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UNITED STATES NAVY
AND
UNITED STATES AIR FORCE

PROJECT SQUID

QUARTERLY PROGRESS REPORT

1 July, 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:

NYU - N6-CRI-11, Task Order 2, NR 220-040
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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, PRF-7R9).**

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

The object of these problems is to determine experimentally the influence of combustion chamber pressure upon the performance of, and heat transfer in, rocket motors. Concentrated nitric acid (98 per cent) and commercial AN-F-58 jet engine fuel are being used as the propellants.

Ten runs have been made using a 500-lb thrust motor (No. WC-5.3.100-1) at chamber pressures of approximately 300 psi and mixture ratios (O/F) varying from 3.5 to 6.5. The performance and heat transfer data acquired on these runs are presented in Table 1. Difficulty was experienced in maintaining a constant flow rate of coolant (water) through the motor jacket. Two differential head pressure recorders have been ordered for providing a continuous record of the rate of coolant flow during a test. A laboratory potentiometer is being employed for checking the temperature measurements of the coolant which are recorded with a recording Brown potentiometer.

Plans were initiated with the Haynes Stellite Division of the Union Carbide and Carbon Corporation, Kokomo, Indiana, to spin nozzle shells from Haynes Alloy 25 (L-605). The fabrication method selected will simplify construction and reduce the cost of experimental rocket motors. Orders have been placed for the nozzles for the rocket motors to be used in investigations at 300, 500, and 700 psi combustion chamber pressure and 500 pounds thrust. The existing combustion chamber will be used with the aforementioned nozzles.

It is planned to secure heat transfer data and rocket motor performance data at 500 and 700 psi combustion pressure in the near future. Rocket motors for investigations at 1000 psi and 1500 psi chamber pressure are being designed.

B. STUDIES OF THE PRINCIPLES OF THE RAM ROCKET. (Pr-Phase 3)

Submitted by: J.V. Charyk, Princeton University

Since interest has been shown in the flow which can be induced by a high velocity hot jet (a rocket motor) and the resulting temperatures of the mixture, the following table has been compiled from 30 tests involving two area ratios and fuels of two markedly different energies. Rich and lean performance is shown in several cases. During the past quarter static tests of the ducted

Table 1: Average Performance and Heat Transfer Data for Rocket Motor No. WC-5.3.100 - 1

Run No.	Thrust T (lbs)	Chamber Pressure P _c (psi)	Mixture Ratio R (O/F)	Specific Impulse I _{sp} (sec)	Charac-teristic Velocity C* (ft/sec)	Heat Transfer (Btu/sq in/sec)		Comments
						Nozzle Heat Transfer q _n	Chamber Heat Transfer q _c	
24	----	304	4.83	----	4010	1.18	0.350	Malfunction of thrust recorder.
"	----	300	4.83	----	3800	1.03	0.305	
25	588	328	4.65	190	4080	1.43	0.453	
26	514	300	5.16	182	4035	1.37	0.413	
"	531.5	319	4.73	185.2	4230	1.29	0.398	
27	479	----	6.47	157.1	----	1.08	0.335	P _c clogged.
"	502	----	5.86	165	----	1.01	0.324	
28	560	296	3.83	187	3830	0.838	0.312	
"	572	301	3.67	188	3830	0.779	0.313	
29	498	----	4.43	178	----	0.892	0.330	P _c clogged.
30	530	287	4.12	195	3400	1.00	0.333	
"	525	287	4.53	183	3270	0.945	0.292	
31	468	----	4.43	165	----	0.847	0.272	P _c clogged.
"	496	----	3.87	175.2	----	0.667	0.273	

(continued)

Table 1 (continued)

Run No.	Thrust T (lbs)	Chamber Pressure P _c (psi)	Mixture Ratio R (O/F)	Specific Impulse I _{sp} (sec)	Charac-teristic Velocity C* (ft/sec)	Nozzle Heat Transfer q _n (Btu/sq in/sec)	Chamber Heat Transfer q _c (Btu/sq in/sec)	Comments
32	452	-----	6.09	142.0	-----	0.836	0.290	P _c clogged.
"	489	-----	4.78	149.0	-----	0.695	0.257	
33	542	-----	4.17	130.5	-----	1.12 avg.	0.42 avg.	P _c clogged.
"	547	-----	4.10	133.6	-----	1.12	-----	
34	557.5	314.5	4.25	184	4010	1.12	-----	
"	565	321	4.24	183.3	4025	1.14	-----	

