously in the combustion chamber, inlet, and tail pipe with three Statham pressure pickups. The data that has been obtained is now being analyzed.

Operation during this period has been severely limited by several injection pump failures. The main difficulty has been the wearing of the cams on the pump shaft during high frequency operation. It is hoped that this will be remedied by the use of tungsten carbide inserts in the cams.

A 4-inch square constant area tube with two 4 foot long glass windows has been constructed for photographic investigation of the intermittent combustion process in a flowing gas. This investigation should furnish information as to the mode of the combustion process and as to the magnitude of the flame velocities that occur under these conditions.

D. GENERALIZED THEORY OF JET ENGINE PERFORMANCE. (CAL-1R8)

Submitted by: J.V. Foa, Cornell Aeronautical Laboratory.

The generalized theory of jet engine performance, described previously, was extended to cover single-flow engines with confined regions of non-steady flow. The generalized equations were applied to the performance analysis of the pulsejet, ramjet, turbojet, intermittent ramjet, ramjet with "rough burning", and turbopulsejet.

E. STUDIES OF VALVELESS PULSEJET CONFIGURATION. (CAL-1R7)

Submitted by: J.V. Foa and G. Rudinger, Cornell Aeronautical Laboratory.

The elimination of the valves of a conventional pulsejet should lead to an engine of greatly improved reliability and increased useful life. Experi-

ments with small scale models, described in Annual Report, January, 1950, have been continued. Tests to investigate their performance in a free air-stream were started. The engine resonated and developed some thrust but further tests had to be postponed until completion of the oscillating shock experiments (See Div. II, Sec. A.) which required the air supply.

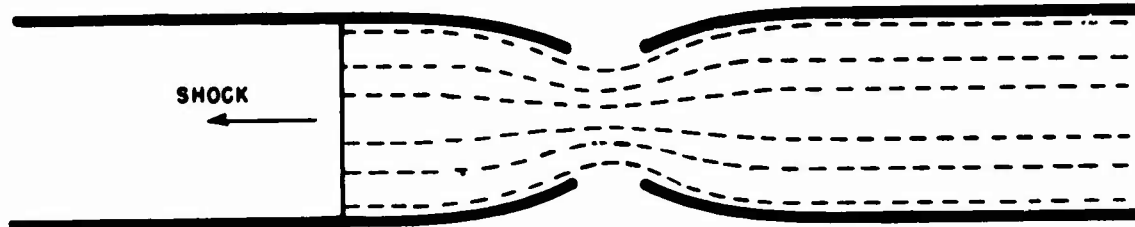


Fig. 3. Suggested inlet and augmeter configuration for valveless pulsejets. The dashed lines indicate the streamline pattern established behind a shock wave.

Figure 3 shows a duct configuration that may be suitable as an air inlet for valveless pulsejets. The design is based on the following principle. A shock passing the constricted region would produce a flow in which the streamlines are curved in such manner that the associated pressure gradient would prevent all or most of the outflow through the opening. On the other hand, following an expansion wave, the same pressure gradient would greatly assist inflow. A similar configuration placed near the tail exit of a valveless pulsejet may act as an augmeter by drawing in air through the opening and exhausting it through the tailpipe. It is planned to check the feasibility of this scheme by means of water analogy and gas dynamic model experiments.

F. INTERMITTENT JET ENGINE WITH WAVE RE-INFORCEMENT. (CAL-1R8)

Submitted by: J.V. Foa and G. Rudinger, Cornell Aeronautical Laboratory

The information acquired in the study of shock motions has led to new ideas concerning the mechanism of wave engines and the basic principle of a new type of such an engine is illustrated in Fig. 4. Both the inlet and the exit of a duct are periodically opened and closed. The interruption of the exit flow produces a shock wave that is reflected forward and backward in the duct. Its strength is maintained by correctly timed intermittent combustion cycles. Since the combustible mixture is precompressed by the shock wave, the engine is essentially a combination of a compressor and a pulsejet. Fig. 5 shows the model that was constructed to test the principle. The inlet valves are the flapper valves of a conventional pulsejet. At the exit, opening and closing is achieved by a rotating disc. For better speed control, the air motor shown in the photograph has been replaced by an electric variable speed drive.

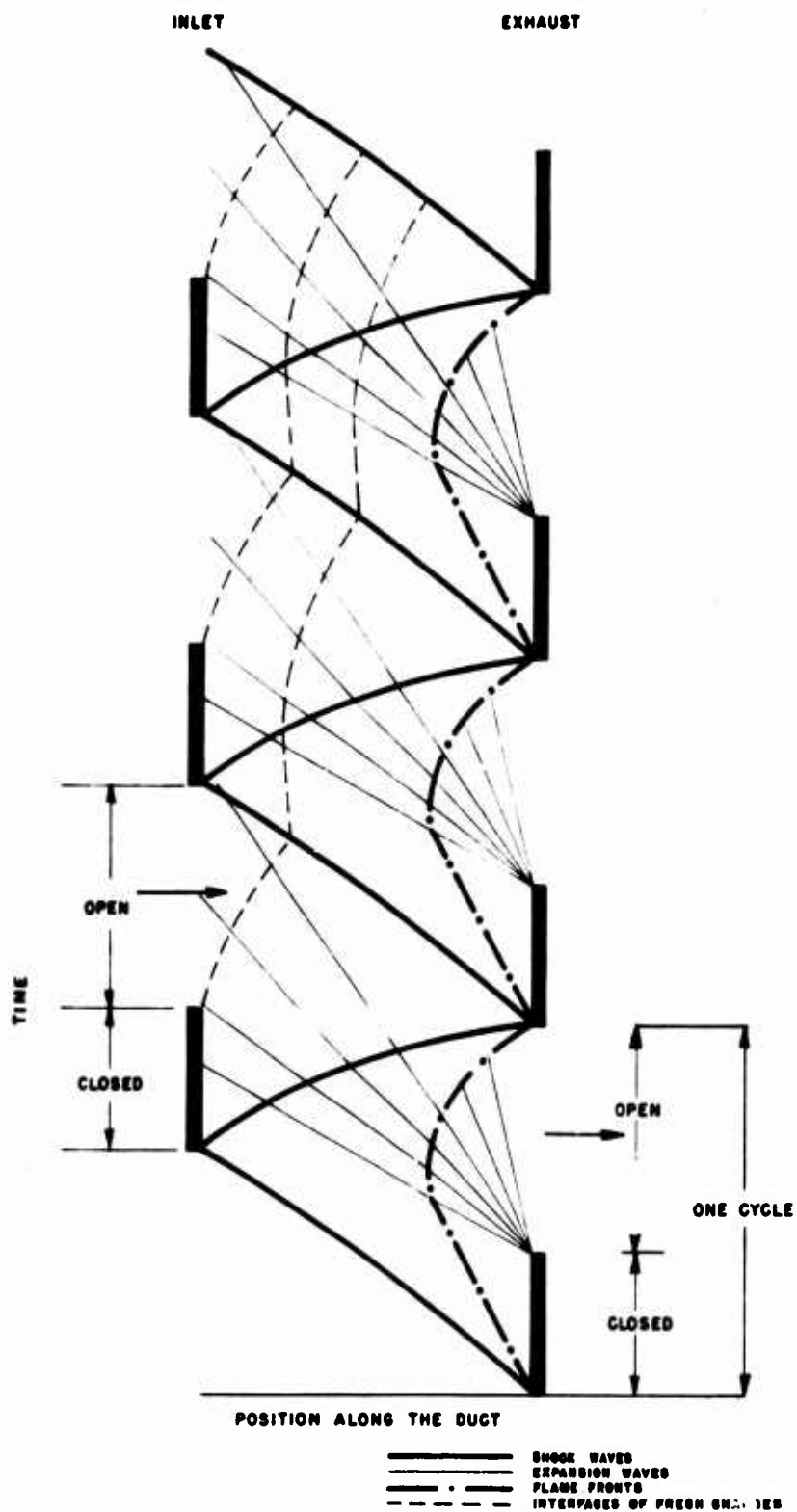


Fig. 4. Principle of a new type of wave engine. (Characteristics diagram)

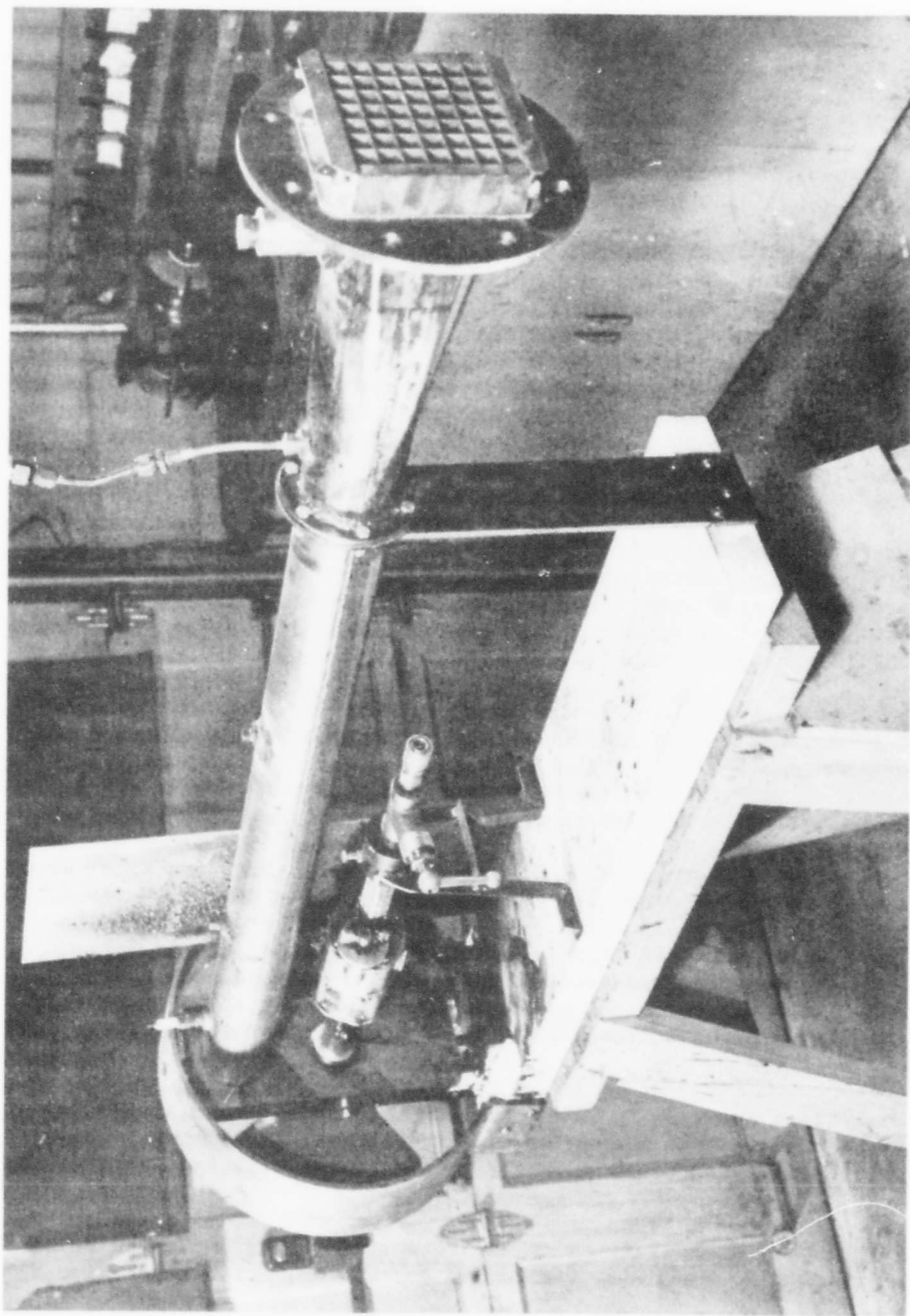


Fig. 5 First model of a new type of wave engine.

Resonating operation of the engine has been achieved for short periods, and a pressure pickup mounted behind the inlet valves indicated peak pressures of about 80 lb/sq.in. However, the combustion process is not yet under control. Various grids are being placed in the duct, and the fuel injection system is being modified to achieve faster combustion. A technical memorandum on this work will be prepared as soon as enough data on thrust and specific impulse become available.

G. THEORETICAL STUDY OF SHROUDED PULSEJET: OPERATION AND PERFORMANCE. (CAL-1R8).

Submitted by: G. Rudinger, Cornell Aeronautical Laboratory.

The thrust developed by a conventional pulsejet decreases sharply at flight velocities of a few hundred miles per hour. This is due to the increasing pressure difference between the ram pressure at the inlet and the static pressure at the tail pipe exit. To eliminate the detrimental effect of this pressure difference, the pulsejet may be placed inside a duct designed to keep the Mach number of the internal flow sufficiently low.

The previous analysis of ducted pulsejets¹ was restricted to optimum duct configurations, and assumed complete mixing of the pulsejet exhaust with the surrounding stream. These investigations are now being extended to the evaluation of off-design performance and are at present restricted to subsonic flight Mach numbers.

From the first series of calculations it appears that the performance of a ducted pulsejet at an off-design flight Mach number is almost as good as the optimum performance at that Mach number. This applies only to flight Mach numbers above 0.6. At lower Mach numbers, the performance drops off rapidly. Most of this drop-off could be avoided if the exit area of the shroud were made variable so as to keep the inlet Mach number at all times equal to the flight Mach number. It was found that making the inlet area variable instead of the exit area would be much less effective. For flight Mach numbers lower than about 0.2, variation of the exit area would no longer be satisfactory. In this range, which approaches static operation, the bare pulsejet would give considerably more thrust than the ducted configuration. It may then become advantageous to prevent all or part of the mixing that takes place between the exhaust of the pulsejet and the shroud exit.

Calculations assuming no mixing showed that considerable improvement could be obtained in this manner at very low flight Mach numbers. Changes in the degree of mixing could possibly be achieved by telescoping the tail

¹G. Rudinger, An Evaluation of the Potential Merits of Ducted Pulsejets, Project SQUID, Technical Memorandum No. CAL-32, October 1949 (to be issued shortly)

pipe or the shroud, or by changing the location of the pulsejet inside the duct. An attempt will be made to calculate the effects of partial mixing on the performance. Other refinements of the theory will include an allowance for friction losses in the duct.

Some data of ducted pulsejets have recently become available from other organizations. This information is now being put into a form that is better suited for a comparison with theory. It is also planned later to carry out small scale experiments to provide those specific pieces of information that cannot be obtained from the test results mentioned.

In the calculated optimum performance of supersonic ducted pulsejets² it is assumed that the effective shock losses correspond to a normal shock at free flight Mach number. A few points were calculated based on the assumption that the shock losses were a minimum, i.e., corresponding to a shock at the throat of the diffuser. While this could never be achieved because of the flow oscillations caused by the pulsejet, calculations of this type indicate the scope of possible improvements by reducing shock losses. The possible gain turned out to be quite considerable at high Mach numbers. For one specific configuration and a flight Mach number of 2.0, it was found that thrust could be improved by 24% and specific impulse by 8%. For lower flight Mach numbers, the possible gain becomes smaller and, e.g., at a flight Mach number of 1.5, the possible gain in thrust has been reduced to 10%.

As an approach to a closer estimate of the effective shock losses, the disturbances that are produced by suddenly interrupting a fraction of the flow in a duct (closing of the inlet valves of the pulsejet) were analyzed on the basis of one-dimensional theory. It was found that for area ratios corresponding to those occurring in ducted pulsejets, the shock waves produced are rather weak. The previous assumption that the effective shock losses correspond to a shock at free stream Mach number, therefore, appears to be too conservative. Attempts to obtain a closer estimate of the effective shock position will be continued.

H. THEORY OF OSCILLATING PISTON ENGINES. (NYU-6R3)

Submitted by: G.E. Hudson, New York University

A part of the work on the lumped parameter theory of an oscillating piston engine is completed, but the remainder has been held up by the pressure of other work. A paper on this subject will probably be issued during the next quarter.

²Rudinger, Technical Memorandum CAL-32.

I. OSCILLATING PISTON ENGINE. (NYU-6R2)

Submitted by: G.E. Hudson, New York University.

Investigation is under way on the behavior of this engine with the results so far obtained showing considerable promise.

J. IDEALIZED PULSEJETS. (NYU-6R1)

Submitted by: G.E. Hudson, New York University

A small amount of additional data has been gathered on the flame motion occurring in the small glass-walled pulsejet engine, but analysis of these records and the procurement of further records has been held in abeyance until the investigation of the schlieren system now being studied under Div. 7, Sec. B is completed. As described therein, this system promises to provide records that can be interpreted quantitatively, thus markedly increasing the value of the records obtained.

Some tests have also been made of a small pulsejet engine to which a resonant tube is attached at the combustion chamber. It has been found that the engine appears to run satisfactorily, except at resonant-tube lengths which are odd multiples of the quarter wave length of the cyclic frequency of the engine. However, more tests must be made before the effect of such a tube can be evaluated.

II. FLUID MECHANICSA. PROPAGATION AND STABILITY OF SHOCK WAVES IN SUPERSONIC DIFFUSERS. (CAL-1R6)
Submitted by: J.V. Foa and G. Rudinger, Cornell Aeronautical Laboratory.

It is possible for a shock in a supersonic diffuser to oscillate wholly inside the diffuser under the influence of high frequency downstream pressure oscillations of such an amplitude that they would push the shock ahead of the throat if they were to occur slowly. A study of this type of shock oscillation is of interest for supersonic jet power plants in which the combustion process is intermittent. The shock motion is being correlated experimentally with the amplitude and frequency of the pressure pulses.

Work on this program has been continued. The experimental setup was described previously¹ and consisted essentially of a small diffuser that was connected to a low pressure chamber through a rotating valve. A by-pass to the valve allowed the amplitude of the pressure oscillations at the exit to be varied. The diffuser inlet was at atmospheric pressure. The maximum frequency of the pressure oscillations that could be obtained was about 180 cycles per second. Both mean pressure and instantaneous pressure at the diffuser exit were recorded. The experiments were carried out with three different diffusers of equal throat and exit areas of 0.68 and 1.23 sq. in. respectively. The lengths of the diverging sections were 11.5, 18.9, and 35.5 inches, respectively.

It was found that in all diffusers, even at the highest possible frequency, the flow could not be stopped completely and the by-pass had to be opened somewhat to prevent the shock from being pushed ahead of the throat. The emergence of the shock could be detected audibly and a correlation between the corresponding pressure amplitude and frequency could thus be established. The results are plotted in Fig. 1. The ordinates plotted are $(p_{\max} - p_{\text{mean}}) / (\Delta p)_{f=0}$. All pressures are measured at the diffuser exit; p_{\max} is the maximum pressure determined from oscillograph records, p_{mean} is the mean pressure, and $(\Delta p)_{f=0}$ is the static pressure increase required to push the shock to the throat in steady flow (zero frequency). The experiments were carried out for various values of p_{mean} and it is seen that the results are practically independent of this parameter.

It was also noted that the pressure recovery in the diffuser during steady flow behaved in a manner that could not be explained on the basis

¹Project SQUID, Annual Program Report, 1 January 1950, Div. II, Sec. A.

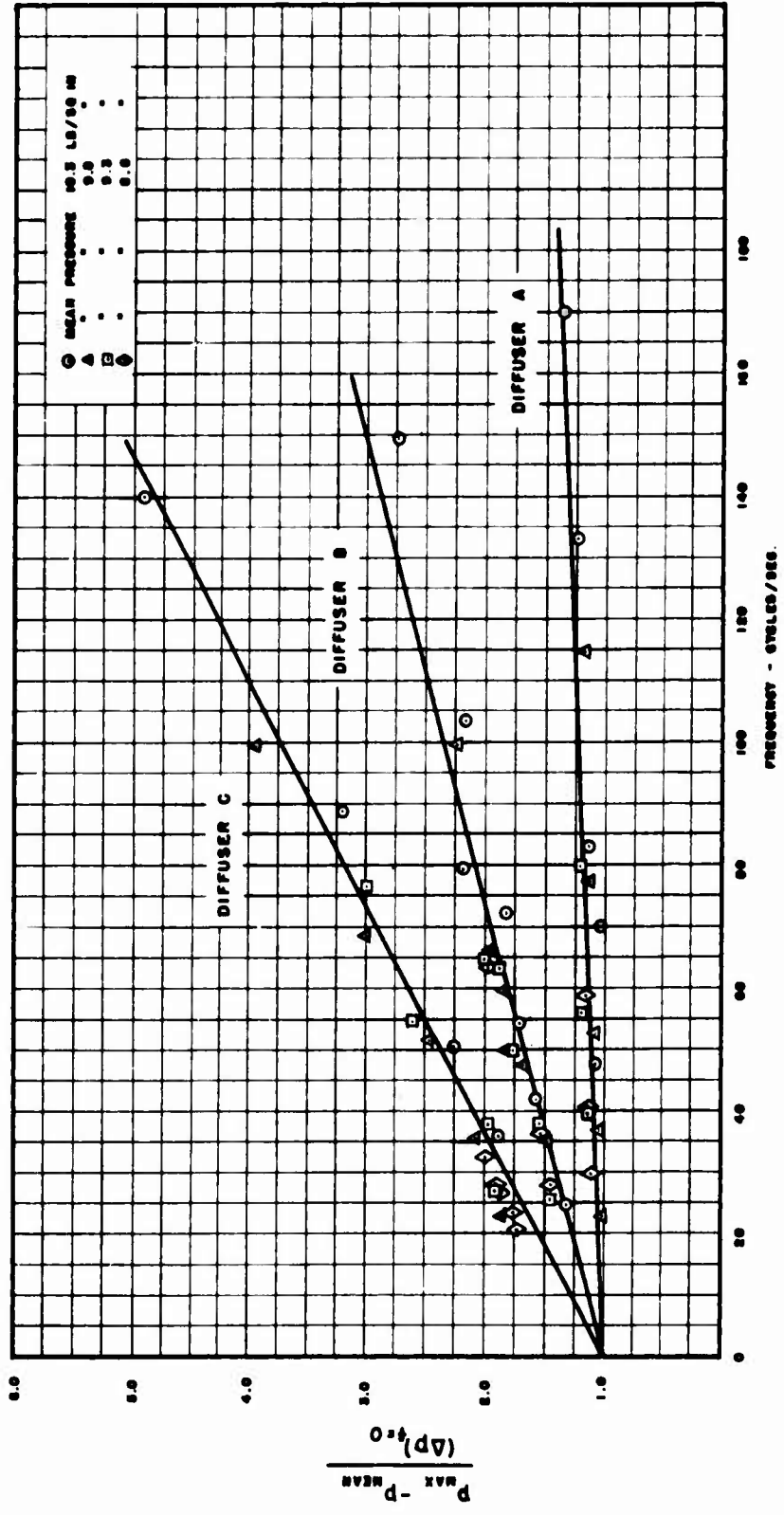


Fig. 1 Maximum amplitude of pressure oscillations at diffuser exit to keep the shock inside the diffuser

Diffuser A 11.5" long
 " B 18.9" "
 " C 35.5" "

of one-dimensional theory. As the shock pattern moved downstream in the channel, the stagnation pressure at the exit dropped at first in the expected fashion but then increased again. In this regime the flow was unstable and the shock pattern oscillated. This is possibly due to some complicated shock wave boundary layer interaction. Schlieren observation² of the flow pattern had shown that a considerable portion of the channel area was taken up by the boundary layer. A more detailed investigation of these phenomena would lead away from the problem under investigation but may be carried out in the future in connection with other problems. A technical memorandum on the experiments described is being prepared.

In order to reduce boundary layer effects, a larger model was constructed for further experimentation at higher pressure. In this case, the Cornell Aeronautical Laboratory air supply will be used and the channel exhaust will be at atmospheric pressure. Preliminary tests have indicated a satisfactory operation of the setup but, so far, no measurements have been taken.

B. EJECTORS AND MIXING OF SUPERSONIC STREAM AND SUBSONIC FLUID STREAMS.
(Pr-3R1)

Submitted by: J.V. Charyk, Princeton University

The first phase of the ejector study program involving non-reacting fluids and aimed at general ejector performance data is nearing completion and a progress report summarizing the main results of these investigations will be submitted shortly. This work has served to make available the information necessary for engineering purposes and to point out salient basic features of the general problem which will serve as a guide in directing the more fundamental investigations in the next phase of the research program. Incidental to this work is the extension of existing facilities to provide a means for varying the properties of the secondary air stream. Work to date has been confined to the static or ejector problem. The planned extension will result in secondary velocities up to sonic speeds and the emphasis of the projected work will be on the investigation of the mixing process itself.

Typical ejector performance data illustrating the effects of some of the variables studied are included here for illustration. Figure 2 depicts the variation of the mass of the secondary air induced and duct thrust as a function of the degree of under or over expansion of the primary jet nozzle. The data are the results of tests involving four primary jet nozzles, with exit dimensions ranging from correct expansion at a primary air stagnation pressure of 29.4 psia to a stagnation pressure of 1000 psia. These tests were conducted over a primary air stagnation pressure range

²Project SQUID, Annual Program Report, 1 January 1950, Div. II, Sec. A.