rocket system have been underway. Energy, momentum, and mass balance determinations have been made. The rocket motor has been operated with liquid oxygen as the oxidizer and with fuels of varying heat content. With these various propellant combinations the rocket has been run over a wide range of mixture ratios in order to permit a systematic evaluation of the energy release in the down-stream portion of the duct due to the after-burning of the rocket exhaust products with the induced air. These tests have also covered two ratios of duct area to rocket exit section areas. As would be expected, the induced mass flow is very dependent on the heat release in the down-stream duct, varying from high values for low energy content fuels at lean mixture ratios to a minimum value with high energy content fuels at rich mixture ratios. Considerable difficulty has been encountered in making exit temperature determinations in the case of the higher energy content fuels since conventional thermocouple methods become rather inaccurate. The temperatures under these conditions are in excess of about 2400°F. In order to illustrate some typical data as to temperatures and induced mass flow ratios a compilation from some of the 30 tests conducted to date is included in Table II. To date only static tests have been conducted, that is, tests in which there is no simulated forward velocity. However, a modification to the existing test set-up is now underway making use of the high pressure air supply as the source of the primary jet in an ejector arrangement which should enable tests to be conducted up to simulated forward speed velocities corresponding to Mach numbers of the orders of 0.6 or 0.7.

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

The studies that have been carried out in this program have been described in Project Squid, Annual Report, January 1949 and January 1950. The investigation has included 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" diameter jet air supply.

Because of injection pump failures during high frequency operation, investigation of subsonic ram-jet configurations has been curtailed. Bench tests of the pump are being made to determine means of overcoming the excessive wear encountered.

Since the pump operates satisfactorily at low frequency (20 cycles per second), the investigation of low frequency intermittent combustion in a flowing gas planned for the new 4" x 4" tube with 4 foot long windows has been started. Schlieren high speed action pictures of the combustion process have been taken at speeds up to 8000 frames per second with an 8 mm. Fastax camera which has been modified so as to give an 8 mm. x 16 mm. frame. A preliminary frame by frame inspection of the pictures seems to indicate that, during combustion of the down-stream moving mixture, flame is "held" by the pilot flame.

Table II
SUMMARY OF HOT JET INDUCTION

DUCT	FUEL	MIXTURE	INDUCTION RATIO $\frac{\text{Induced Flow}}{\text{Jet Flow}}$	MIXTURE TEMP. End of Duct Of
$\frac{A_d}{A_t} = 256$ Duct Dia. = 6"	J. P. 3 Fuel Oil	Rich O = 1.50 $\frac{O}{F}$	7.60 *	Above 2400 **
		Lean O = 3.30 $\frac{O}{F}$	13.00	1250
Noz. Dia. = .375"	.75 Alcohol .25 Water	Rich O = .90 $\frac{O}{F}$	9.00	1400
		Lean O = 2.80 $\frac{O}{F}$	17.20	500
$\frac{A_d}{A_t} = 455$ Duct Dia. = 8"	J. P. 3 Fuel Oil	Rich O = 1.20 $\frac{O}{F}$	6.60	Above 2400
		.75 Alcohol .25 Water	7.00	1600
Noz. Dia. = .375"		Lean O = 2.60 $\frac{O}{F}$	12.90	600
* - 24° ** - 50°F Taken 5' 1' Down-stream of Rocket				

O = Oxidizer = Liquid O₂
 F = Fuel
 A_d = Duct Area
 A_t = Primary Jet Throat Area

A one-dimensional theory of the pressure rise occurring during intermittent combustion in a constant area tube has been evolved assuming the above picture of a stationary flame. The gas dynamics of this combustion process is shown in the time-distance plane in Fig. 1. The mixture, which moves from left to right, is continually ignited by a flame held at the pilot flame ignition source. Shock waves are propagated upstream and downstream, the upstream shock precompressing the unburnt mixture. The downstream end of the burnt gases is an entropy discontinuity surface on both sides of which the pressure and flow velocities are equal. Assuming small pressure drop across the flame, constant specific heats, zero mol. change during reaction, and isentropic shock waves, the following formula has been obtained for the pressure ratio of the mixture compressing shock:

$$\frac{p_1}{p_0} = \left[1 + \frac{(\gamma - 1) M_0 q}{2(2 + q)} \right]^{\frac{2}{\gamma - 1}}$$

where: $q = \frac{Q}{C_p T_1}$ dimensionless heat release

Q heat release across flame, Btu/lb. air

C_p specific heat at constant pressure, Btu/lb. °R

γ ratio of specific heats

T_1 compressed unburnt mixture temperature, °R

M_0 initial flow Mach number

This formula is plotted in Fig. 2 and indicates that for given q , the pressure ratio $\frac{p_1}{p_0}$ increases monotonically with flow Mach number. This trend has been observed (see Project Squid Annual Report, January 1950). Plans include continuing the high speed photographic studies to determine whether this preliminary view of the intermittent combustion process is correct.