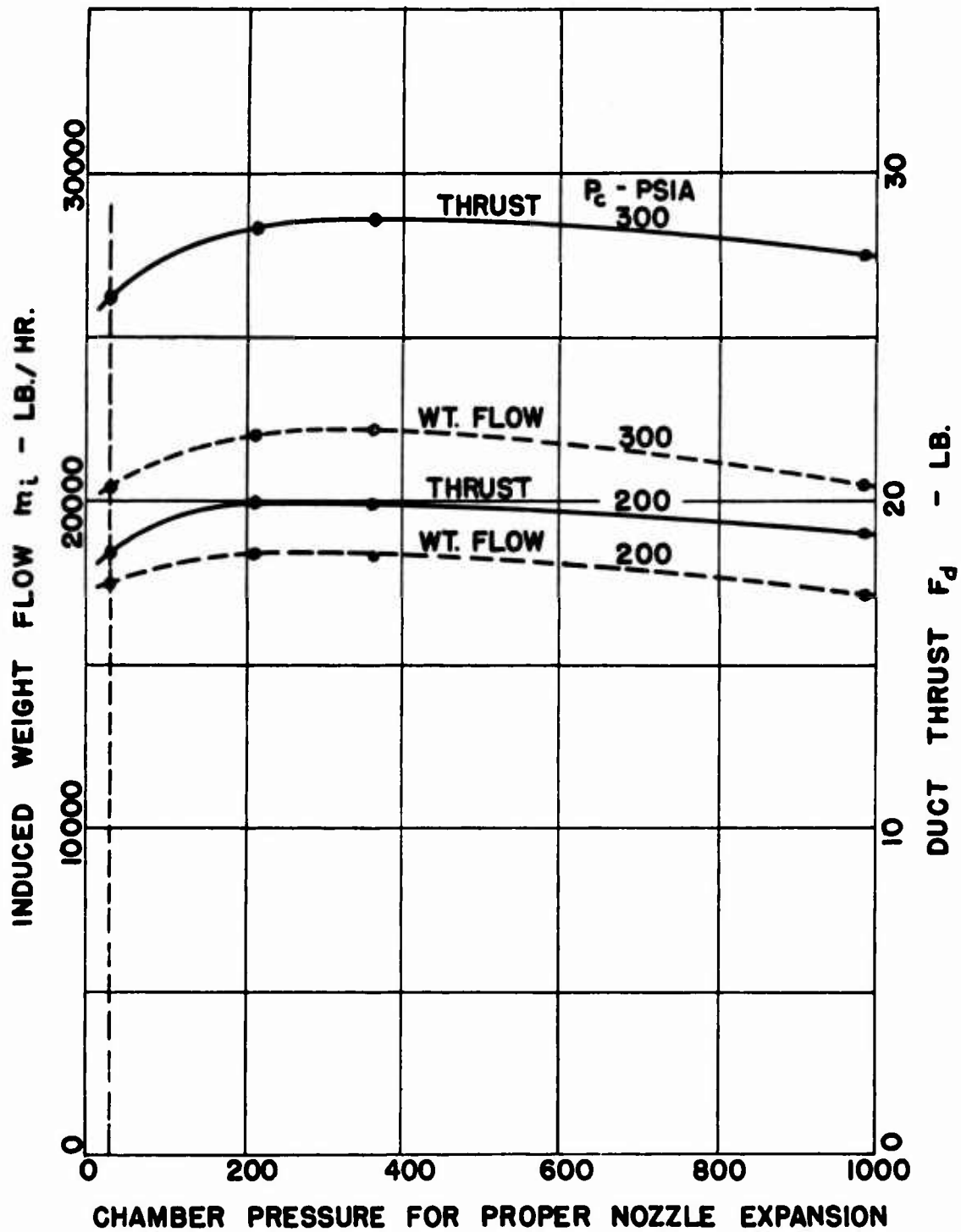


Fig. 2. Air induction versus degree of under or overexpansion of primary jet nozzle.

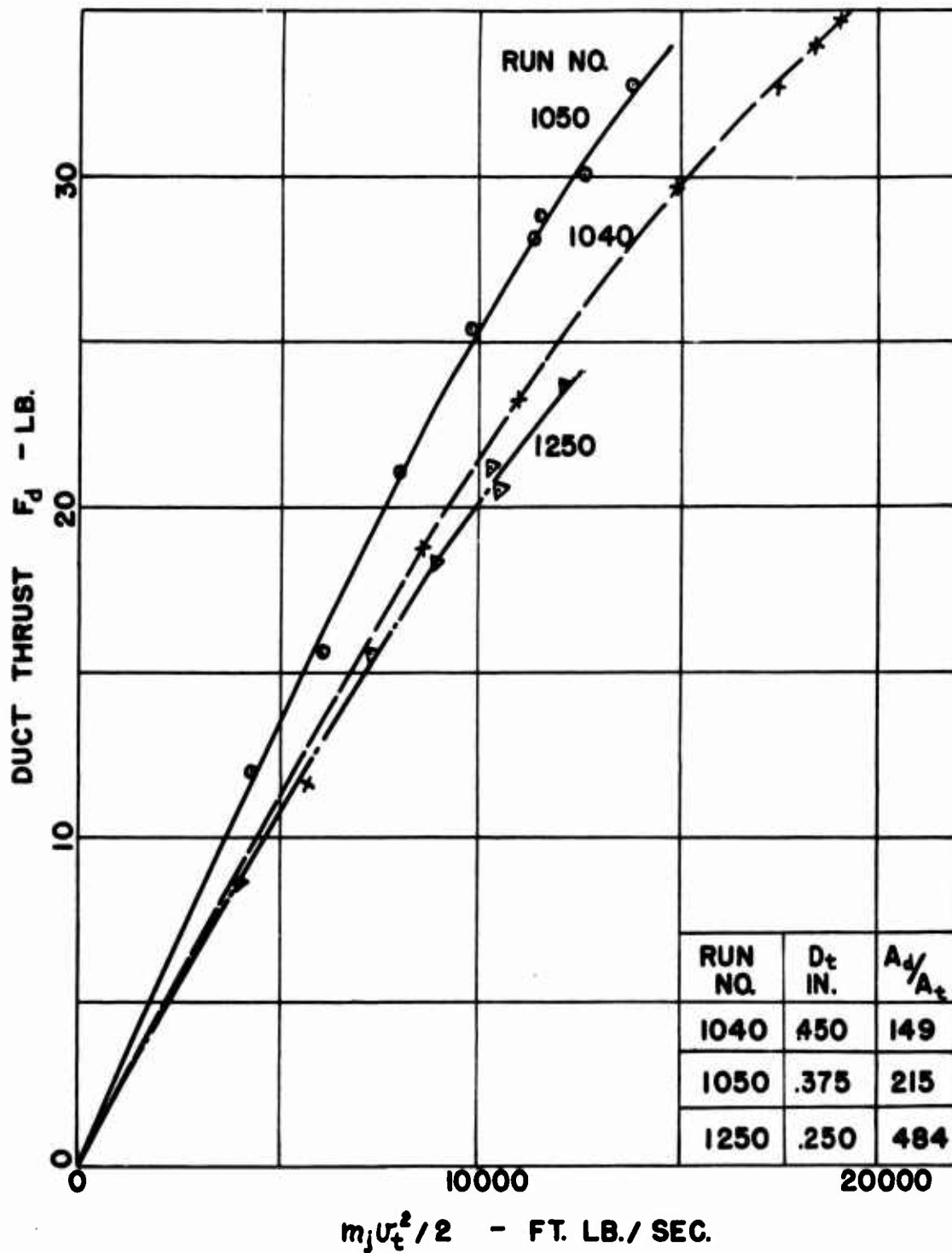


Fig. 3. Duct thrust versus primary jet kinetic energy.

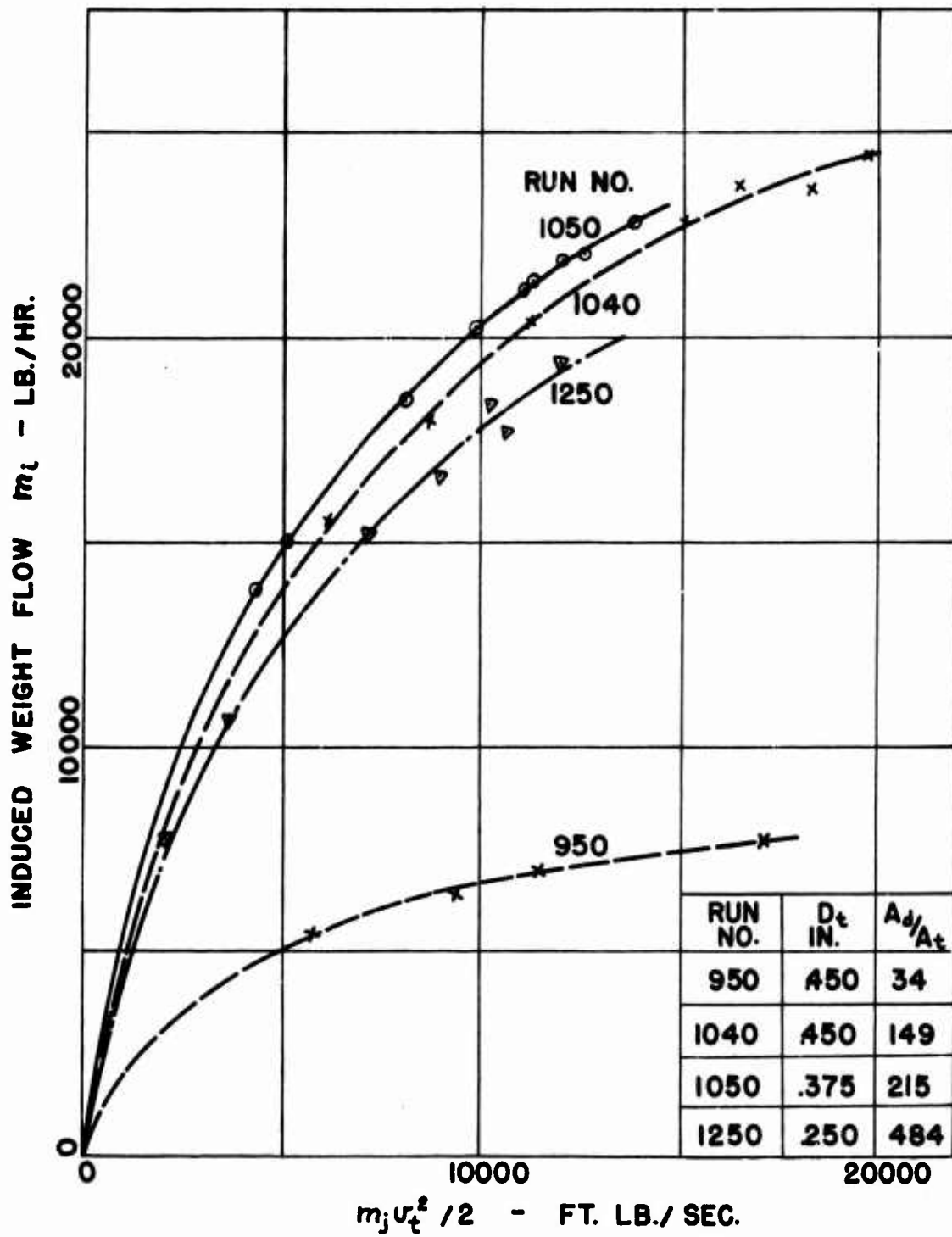


Fig. 4. Mass of secondary air induced versus primary jet kinetic energy.

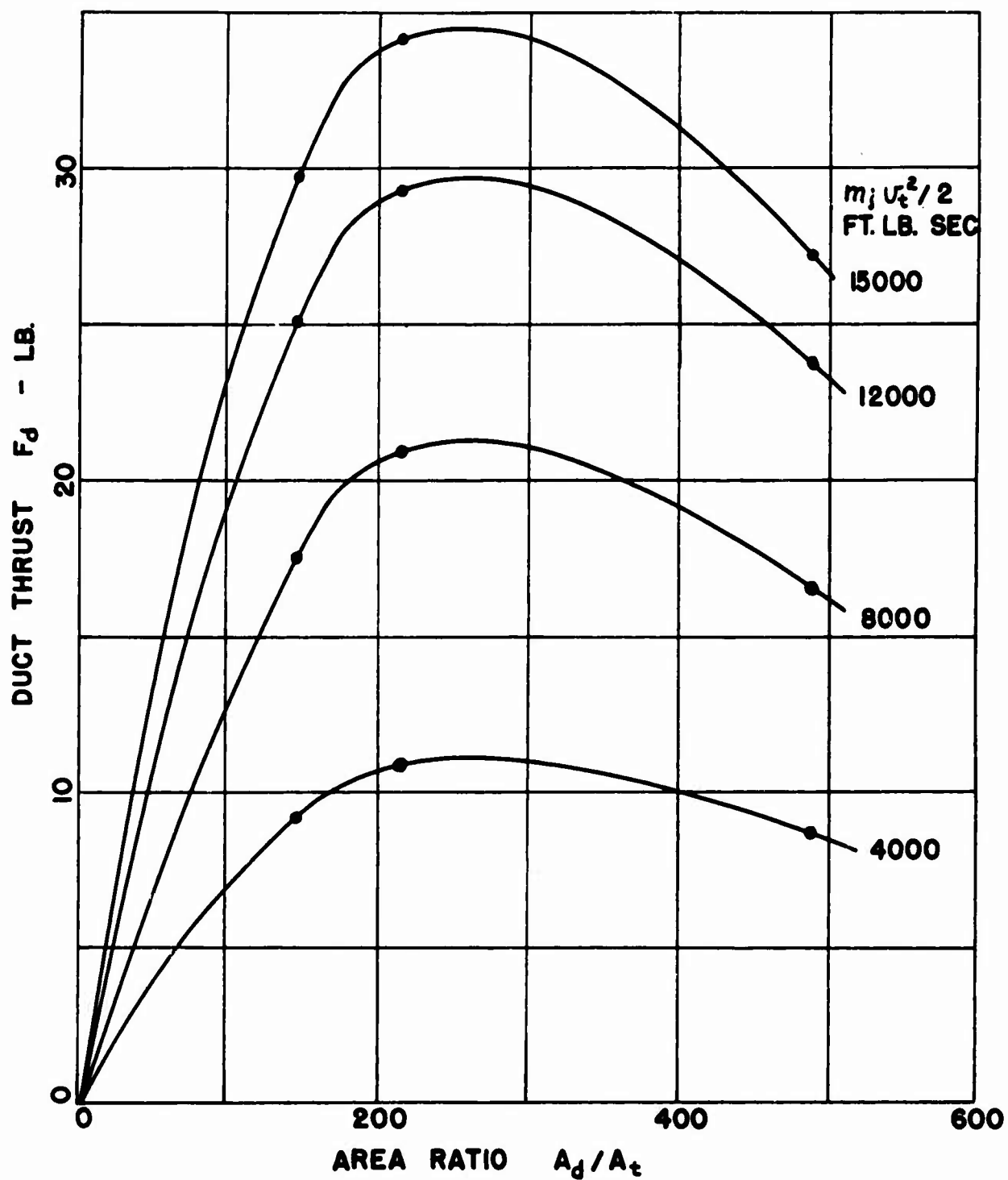


Fig. 5. Duct thrust versus area ratio.

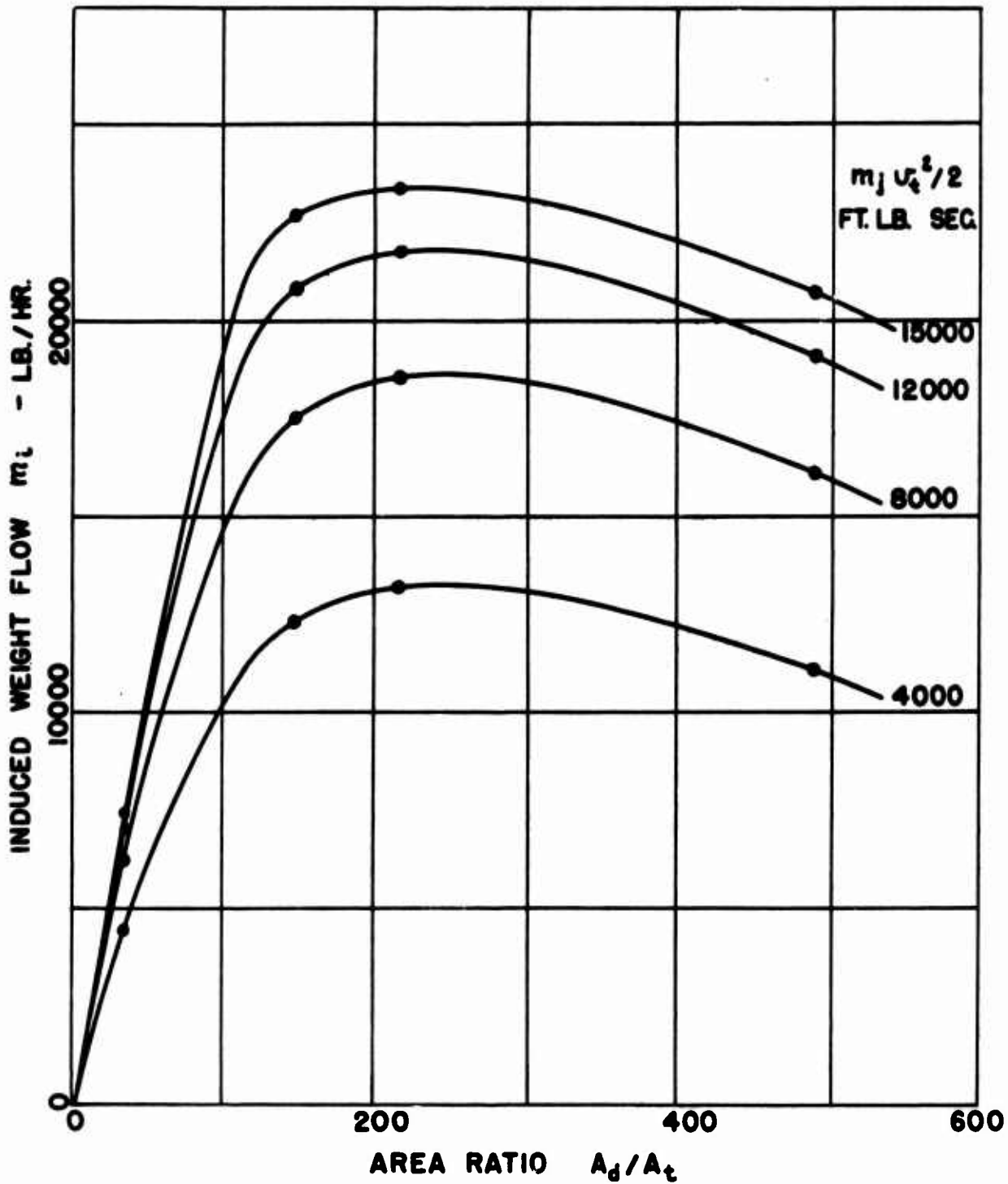


Fig. 6. Mass of secondary air induced versus area ratio.

from 100 psia to 400 psia, and thus ejector performance was determined over a wide range of conditions of under and over expansion. Flow separation occurs in the over-expanded case and the conditions for flow separation appear to be roughly in agreement with the results of previous investigators.³ As indicated, performance is best in the correctly expanded case, but the effect of incorrect expansion is not of major importance. This fact enabled ejector performance data to be determined with reasonable accuracy by using a given primary jet nozzle and conducting tests by simply varying the stagnation pressure of the primary air in steps.

In practice it proved much more simple to adjust the area ratio of the primary stream to the secondary stream by varying the size of the primary jet rather than the diameter of the mixing duct. As a result, in order to present comparative data for different area ratios, the primary jet stagnation pressure is no longer a useful independent parameter. Ejector performance data is plotted, therefore, for the different primary jet throat sizes against the primary jet throat kinetic energy as shown in Fig. 3 and Fig. 4. These data are cross-plotted in Fig. 5 and Fig. 6 to show performance as a function of the ratio of duct area to primary jet throat area.

C. THE THEORY OF TURBULENCE WITH PARTICULAR EMPHASIS ON THE CASE OF ISOTROPIC TURBULENCE. (JHU-Ph. 2)

Submitted by: Ion Carstoiu, Johns Hopkins University.

The work of Oseen^{4 5 6} and Leray⁷ on the appearance of irregular solutions of the Navier Stokes equations has been studied with some care. It is felt that these ideas may play a significant role in turbulence theory. The results of Oseen and Leray were all obtained in terms of variables in the physical space. We are now attempting to compare these results with those that have been obtained in the Fourier transform space. Further, Oseen considered the conditions under which a vortex field could become irregular. Since this appears to be a profitable line of attack, we are attempting to apply the methods of Leray to the same problem. In the case of both the Fourier transform and the vortex field, our work has

³M. Summerfield, C.R. Foster, W.C. Swan, "Flow separation in overexpanded supersonic exhaust nozzles." Paper presented at Institute of Fluid Mechanics and Heat Transfer, Los Angeles, June 22, 1948.

⁴C.S. Oseen, "Neue Methoden und Ergebnisse in der HYDRODYNAMIK," Akademische Verlagsgesellschaft M.B.H., Leipzig, 1927. Par. 7, p. 66-82.

⁵C.S. Oseen, "Sur la representation analytique de la vitesse dans certaines problemes, d'hydrodynamique," Nova Acta Regiae Societatis Scientiarum Upsaliensis, ser. IV, Vol. 4, No. 9 (1917) p. 1-77.

⁶C.S. Oseen, "Sur les formules de Green generalisees qui se presentent dans l'hydrodynamique et quelques unes de leurs applications," Acta Mathematica, tome 34 (1911) p. 205-284.

⁷Jean Leray, "Sur le mouvement d'un liquide visqueux emplissant l'espace," Acta Mathematica, tome 63 (1934) p. 193-248.

not as yet produced results that are complete enough to be reported in detail.

D. THEORY OF GAS JET FORMATION. (NYU-7R2)

Submitted by: G.E. Hudson, New York University.

The technical memorandum summarized in the Annual Program Report, 1 January 1950, on certain problems of incompressible viscous flow has been completed and forwarded to Princeton. Further work on the mathematical formulation of such flows awaits the gathering of more complete data under problem NYU-7R1 (See Div. II, Sec. E.), since such information is required before it can be determined whether a suitable physical model can be constructed.

E. EXPERIMENTS ON GAS JET FORMATION. (NYU-7R1)

Submitted by: G.E. Hudson, New York University.

As in the work on the glass-walled pulse jet engine (See Div. I, Sec. J), the collection of further data on the experiments described in the 1 January 1950 Annual Program Report, awaits completion of the investigation on the new schlieren system described under Div. 7, Sec. B.

F. LARGE AMPLITUDE GAS VIBRATION THEORY. (NYU-7R6)

Submitted by: G.E. Hudson and R. Shaw, New York University.

Considerable progress has been made in the solution of the general equations covering large amplitude gas vibrations, and a paper on the subject is in preparation.

This theory has advanced to the point where it is possible to write down a complete and explicitly analytical description of the motion in the region of interaction of two arbitrary simple waves in one-dimensional motion of a compressible fluid. Such simple waves might be generated by a piston at each end of a tube filled with gas, each moving in an arbitrary fashion. From the equations of the positions of the pistons as functions of time, initial data can easily be calculated along the two (curved) initial characteristics which separate the interaction region from the simple wave regions adjacent to the pistons. The solution then expresses points (x,t) of the interaction region explicitly as functions of the flow velocity u and the sound speed c , involving the initial data and integrals of these data.

The method applies to gases with an adiabatic exponent

$$\gamma = \frac{3}{1}, \frac{5}{3}, \frac{7}{5} \text{ (air)}, \frac{9}{7}, \dots$$

However, new techniques are being developed through which it is expected that not only can these results be extended to all values of γ , but that the solutions can be put into even a more simple and elegant general form. Mathematically, the most interesting step in this direction is a method whereby any solution of the linear wave equation in n dimensions depending only on the radial distance and time, can be converted into a solution for an m -dimensional space by introducing a complex parameter and integrating along an appropriate contour. n and m can be any real numbers. Thus, radial solutions for an even number, or, indeed, a fractional number of spacial dimensions can be written in a form analogous to those, familiar in the case of odd dimensions, exhibiting waves traveling out from and in toward, the origin.

G. LARGE AMPLITUDE GAS VIBRATION SOURCE. (NYU-7R5)

Submitted by: G.E. Hudson, New York University.

Construction of the large amplitude piston drive from a motorcycle engine is underway.

III. H E A T T R A N S F E R**A. EXPERIMENTAL STUDY OF LIQUID INJECTION INTO A GAS STREAM, WITH REFERENCE TO TRANSPIRATION COOLING OF ROCKET MOTORS. (PRF-7R10).**

Submitted by: E.L. Knuth, Purdue University.

The problem is to determine the feasibility of cooling rocket motor nozzles (and walls) by transpiration cooling through parallel disks. However, before a rocket motor utilizing transpiration cooling through parallel disks can be designed, the flow characteristics of a fluid injected into a moving gas stream must be known. To determine these characteristics is the purpose of the immediate investigations.

The general plan of attack is to inject, in various manners, fluids having different properties into a moving air stream and to observe the effects of the variables on the critical velocity of injection. (Critical velocity of injection has been defined as the "average velocity of the coolant in the injector at the time that the maximum rate of coolant flow is obtained without encountering visible separation of the coolant from the test section wall".) Construction of the basic test section and running of fourteen groups of tests was accomplished prior to the period covered by this report.

Additional slot blocks for the test apparatus¹ have been designed and fabricated. These blocks change the conditions of fluid injection making it possible to investigate the following: the effect of coolant injection angle; the effect of injecting the coolant at the transition from a horizontal to an inclined flow section; the effect of injecting the coolant from an inclined surface.

Several check runs have been made to substantiate previously reported results. In addition, the surface tension, density, and viscosity of the injection liquids have been determined.

Immediate plans for the future include the study of the effect of gravity, by inverting the test section, and the effect of the size of the main fluid stream.

B. THEORY OF NON-LINEAR HEAT CONDUCTION IN SOLIDS. (NYU-7R9)

Submitted by: G.E. Hudson and M.J. Storm, New York University

As was stated in the last Annual Program Report, it has been found possible to transform the one-dimensional non-linear heat conduction

¹Project Squid, Annual Program Report, 1 January 1950, Div. 3, Sec. A.

equation

$$\frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) = S \frac{\partial T}{\partial t}$$

(where T is the temperature of the metal at time t and position x , K is the thermal conductivity, and $S = \rho c_p$ is the product of the density and the specific heat at constant pressure), into one in which the thermal parameters only appear in the combination

$$\frac{d}{dQ} \ln \sqrt{\frac{S}{K}}$$

where

$$Q = \int_{T_0}^T \sqrt{KS} dT$$

T_0 being some arbitrary temperature. The transformed equation has been solved for the case of a semi-infinite metal rod under the mathematical assumption that

$$\frac{d}{dQ} \ln \sqrt{\frac{S}{K}}$$

is a constant. During the past quarter, progress has been made in investigating theoretically the relations between the thermal parameters.