D. STUDIES OF INTERMITTENT JET ENGINE OPERATION. (CAL-1R1)

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 work on a new type of such engines was started recently.¹ Both the inlet and outlet are periodically opened and closed. The interruption of the exit flow produces a shock wave that is reflected forward and backward in the duct and its strength is maintained by correctly timed valving. Since the combustible mixture is pre-

¹ Project SQUID, Quarterly progress Report, 1 April 1950

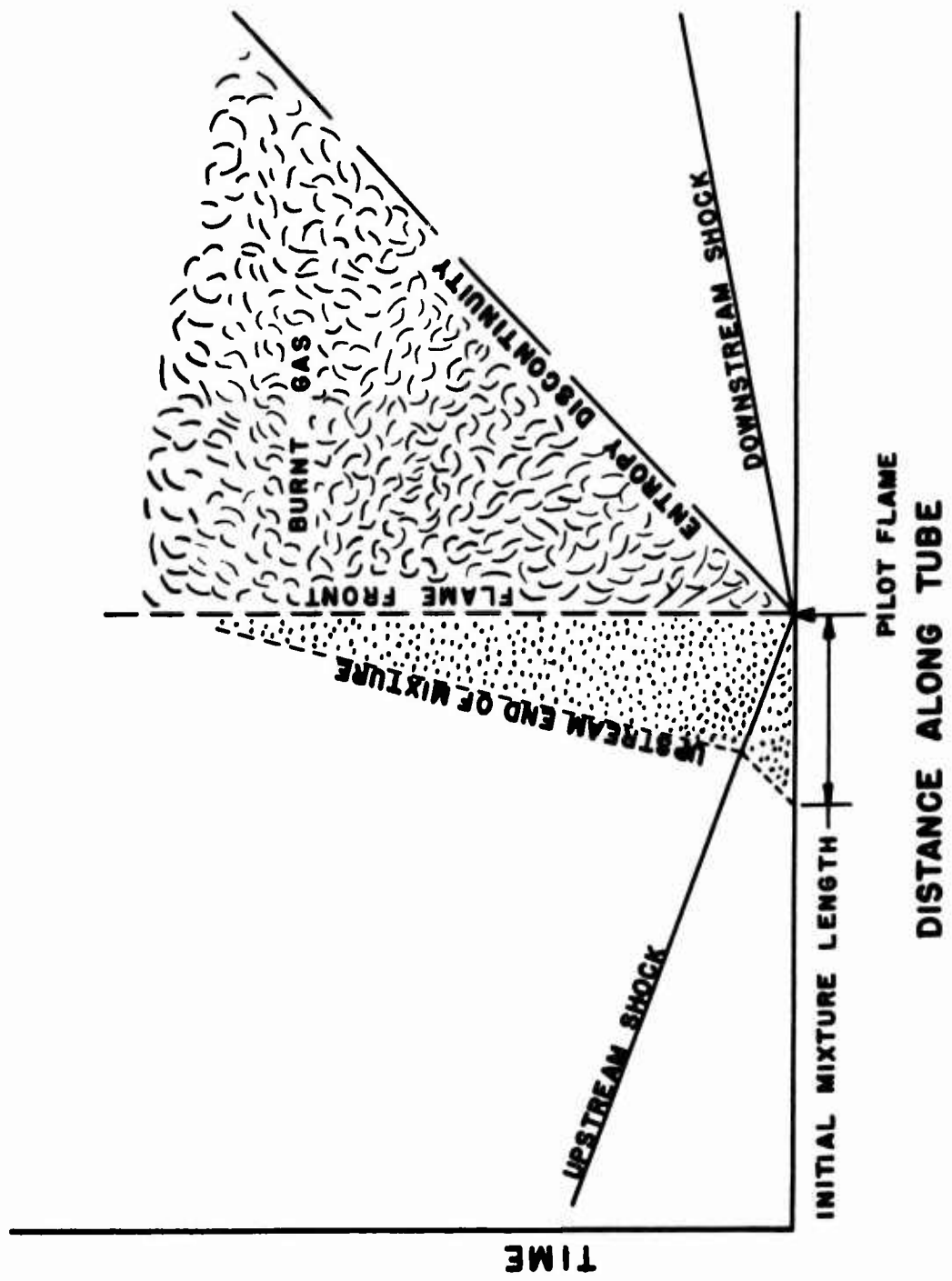


Figure 1

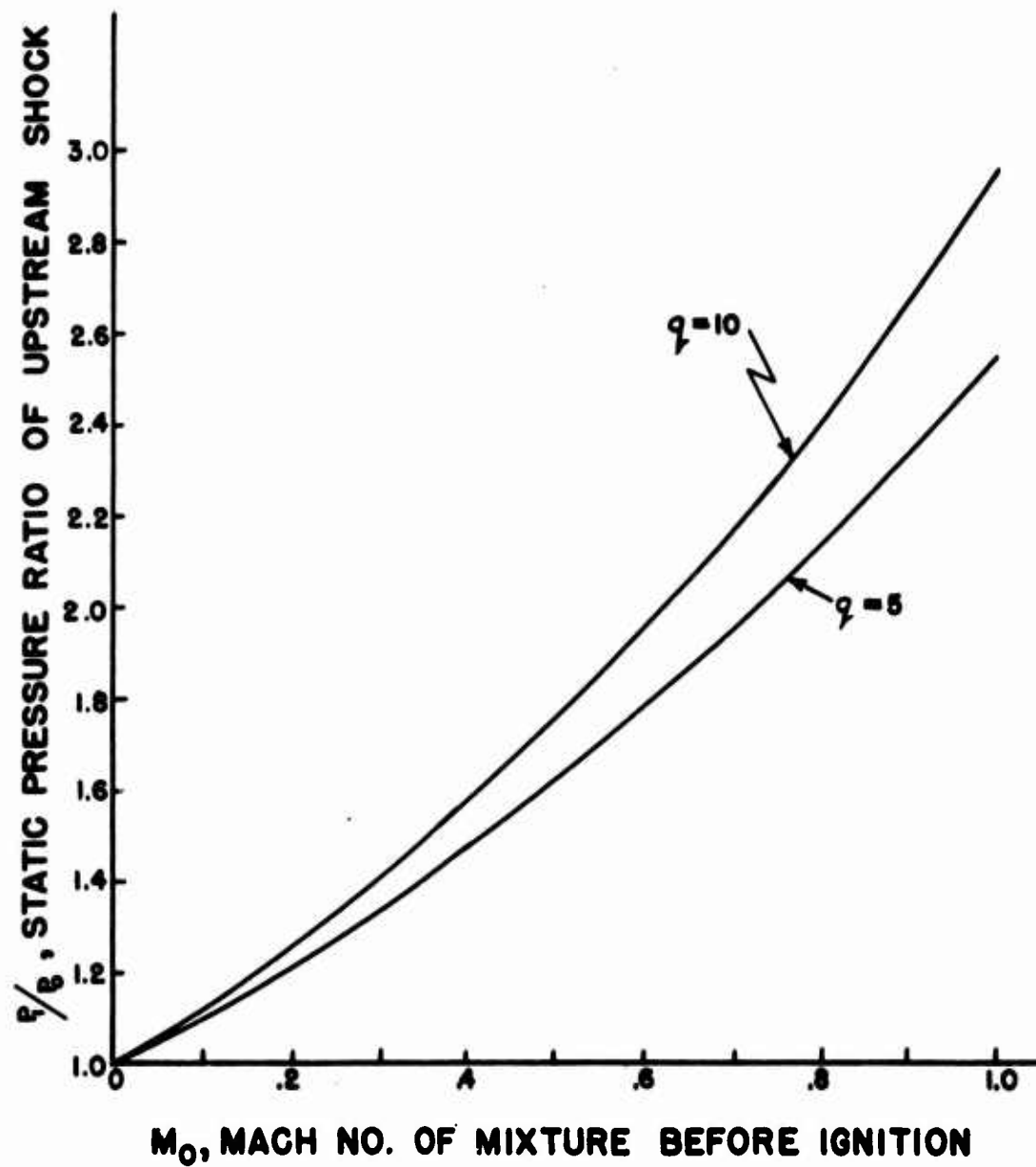


Figure 2

compressed by the shock wave, the engine is essentially a combination of a compressor and a pulsejet. The inlet valves are at present the flapper valves of a conventional pulsejet. At the exit, opening and closing is achieved by a rotating disc.

The combustion chamber of the model engine was rebuilt and now forms a section of 5 inch diameter with the rest of the duct of 3 inch diameter. Satisfactory burning was obtained without any turbulence producing grids. The spark was required for starting only.

The engine was transferred to a thrust stand and a condenser-type pressure gauge was mounted near the flapper valves. The measured thrust was approximately 16 pounds. So far, it has not been possible to determine the best performance of the engine since the life of the flapper valves was too short to allow for optimum adjustment of all operating conditions. Fig. 3 shows a photograph of a valve bank that had been in use for only about 30 seconds. The reason for this rapid failure has not yet been established and further work is required before any explanation can be given. The pressure records do not show any excessive pressures and the valves never become heated by burned gases (the combustion chamber is located at the exit end).

An attempt is being made to record instantaneous gas density by means of the fringe shift in a simple setup based on the interference of two light beams (Young's experiment). Work so far has consisted merely of preparation of the program. Some minor optical components have been ordered but have not yet been received.

A start has been made to study the boundary conditions at open ends of a duct during inflow. It is customary to assume that the steady flow conditions for isentropic flow - the outside pressure is the stagnation pressure for the flow in the inlet - can be applied also to nonsteady flows. It was claimed², however, that the flow constriction which is produced by vortex formation during inflow should be considered. An attempt will be made to evaluate how significant such variations from the customary boundary conditions would be. This work has only been started and no results are as yet available.

The first part of a study dealing with the performance analysis of single-flow jet engines has been completed (SQUID Technical Memorandum No. CAL-28). This analysis is based on a generalized method, which makes use of a set of continuously variable parameters to describe the modes of compression, heating and expansion. The results are expressed in terms of fuel specific impulse for given values of the air specific impulse at various flight Mach numbers. The results indicate that the most economical jet powerplant would be one in which heat is added within a confined region of nonsteady flow, the outflow from the engine being steady. An extension of this work is now in

²F. Schultz-Grunow, Der Carnotsche Stossverlust in nichtstationärer Gasstromung, A.A.M.M. 29, 257-267, 1949.

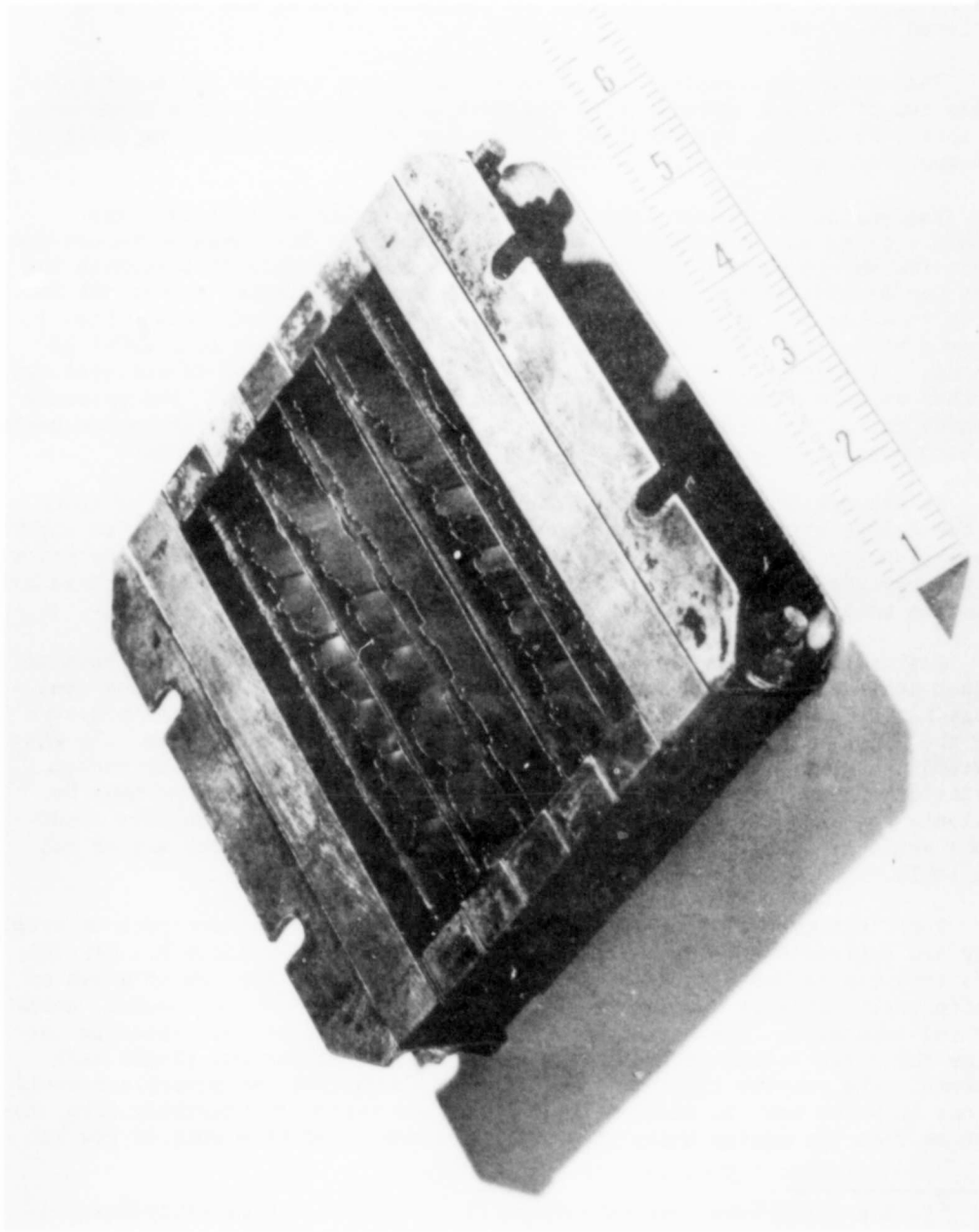


Figure 3

progress.