On the assumption of an Einstein model for the metal crystal, in which each atom is supposed to behave as a simple harmonic oscillator, vibrating about its mean position with a single frequency, it has been possible to show without any empirical assumptions that the product Kc_v is essentially a constant.

For purposes of application to the heat conduction equation, it would be preferable to have a relation between K , ρ , and c_p . However, the assumption that the atoms behave as harmonic oscillators limits the theory, as is well known, to constant volume phenomena. As Debye first pointed out, no thermal expansion can occur in such a model, it being necessary to consider the atoms as vibrating like anharmonic oscillators before thermal expansion can take place. Thus, to be consistent with the above model, the specific heat at constant pressure would have to equal that at constant volume, which, of course, is not borne out experimentally; to circumvent this difficulty, further theoretical investigations are being made. At any rate, since experimentally c_v and c_p differ by only a few percent for metals and the variation of density ρ with temperature is not large, it can be expected that $KS = K\rho c_p$ would be essentially constant for temperatures greater than the Debye temperature, and this assumption is fairly well justified by examination.

of the available empirical data. Then, starting with the fact that K_S is constant, it can be shown that

$$\frac{d}{dQ} \ln \sqrt{\frac{S}{K}}$$

is only slightly dependent on temperature in the temperature range considered.

In connection with the theoretically obtained relation that K_C is a constant, it may be noted that Hume-Rothery in "The Metallic State," combined the empirical Gruneisen relationship, namely, that the specific resistance is approximately proportional to the product of the absolute temperature and the atomic heat (C_p) with the Wiedemann-Franz Law, to obtain the semi-empirical relationship.

$$K C_p = \text{constant.}$$

The solutions of the non-linear equation will be compared with those obtained from the usual linearized theory in order to estimate the errors involved in neglecting the variation with temperature of the thermal coefficients; and the possibility of applying this method to different forms of the heat equation subject to appropriate boundary conditions will be investigated.

C. VISUAL STUDY OF HEAT TRANSFER FROM A VERTICAL TUBE TO A GAS WITH FREE CONVECTION WITH OR WITHOUT FORCED COUNTERFLOW. (Del-1R2)

Submitted by: S.A. Guerrieri, University of Delaware.

The apparatus on which the air studies of heat transfer by natural convection will be done has been completed. It consists of a vertical tube, two opposing walls of which one of glass. The two other walls are formed by electrically heated metal plates. The flow patterns in the gas within the tubes are studied by schlieren photography and by temperature readings from traveling thermocouples. All auxiliary equipment has been installed, including the schlieren apparatus.

Trial runs on this unit have been made with varied heat input and varied counterflow air rates; plate temperatures and temperature profiles between the plates were measured for each condition. Schlieren photographs were taken for all preliminary experimental runs.

The experiments may be conducted in one of two ways; one method is to aim for uniform wall temperatures by careful adjustment of power input and allow the heat flux to vary with position. The other is to adjust power input so as to give a constant heat flux over the entire plate wherein surface temperature varies with position. Preliminary runs have indicated that a 10°F maximum variation in local plate temperatures may be expected

with careful adjustment of the power input to the strip heaters when operating according to the first method. It was not attempted during the trial runs, to regulate power input to the strip heaters so as to give a constant heat flux over the entire plate, but during later experimental runs this will be tried.

During the trial runs, several serious defects were discovered. The temperature profiles between the plates were not symmetrical about the centerline. The temperatures were higher at the plate through which the thermocouples are extended than at the other plate. At first, heat conduction along the thermocouples was thought to be solely responsible for this temperature pattern, but observation of the schlieren image projected on a screen indicated that heated air may be flowing around the thermocouple carrier and jetting into the central part of the test section. This phenomenon is probably at least partly responsible for the observed temperature profiles. The thermocouple wells have been reconstructed to remove this defect but have not yet been tested.

In runs with high heat input, it was also noted that the discharge pressure of the blower supplying the counter-flowing cool air was not sufficient to give the desired range of air rates. This blower was originally installed because it was available from war surplus at nominal cost, and although at the time it was decided to use it, there was some doubt as to its adequacy. It is planned to replace this blower with a more suitable one.

This schlieren apparatus presented problems inherent in any photographic setup, such as the type of photographic film and exposure times to be used. During the trial runs, various photographic films and exposure times were tried, but a completely satisfactory combination has not been obtained. It is planned to continue experimenting with different photographic techniques until a fully satisfactory one is developed.

When the improvements outlined above have been made a series of runs will be made with varied heat input and varied flow rates.

D. EXPERIMENTAL STUDY OF HEAT TRANSFER FROM A VERTICAL TUBE TO A LIQUID WITH FREE CONVECTION. (Del-1R1).

Submitted by: S.A. Guerrieri, University of Delaware.

To study the effects of the various controlling factors in turbine blade cooling, a static model has been set up in which the heat is transferred from a vertical tube to the test liquid which fills it. Traveling and stationary thermocouples are used to obtain temperature profiles of the system. The heat transfer tube is warmed by immersion in a bath of heated oil. From a knowledge of the specific heat and flow rate of the oil and of the specific heat and quantity of the test liquid, a heat balance can be established. The ultimate aim is to determine heat transfer coefficients.

During the past quarter the tubular test unit has been rebuilt and put back into operation. Some small leaks in the test apparatus have been found and repaired. Mixing devices of the disk-doughnut type have been made

and installed on the heat transfer oil lines to insure accurate heat balances. Minor changes in piping have been made to ensure a more steady water supply from the constant head tank, and a section of flexible metal hose has been inserted between the oil circulating pump and the test apparatus in order to damp out mechanical vibrations. Heat transfer studies with water will not be resumed.

A heat exchange apparatus has been constructed to determine the specific heat of the heating oil used in these experiments. It is necessary to know accurately the specific heat of the heating oil since precise heat balances are dependent on it.

In order to test the accuracy of the temperatures measured by the wall and the traveling thermocouples in the test apparatus, a simple but similar unit has been constructed which contains one traveling thermocouple and one wall thermocouple identical in construction and arrangement to those used in the research. Thermocouples lying in isothermal zones in the tube wall and in the liquid are provided to check the temperature measurements made by the former thermocouples. With this apparatus it will be possible to compare the readings obtained with the two arrangements of thermocouples and to develop, if necessary a calibration for the thermocouples used in the research to allow for possible errors due to heat conduction along the thermocouple leads.

E. A THEORETICAL INVESTIGATION OF THE TEMPERATURE FIELD IN THE LAMINAR BOUNDARY LAYER (COMPRESSIBLE FLUID) ON A POROUS FLAT PLATE WITH FLUID INJECTION. (PIB-3R2)

Submitted by: S.W. Yuan, Polytechnic Institute of Brooklyn

A theoretical investigation of the heat transfer in the turbulent boundary layer on a sweat-cooled plate has been continued. In this investigation the laminar sublayer is assumed to exist between the turbulent core and porous wall. In order to determine the thickness of this laminar sublayer as a function of the length (x) in the direction of flow, the variation with x of the velocity, U_δ , at the outer edge of the laminar sublayer must be known. It may be noted that the velocity corresponding to U_δ is a constant in the laminar flow over a flat plate.

Since the laminar sublayer is extremely thin, it was assumed that the measured turbulent shearing stress near the wall was equal to the viscous shearing stress of the laminar sublayer. With this assumption it is found that the velocity U_δ is a function of the thickness of the laminar sublayer as well as of the local Reynolds number.

The velocity profile inside the laminar sublayer is assumed to be a certain exponential function of y , the distance inside the laminar sublayer. This function satisfies the required boundary conditions and is linear in y when the velocity of injected fluid becomes zero. Furthermore, as the velocity of injected fluid increases, the slope of the velocity profiles at the wall decreases; thus shearing stress at the wall

decreases as the velocity of injected fluid increases. With this assumed profile the solution of the integral relation of the momentum equation gives the thickness of the laminar sublayer as a function of length in the direction of flow.

The inflection points of the velocity profiles inside the laminar sublayer obtained from this solution indicate instability of this layer with injection. It is known that the laminar boundary layer becomes unstable at a considerable shorter distance from the leading edge for a plate with injection than for an impermeable plate. It is believed that beyond the critical Reynolds number of the sublayer where the instability begins any further growing of the sublayer would cause it to mix with the turbulent boundary layer. Subsequently, a sublayer with constant thickness would exist. The stability conditions for the laminar sublayer will be investigated in order to determine this critical Reynolds number and, in turn, the thickness of the laminar sublayer.

At the present time there is no available information on the turbulent wall shearing stress for a porous plate with fluid injection, although the experiments discussed above will provide this information. However, the data obtained for an impermeable wall was used in the above analysis. It has been learned from this investigation that the viscous shearing stress in the laminar sublayer decreases as the velocity of injection fluid increases, and the same reasoning would apply to the turbulent stress near the wall. By applying the momentum theory of the boundary layer with fluid injection, namely, that the measured turbulent shearing stress near the wall equals the momentum loss in the boundary layer one obtains the friction coefficient as a decreasing function of the injected fluid velocity. This result agrees with the statement indicated above. The results obtained so far in the present investigation are valid only for very small mass fluid injection.

The work thus far completed on an analysis of compressible laminar boundary layers in axial pressure gradients has been checked in detail. The implications of the method used here, namely the replacement of the energy, as well as the momentum, differential equation by an integral condition, have been further investigated for the flow over a flat plate. Comparison of heat transfer coefficients thus obtained with values obtained by more exact methods for the case of Prandtl number equal to unity shows satisfactory agreement. Previously, similar conclusions had been reached by a study of skin-friction coefficients. Further investigation shows the effect of the parameter Prandtl number: increasing the Prandtl number increases the heat transfer at the wall.

A study of the two general ordinary differential equations which have been derived has been continued, and further general conclusions have been reached. These concern, for example, the effect of fluid injection and adverse pressure gradient on boundary layer thickness and point of separation, as well as the effect of Reynolds number on skin-friction and heat-transfer coefficient.

A numerical solution for the case of a linear potential velocity distribution is about to be started.

Two other theoretical investigations have recently been initiated: analysis of the heat transfer in the laminar, compressible boundary layer on (1) a sweat cooled plate with temperature gradient along the wall and on (2) a flat plate with horizontal fluid injection along the wall. There is no progress to report on these as yet.

F. AN EXPERIMENTAL INVESTIGATION OF THE STABILITY OF THE LAMINAR BOUNDARY LAYER ABOVE THE SURFACE OF A POROUS FLAT PLATE WITH FLUID INJECTION.
(PIB-3R1)

Submitted by: S.W. Yuan, Polytechnic Institute of Brooklyn

During the past quarter the boundary layer velocity surveys measured with and without injection on a porous flat plate in the turbulence channel have been analyzed. The location of the porous plate, which is part of the channel wall, at a section more than 60 breadths downstream from the entrance bell, makes it difficult to obtain a purely laminar boundary layer at the leading edge of the porous section. The use of the suction slot at this leading edge has not proved to be entirely satisfactory in withdrawing the old boundary layer and establishing a new boundary layer on the porous wall.

However, certain qualitative results can be obtained from the analyzed data. These data were obtained by using a hot wire anemometer at free stream velocities of from 11.5 to 14.9 feet per second without injection through the porous section and with injection corresponding to injection ratios (v_0/U) of from 0.020 to 0.026. In general the effect of injection in these ranges is to increase the boundary layer thickness and to cause transition at lower local Reynolds numbers. These qualitative results are in agreement with the theoretical investigations of laminar boundary layer velocity profiles and stability.

In order to overcome the above-mentioned difficulties and to exploit the experimental techniques developed during this investigation, the construction of a new test setup is under way. In this new arrangement a continuous porous plate which is made of the same material as will be used in the high temperature channel is being placed in the side panel of the turbulence channel immediately downstream of the entrance bell. The walls of the channel will be adjustable so that the axial pressure gradient induced by the injected fluid can be effectively canceled. With this arrangement and with the use of the new porous material, quantitative results for comparison with the laminar boundary layer theory and for providing the fundamental data for the turbulent boundary layer analysis should be obtainable.

A large portion of the effort this quarter on this problem assignment has been devoted to investigating whether or not transition by trans-

verse contamination as reported by Charters² will dictate a change in the design of the high temperature channel, in which velocity, and temperature fields and laminar transition points are to be investigated under conditions of fluid injection and heat transfer. Since transition points were to be measured, it was necessary to insure that transition is not induced from the corners of the channel into the laminar layer along the centerline of the porous wall before transition would occur on an infinitely wide porous plate. Careful tests on the entrance bell of the turbulence channel have been carried out. These indicate that, provided this bell is carefully faired and smooth, no transition will be induced by the corners of the channel.

These results indicate that the proposed channel cross section, namely 2.5 x 20 inches, will be satisfactory. Thus the purchase orders, which cover the heater, blowers, and ducting, and which have been delayed until this question of transverse contamination was settled, can now be placed.

G. EXPERIMENTAL DETERMINATION OF RADIATIVE AND CONVECTIVE HEAT TRANSFER COEFFICIENTS FOR GASES UP TO 2000°F. (PRF-5R1, PRF-5R2)

Submitted by: J.M. Smith, Purdue University.

In order to understand the transfer of heat from jet engine gases to engine walls, the relative contribution of radiative heat transfer from gases at high temperatures is being investigated. Using non-radiative gases only, the convective heat transfer coefficient will be evaluated. Then, using radiating gases, the total heat transfer is to be measured, and the radiative contribution obtained by subtracting the convective transfer from the total.

The experimental apparatus consists of a heat transfer tube, through which the hot gases flow at a measured rate, and the tube is surrounded by a jacket cooled by a liquid to permit calorimetric measurements.

Reconstruction of the equipment has been completed. Modifications of the equipment include the construction of a fluid jacket surrounding the test section, equipment to counter-balance the weight of the column, an adiabatic gas mixing device to supplant the disk-doughnut type previously employed, and construction of smaller diameter thermocouple shields to allow more complete investigation of the radial gas temperature gradient. It is anticipated that wall thermocouples will be installed and measurement of heat transfer coefficients for air undertaken in the coming quarter.

²A.C. Charters, Jr., Transition between Laminar and Turbulent Flow by Transverse Contamination, NACA TN 891, 1943.

A fluid jacket was constructed to allow calculation of a thermal balance. It was necessary to provide an expansion bellows to allow for the difference of expansion of the cool jacket and the hotter test section.

A system of pulleys has been placed above the test section to support the entire weight of the column by stranded cable attached to the fluid jacket. This is deemed necessary in view of the high-temperature failure of previous equipment.

Since previous experimental data indicated the disk-doughnut gas mixing device had significant effect on heat transfer, it was decided to eliminate this effect by placing an adiabatic gas mixing device at the exit of the test section. Concentric tubes and baffles cause the gas to change direction 360 degrees.

Concentric thermocouple radiation shields have been prepared to allow a traverse of the test section entrance within $5/16$ of an inch of either wall. Copper-constantan thermocouples have been prepared to measure test section wall temperatures.

Installation of the thermocouples should be completed shortly and preliminary tests of the equipment will be made. Upon completion of these tests, measurements of heat transfer coefficients for air will be taken.

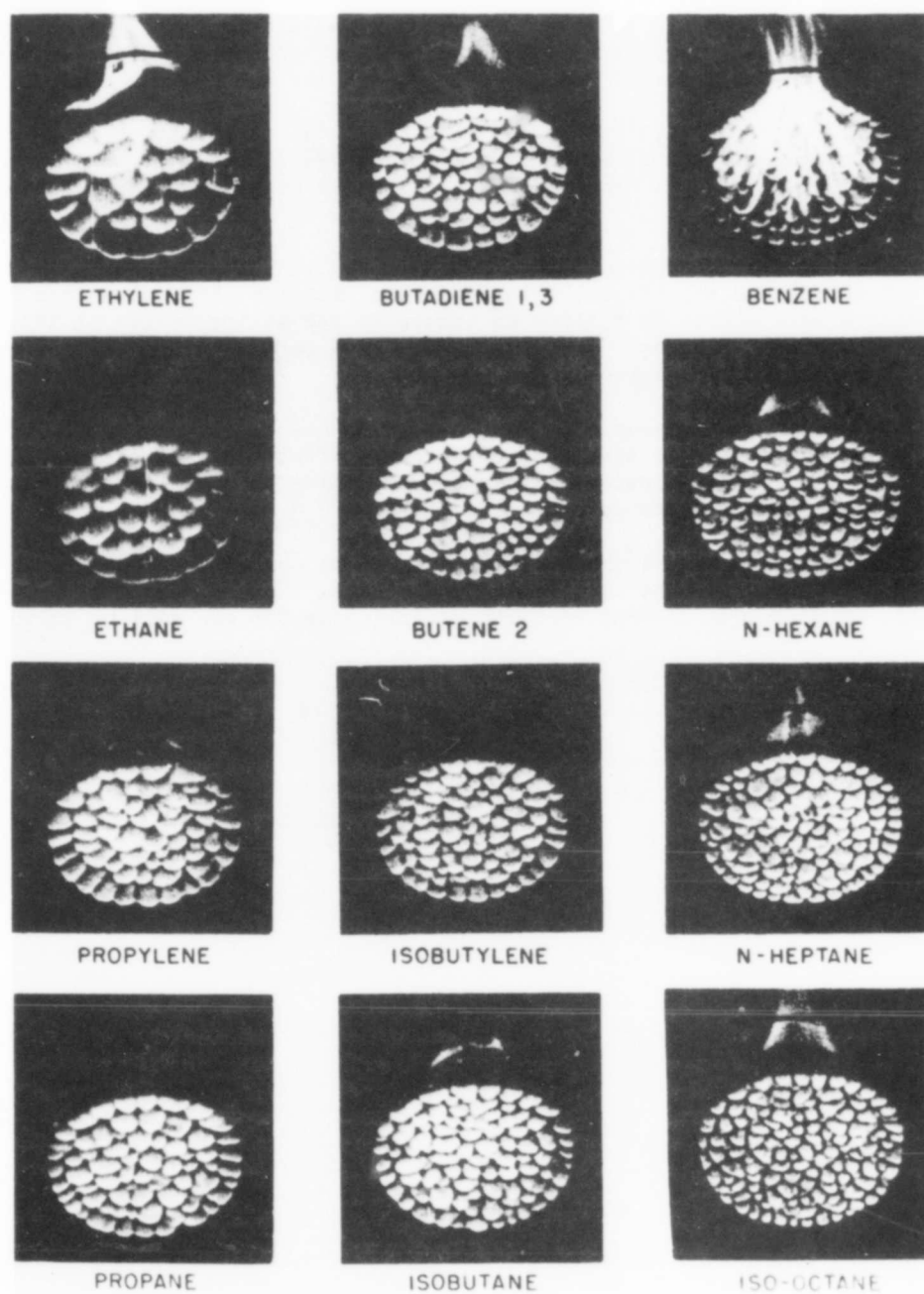


Fig. 1. Cellular flames of rich hydrocarbon-air-nitrogen flames at atmospheric pressure. Tube inner diameter 10.0 cm.

IV. CHARACTERISTICS OF FLAMES

A. INVESTIGATIONS OF THE BEHAVIOR OF FLAMES BURNING IN TUBES, WITH EMPHASIS ON CELLULAR STRUCTURE. (CAL-2R5)

Submitted by: J.V. Foa and G.H. Markstein, Cornell Aeronautical Laboratory

The work on cellular flames in tubes has been extended to the fuels n-hexane, n-heptane, iso-octane (2,2,4-trimethylpentane) and benzene. Since these hydrocarbons are liquid at room temperature and atmospheric pressure, their vapors were introduced into the mixture by bubbling part of the air-nitrogen mixture through a flask filled with the fuel. Fuel concentration was adjusted by varying the fraction of air-nitrogen mixture which by-passed the flask. Again compositions were used for which the flames remained almost stationary. This was accomplished, as in previous work, by starting with very rich mixtures which gave flames burning on top of the tube and then gradually reducing the fuel concentration until the flame entered the tube. No attempt was made to measure fuel concentration. However, it could be estimated fairly well from the appearance of the flames, particularly in the vicinity of stoichiometric composition, on the basis of the experience gained with the lower, normally gaseous, hydrocarbons.

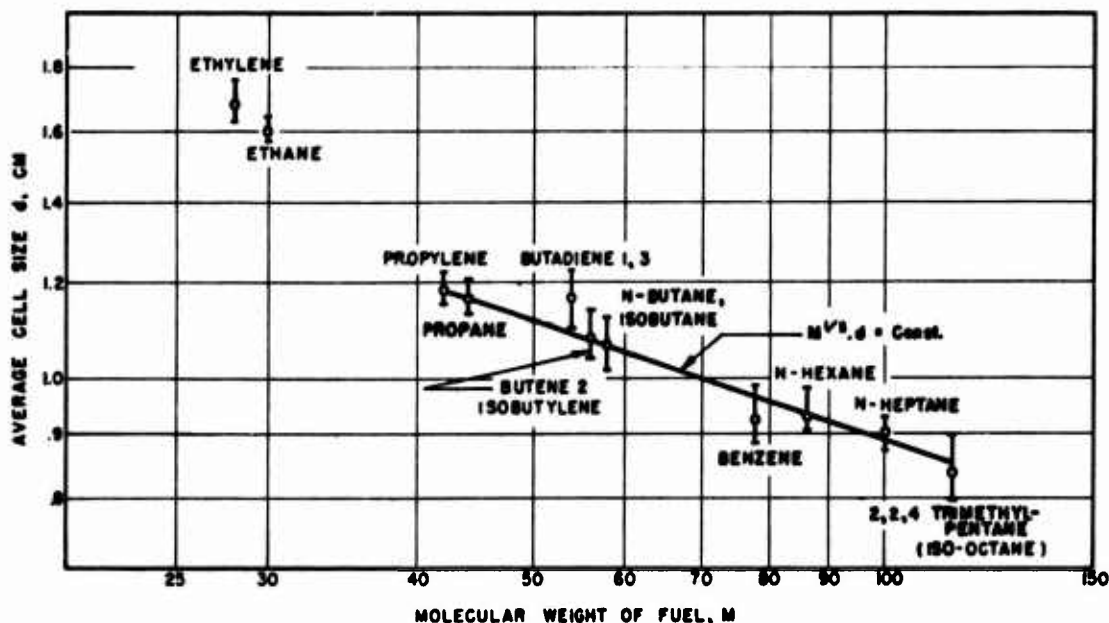


Fig. 2. Average cell size of rich hydrocarbon-air-nitrogen flames at atmospheric pressure vs. molecular weight of fuel.

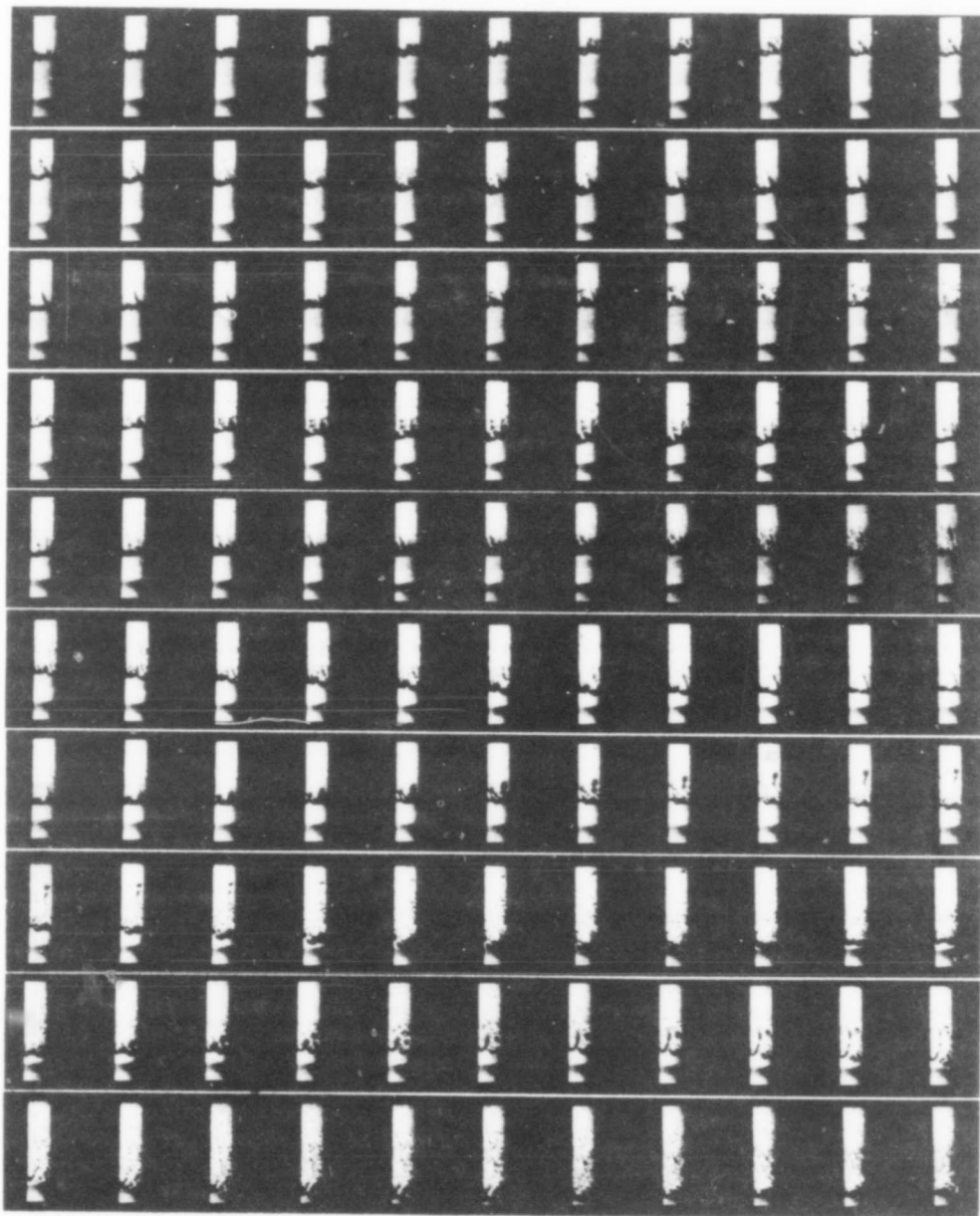


Fig. 3. High-speed schlieren movie of vibratory flame motion in tube of rectangular cross section. About 3000 frames per second. (Sequences are consecutive from top to bottom; in each sequence time increases from left to right.)