A separate analysis of ducted jet powerplants is growing out of the study of ducted pulsejets and is described as part of that problem.

E. INVESTIGATION OF A VALVELESS PULSEJET. (CAL-1R7)

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

Investigation of a valveless pulsejet. A gas dynamic model of a valveless pulsejet is being prepared for the testing of the flow valve described previously.¹ The experimental setup, consisting of a small shock tube (4 feet long and having a square cross section of 1-1/2 inches) with the model placed in the test section, is almost completed.

No tests were carried out with valveless pulsejet models during this quarter, but the experiments will be continued with performance measurements in a free air stream.

F. THEORETICAL STUDY OF SHROUDED PULSEJET: OPERATION AND PERFORMANCE.

(CAL-1R8) Submitted by: J.V. Foa and G. Rudinger, Cornell Aeronautical Laboratory

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

The performance of the shrouded pulsejet had previously³ been calculated on the basis of reasonable assumptions for the thrust and fuel consumption of the pulsejet alone. This work was continued in an attempt to evaluate the importance of the mixing of the pulsejet exhaust gases with the remainder of the flow through the duct. The flow through and around a submerged pulsejet (or any other type of primary engine) will adjust itself so that the fuel consumption, air/fuel ratio and available thrust of the primary engine form a set of compatible values. Given the fuel consumption and the air/fuel ratio, one may therefore calculate the maximum possible over-all performance of a ducted engine without specifying the type of the primary engine.

If the combustion efficiency of the primary engine is less than 100%, its exhaust will still contain some combustible mixture which may or may not be completely burned before leaving the outer duct. Three cases are being

³G. Rudinger, An evaluation of the potential merits of ducted pulsejets, Project SQUID Technical Memorandum No. CAL-32, October 1949.

considered: (a) the exhaust gases of the primary engine mix completely with remaining flow through the duct and the fuel not burned in the primary engine is completely burned during the mixing process, (b) mixing is again complete but no further burning takes place, (c) no mixing takes place and the shroud merely acts as a device to control the pressure at the exhaust of the primary engine. Some of the results obtained are shown in Figs. 4 and 5 for the following conditions: The cross-sectional area of the primary engine A_p is 60% of the maximum duct area A_{max} . The fuel consumption, W_f , in pounds of fuel per second is proportional to the static pressure p_1 at the exit of the duct inlet diffuser; its numerical value is given by $W_f/p_1 \cdot A_{max} = 1.0 \cdot 10^{-4} \text{ sec.}^{-1}$. The combustion efficiency η_c of the primary engine is 80%. The exhaust conditions are taken according to the three cases outlined above and the exhaust nozzle is designed for complete expansion. Fig. 4 applies to an air/fuel ratio of $\infty = 24$ and shows the maximum possible thrust T of the entire engine (in the form of the nondimensional parameter $T/p_0 A_{max}$ where p_0 is the free stream static pressure) for the three cases, considered as function of the flight Mach number M_0 . The thrust of the entire engine is here defined by $T = M(u_e - u_0)$ where m is the mass flow through the engine, u_e the exhaust velocity and u_0 the flight velocity. For comparison, the thrust of a ramjet operating at the same fuel consumption and air/fuel ratio is also shown by the two dashed curves corresponding to combustion efficiencies of 80% and 100%, respectively.

The effect of ducting on the operation of the primary engine depends on the mechanism of the primary engine itself and can therefore not be evaluated in general. In the particular case of the ducted pulsejet, not enough is known about the operating mechanism of the pulsejet to predict the effect of ducting. Since the flow through and around the primary engine adjusts itself automatically to compatible conditions, the value of the air/fuel ratio cannot be predicted in general. Charts similar to Fig. 4 were therefore prepared for a wide range of air/fuel ratios. Fig. 5 shows the result for the above mentioned exit conditions of complete mixing but no burning (case b) for values of ∞ between 15 and 60. All other conditions are the same as for Fig. 3.

These curves have been obtained without making any assumptions as to the mechanism of the primary engine. They hold therefore for any ducted engine assuming only that it will operate under the specified conditions. For example, since a conventional pulsejet will only operate within a limited range of ∞ (say, between $\infty = 24$ and $\infty = 40$), the best possible performance of the ducted pulsejet would lie in the region bounded by the curves corresponding to these values of ∞ . At present, it does not seem possible to predict whether or not the pulsejet would actually resonate in the duct under these conditions.

This work is being continued to obtain further data, including an evaluation of the specific impulse and a comparison with single flow engines.

In the particular case of the ducted pulsejet, an attempt is also being made to estimate the validity of the assumption that the pulsating flow through

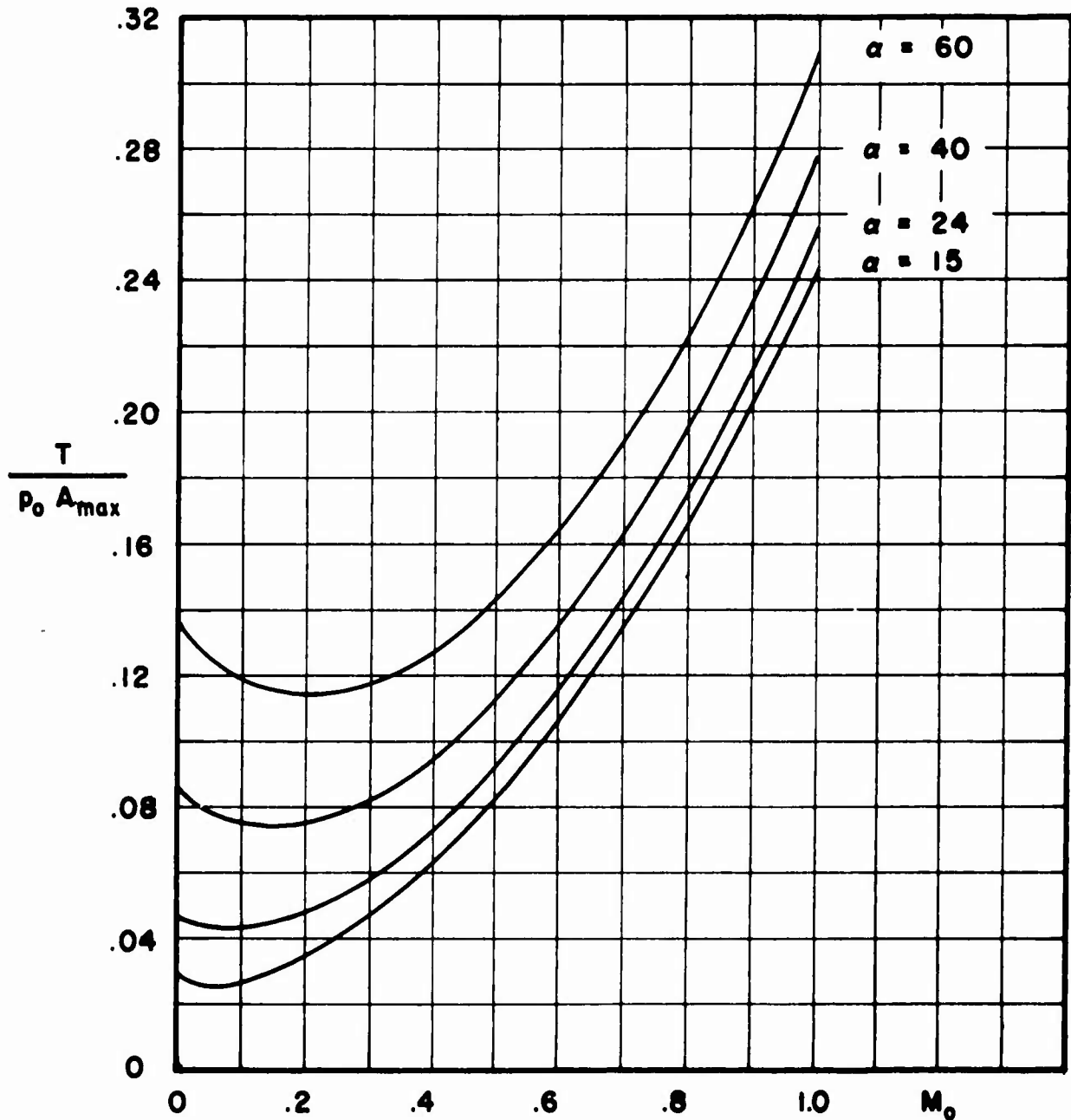


Figure 4 Thrust of a ducted engine vs. flight Mach number for various exhaust conditions:

- (a) Complete mixing and burning of the exhaust gases of the primary engine with the remaining flow through the duct.
- (b) Complete mixing but no burning.
- (c) No mixing.