Benzene flames differed from the other hydrocarbon flames studied by the intensive yellow radiation due to formation of carbon, a well-known characteristic of aromatic fuels. This radiation was emitted in part from vertical streaks or bands which appeared to originate above the ridges between the cells. While this phenomenon occurred also to some extent in very rich mixtures of the other hydrocarbons, with benzene it persisted even close to stoichiometric composition. Therefore, a dark-blue filter had to be employed in the photographic work with this fuel.

Cellular flames of the majority of the fuels which have been investigated hitherto are shown in Fig. 1. Methane has not been included because it did not give cellular flames. Flames of n-butane have been shown previously;¹ they did not appear different from the isobutane flame.

The results of determinations of average cell size are summarized in Table I. A logarithmic plot of average cell size, d, versus molecular weight of the fuel, M, Fig. 2, showed that with few exceptions the data could be represented remarkably well by $M^{1/3} d = \text{Const.}$ (The circles in Fig. 2 are mean values determined from at least five flame photographs; the vertical lines indicate the spread of values from individual photographs.)

Fuel	Average cell size d, Molecular weight, $M^{1/3} d$		
	cm	M	
ethylene	1.68	28	5.10
ethane	1.60	30	4.97
propylene	1.13	42	4.10
propane	1.16	44	4.09
butadiene 1,3	1.16	54	4.38
butene 2, isobutylene	1.07	56	4.09
n-butane, isobutane	1.06	58	4.10
benzene	0.92	78	3.93
n-hexane	0.93	86	4.10
n-heptane	0.90	100	4.17
2,2,4 trimethyl pentane	0.84	114	4.08

No theoretical explanation for this empirical relation has yet been found. Values of $M^{1/3} \cdot d$ are also given in Table I. If the values for ethylene and ethane (which gave very "weak" cell structures), butadiene 1,3 (the only di-olefin studied) and benzene (the only aromatic studied) are excluded the others agree within $\pm 1.7\%$ with their mean value.

¹Project Squid, Annual Program Report, 1 January 1950, Cornell Aeronautical Laboratory, Div. IV. Sec. A.

A technical memorandum on the work of cellular flames is being prepared. Further work on cellular flames is planned, particularly on the effect of hydrogen and other additives.

The experiments on vibratory flame motion were continued with preliminary runs employing a new flame tube of rectangular cross section with glass sidewalls. High-speed schlieren movies taken with transversal observation confirmed previous findings, obtained with axial observation in circular tubes, about the periodic appearance and disappearance of cellular structure during vibratory flame motion. Beyond this result, they showed phenomena, notably during oscillations of large amplitude, which could not be studied adequately by axial observation. Fig. 3 shows a sequence of high-speed schlieren movie frames of vibratory flame motion in the new tube. As in previous work, the flame propagated from the open top to the closed bottom. The movie shows passage of the flame through a portion of the lower half of the tube. A rather extended zone of turbulent burning appears behind the main flame front, presumably composed of islands of unburned gas which are shed by the main flame front in periodic sudden bursts. It is interesting to note that this flame structure is identical with that of a highly turbulent flame, according to Shchelkin.² An essential difference, however, lies in the mechanism which causes the flame to assume this structure. Stream turbulence in the unburned gas, which alone was considered to cause the disruption of the flame front by Shchelkin, was virtually absent under the conditions under which Fig. 3 was obtained. As discussed on previous occasions,³ it seems most likely that the effect of periodic accelerations on flame front stability is the cause of flame front break-up during vibratory flame motion.

As in previous work, recording on the movie of the pressure variations near the closed end of the tube appeared necessary for obtaining as much information as possible on the coupling between motion of the gas column and structure and motion of the flame front. Formerly this was done by photographing the screen of an oscilloscope, connected to the pressure pickup, on the high-speed movie. This technique was not very satisfactory, particularly at the high frame rates necessary in this work, owing to underexposure because of insufficient light output from the scope. A modification of this technique was therefore developed which makes use of a mirror galvanometer. Light from this galvanometer entered the camera through a right-angle prism, the edge of which served as schlieren knife-edge. An electronic bridge circuit was designed and built for coupling the low-impedance galvanometer to the output of the receiver of the pressure pickup. Operation of this device in preliminary work appeared to be entirely satisfactory.

²K.I. Shchelkin, J. Tech. Phys. (USSR) 13, 520 (1943), NACA TM No. 1110 (1947).

³Project Squid, Annual Program Report, 1 January 1950. Div. IV, Sec. A.

Theoretical work on flame front stability has been continued. In previous work, the physico-chemical properties of the combustion zone were introduced by a single parameter, which characterized the dependence of burning velocity on curvature of the flame front. However, the additional possibility of variations of temperature of the burned gas with curvature cannot be excluded, since the reaction does not necessarily go to completion in the primary reaction zone, particularly in rich flames. Thus a second parameter, linking temperature of the burned gas with flame front curvature, was introduced. Furthermore, the first order solutions of the hydrodynamic equations in the burnt gas had to be generalized in order to account for temperature and density variations and heat conduction. The result of the treatment showed that the effect of temperature variations on flame front stability, similar to the effect of variations of burning velocity, increases with decreasing wave length of the distortion of the flame front.

The effect is stabilizing or unstabilizing, depending on whether the temperature is higher or lower than the average in regions where the flame front is convex toward the burned gas. It does not seem possible, on the basis of the present limited knowledge of the kinetics of combustion reactions, to estimate the relative importance of burning velocity and temperature changes, or even to determine the sign of these changes with respect to flame front curvature. It seems likely that the effect of temperature variation is relatively unimportant, and probably unstabilizing, since one would expect a slightly lower temperature above the ridges separating the cells, where combustion is presumably less complete (carbon formation in very rich flames).

It is planned to issue a memorandum on the theoretical work in the near future.

B. EXPERIMENTAL STUDIES OF FLAMES ISSUING FROM BURNERS. (CAL-2R6)

Submitted by: G.H. Markstein, Cornell Aeronautical Laboratory

The emphasis in this problem in the past was observing the effect of artificially created disturbances upon the structure of burner flames. Work on the technique of flow visualization in non-steady burner flames by means of smoke traces is continuing, but no significant progress can be reported at this time. Some experiments on the question of the "open tip" of burner flames are planned. Exploratory work had shown that open tips were obtained in all mixtures which gave cellular flames in tubes. In order to extend this work to flow velocities and compositions beyond the blow-off limits, an annular pilot flame will be used.

C. EXPERIMENTAL STUDY OF THE STABILITY CONDITIONS, THE FLUCTUATIONS, AND OTHER PROPERTIES OF TURBULENT FLAMES WITH THE HELP OF THE HOT-WIRE ANEMOMETER. (DEL-2R2)

Submitted by: Kurt Wohl, University of Delaware

This problem is concerned with the question how the properties of high velocity flames, such as ignitability, stability, and "burning velocity", depend on turbulence and other types of fluctuations in the unignited gas stream and in the ignited gas stream upstream of, and inside the flame.

The flames studied are stabilized by a flame holder in a high velocity stream of a homogeneous propane-air mixture. The emphasis is placed on the measurement of fluctuations with the help of the hot-wire anemometer. However, measurements are also made of the static pressure and head pressure, and of the local composition of the flame gases.

The hot-wire anemometer constructed is of the constant resistance type and makes use of the push-pull amplifier circuit described by Ossofsky.⁴

It was reported in the Annual Report of 1 January 1950 that stable operation of the circuit has been attained and that the instrument responds to velocity fluctuations in an air stream. During the last months work has been concentrated on various electrical checks of the instrument and minor revisions of construction.

It has been stated by Ossofsky and also Kovaszny⁵ that for satisfactory operation of the constant temperature anemometer the frequency response of the amplifier must be about twice or three times the maximum frequency desired in turbulence explorations. The amplifier constructed here has been tested and found suitable, being flat within 1 decibel from 10 to 70,000 cycles. Since the upper limit desired for turbulence investigation is 20,000 cycles/second, this frequency response is adequate. The amplifier shows only a 85% reduction in gain at 320 kc and a measurable response is observable even at 1.0 megacycle.

In order to avoid oscillations, it is further necessary that if an "in-phase signal" is applied, i.e. when both the top and bottom input grid are tied together, the output of the amplifier must be less than the input (though the single signal is amplified 1200 times). Also it is desirable that this so-called "in-phase degeneration" be returned to the amplifier out of phase with the input signal.

If the amplifier were perfectly symmetrical, the in-phase output would approach zero. Actually, we have found that the most important single factor in reducing this in-phase degeneration to a suitable value is precise matching of tubes which depends greatly on the equality of filament supply potential to each tube. Other factors which have appeared to aid in minimizing the in-phase degeneration have been: elimination or rerouting of

⁴E. Ossofsky, Rev. Scient. Instr. 19, 881-9 (1948).

⁵L. Kovaszny, Simple Analysis of Constant Temperature Feedback-Hot-Wire Anemometer, Aero/JHU CM-478, June 1, 1948.

shielded leads which run from later stages of the amplifier to preceding stages; provision of separate grounding points for shielded leads near the amplifier stages where they connect; adjustment of critical resistances to give equal values on the top and bottom sides. At present, the in-phase degeneration of the amplifier is such that the output signal is about $\frac{1}{6}$ the input signal at frequencies up to 70,000 and rises to about $\frac{1}{2}$ the input signal at 250 kilocycles and remains at a low level up to 20 megacycles.

The frequency response measurements and the in-phase degeneration comprise the two main performance tests of the amplifier alone. There remains the test of the Wheatstone bridge arrangement which is combined with the amplifier. Work on this phase is under way.

Construction of a second amplifier which is required for measuring the scale of turbulence has been started. Permanent filament supplies for each amplifier are being constructed.

It has been found that a hot-wire anemometer probe of platinum wire can conveniently be constructed by silver soldering the platinum wire to nickel supports.

It is expected that turbulence measurements with the hot-wire anemometer can be started in a few months' time.

D. EXPERIMENTAL DETERMINATION OF THE TEMPERATURE DISTRIBUTION IN NON-LUMINOUS FLAMES OF VARIOUS TYPES. (DEL-2R3)

Submitted by: Kurt Wohl, University of Delaware

The apparatus developed for measuring local spectral line-reversal temperatures of flames is designed to combine high accuracy with high operational speed and rigidly controlled change of experimental variables. The apparatus is of the stationary laboratory type. Any vertical burner of one foot diameter or less may be installed for study. Horizontal flame chambers up to one foot diameter and two and one half feet long could be handled.⁶ The light beam can be focussed at a point in the flame or passed through the flame as a parallel pencil. The parallel pencil system possesses the great advantage of requiring only small apertures (3mm or less) in the walls of a combustion chamber. Temperatures can be determined with random error of less than $\pm 5^{\circ}\text{F}$ under optimum conditions. Tests made with the incomplete apparatus average one minute or less per point, including four to six checks. Double checked measurements have been taken at rates as high as three per minute. This time requirement may be halved under optimum conditions when the apparatus is complete.

⁶At present the apparatus is used for studying open flames burning above tubes of about 1 inch or less in diameter.

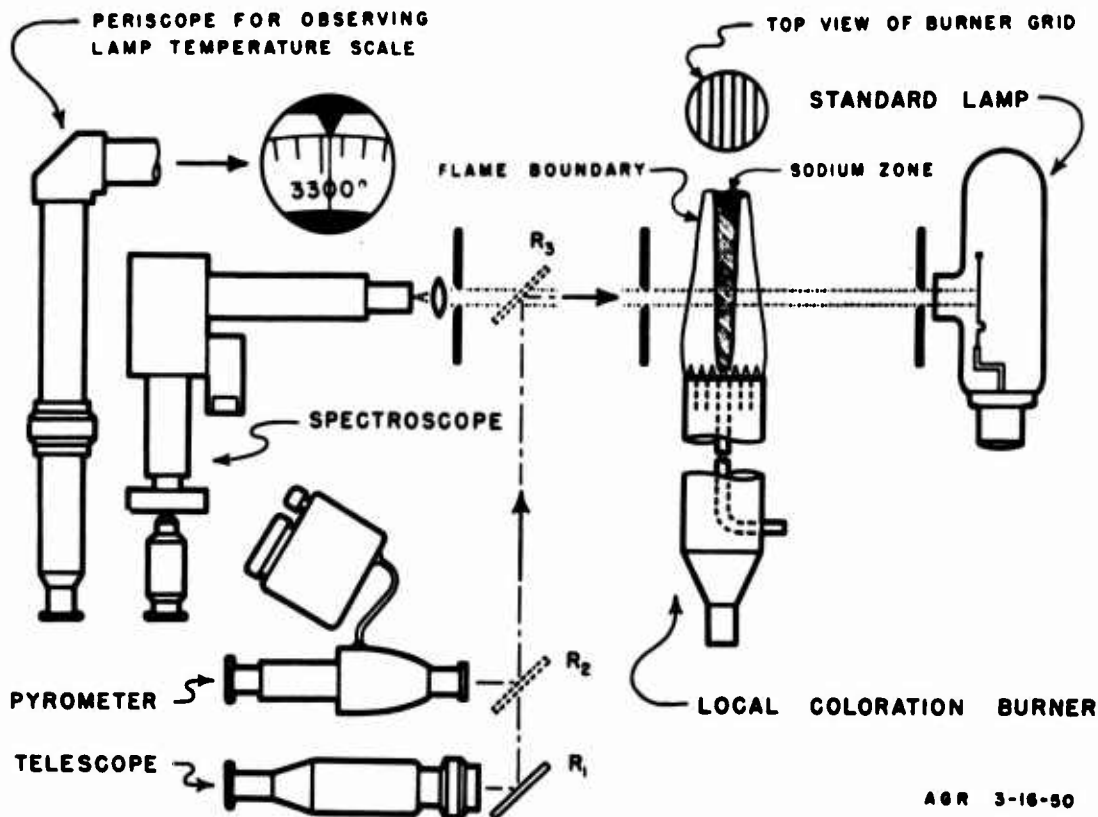
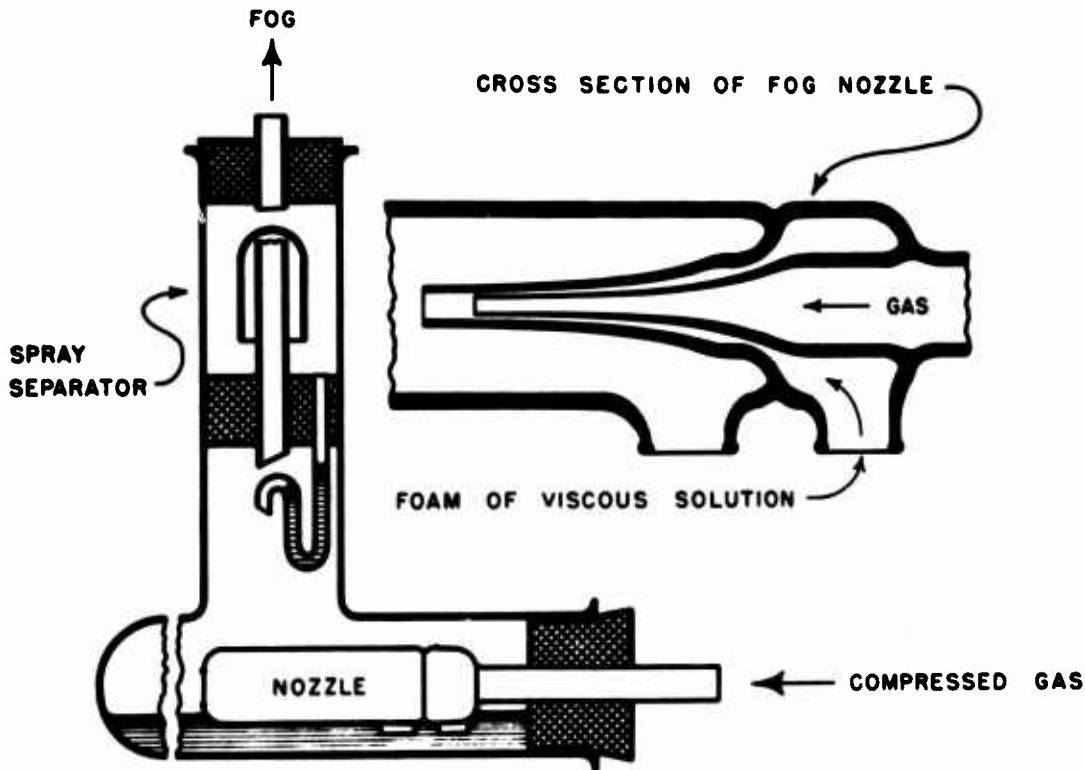


Fig. 4. Apparatus for measuring flame temperatures by the spectral line-reversal method.

The arrangement of the optical system is shown in Fig. 4. Light from the standard lamp passes through the flame and into the spectroscop through two iris diaphragms and a condensing lens. The resulting spectrum is viewed through a microscope which provides higher magnifications than those obtainable with regular eyepieces. The location of the optical axis relative to the flame can be checked with the telescope. For this purpose the hinged mirror R_3 is raised so that the optical axis is switched over to mirror R_1 and the telescope. In order to check the calibration of the standard lamp the pyrometer may be sighted down this axis by raising mirror R_2 or it may be swivelled around so that it sights the lamp filament directly. By alternate use of these pyrometer sights the effect of lenses, mirrors and chamber windows upon the lamp calibration may be evaluated.

The standard lamp temperature is indicated by a Brown "Electronic" self-balancing precision potentiometer which measures the potential drop across a calibrated shunt in series with the lamp. The potentiometer scale is illuminated by yellow light of variable intensity and is read through a periscope, the eyepiece of which is located to the left of the spectroscop



AGR 3-16-50

Fig. 5. Fog generator.

eyepiece. With the room darkened, the operator can observe in this way line-reversals with his right eye, and can at the same time, without moving his head, read the potentiometer with his left eye by momentarily illuminating the scale. This system eliminates the major causes of the eyestrain previously encountered and makes possible continuous observations for periods of 20-60 minutes. The current through the standard lamp is regulated by a motor driven rheostat. Tests of this equipment have revealed two advantages in addition to the convenience of "push button" control. The first is that of appreciably increased speed of operation. The second is that of increasing the accuracy of the data. By eliminating the mechanically rigid connection between the operator's hand and the rheostat contacts this "push button" control eliminates any possibility of unconsciously pulling the data one way or another.

The burner is supported by a rotary mount which permits unlimited rotation of the burner about its central axis. This turntable is mounted upon a mechanism which varies the position of the burner with respect to the optical axis horizontally and vertically under remote control. This position is defined with an accuracy of 0.01 mm in the vertical plane normal to the optical axis.

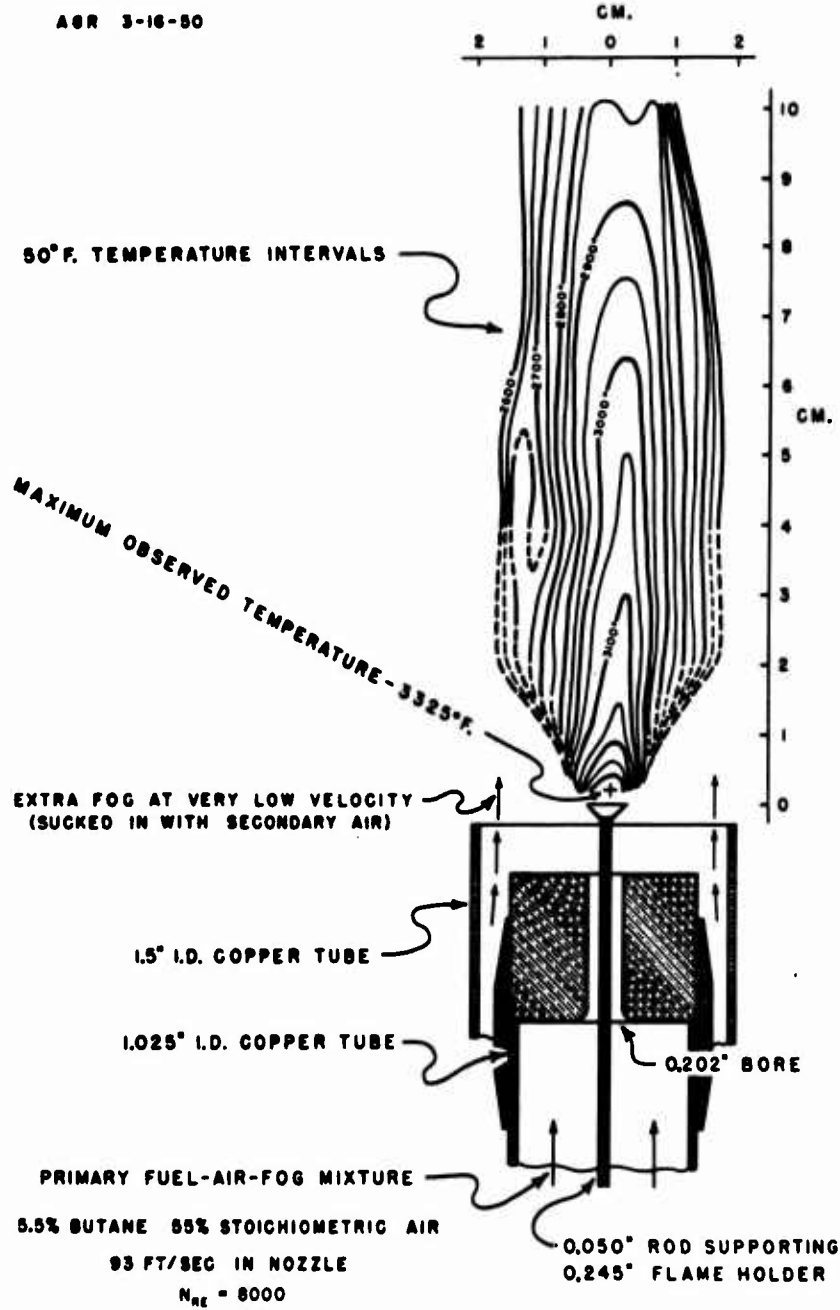


Fig. 6. Isotherm chart for a totally colored turbulent butane-air flame.

The control unit is provided with clickers which enable the operator to traverse the burner in precise increments without moving his eye from the spectroscope.

The flame is colored with a fog of a solution of NaCl in a mixture of 85% glycerin and 15% water. This fog is produced by a special nozzle of the type illustrated in Fig. 5. Gas is fed to the inner nozzle under a pressure of about 25 p.s.i.g. Liquid is sucked into the gas jet through the annular space between the first and second nozzles. The separator in the vertical leg of the fog producer removes any coarse droplets which might be carried upward by the gas stream. The resulting fog is exceptionally stable and may be piped through smooth conduits like any gas. It passes through columns of dry sand and cotton fiber with barely detectible loss. Although wetted columns of these materials will remove it to some extent the relatively strong action of high velocity water sprays is required to remove this fog from a gas stream.

The fog may be introduced into only a small portion of the gas creating coloration of the flame only along the stream lines of this portion. Usually coloration was applied to a narrow sheet passing through the flame axis and oriented perpendicular to the optical axis.

The apparatus is now complete except for the permanent electrical controls and the precision fuel and air metering system. These will be finished in the near future. Temporary electrical and flow controls have been used for testing the system and making a number of measurements.

A satisfactory agreement of the measured maximum flame temperature with the thermodynamic temperature for adiabatic combustion has been ascertained previously. (Report UD-100-I submitted to Pratt and Whitney Aircraft on March 10, 1949). The check will be repeated.

One of the flames studied recently is a totally colored turbulent butane flame burning from a flame holder above a tube in air. The results are presented in the isotherm chart of Fig. 6. It is remarkable that the point of maximum temperature is located so close to the flame holder. Also it should be emphasized that the fold in the isotherms observed in the left side of the flame is reproducible. Along the vertical axis the random error of temperature measurements varies from $\pm 10^{\circ}$ to $\pm 25^{\circ}\text{F}$. The higher value applies to the very thin lower portion just above the flame holder and to the upper zones where the turbulent fluctuation is large. At the boundaries of the flame the random error rises to $\pm 50^{\circ}\text{F}$, primarily because of the combination of steep temperature gradients and large turbulent fluctuations. The dashed portions of the isotherms are extrapolations based upon visual observation of the flame and its shadow picture.

When the apparatus has been completed a locally colored two-dimensional analogue of this flame will be studied to determine the true average temperature pattern and its relationship to the visible flame and the shadow picture

of the flame. It is hoped that measurements will then be possible in the regions of the extrapolated isotherms of the present chart. It is further planned to obtain the temperature patterns of a number of other laminar and turbulent flame types.

V. C H E M I C A L R E A C T I O N K I N E T I C SA. KINETICS OF DECOMPOSITION AND OXIDATION OF GASEOUS BORON COMPOUNDS.
(Pr-2R2)

Submitted by: R.N. Pease, Princeton University

Diborane (B_2H_6) and aluminum borohydride ($Al(BH_4)_3$) are being studied.

With respect to diborane, a preliminary investigation of the kinetics of decomposition has been completed and will shortly be published. The interaction with oxygen is being examined at present.

It appears that small amounts of oxygen have very little effect on the stability of diborane even at temperatures ($100^\circ C$) where the normal decomposition is proceeding. Thus there does not seem to be either an acceleration or inhibition of the normal decomposition by oxygen. With larger amounts of oxygen, explosion occurs after an induction period--presumably due to interaction with one of the higher diboranes which are formed.

With respect to aluminum borohydride, earlier studies had shown that this substance led to explosion of ethylene-oxygen mixtures after an induction period. Subsequent work has shown that the borohydride and ethylene interact, and further that oxygen accelerates this reaction. The nature of this acceleration, which precedes the explosion, is being studied.

B. INTERACTION OF HYDROGEN ATOMS WITH OXYGEN AND HYDROCARBONS. (Pr-2R4)

Submitted by: R.N. Pease, Princeton University

The reaction of hydrogen atoms from a Wood's discharge tube with oxygen-hydrocarbon mixtures had been under investigation.

Current work in this field relates to attempts to trace the interaction of oxygen atoms from a discharge tube at low pressure with ammonia and with hydrazine (N_2H_4). With respect to ammonia, an explosive compound appears to condense out in the liquid nitrogen trap. With respect to hydrazine, a reaction occurs in which ammonia and nitric oxide are among the products.

C. KINETICS OF THE NON-CATALYTIC OXIDATION OF AMMONIA. (Pr-2R5)

Submitted by: R.N. Pease, Princeton University

The non-catalytic oxidation of ammonia is apparently repressed partially by ammonia itself. A study of this system is being made in a constant-volume

system at pressures below atmospheric, and a search for intermediates is in progress.

D. PHOTOCHEMICAL EXPLOSION OF HYDROGEN-CHLORINE MIXTURES. (Pr-2R6)

Submitted by: R.N. Pease, Princeton University

Hydrogen-chlorine mixtures are exploded by illuminating with a photo-flash bulb of known output. Limits of explosibility are being determined by varying the distance between light source and the reaction bulb. It is hoped in this way to determine the minimum radiant energy required for explosion as a function of the composition of the hydrogen-chlorine mixture. Photo-sensitisation of hydrogen-oxygen mixtures by means of chlorine will also be studied.

E. PHOTOCHEMICAL SENSITIZATION OF THE REACTION IN PROPANE-OXYGEN-AZOMETHANE MIXTURES. (NYU-7R7)

Submitted by: H.A. Taylor and M.D. Scheer, New York University

The progress of the reaction taking place in a mixture of oxygen, propane, and azomethane while it is being irradiated by ultraviolet light from a mercury arc lamp is followed using manometers and a gas analysis system. Measurements made on the propane-oxygen-azomethane reaction at azomethane concentrations varying from 35 per cent to 10 per cent of the total mixture volume, indicate that there is no noticeable change in reaction products with change in azomethane concentration. Using mixtures in which the partial pressures of the components were about 10 mm Hg of azomethane, 40 mm Hg propane, and 40 mm Hg oxygen, no significant change in total pressure was observed as a result of reaction at a temperature of 35°C. The approximate amounts of the following products obtained are (expressed in mole per cent of the total products): 0.5 - 1.0 per cent CO; 0.2 - 0.5 per cent H₂; 5.0 - 10.0 per cent of a compound or compounds containing a single atom of oxygen per molecule (probably water with trace of low-carbon carbonyl compounds.)

These experiments complete the series of preliminary runs made to test the operation of the apparatus. The next series of experiments will be made at partial pressures similar to these, but at temperatures varying between 35°C and 200°C.

F. EXPERIMENTAL STUDY OF ROCKET MOTOR PERFORMANCE, WITH REFERENCE TO THE PARAMETERS AFFECTING COMBUSTION PROCESSES. (STUDY OF L*) (Pr-Ph. 5)

Submitted by: J.V. Charyk, Princeton University

During the past three months, the experimental setup for the gas propellant rocket studies has been modified to permit studies at higher chamber pressures. The initial successful tests were carried out at 250 psia

using oxygen and meth-
 and. The redesigned
 motor has an improved
 cooling system and an
 injector of more satis-
 factory design and the
 test facility has been
 modified to permit cham-
 ber pressures up to 450
 psia.

Included in the
 new instrumentation is
 an automatic flow ratio
 controller which auto-
 matically records the
 flow rates and main-
 tains a constant mix-
 ture ratio. Pneumsti-
 cally-controlled prop-
 ellant valves of high
 capacity have also been
 installed to eliminate
 the large pressure drops
 encountered in the elec-
 tric valves used pre-
 viously.

In connection with
 the studies of rocket
 motor performance with
 premixed propellants,
 flow tests are in prog-
 ress utilizing porous
 stainless steel plugs which are to be utilized in the role of injectors in
 the rocket studies. These plugs are $\frac{1}{8}$ -inch thick and were machined in the
 form of $1\frac{1}{4}$ -inch diameter discs for ease of installation in the present
 rocket chambers.

Some of the calibration data is shown in Fig. 1 and the quadratic re-
 lationship between pressure drop and weight flow as indicated in the tests
 at the Jet Propulsion Laboratory of the California Institute of Technology¹

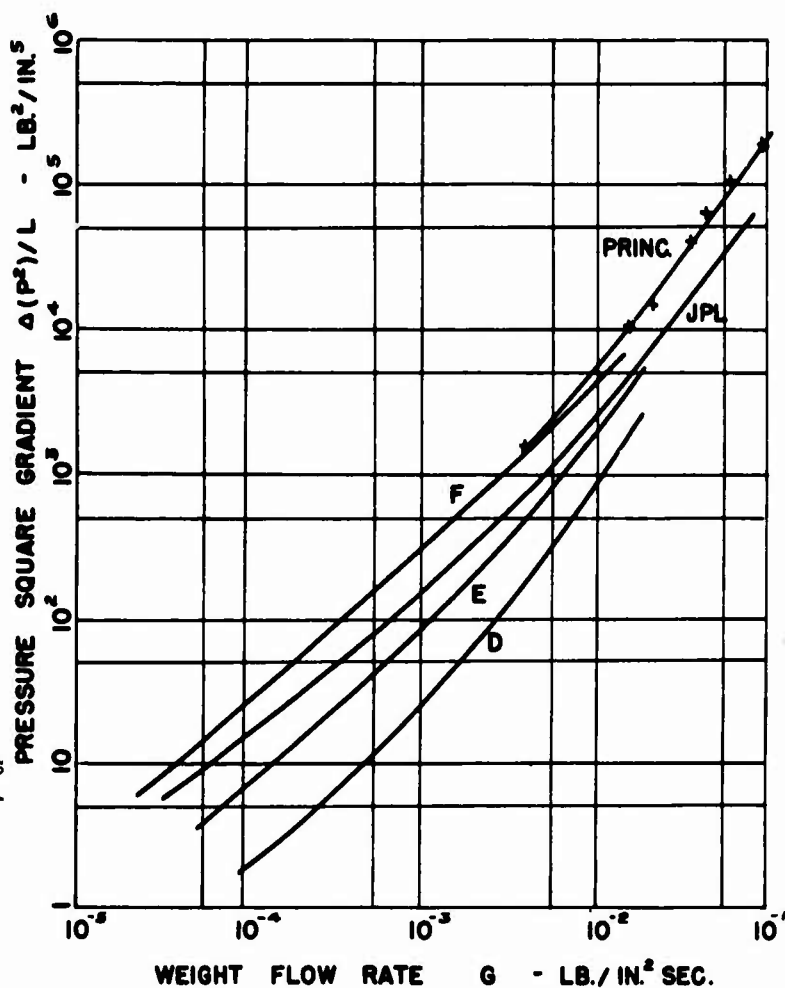


Fig. 1. Porous plug flow calibration

¹Jet Propulsion Laboratory, Progress Report No. 4-111, "The Fluid Flow Through Porous Metals," Leon Green, Jr., August 17, 1949.

and the Micro-Metallic Company² is further corroborated. On the basis of these tests, a porosity has been selected to give a reasonable pressure drop for the desired weight flow of propellant gases. These injector plugs are being installed in several rocket motors and premixing tests are scheduled for the near future.

G. EXPERIMENTAL INVESTIGATION OF IGNITION LAG OF SPONTANEOUSLY IGNITABLE PROPELLANTS. (PRF-7R3)

Submitted by: S.V. Gunn, Purdue University

The object of this problem is to determine the effect upon the ignition lag of hypergolic liquid propellants of the following variables: temperature of propellants before mixing, mixture ratio, manner of mixing, and additives to either the oxidizer or the fuel. For the purposes of this investigation, ignition lag is defined as the time interval between the instant of contact of the propellants and the emission of visible light from the reaction as indicated by a photoelectric cell.

A survey of the literature pertaining to ignition lag research work revealed that as yet no correlation has been obtained between the results from open-cup tests and those from rocket motor operation. There also appears to be a lack of data on the effect of temperature before mixing upon the ignition lag of propellant combinations employing white fuming nitric acid as the oxidizer.

A series of twenty open-cup ignition lag measurements were made at room temperature for nitric acid, furfuryl alcohol, and aniline propellant combinations. The arithmetic average of the results are given in Table I. The reaction between RFNA and furfuryl alcohol was most violent.

Bipropellant System		Ignition Lag (Average)
Oxidizer	Fuel	
WFNA	Furfuryl alcohol	0.032 sec
WFNA	(Furfuryl alcohol - 80% (Aniline - 20%	0.014 sec
WFNA	Aniline	0.24 sec
RFNA	Furfuryl alcohol - (freshly distilled)	0.155 sec
	Furfuryl alcohol - (aged)	0.140 sec
	Furfuryl alcohol - (pot residue)	0.125 sec
RFNA	Aniline	0.090 sec

²Data sheet on "Surfamax" stainless steel filters, Micro-Metallic Corporation, 193 Bradford Street, Brooklyn, N. Y.

H. CATALYSIS OF THE REACTIONS OF NON-HYPERGOLIC PROPELLANTS. (PRF-7R5)

Submitted by: C.H. Trent and C.M. Ehresman, Purdue University.

This project is concerned with the study of the reactions of hydrocarbon fuels, such as AN-F-58 jet engine fuel, with white fuming nitric acid (WFNA), the ultimate objective being to make the reactions self-igniting (hypergolic), if possible, by the addition of substances broadly classified as catalysts. The main problem has been divided into three parts: (1) measurement of the temperature history for the reactions between liquid hydrocarbons and liquid WFNA; (2) research on the behavior of liquid hydrocarbons with the gases produced by boiling WFNA; and (3) the determination of the chemical species formed as the result of the reaction between AN-F-58 jet engine fuel and WFNA. This report is concerned with the progress made on problems 1 and 2.

1. Measurement of the temperature history³ for the reactions between liquid hydrocarbons and liquid WFNA. The determination of the temperature history for fuels hypergolic with WFNA has been continued. The rates of temperature rise for aniline, o-toluidine, m-toluidine, and 1,3,4-xylydine when reacted with WFNA were measured. It was previously reported⁴ that the slopes of these time-temperature curves were not reproducible to the desired degree of precision. Subsequently, the data obtained from these experiments were subjected to statistical analysis in order to determine the degree of correlation. This analysis has led to the following conclusions:

(1) If the logarithm of the temperature is plotted versus time, a curve results with an initial straight line portion conforming to the general equation $\text{Log } T = mt + b$, where m is the rate of change of temperature with time.

(2) The analysis of the curves for the temperature history for aniline-WFNA, aniline-WFNA, m-toluidine-WFNA and 1,3,4-xylydine-WFNA as previously measured⁵ shows that the slopes of these curves and the points at which the curves deviate from linearity are significantly different; that is, the probability is 5 in 100 that they are the same. However, within the group, aniline-WFNA and m-toluidine-WFNA produce parallel time-temperature curves, indicating that the rates of temperature rise for aniline and m-toluidine reacted with WFNA are substantially the same.

It has not yet been determined what effect the response rate of the thermocouple has upon the general shape of the time-temperature curves.

³Project Squid, Annual Program Report, 1 January 1950, Div. 5, Sec. G.

⁴Ibid.

⁵Ibid.

The design and construction of an improved apparatus for measuring reaction temperature more precisely is in progress and will be continued. Upon completion of the apparatus, the time-temperature curves for the previously mentioned propellant combinations will be redetermined. Experiments to determine a correction factor for the response of the thermocouple employed are to be undertaken.

2. The behavior of liquid hydrocarbons submerged in the gases produced by boiling WFNA. The immediate problem under investigation is the determination of the minimum temperature at which hydrocarbon fuel droplets will ignite spontaneously in an atmosphere of WFNA vapor.

The design and construction of the reaction apparatus is being continued. The main element of the equipment is a vertical glass reaction tube five feet long filled with WFNA vapor at a controlled temperature. The hydrocarbon fuel droplet will fall freely through the WFNA vapor. During a series of runs the temperature of the WFNA vapor will be increased until ignition occurs.

A photographic record will be made of the descent of the droplet to obtain information regarding the physical changes taking place. A stroboscopic light will be used to illuminate the droplet.

I. OXIDATION KINETICS OF HEAT-RESISTANT ALLOYS. (PRF-3R1)

Submitted by: H.J. Yearian, Purdue University.

Precision X-ray diffraction measurements of the high and low parameter spinel type oxides formed on chromium steels show that the parameter of each type decreases slightly as the temperature or time of oxidation is increased. The high parameter spinel and its accompanying Cr_2O_3 disappear when the oxygen pressure is increased to 2 atmospheres.

Formation of Fe_3O_4 by CO-CO_2 reduction of Fe_2O_3 has not yet progressed to the desired $\text{FeO-Fe}_3\text{O}_4$ equilibrium which should give an iron-rich Fe_3O_4 , possibly having a parameter higher than normal.

The formation of oxide films has been studied in several ways. Seven chromium steels, two carbon steels, and a 20Cr-80Ni alloy have been oxidized at 310°C and examined by electron micrography. At time up to 13 hours the chromium alloys show a uniform film having a pebble-like surface, the size of the granules decreasing with increasing chromium content, except for a 5 per cent chromium steel which gives a vein-like structure. The carbon steels grow a rough, crusty oxide which tends to obscure pearlite structures. An additional one-hour oxidation of the more resistant alloys at 500°C produces isolated crystalline masses on the uniform film. Similar results are obtained in 15 to 30 minutes at 500°C without previous treatment at lower temperatures. All films show the Fe_2O_3 electron diffraction pattern after stripping; 10-20 carbon steel gives some additional Fe_3O_4 .

The same five regions of the oxide formed on a 26 per cent chrome-steel have been electron micrographed at various stages of oxidation at 500°C in air. After 5 minutes the pebble texture becomes pronounced, and after 10 minutes isolated 0.1 to 0.3 micron diameter nodules are formed which grow as oxidation proceeds. Additional nodules continue to form at random positions.

Electron diffraction studies by reflection from the surface of oxide films on 5 to 26 per cent chromium alloys and by transmission through the stripped films have been compared and correlated with electron micrographs. One cycle of heating for 5 minutes at 500°C gives only the pebble texture; the surface and bulk structure are both Fe_2O_3 .

The electrical resistance of films on 17 per cent and 13 per cent chromium alloys have been measured over the temperature interval from 20°C to 120°C. The activation energy for conduction tends to have two values corresponding, perhaps, to "intrinsic" and "impurity" semi-conductor values.

Additional X-ray diffraction data of the oxide scale formed on 5 to 26 per cent chromium steels oxidized in air have been taken, but the films have not yet been completely analyzed to compare with the earlier results.⁶

Completion of precision measurements and calculations of the diffraction patterns obtained in oxygen and air previously reported⁷ show a trend not evident from the less precise measurements. Under high rate of attack conditions an oxide of the spinel structure (magnetite type) was found, the parameter of which lay within the range $8.38 \pm .01$ KXU. (1 KXU = 1.00202×10^{-8} cm). A similar spinel with a parameter in the range $8.43 \pm .01$ KXU was found on the 26 per cent alloy when oxidized in one atmosphere of oxygen and also on the 13 and 17 per cent alloys oxidized in air at low temperatures. It is now evident that there are regular trends of variation within these limits. For both types of spinel the lattice parameter decreases slightly as either the time or temperature of oxidation is increased. The high parameter material (on the 26 per cent alloy oxidized for 20 hours) shows a change from $8.438 \pm .005$ KXU at 775°C to $8.425 \pm .005$ KXU at 1100°C. Over a similar temperature range the low parameter oxide decreases from $8.390 \pm .005$ KXU to $8.370 \pm .005$ KXU. There seems to be little change of parameter with alloy composition (except as the spinel phase may disappear, or change from the low to high parameter type⁸).

The fact that occurrence of the high parameter spinel is favored by the presence of Cr_2O_3 in the scale and by reduction of the severity of oxidation conditions has been further substantiated by oxidation in higher pressures of oxygen. For one atmosphere of oxygen this spinel was found

⁶Project Squid, Annual Program Report, 1 January 1950, Div. V, Sec. H.

⁷Ibid.

⁸Ibid.

at all temperatures up to 1160°C. It is still present for oxygen pressures of 1.7 atmospheres, but at 2 atmospheres it is not observed at temperatures of 1000°C and 1100°C. Cr₂O₃ also disappears from the scale under these conditions.

Investigation of the possibility that the high parameter spinel is an iron-rich Fe₃O₄ has continued. Reductions of Fe₂O₃ in mixtures of CO and CO₂ have been carried out at 900°C. By systematically increasing the proportion of CO one should cross the FeO-Fe₃O₄ equilibrium concentration and thereby obtain the most iron-rich Fe₃O₄ possible (for this temperature). This point has not yet been reached; the conditions still correspond to the Fe₃O₄ single phase region and the parameters obtained are in the neighborhood of 8.38 KXU. The difficulties have been in obtaining complete conversion of the Fe₂O₃ and in attaining a suitable quenching action. At present the reaction vessel is flushed with nitrogen, withdrawn from the furnace and cooled in a water jacket. A furnace is now under construction in which the sample may be withdrawn from the furnace directly into a water-cooled portion of the reaction vessel.

It has been found that the thin oxide films formed on 5 to 26 per cent chromium steels under a variety of conditions⁹ give essentially the same electron diffraction patterns, i.e., Fe₂O₃-Cr₂O₃ with a very small amount of Fe₃O₄, but that they are characterized by a different physical appearance as revealed in electron micrographs. As oxidation goes on crystalline masses form on the more or less uniform film and grow in size and number with increasing time of oxidation and with decreasing chromium content of the alloy.

These observations have been extended to a wider variety of alloys. Armco 5, 13, 17, and 26 per cent chromium, Haynes-Stellite 5 per cent chromium, Allegheny 446 (23-30 chromium), SAE 10-20, 18-8 stainless and 20 Cr-80Ni alloys have been oxidized in air at 310°C for 45-minute and 90-minute periods and replicas of the oxide surface have been examined in the electron microscope.

At this temperature the chromium-bearing alloys show the development of a fairly uniform pebble-like surface in which the size of granules decreases from 0.1-0.15 micron to less than 0.1 micron as the chromium content increases. On the 5 per cent chromium alloys, particularly the Armco sample, a continuous network of vein-like ridges of 0.1 to 0.2 micron width and height is formed instead of the matte surface. The number and size of both types of irregularities may vary by a factor of approximately two, from one metal grain to another, but there seems to be no systematic variation of the structure with proximity to grain boundaries, carbide inclusions, etc. The film formed over the carbides themselves is very thin and structureless.

⁹Project Squid, Annual Program Report, 1 January 1950, Div. V, Sec. H.

The treatment has been continued to 13 hours of oxidation at 310°C and an additional 1 hour at 500°C on the Allegheny 446, 18-8, 20Cr-80Ni and the die steel alloys. The irregular crust on the die steel becomes increasingly rough, but for the other metals the 0.1-micron pebble surface persists with the additional formation at 500°C of isolated, randomly distributed crystalline masses 0.2 to 0.5 micron in size. Similar results are obtained on other samples of 13, 17, and 26 per cent chromium, 446 and 18-8 alloys oxidized for 15 and 30 minutes at 500°C without the previous oxidation at 310°C.

Examination of the above films by transmission, after stripping at the conclusion of the runs, confirmed the examination of the surfaces by the replica technique. Electron diffraction of the stripped films gave Fe_2O_3 - Cr_2O_3 with very little deviation from Fe_2O_3 and practically no indication of Fe_3O_4 except for the SAE 10-20 steel. Thus at least the thinner portions of these films have similar crystal structures, to the available accuracy of electron diffraction, as discussed previously.¹⁰

Experiments to follow the formation of the localized nodules on the oxide films have been made. A technique has been developed whereby it is possible to take replicas of the same area of sample and relocate the same fields in the electron microscope at various stages of oxide growth. Five fields of the surface of a 26 per cent chromium steel have been photographed periodically during its oxidation at 500°C in air. No change is observed during four 1-minute heating cycles. (The maximum temperature reached in these short times is approximately 300°C.) After an additional 5-minute period of oxidation, a slight pebble-like texture is formed which becomes more pronounced as oxidation progresses. When a second 5-minute period of oxidation is allowed, a few isolated larger crystallites of 0.1 to 0.3 micron size are found. With further oxidation these grow slowly; the smaller ones grow somewhat more rapidly than the larger, and new ones suddenly appear. The position of these growths seems to be quite random. Whether they are initiated by the sudden expansion of one of the pre-existing "pebbles" or whether they involve a completely new nucleation is not yet clear.

Attempts have been made to remove the film in order to see whether the local growths reform at the same points on the alloy or at different positions, but all successful stripping methods have changed the metal surface excessively. Similar experiments will be tried with lower chromium alloys for which the ease of stripping is much greater.

Experiments have been started from which it is hoped to determine the structural difference between the uniform film base and the protuberances which grow upon it. These experiments consist of oxidizing in air for increasing periods of time, and, after each period, examining the oxide,

¹⁰Project Squid, Annual Program Report, 1 January 1950, Div. V, Sec. H.

first, by electron diffraction in reflection from the surface (interpretation assisted by electron micrographs of surface replicas) and, second, by transmission electron diffraction (interpretation monitored by transmission electron micrographs).

Experiments of this kind have been completed for the first cycle of 5 minutes' oxidation at 500°C for Armco 5, 13, 17, and 26 per cent chromium steels.

For this oxidation time, oxides on the latter three alloys are in the initial pebble stage and the 5 per cent alloy shows the interlacing vein structure; there are no large crystals present. The stripped films show the films to be quite uniform, tightly packed aggregates of small crystallites increasing in size from approximately 0.05 micron to 0.1 micron on the 26 per cent and 13 per cent alloys respectively. The "pebbles" observed by surface replica seem to represent variations in thickness of these individual crystallites. It is not surprising, therefore, that the reflection and transmission diffraction patterns show the same structure. In the case of the 5 per cent alloy, the veins are thick enough to be practically opaque, and therefore do not contribute to the transmission diffraction. These veins are also numerous enough to partially shield the uniform film in the reflection experiments. One could expect to find, therefore, some difference in the two types of diffraction if the structure of the material in the veins and film is different. No such variation is yet observed; all patterns for the 5 per cent as well as the other alloys conform to that of Fe_2O_3 . Similar comparisons should be possible for the large crystalline growths and films on the higher chrome alloys when the time of oxidation is increased. All of these films show a pronounced orientation of the Fe_2O_3 crystallites with their (111) planes nearly parallel to the substrate.

Attempts to find differences between the properties of the films which depend on chromium content of the alloy have been continued.

The oxide films produced on 17 and 13 per cent chromium steels when heated in air for two minutes at 950°C have been electrolytically stripped and their resistance measured over the temperature range of 20°C to 120°C. resistance of 2 to 3 mm squares of film varies in the range of 10^{10} to 10^{13} ohms at 20°C and 10^8 to 10^9 ohms at 100°C. The conductance, C , increases with temperature according to the exponential relation appropriate to semi-conductors, $C = C_0 \exp. (-E/kT)$. The total range frequently consists of two parts. For the higher temperatures the activation energy, E , has values of .6 to .8 electron volts in different samples, and at the lower temperatures the value is approximately half this. This behavior suggests that the higher value may correspond to the "intrinsic" semi-conductor and the lower set of values to the effect of impurities. When the films are heated in air or in a rough vacuum (10^{-3} mm Hg) to temperatures above approximately 100°C, their resistance frequently decreases irreversibly and thereafter varies with the lower activation energy. This also corresponds to the effect of fixation of more impurity centers. Whether this is due to oxidation or to

reaction with the support base (glass) or residues of the stripping process will be investigated.

No systematic differences between the resistance of the oxides formed on the two alloys have yet been found. This may be possible when thickness measurements are available so that the resistance measurements may be converted to resistivity values. It is planned to measure thickness by optical interferometric methods. Quartz plates on which to mount the films have been received but have not yet been polished optically flat.

The X-ray diffraction studies will be extended to higher temperature oxidations in air and in oxygen at reduced pressures and correlated with chemical analyses. Attempts to synthesize and analyze spinels of variable parameter will be continued.

The problem of the thin film including its growth, the structure of the crystalline nodules formed on it, the nature and cause of film imperfections and their correlation with oxidation resistance will be extensively investigated by electron diffraction in reflection and transmission, by electron micrographs, microchemical analysis, and radioactive tracer techniques.

Measurement of electrical properties, particularly the resistance, will be continued with the intent of finding correlations with oxidation resistance. It is hoped that these measurements may be extended to include Hall effect determinations of the sign of electrical carrier. It may also be possible to devise equipment suitable for measuring the contact potential between metal and oxide at the temperature of oxidation.

VI. S P E C T R O S C O P Y O F C O M B U S T I O N

A. THE STRUCTURE OF THE HYDROCARBON FLAME BANDS. (NYU-7R8)

Submitted by: G.M. Murphy and L. Schoen, New York University

The identity of the emitter or emitters causing the "Vaidya," or hydrocarbon, flame bands are not known. To clarify this point, the spectra of hydrocarbons which have isotopes of carbon and hydrogen present are being observed. The band shifts caused by the isotopes are expected to make possible the identification of the responsible emitters.

Low radiation intensity in the region 3000 - 4000 Å has continued to cause difficulty in recording clearly the hydrocarbon flame bands with the 3 meter grating spectrograph. In order to increase the concentration of oxygen atoms at the nozzles, the current in the discharge tube has been increased from 400 to 700 milliamperes and parts of the high vacuum system have been redesigned to provide higher pumping speeds. In addition, the optical system is now being revised to obtain a more uniform illumination of the slit.

B. EFFECT OF COMBUSTION CONDITIONS ON THE SPECTRA OF HYDROCARBON FLAMES AT LOW PRESSURES. (CAL-2bR9)

Submitted by: J.T. Grey, Cornell Aeronautical Laboratory

Except for necessary adjustments from time to time, changes in the burner instrumentation are complete, and studies of the effect of pressure on a methane-oxygen flame are being continued.

At this time a particular effort is being made to extend these studies through a wider pressure range than was possible in our earlier work. It is expected that a more concise pressure dependence can be established. The upper burner pressure limit has been raised from about 45 mm to about 80 mm while the lower limit has remained unchanged at about 20 mm.

In a further effort to study pressure effects on the intensity of the CH, OH, and C₂ radicals in methane flames, a pressure tap was inserted through the center of the burner tube¹ in such a manner that it could be

¹G.H. Rothgery and J.T. Grey, "Application of Spectrography to the Study of Reaction Mechanisms in Low Pressure Flames, Instrumentation and Preliminary Studies in the Ultraviolet," Project Squid Tech. Memo-CAL-22.

raised or lowered to any desired height inside or above the tube. Thus pressure readings could be made at any point in that portion of the burner tube which extends from the burner lip to the orifice through which the pre-mixed gases are introduced. Pressure readings were taken downward from a point approximately one inch (the maximum height of the flame) above the burner lip with and without the flame.

This auxiliary pressure tap was inserted for the purpose of ascertaining pressure differences, if any, that might exist in the region of the flame as compared to the total pressure of the burner proper, i.e., the volume enclosed by the burner mantle.

The fact was established that as compared to total burner pressure customarily recorded, no pressure differences existed in any part of the burner tube or at the burner orifice, with or without the flame. However, it was found that the continued use of this second pressure tap was not feasible during actual burner experiments for the recording of spectrographic data on the flame, since it caused a distortion in the flame front.

The effective rotational temperatures of the CH (3900) and OH (3064) bands are being computed and the tedious manipulations required to reduce the spectrographic data are progressing satisfactorily.

C. A SPECTROPHOTOMETRIC STUDY OF LOCAL FLAME RADIATION. (Del-2R6)

Submitted by: Kurt Wohl, University of Delaware

The characteristic radiation of non-luminous flames has been studied from the ultraviolet to the infrared. In the ultraviolet and visible spectral regions, radiation is due to various radicals and is mostly of chemiluminescent character.

The relative contributions of the different radicals to flame radiation vary strongly with the conditions and the progress of burning. These relative contributions, therefore, indicate the local conditions which arise in burning and thus reflect the sequence of events which occur in the gas passing through the steady flame. Measurement of flame radiation may be used in connection with jet propulsion to indicate the rate and type of the combustion process at a certain place and may thus serve as a base for guiding the combustion process in the desired manner.

The question of how far those radicals which are observable by their radiation are essential carriers of the combustion reactions is still open. But even if they are mere by-products of the combustion reactions, they can fulfill the important function of indicating which of these processes is prevalent. From this point of view attention should also be given to variations in the ratio of radiation intensities emitted by the same radical in different spectral regions.

It seems that a determination of the absolute concentrations of the light-emitting radicals cannot easily be accomplished at present. As a substitute the absolute energy emitted in a certain volume of the flame in a certain spectral region can be ascertained. The opinion is held that data on the relative radiation energies provide a first estimation of relative radiation energies provide a first estimation of relative radical concentrations; and the data on absolute radiation energies will form a base for calculating radical concentrations when the spectroscopic and kinetic information required for these calculations becomes available.

Flame radiation in the infrared region of the spectrum consists mostly of the vibration-rotation bands of the normal molecules H_2O and CO_2 and of the radical OH . It seems that the infrared radiation which is emitted in the main reaction zone has to some degree the character of chemiluminescence. Outside the main reaction zone radiation seems to be mostly thermal. Predictions for any unexplored flame or flame zone can hardly be made. Observation of the intensity of the infrared radiation in different flame regions and at different overall conditions should give information on the problem of how the distribution of molecules over its vibrational levels is affected by chemical processes. Where the infrared radiation is thermal, it is advantageous to use an absorption-emission method in the infrared for measuring flame temperatures, for it should be possible in this way to extend the range of optical methods of temperature measurement to lower temperatures than can be covered by the sodium line-reversal method.

The phase of the work which is concerned with instrumentation is virtually completed. A spectro-photometric apparatus has been constructed which makes it possible to traverse through the spectrum for any point of the flame as well as through a flame cross section for any wave length of light. Either type of curve is continuously recorded on a Brown Electronik High Speed Strip Chart Recorder. In this way the distribution of any type of radiation through the flame can be rapidly ascertained.

In view of the small radiation intensities, a Perkin-Elmer infrared spectro-photometer has been chosen which combines high light sensitivity with medium dispersion. A quartz prism has been inserted which is used for the total spectral range from 0.28 microns to 2.5 microns. A lithium fluoride prism, now on order, will extend the spectral limit of investigation further. For the ultraviolet and visible range, a photomultiplier tube is used. A photomultiplier tube with a quartz envelope which will extend the range to 0.24 microns has just been received. For the infrared range a lead sulfide photo-conductive cell takes its place. It is sensitive up to about 2.6 microns. Efforts are made to obtain a lead selenide photo-conductive cell which is sensitive up to nearly 4 microns.

The factor of the spectral sensitivity of the phototube is eliminated by using a tungsten-in-quartz lamp as a comparison standard for all wave lengths. The lamp is calibrated with respect to brightness temperature as

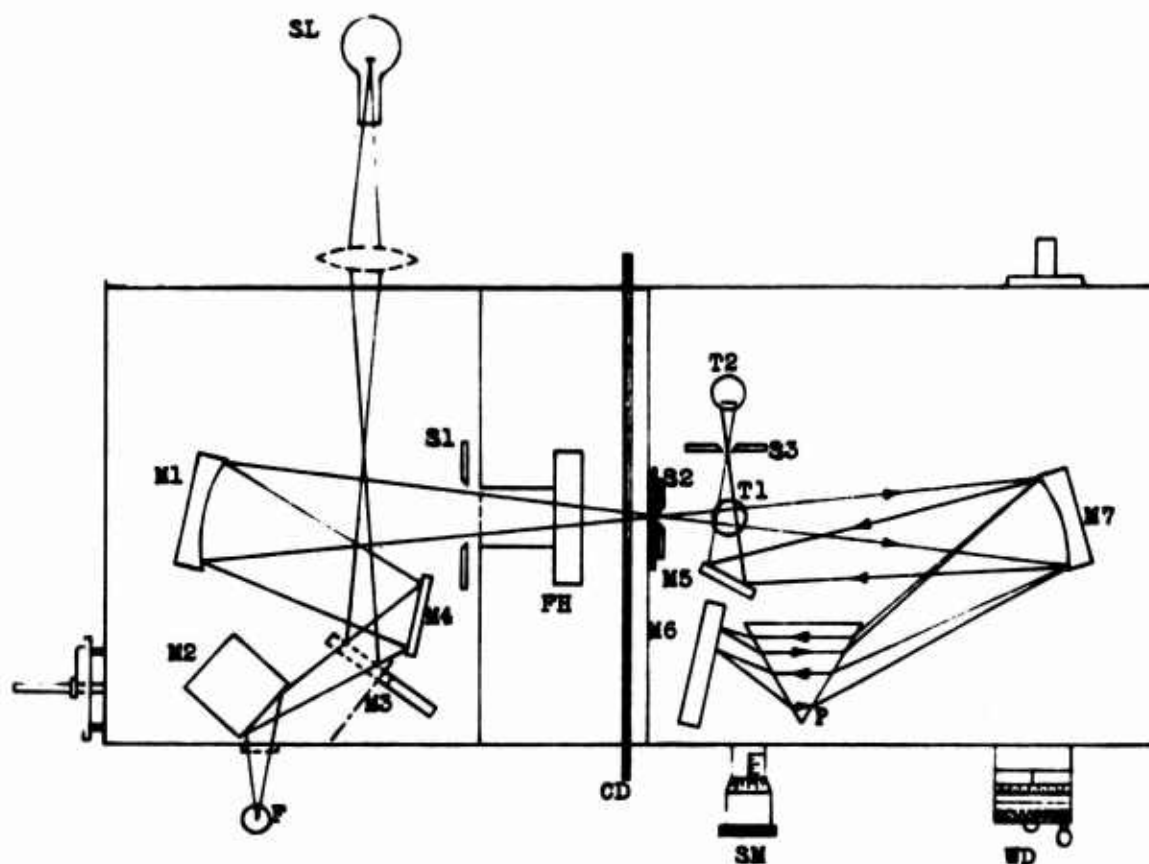


Fig. 1. Spectrophotometer

<u>Symbol</u>	<u>Item</u>	<u>Symbol</u>	<u>Item</u>
SL	Quartz-window standard lamp	M5	Flat mirror
SM	Slit width control mechanism	M6	Littrow mirror
WD	Wavelength drum	M7	Parabolic mirror
CD	Chopping disc	P	Prism
F	Flame	S1	Aperture control slit
FH	Filter holder	S2	Entrance slits
M1	Parabolic mirror	S3	Exit slit
M2	Rotating mirror for flame scanning	T1	Phototube position for total radiation reception
M3	Radiation source selection mirror	T2	Phototube position for spectral radiation reception
M4	Flat mirror		

well as to energy flux. A general physical lay-out of the instrumental arrangement is given in Fig. 1.

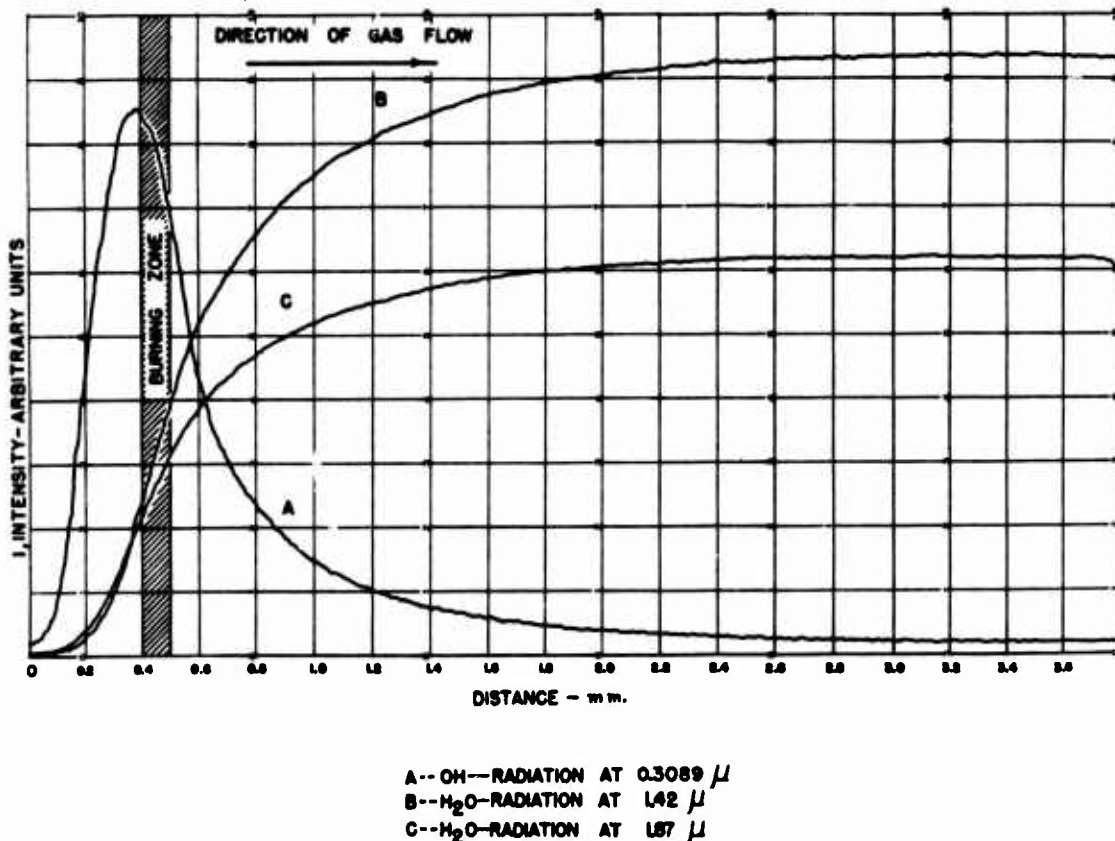
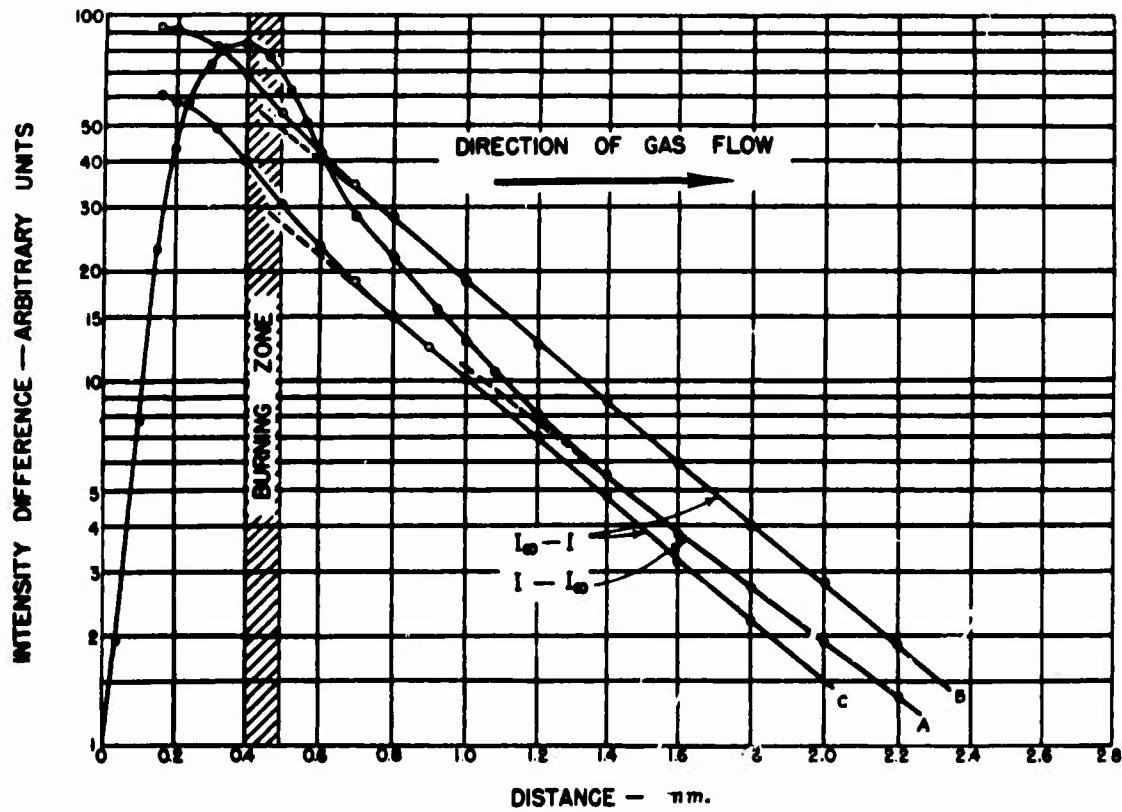


Fig. 2. Traverse through a plane flame front of a 3.60% butane-air flame.

The low intensities of the radiation studied made it necessary to develop a high gain amplifier in which the light chopping system was used for noise attenuation. It was found that a much greater stability with the same degree of noise attenuation can be achieved if the conventional and previously used parallel-tee feedback is abolished, and if instead a commutator, mounted on the same shaft as the chopping disk, is used as the frequency selective device. With the sharply tuned parallel-tee circuit the phase relation of the input and output tended to drift, causing an unpredictable variation in the conversion of a.c. to d.c. by the commutator.

An investigation has been made of the radiation types emitted from the characteristic reaction zones of a number of laminar two-dimensional butane air flames at one atmosphere. The reaction zones and the emitters of radiation observed in these zones are tabulated in Table I.

Fig. 2 shows a few examples of recorder traces obtained by traversing a plane two-dimensional primary burning zone perpendicularly to the plane. The OH radiation has its maximum at the beginning of the visible burning zone and decays relatively slowly. About the same rate of decay is observed



A--OH--RADIATION AT 0.3089 μ
 B--H₂O--RADIATION AT 1.42 μ
 C--H₂O--RADIATION AT 1.87 μ

Fig. 3. Semi-logarithmic plot of radiation intensities shown in Fig. 2.

	Primary burning zone	Post-primary zone	Secondary burning zone (in case of rich flames)
Ultra-violet and visible	CO, CN, CH CO flame bands (CO* ₂) Ethylene flame (Vaidya) bands (CHO)	CO flame bands (CO* ₂) CH	CO flame bands (CO* ₂) OH
Infrared	H ₂ O	H ₂ O	H ₂ O

(The symbols CO*₂ and CHO will be used to denote the CO flame bands and the Vaidya bands, though the interpretation of these bands is still uncertain)

with the CO_2 radiation. CHO radiation is less persistent, and CH and CC radiation disappear most rapidly. The radiation curves do not drop to zero at a large distance from the primary burning zone but approach asymptotically a finite value which is about 2% of the maximum intensity. The cause for this small amount of residual radiation is being investigated now. The curves for the infrared water radiation pass smoothly through the visible burning zone and reach asymptotically a maximum value. This indicates that the infrared radiation is of a thermal nature.

The radiation intensity of OH , CO_2 and CHO , shortly after the primary burning zone, begins to decrease logarithmically with increasing distance from the burning zone. This is shown for OH radiation in Fig. 3. For this plot the small residual radiation mentioned above has been subtracted from all intensity values. The rise of the curve above the straight line in the neighborhood of the primary burning zone seems to be only apparent. It was found recently that in this region other radicals, such as CO_2 , contribute to the radiation at 0.3089 microns. A more detailed analysis of the radiation curves is under way.

It was further found that the infrared water radiation intensity rises towards its maximum value logarithmically, as is also shown in Fig. 3, for two peaks of the infrared band system. The slopes of the infrared radiation curves are negative, just as the slope of the OH curve, because in the case of the infrared radiation the difference between the maximum intensity and the local intensity has been plotted as ordinate. It is remarkable that the slopes of the three curves of Fig. 3 are nearly identical. They probably reflect the same overall process, namely the approach of thermal equilibrium.

Work in the immediate future will be concerned with a more detailed experimental and theoretical analysis of the local radiation of two-dimensional flames.

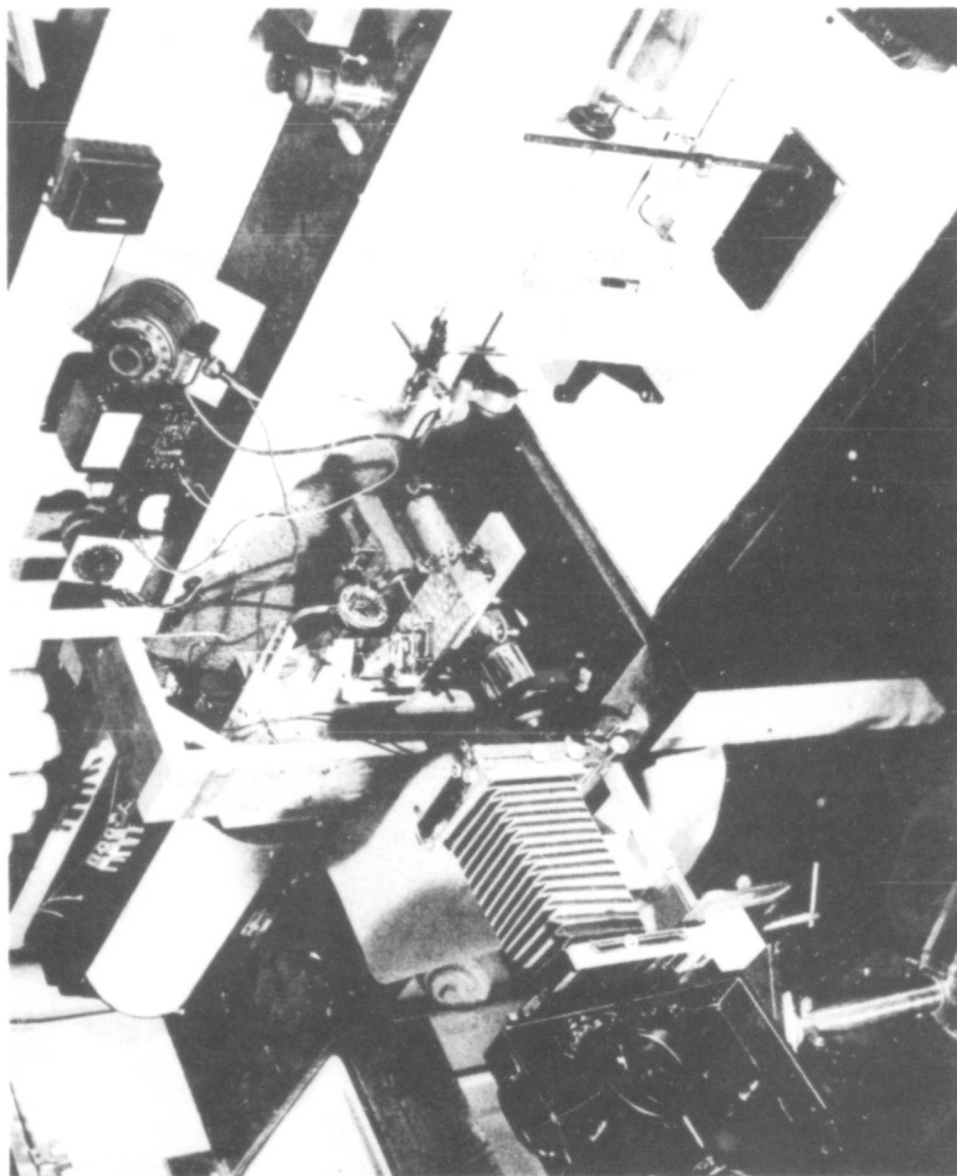


Fig. 1 Interferometer Experimental Set-up

VII. I N S T R U M E N T A T I O N
A N D T E S T I N G E Q U I P M E N T

A. DEVELOPMENT OF OPTICAL TECHNIQUES FOR MEASURING THE STATISTICAL PROPERTIES OF TURBULENCE IN HIGH VELOCITY FLOWS. (JHU-Ph. 1)

Submitted by: L.S.G. Kovaszny, Johns Hopkins University

Two different optical techniques are being investigated presently under this phase: the shadow method and the interferometer method.

Since the optical methods respond inherently to density fluctuations in the medium, they can be checked against the hot-wire anemometer in the low speed range where no density fluctuations due to compressibility effects occur but known density disturbances can be caused by introduction of heat.

The hot-wire anemometer is a well tested instrument for measuring both velocity and local temperature fluctuations in a low speed flow. A turbulent temperature "spottiness" can be introduced by a heated grid and the resulting density fluctuations are completely determined by the temperature fluctuations. Therefore, the statistical data obtained by optical technique can be checked against hot-wire measurements.

Since the interferometric studies were made with a borrowed interferometer most of the work during the last quarter was concentrated on taking interferograms under controlled conditions in order to permit the return of the instrument at an early date.

The experimental set-up is shown in Fig. 1. A high pressure mercury lamp is used as a light source (right). A Michelson type interferometer produces the vertical interference fringes (center). The air jet is blown from upper left to lower right through the heated grid and through one arm of the interferometer. The fringes are focused on a slit and a continuous record is taken by the film recorder camera (lower left). A typical record is shown in Fig. 2. The slanted lines in the interferogram suggest that the turbulent pattern is being swept across the aperture almost unaltered. The interferograms are being traced by a two-dimensional travelling microscope arrangement, shown in Fig. 3.

The data thus obtained are being analyzed now and the detailed results will be reported later. However, a few preliminary conclusions can already be drawn. The principal one is that the applicability of the

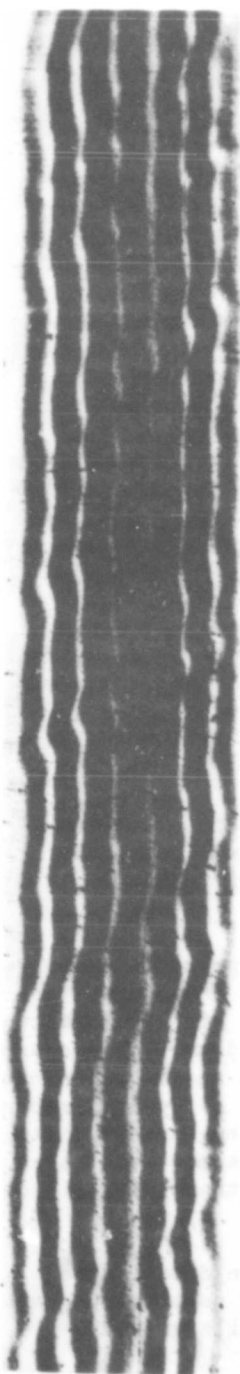


Fig. 2. Time Record of Interferometer Fringes

interferometer technique for measuring turbulent density fluctuations is limited to large density fluctuations and also to large dimensions. This is necessary in order to obtain fringe shifts of the order of one fringe width for accuracy in measurement. Although the time resolution of the interferometer can be better than that of a hot wire, the space resolution is necessarily poorer. Consequently, the overall frequency response can not be expected to be higher than it is with hot-wire techniques. Its main application will be in highly turbulent flows where no probes can be introduced. Quantitative data for regions of turbulent fluctuation during combustion (behind flame fronts), may be obtained where the hot-wire technique has not yet succeeded.

After analyzing the data obtained, a series of hot-wire measurements will be carried out for comparison, and finally evaluation of the relative merits of the two methods will be attempted.

B. DEVELOPMENT OF RONCHI-SCHLIEREN APPARATUS. (NYU-8R4)

Submitted by: R. Kraushaar, New York University

A system similar in layout to that used for making Ronchi tests, and suitable for making quantitative schlieren measurements, has been developed. (See Fig. 4.) In this system, the slit at the source is replaced by a grid, or grating, and the usual Ronchi grid ordinarily placed at or near the conjugate focus is retained, the two grids being geometrically identical. It has been found that the best definition is obtained when the grating or grid spacing is equal to the grating line thickness with the number of lines (shadows of the second grating) that appear in the field of view (Fig. 5) a function of the position of the second grating with respect to the image of the first. In connection with the adaptability of this system, it is interesting to note that horizontal and vertical density gradients may be differentiated by using crossed gratings; or by placing an ordinary schlieren knife edge perpendicular to the grating lines. In this way, the relative sensitivities of the system in the two directions may be adjusted as desired.

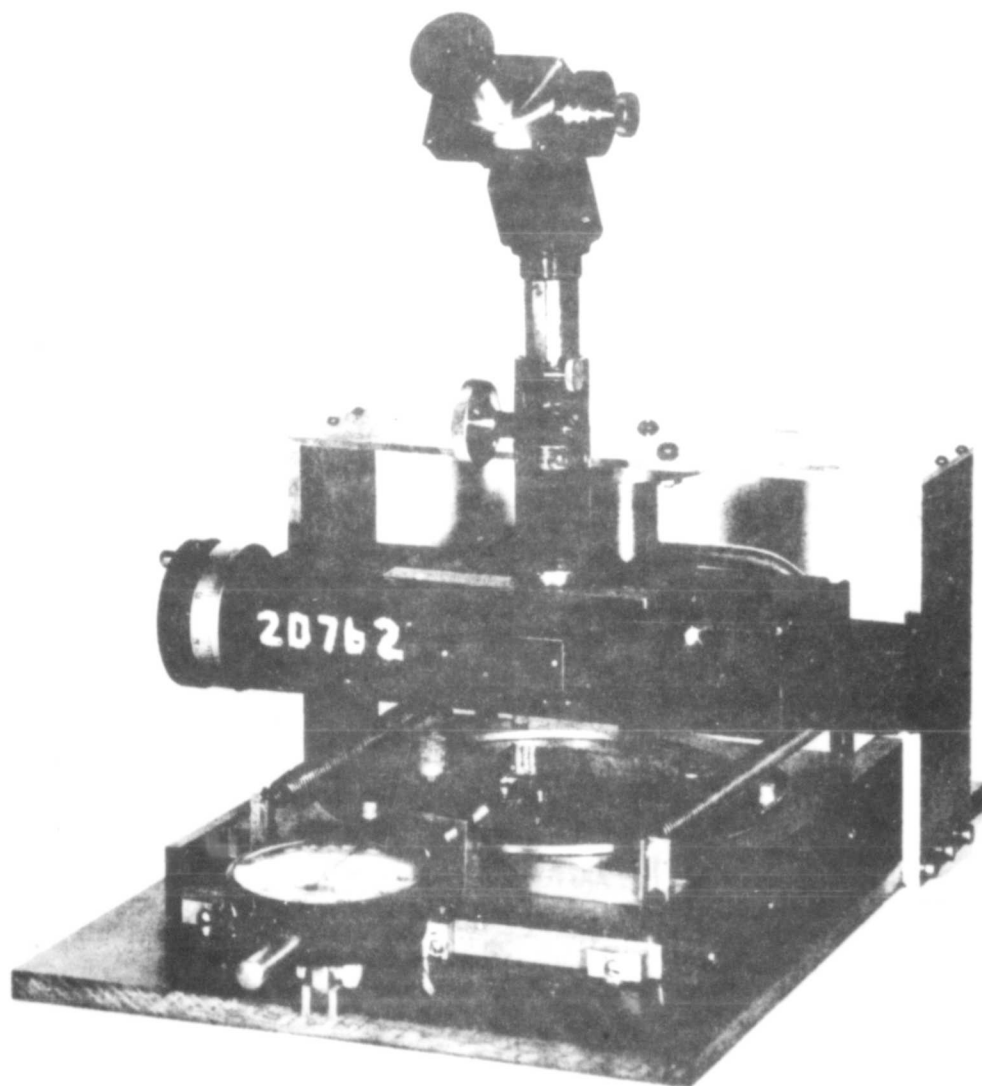


Fig. 3. Two-dimensional traveling microscope

An elementary geometrical optical analysis of the system has been carried out for the case in which there is present a two-dimensional density inhomogeneity. This study indicates that if X_m is the measured deviation of the m^{th} line, m being reckoned from some line (the zeroth) which is not deviated, the density ρ_m at a point in the inhomogeneity initiating the deviation X_m is

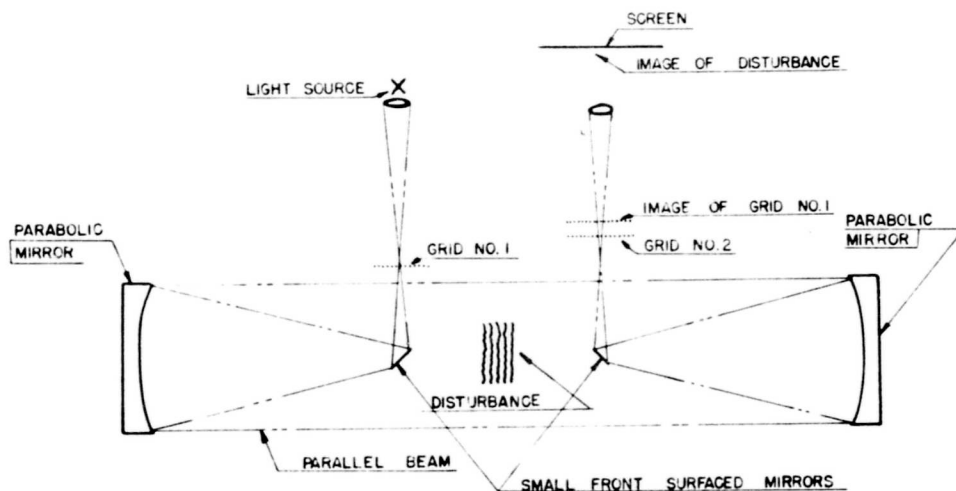


Fig. 4. Modified Ronchi-schlieren system developed at New York University

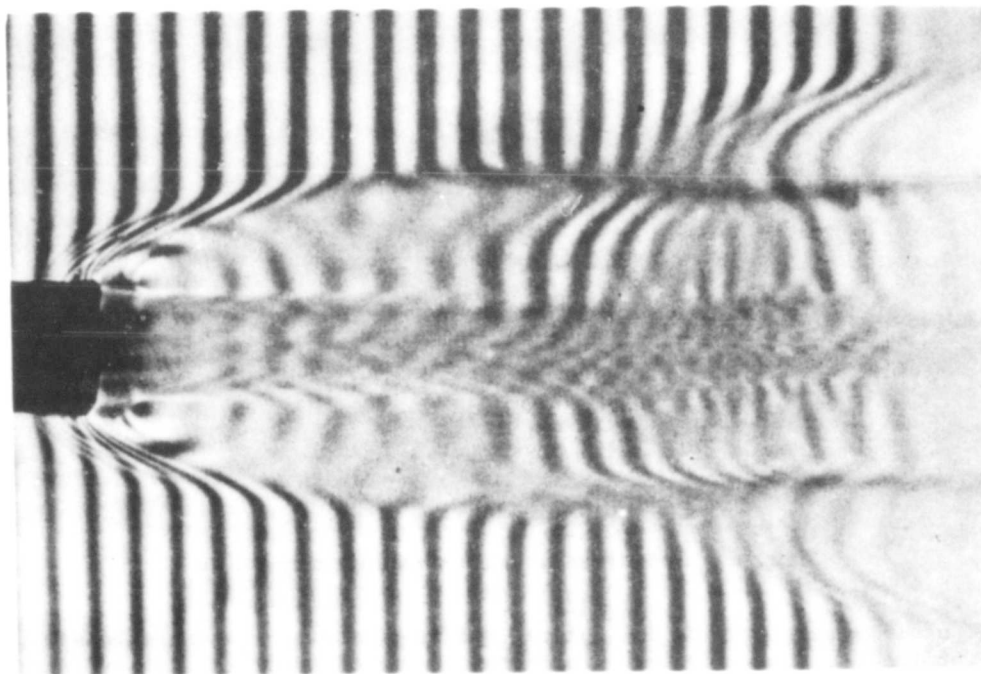


Fig. 5. Photograph of Bunsen burner flame taken with optical system shown in Fig. 4.

given by

$$\rho_m = \frac{\rho_0}{n_0 - 1} \left\{ n_0 \exp \left[\frac{1}{b} \frac{1}{hd} \sum_{i=0}^m x_i \right] - 1 \right\}$$

where

- ρ_0 = density at the undisturbed point
- n_0 = index of refraction at the undisturbed point
- b = number of grating lines per unit length
- h = thickness of two-dimensional inhomogeneity
- d = distance of the second grating from the viewing screen

The details of this analysis and a complete description of the system in both its simple and combined forms will be contained in a report now in preparation.

C. TEMPERATURE MEASUREMENTS OF ROCKET EXHAUST JETS. (NYU-8R1)

Submitted by: J.H. Hett, New York University

Measurements of the temperature of rocket exhaust gases made with the temperature measuring equipment developed at New York University¹ have indicated that the temperature of these gases fluctuates in a periodic fashion. Since this work was done at the General Electric Company's Malta Test Station in connection with a classified rocket development project, details of the phenomena observed cannot be given in this report.

D. REDUCTION OF TEMPERATURE DEPENDENCE IN PRESSURE GAGES.

Submitted by: J.H. Hett and R.W. King, Jr., New York University

To increase the usefulness of the New York University pressure gage, methods to reduce its temperature dependence are under study. A number of experiments have been made with bi-metallic diaphragms, using various thicknesses. Reversal of drift direction has been obtained and is being studied.

E. SURFACE TEMPERATURE DETERMINATION BY X-RAY DIFFRACTION METHODS. (PIB-3R3)

Submitted by: A. Bender, Polytechnic Institute of Brooklyn

During this quarter, the feasibility of employing X-ray diffraction methods to obtain the surface temperature of a porous copper alloy material, which will be used in the investigation of temperature profiles in boundary layers on porous walls, was determined. This required the calibration of Cu alloy for changes in the characteristic diffraction line position corresponding

¹J.H. Hett and J.B. Gilstein, Journal of the Optical Society of America, Vol. 39, No. 11, November 1949, p. 909.

to changes in surface temperature. The method employed in the calibration was identical to the technique described in a technical memorandum.²

The X-ray diagram of the copper alloy, taken at room temperature, gave "coarse" lines, i.e., the characteristic $K\alpha$ line was made up of clearly spaced Laue spots with a sufficient distribution to identify a "line" unmistakably. This spotty line was caused by the large crystallate particle structure of the porous copper alloy.

When the copper alloy was heated to 300°F, the $K\alpha$ lines moved a distance of 0.4 centimeters. At 365°F the spots of the $K\alpha$ lines became so diffused that it was difficult to locate the exact position of the line. Practically no spots were obtained at 1065°F, indicating the possible crystallate structure of the material or the formation of an oxide which had altered the character of the surface. It can be concluded, therefore, that the X-ray method for measuring the surface temperature gradient of the porous copper alloy is feasible up to 300°F.

Investigation of a second problem, which may be considered part of the more general study of the problem of surface temperature measurement by X-ray methods, was initiated during this quarter. This study consists in determining the shift of the diffraction lines from a surface subject not only to temperature changes but also to mechanical stresses. The apparatus prepared for this study has been completed and is relatively simple. A sample of stainless steel x-x-x AISI No. 347 previously used in temperature measurements was held across the open part of a C clamp. Bending stresses were imposed by a screw rotating through the center of the clamp and bearing against the center of the sample.

It is planned to obtain X-ray diagrams at fixed stress increments created by equal angular rotation of the screw. The study has been temporarily halted to obtain data on the use of X-rays in the measurement of the density of gases.

F. MEASUREMENT OF GAS DENSITY BY X-RAY ABSORPTION. (PIB-3R4)

Submitted by: A. Bender, Polytechnic Institute of Brooklyn.

Since X-rays are absorbed by gases, it was deemed possible to determine the density in a highly localized region of a gas flow by correlating X-ray absorption against density. Although the idea is not new, a general estimate indicated that a means of rapidly measuring small density changes with monochromatized soft or long wave X-radiation using modern counters might be developed. Preliminary experiments revealed the possibility of employing chromium radiators in conjunction with a G-M counter to observe density

²A. Bender and I. Fankuchen, "Surface Temperature Determination by X-ray Diffraction Technique," Project Squid Tech. Memo. PIB-5.

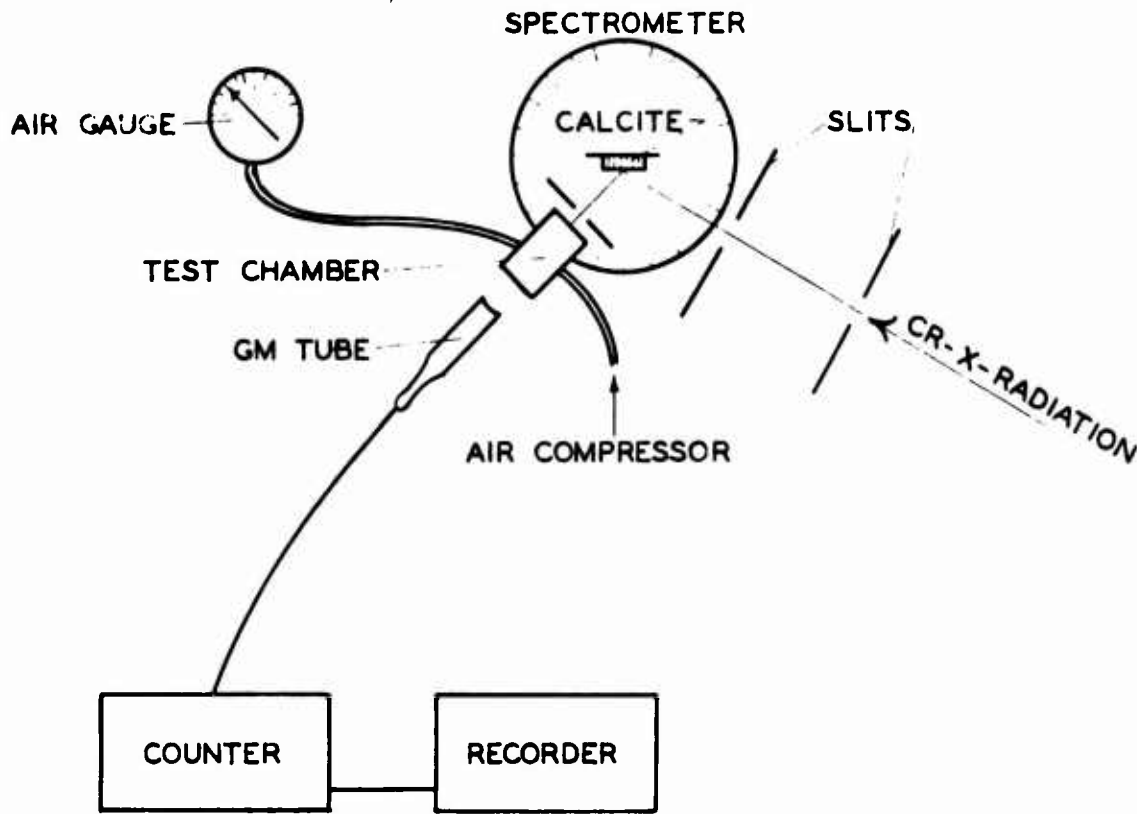


Fig. 6. General schematic of equipment

changes corresponding to pressure changes on the order of one to two psi over approximately a one-inch path.

The experimental set-up to measure changes in air density under static conditions by air absorption of Cr radiation consisted of an A-2 type Machtell, a Cr target tube and a Norelco power supply, a pair of vertical slit systems, a calcite monochromator, and a cylindrical air chamber. Along the X-ray path this chamber was followed by a G-M detector and a Norelco counter used in conjunction with a Brown recorder. The physical arrangement of the apparatus is shown in Fig. 6.

After the X-rays were collimated by the slit system (approximate width 0.3mm) they are diffracted by a large clear crystal of calcite. The diffracted Cr $K\alpha$ line is aligned with the axis of a cylindrical air chamber so as to enter and leave it through beryllium windows. A universally mounted G-M tube placed directly in front of the beryllium window detects the X-rays. Pressure in the air chamber, 3" long and $1\frac{3}{4}$ " diameter, was supplied by an air compressor, and the pressure was read from gages in the line.

The procedure consisted of taking counts at 64 second intervals, clocked automatically by the timer in the counter. Three individual readings were

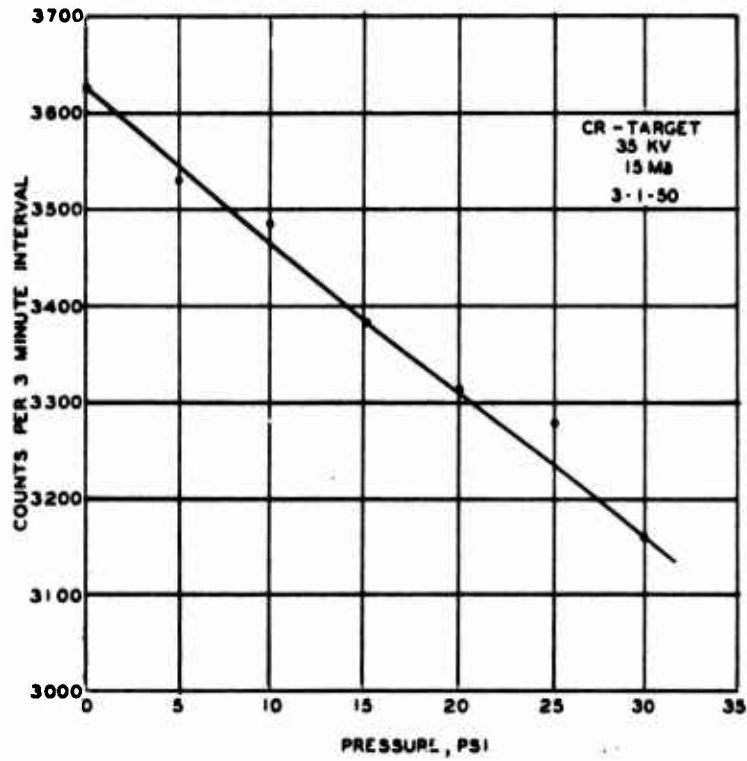


Fig. 7. Absorption of X-rays (Cr-radiation) by air.

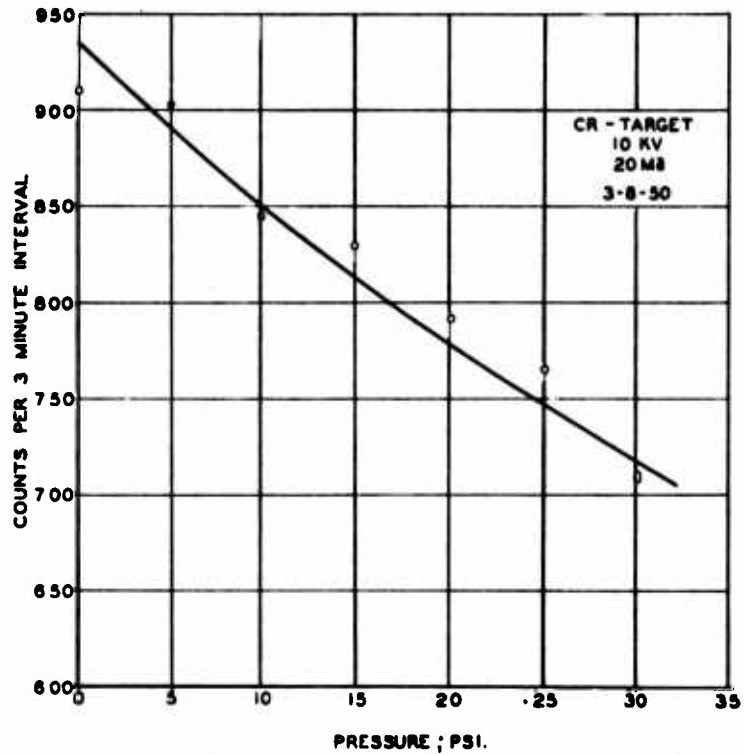


Fig. 8. Absorption of X-rays by air.

made at 5 psi increments. The results are shown in Fig. 7 and Fig. 8. In Fig. 8 the plate voltage was cut down in an attempt to eliminate as much white radiation as possible. An examination of the curves will show that the air absorption of X-rays follows fairly closely the logarithmic law $I = I_0 e^{-ux}$, where I_0 represents the initial intensity, u the linear absorption coefficient of the material, and x the length of the absorbing material. However, the data indicate poor reliability in reading pressure changes of 5 psi over the time interval during which the X-ray intensity was monitored. There is no doubt that the accuracy would be increased by taking X-ray counts over a longer interval of time, but this would defeat the purpose of obtaining accurate data in a minimum time.

The experimental data followed, with a reasonable range of experimental error, the theoretical calculations of the per cent absorption of X-rays. These calculations indicate that there must be an optimum wave-length (longer than Cr $K\alpha$) which would be strongly absorbed by air, and thus meet the required conditions of sensitivity and short response time. For example, it appears that as many X-rays having a wave length of 5.17 A would be absorbed in passing through 1 cm. of air as would chromium radiation, 2.285 A, passing through 10 cm of air.

It is apparent that the absorption method using Cr radiation for observing pressure changes of under 5 psi for short time intervals would produce unreliable data with the equipment used in this work. Where time is not a factor, this method for measuring gas density would be highly reliable.

Nevertheless, it is felt that this problem can be solved by overcoming some of the experimental obstacles. It is therefore planned to continue the experimental work along the following lines:

1. Equipment will be set up using a removable target tube so that target materials which would yield wave lengths in the order of 5 A⁰ will be investigated. This would include semi-conductors of phosphorous, sulfur, or chlorine all yielding X-radiation near 5 A⁰.

2. The G-M tube will be supplanted by a scintillation counter. In a recent conversation with Dr. Kallmann of New York University it was learned that an improved scintillation counter was far more sensitive to soft X-rays than the present G-M counter.

G. SAMPLING IN INHOMOGENEOUS GAS STREAMS. (Del-2R5)

Submitted by: Kurt Wohl, University of Delaware

It has been found in recent years that a gas sample taken in an inhomogeneous gas stream, as e.g. in the stream of exhaust gases of a jet propulsion chamber, usually does not have the same composition as the average gas pencil which hits the probe. In order to clarify this situation an apparatus has been built in which a great number of parallel streams of

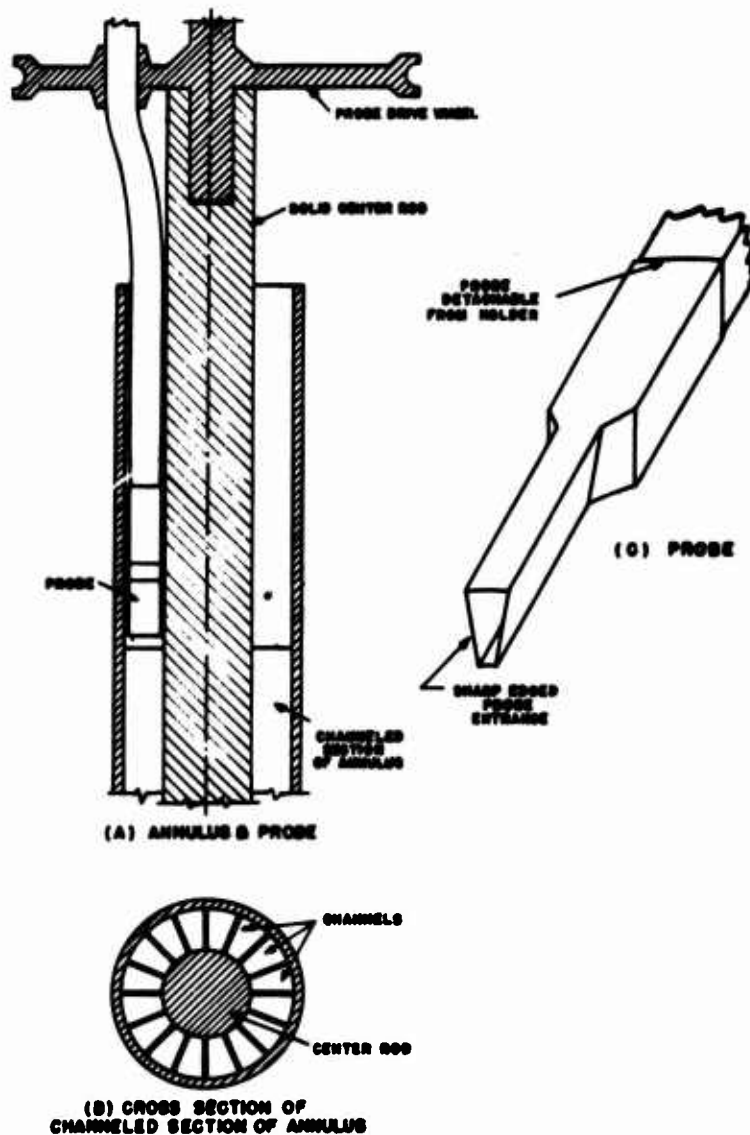


Fig. 9. Apparatus for taking samples in inhomogeneous gas streams.

equal velocities through the alternate channels in the annulus between a solid center rod of 1-inch diameter and the walls of an outer tube of 2-inches I.D. Above the channelled section of the annulus, the probe is permitted to rotate and sample the gas.

It has been found previously that a nearly correct sample (containing 50% CO₂) can be withdrawn from a non-homogeneous gas stream when a sharp edged probe which opens into a buffer space is used, and when the velocity with which the sample is drawn into the probe is equal to the free stream

two gases of equal cross section are produced, and a probe travels across them and takes an average sample. The specific feature of the arrangement is that it is precisely known what the composition of the average sample would be if the composition of the sample were at any moment the same as that of the gas upstream of the probe. A number of the quantities on which the result of sampling will depend can easily be varied, e.g. the velocity of the gas stream, the sampling velocity, the size and shape of the opening of the probe, the space between the opening of the probe and the valve over which the main pressure drop from one atmosphere to the pressure in the pump occurs, the distance between the probe and the ports from which the gas streams emerge, and other quantities, e.g. the velocity of travel of the probe perpendicular to the direction of the gas flow.

The apparatus is shown in Fig. 9. A non-homogeneous stream is made by sending air and CO₂ at

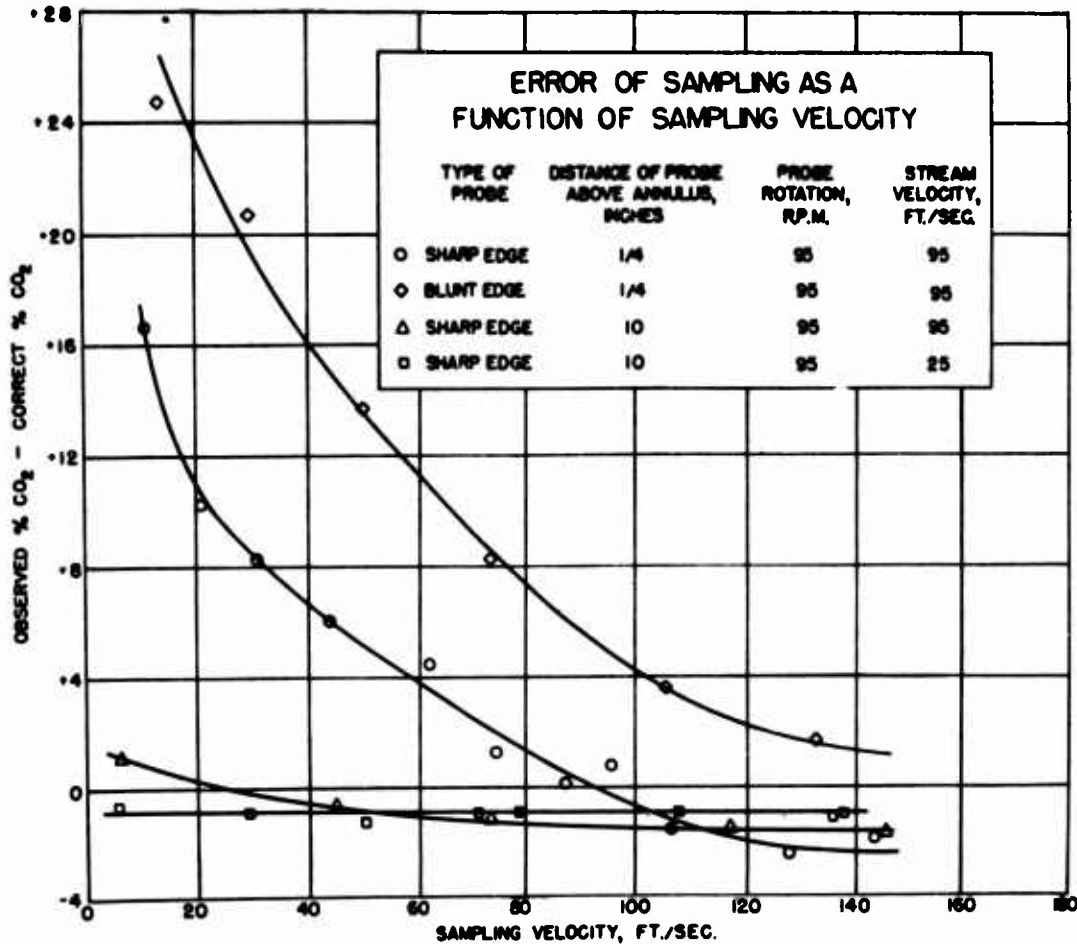


Fig. 10.

velocity of the non-homogeneous gas stream. When the sampling velocity is lower than the velocity of the gas stream, the percentage of the heavier gas CO₂ in the sample is too high and vice versa. This has been tested for velocities ranging from 25 to 95 ft/sec, and for rotational speeds of the probe ranging from 24 to 95 rpm. In these experiments as well as in those which are described below the cross section of the probe opening was equal to that of one channel in the annulus. (Report UD-101-I, submitted to Pratt and Whitney Aircraft on January 4, 1950).

It has been found since that when the rotational speed is reduced to 8 rpm the composition of the sample becomes erratic, especially at high sampling velocities. This seems to be due to the fact that the volume of one pulse of CO₂ or air under these circumstances becomes commensurate with the volume of the sampling chamber.

These experiments have mostly been performed with a distance between the channel openings and the probe as small as $\frac{1}{4}$ inch. When the distance is increased to 10 inches the sampling errors which are encountered in case of differences between sampling velocity and stream velocity decrease because of homogenization of the gas stream, as is shown in Fig. 10. With a stream velocity of 25 ft/sec the composition of the sample is nearly correct and independent of the sampling velocity, while with a stream velocity of 50 ft/sec, and especially of 95 ft/sec, noticeable errors occur. This shows that 10 inches behind the channel openings mixing is more perfect when the gas velocity is low.

It was anticipated that the sampling error would increase if the sharp edged probe used so far were replaced by a blunt one. Such a probe was made by soldering to both sides of the probe shown in Fig. 9 pieces of brass of the thickness of one channel opening. Experiments with this probe confirmed expectations. The deviations were especially pronounced if the stream velocity was high (See Fig. 10).

The sampling experiments planned for the immediate future will be concerned with the effect of the size of the probe opening in case of sharp and blunt edges, and with the effect of introducing immediately behind the probe opening (1) a narrow restriction, and (2) a large buffer space. It is hoped to arrive finally at a recommendation for the construction and operation of a probe for use in combustion investigations.

H. DESIGN, CONSTRUCTION AND INSTRUMENTATION OF THE PURDUE ROCKET LABORATORY. (PRF-7R1)

Submitted by: C.M. Beighley and J. Fisher, Purdue University

This report deals with the development of a rocket testing laboratory at Purdue University capable of testing small rocket motors (500-lb thrust) operating at high combustion chamber pressures. The laboratory is intended to be equipped with facilities for the investigation of such basic problems as heat transfer, propellant ignition, propellant chemistry, and instrumentation associated with rocket motor research.

The propellant tank weighing system for Test Cell No. 2 has been modified to eliminate various sources of error found to exist in the apparatus installed in Test Cell No. 1. The propellant weights are measured by means of Wiancko electrical force-transducers through a system of counter balanced weigh-tanks. Inlet and outlet propellant lines, constructed of 1-inch tubing, incorporate U-shaped turns arranged to cancel effectively external forces on the tanks due to the Bourdon effect when the lines are pressurized.

Experience obtained during the operation of Cell No. 1 indicates the advisability of employing electrical instrumentation in so far as possible. A preliminary investigation is being conducted to determine the feasibility of operating simultaneously a Brown self-balancing potentiometer, a Con-

solidated type - 5-114 recording oscillograph and a milliammeter from a single Wiancko pickup through a Wiancko coupling unit. The results of tests to date indicate that the bridge type of circuit used to connect these instruments and the Wiancko pickup will be satisfactory.

VIII. H E A T R E S I S T A N T M A T E R I A L S

A. CYCLIC LOADING EFFECTS ON CREEP PROPERTIES OF SHEET MATERIALS. (CAL-3R3)

Submitted by: L.W. Smith, Cornell Aeronautical Laboratory

High temperature dynamic creep experiments have been in progress on Armco iron to evaluate the effects of temperature, stress, amplitude of fluctuating stress, and frequency of sine wave variation of stress on the creep properties of this material.

A complete series of tests have been completed at 1000°F and a mean stress of 6,000 psi. These tests were run at frequencies of 1.5, 10, 100 and 1725 cycles of stress per minute. Amplitude of the fluctuating stress was varied between 0 and 50% of 6,000 psi mean stress. Constant creep rates versus amplitude of fluctuating stress was plotted on semi-log paper for the various frequencies. These series of curves showed that creep rate was greatest at the highest amplitude and lowest frequency. As frequency increased, the creep rate approached the rate for the 6,000 psi static creep test. The effect of the fluctuating load amplitude on creep rate decreased as frequency increased. Another series of curves were made on log-log paper for various amplitudes with creep rate versus frequency. These plots indicated that curves were approaching a minimum value (creep rate), possibly the static test value, as frequency increased to 1725 cycles per minute.

The effect of temperature on the creep rate under fluctuating load and frequency is to be further investigated. A new series of tests are planned for Armco iron at 800°F under higher loads with similar frequency ranges.

B. HIGH-TEMPERATURE TENSILE TESTING OF SHEET MATERIALS. (CAL-3R2)

Submitted by: L.W. Smith, Cornell Aeronautical Laboratory

The influence of dissolved carbon on the high temperature deformation properties of iron is of interest for several reasons. In the first place, the role played by interstitially dissolved alloying elements in the creep process has not been investigated specifically. The system of iron and carbon is suitable for such a study. Secondly, the effect of carbon on the creep strength of commercial ferritic steels has been examined only for carbon contents well in excess of the solubility limit at the temperature of test. While such studies have correlated creep properties of steels with the quantity and form of occurrence of carbon existing as a carbide phase, no information is available concerning the influence of carbon retained in interstitial solid solution.

Preliminary experiments have been made with Armco iron creep specimens in order to determine whether carbon variations in the range of approximately 0.005% to 0.02% produced any significant effect on creep strength. Decarburized specimens have been prepared from Armco iron sheet stock, with an original carbon of 0.02%, by treating with wet hydrogen at 1300°F. Comparison creep tests conducted at 1000°F in air on both the decarburized iron and the original stock, pretreated at 1300°F in dry hydrogen, have shown that a removal of approximately 0.02% carbon from the alpha iron matrix results in a six fold increase in creep rate. These results indicate an effect of sufficient magnitude to warrant continued study on a more detailed basis.

At the creep test temperature of 1000°F, only a fraction of the 0.02% carbon is in solution. If the dissolved carbon is the major cause for the difference in creep strength between the original and decarburized specimens, an even wider difference in creep behavior should result at 1300°F where practically all of the 0.02% carbon may exist in solution in the ferrite.

In the course of preparing wet hydrogen treated iron, a decrease in nitrogen content may result together with the loss of carbon. To eliminate this variable in composition, a series of specimens are now being prepared all of which have received an original wet hydrogen treatment at 1300°F. Part of these specimens will be recarburized without introduction of nitrogen and comparison creep tests will be conducted in the temperature range of 800°F to 1300°F. At creep test temperatures above 1000°F, it is planned to use an atmosphere of dry argon to prevent change of carbon and nitrogen contents during the course of the creep tests. Representative chemical analyses will be obtained for all treatments to determine carbon and nitrogen contents accurate to $\pm 0.001\%$.

C. HIGH-TEMPERATURE FATIGUE TESTING OF SHEET MATERIALS. (CAL-3R4)

Submitted by: L.W. Smith, Cornell Aeronautical Laboratory

It is well known that increasing the temperature of a metal results in increased plasticity, and that as plasticity increases the susceptibility to crack propagation decreases. This effect is postulated as being due to the increased ability of the metal to yield locally at the base of the notch and redistribute the stress. It was thought that the increased plasticity brought about by high temperatures might offset some of the deleterious effects of notches on fatigue strength and that the precautions taken to eliminate notches in assemblies operating at ordinary temperatures might not be as essential when the operating temperature is raised.

In order to check the magnitude of the notch effect, a survey program was started on the high temperature alloy S-816 which was the best of the

alloys evaluated in the previous work.¹ Bending fatigue tests were run on .042" sheet using a pneumatic fatigue machine. Notches were made at the critical section by machining a sharp V-groove .003" deep on both sides of the specimen so that the grooves were directly opposite one another. The deflections were determined which would cause failure in the range of 20,000 to 1,000,000 cycles. The curves have been plotted for 1400°F and 1600°F. The curves for the notched specimens lie parallel to those determined for unnotched specimens but at a lower stress level. The .003" notches in the .042" sheet stock cause the 1400°F curve to be lowered so that it is equivalent to raising the operating temperature to 1700°F. The effect of notches is apparently of considerable importance even at relatively high operating temperatures.

The rather small .003" deep notches represent a goodly proportion of the cross section of the .042" specimen. If the two notches are considered, .006" or one seventh of the thickness of the specimen has been removed. This might seem to be rather drastic. However, if we consider that the tests are of the constant deflection type, the notches actually remove the more highly stressed outer fibers and allow the same deflections to be reached at a lower applied stress. Opposing this effect is the tendency of the deflection curve to be rather abrupt at the notch and thereby increase the stress locally. Evidently the latter effect overshadows the former in these tests.

D. SIGMA PHASE STRENGTHENING OF HIGH-TEMPERATURE SHEET ALLOYS. (CAL-3R5)
Submitted by: L.W. Smith, Cornell Aeronautical Laboratory

Possible utilization of the hard sigma constituent as a strengthener in the chromium-nickel stainless steels represents the more practical objective of this study. In the course of making comparison creep tests between sigma free and sigma bearing steels it has been found most desirable first to obtain background data defining the time-temperature-% sigma phase relationships for a particular composition. Accordingly, aging and metallographic experiments are currently in progress for the purpose of defining the reaction rate, quantity, and mode of occurrence of the sigma constituent in the 1200°F to 1800°F temperature range for the following stainless steels: types 302-B, 309, 310, 314, 316, 321, and 347. Sigma phase has been found in sizable quantities in all of the alloys listed other than 321 and 347 for exposure times up to 500 hours. Maximum aging times of 1000 hours will be used at all temperatures through 1600°F.

On the basis of the results of the above mentioned aging tests, 1500°F has been selected as a suitable temperature for forming reasonable quantities

¹F.J. Gillig, Short Time High Temperature Bending Fatigue Properties of Sheet Materials, Project Squid Technical Memorandum No. CAL-30, September 8, 1949.

of sigma phase in 1000 hours for the annealed 302-B, 309, and 316 steels. Sheet stock of these three materials in both the initially annealed and 25% cold worked condition are in the process of aging and subsequently will provide creep test specimens for comparison with fully annealed, unaged material. Reference creep and rupture data have been obtained at 1200 and 1500°F for the annealed 309 and 316 steels and similar tests are in progress for the 302-B alloy. Detailed results obtained on the 314 grade have been reported previously.²

Upon completion of the 1000 hours aging treatment at 1500°F, the sigmatized 309, 316, and 302-B materials will be subjected to creep and rupture testing at 1200°F and 1500°F for comparison with the results obtained on the annealed stock. Such comparison data should indicate in what manner the sigma constituent influences the high temperature creep properties of these alloys.

The semi-quantitative time-temperature-% sigma results will be analyzed from a reaction rate standpoint in order to examine more closely the characteristics of sigma phase formation in these alloys.

²Glen J. Guarnieri, James Miller, Frank J. Vawter, The Effect of Sigma Phase on the Short Time High Temperature Properties of 25 Chromium-20 Nickel Stainless Steel, Project Squid Technical Memorandum No. CAL-26, May 1, 1949

APPENDIX A. OUTLINE OF STUDIES CONDUCTED
BY AFFILIATED UNIVERSITIES

Studies sponsored by Project Squid and conducted at the affiliated universities are divided into various phases of work. Each phase is, in turn, divided into specific research problems. For the convenience of the reader the work of each university is outlined below.

While the problem titles used in the body of this report are more descriptive of the activity within the problem, the titles given below are those contractually approved. In cases where the two titles differ, correlation can be established by means of the problem numbers.

POLYTECHNIC INSTITUTE OF BROOKLYN

Phase 3

Phase Leaders: R.P. Harrington and S.W. Yuan

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

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PIB-3R1. An experimental investigation of the stability of the laminar boundary layer above the surface of a porous flat plate with fluid injection	31
PIB-3R2. A theoretical investigation of the temperature field in the laminar boundary layer (compressible fluid) on a porous flat plate with fluid injection	29
PIB-3R3. Measurement of pulsejet wall temperatures by X-ray diffraction methods	71
PIB-3R4. Measurement of gas density by X-ray absorption	72

CORNELL AERONAUTICAL LABORATORY

Phase 1

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

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

	<u>Page</u>
CAL-1R6. Propagation and stability of shock waves in supersonic diffusers.	13
CAL-1R7. Investigation of valveless pulsejets.	6
CAL-1R8. Study of the operation of shrouded pulsejets6, 7, 10

Phase 2a

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

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

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CAL-2R5. Combustion tube studies.. . . .	35
CAL-2R6. Burner experiments.	39

Phase 2b

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

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

	<u>Page</u>
CAL-2R9. Investigation of the effect of combustion conditions on the spectra of hydrocarbon flames at low pressures	59

Phase 3

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

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

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CAL-3R2. High-temperature tensile testing of sheet materials	81
CAL-3R3. High-temperature short-time creep testing of sheet materials	81
CAL-3R5. Sigma phase strengthening of high-temperature sheet materials.	83
CAL-3R4. High temperature fatigue testing of sheet materials . .	82

UNIVERSITY OF DELAWARE

Phase 1

Phase Leader: S.A. Guerrieri

Heat transfer in passages with free convection and counter flow: (a) The visual study is to be carried out using a vertical rectangular duct having two opposing glass walls with provision to heat the middle portion. Free convection will be upward but arrangement will be made to force air downward at a controllable velocity. By means of spark photography, the resulting gas can be studied. (b) The quantitative study is to be carried out with emphasis on the cooling effect of liquid under conditions of free convection with forced counterflow. Various liquids will be chosen so as to give a wide variation in the Grashof number.

	<u>Page</u>
Del-1R1. The quantitative study is to be carried out with emphasis on the cooling effect of liquid under conditions of free convection with forced counterflow. Various liquids will be chosen so as to give a wide variation in the Grashof number	28
Del-1R2. The visual study is to be carried out using a vertical rectangular duct having two opposing glass walls with provision to heat the middle portion. Free convection will be upward but arrangement will be made to force air downward at a controllable velocity. By means of spark photography, the resulting flow can be studied.	27

Phase 2

Phase Leader: Kurt Wohl

To investigate experimentally several of the basic problems associated with gaseous combustion including: (a) flame type intermediate between self-propagating and diffusion flames, (b) the stability conditions, the fluctuations, and other properties of turbulent flames, (c) the temperature distribution

in flames, (d) the local velocities in flames with the help of the method of stroboscopically illuminated powder particles, and (e) sampling in non-homogeneous gas streams.

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Del-2R2. A study of the stability conditions, the fluctuations, and other properties of turbulent flames with the help of the hot-wire anemometer.	39
Del-2R3. A study of the temperature distribution in flames of various types.	41
Del-2R5. A study of sampling in nonhomogeneous gas streams . . .	75
Del-2R6. A spectrophotometric study of local flame radiation. . .	60

JOHNS HOPKINS UNIVERSITY

Phase 1

Phase Leader: L.S.G. Kovaszny

	<u>Page</u>
To develop optical techniques for measuring the statistical properties of turbulence (intensity, scale, correlation, spectrum, etc.) in high-velocity flows for which measurable density fluctuations occur.	67

Phase 2

Phase Leader: Ion Carstiou

	<u>Page</u>
To make contributions to the fundamental theory of turbulence with particular emphasis on the case of isotropic turbulence. . . .	21

NEW YORK UNIVERSITY

Phase 6

Phase Leader: G.E. Hudson

Associates: J. Jeffress and L. Lemelson

In connection with pulsejets, ramjets, rockets: to investigate both by theory and experiment: (a) combustion and fluid flow processes in pulse jets having simple or idealized configurations, and (b) high effective burning rates and large amplitude gas vibrations in jet propulsion devices.

	<u>Page</u>
NYU-6R1. Idealized pulsejets	12
NYU-6R2. Oscillating piston engine	12
NYU-6R3. Theory of oscillating piston engine	11

Phase 7

Phase Leaders: G.E. Hudson and I. Amron
 Associates: R.J. Kraushaar, J. Neuringer,
 M.D. Scheer, L. Schoen, R.P. Shaw, M. Storm

In connection with jet propulsion devices: To make an experimental and theoretical study of the physical phenomena whose fundamental importance is indicated by the studies of Phase 6, including: (a) fluid jet formation, (b) the interaction of combustion and fluid flow, (c) large amplitude gas vibrations in tubes, and (d) ignition and combustion.

	<u>Page</u>
NYU-7R1. Experiments on gas jet formation	22
NYU-7R2. Theory of gas jet formation.	22
NYU-7R5. Large amplitude gas vibration source.	23
NYU-7R6. Large amplitude gas vibration theory.	22
NYU-7R7. Photo-ignition	48
NYU-7R8. Hydrocarbon flame bands	59
NYU-7R9. Theory of nonlinear conduction in solids	25

Phase 8

Phase Leader: J.H. Hett
 Associates: R.W. King, J.B. Gilstein

In connection with jet propulsion devices: to develop further and use pressure, temperature, fluid velocity, and density instrumentation, and other pertinent observational techniques needed to collect the data for the studies and investigations of Phases 6 and 7.

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NYU-8R1. Temperature measurement	71
NYU-8R2. Effect of temperature on pressure gauges	71
NYU-8R4. Three-dimensional schlieren apparatus	68

PRINCETON UNIVERSITY

Phase 2¹

Phase Leader: R.N. Pease

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

	<u>Page</u>
Pr -2R2. Kinetics of combustion of gaseous boron compounds . . .	47
Pr -2R4. Interaction of hydrogen atoms with oxygen and hydrocarbons.	47
Pr -2R5. Kinetics of noncatalytic combustion of ammonia . . .	47
Pr -2R6. Photochemical explosion of hydrogen-chlorine mixtures	48

Phase 3

Phase Leader: J.V. Charyk

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.

	<u>Page</u>
Pr -3R1. Investigation of ejectors and mixing of subsonic and supersonic fluid streams.	15
Pr -3R2. Investigation of mixing of rocket exhaust jet with induced air stream; problems of fuel injection and subsequent burning in mixture.	4

Phase 4

Phase Leader: A. Kahane

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

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

	<u>Page</u>
Pr -4R1. Investigation of a valveless intermittent-jet engine	5

Phase 5

Phase Leader: J. V. Charyk

To make preliminary studies of rocket motor performance under certain particular conditions with a view to gaining some insight into the factors affecting combustion in a rocket and to endeavor to translate such information into the establishment of basic parameters governing rocket combustion chamber processes . . .	<u>Page</u> 48
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PURDUE UNIVERSITY

Phase 3

Phase Leader: H.J. Yearian

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

PRF-3R1. Oxidation of heat-resistant alloys.	<u>Page</u> 52
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Phase 5

Phase Leader: J.M. Smith

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

PRF-5R1. Convection heat-transfer coefficients for gases at high temperatures.	<u>Page</u> 32
PRF-5R2. Relative importance of convection and radiation heat transfer for gases at high temperatures up to 2000°F . . .	32

Phase 7

Phase Leader: M.J. Zucrow

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

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PRF-7R1. Design, construction and instrumentation of a rocket test facility	78
PRF-7R3. Investigation of ignition lag of spontaneously ignitable propellants	50
PRF-7R5. Catalysis of the reactions of non-hypergolic propellants	51
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D I S T R I B U T I O N L I S T

1. Army-Navy-Air Force Guided Missiles Mailing List No. 11 dated 15 April 1950, as amended, Parts A,b,C, D.
2. R. Courant, New York University.
3. E.R. Gilliland, Massachusetts Institute of Technology.
4. A.B. Kinzel, Union Carbide and Carbon Research Laboratory.
5. E.S. Roberts, Chemical Construction Co.
6. H.S. Taylor, Princeton University.
7. Theodore von Karman, Scientific Advisory Board, United States Air Force.
8. J.V. Charyk, Princeton University.
9. F. Clauser, Johns Hopkins University.
10. J.V. Foa, Cornell Aeronautical Laboratory.
11. R.P. Harrington, Polytechnic Institute of Brooklyn.
- 12./32. M.W. Woody, New York University.
33. M.J. Zucrow, Purdue University.
34. K. Wohl, University of Delaware.
35. G. Markstein, Cornell Aeronautical Laboratory.
36. R.N. Pease, Princeton University.
37. P. Libby, Polytechnic Institute of Brooklyn.
38. S.A. Guerrieri, University of Delaware.
39. L. Lees, Princeton University.
40. G. Rudinger, Cornell Aeronautical Laboratory.
41. J.M. Smith, Purdue University.
42. S.W. Yuan, Polytechnic Institute of Brooklyn.
43. M. Balicki, Polytechnic Institute of Brooklyn.
44. P.K. Porter, Cornell Aeronautical Laboratory.
45. H.J. Yearian, Purdue University.
46. I. Fankuchen, Polytechnic Institute of Brooklyn.
47. J.T. Grey, Cornell Aeronautical Laboratory.
48. H.J. Shafer, Princeton University.
49. A.P. Colburn, University of Delaware.
50. G.S. Meikle, Purdue University.
51. H.k. Moffitt, Cornell Aeronautical Laboratory.
52. R.J. Woodrow, Princeton University.
53. H.K. Work, New York University.
54. R. Spence, Johns Hopkins University.
55. A. Kahane, Princeton University.
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ABSTRACT:

A quarterly progress report on the Squid jet propulsion project is presented. Comprehensive data are given on work accomplished on jet propulsion engines, fluid mechanics, heat transfer, characteristics of flames, chemical reaction kinetics, spectroscopy of combustion, instrumentation and testing equipment, and heat-resistant materials. Studies sponsored by Project Squid and conducted at affiliated universities are also outlined.

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