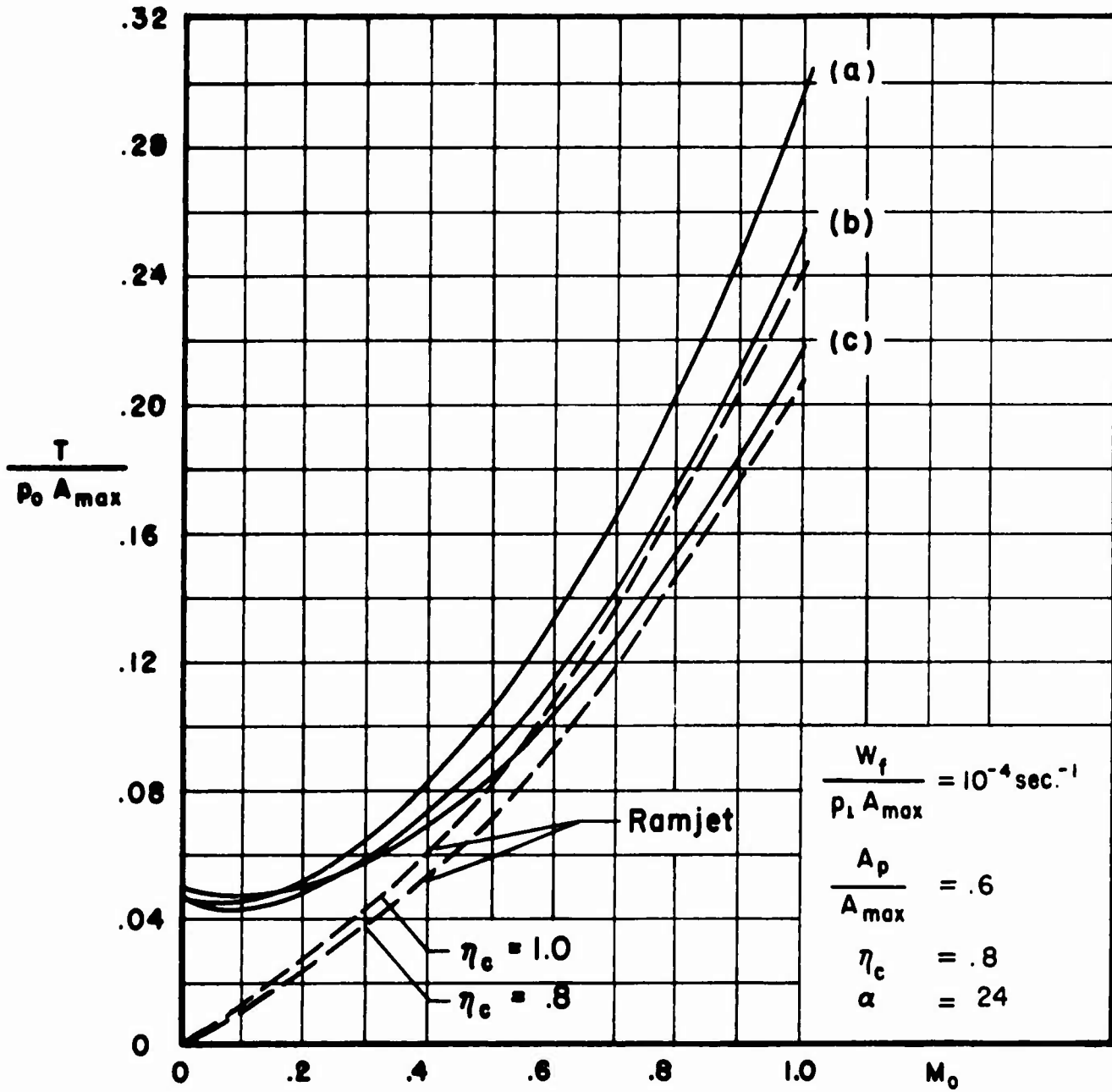


Figure 5 Thrust of a ducted engine vs. flight Mach number for case (b) of Fig. 4 and for various values of the air/fuel ratio.

the duct can be replaced by an equivalent steady flow.

This assumption had to be made to permit analysis of the problem at all. It is certainly reasonable to operate with mean values of the flow parameters as long as the oscillations of the parameters are small compared to their mean values. However, pressure measurements near the tail pipe exit of a small (valveless) pulsejet showed that pressure ratios of the order of two may occur there. Further theoretical and/or experimental work is being planned in this connection to establish the limitations of the steady flow approximation.

G. OSCILLATING PISTON ENGINES. (NYU-6R2)

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

Work on an engine of this type has been continued during this quarter (1) to investigate the effect of using part of the energy of the burning gases to compress the mixture before ignition during the next cycle, and (2) to investigate a mechanism that, by relatively simple modification, could be used to produce high amplitude gas vibrations with controlled boundary conditions for use in problem 7R5.

Development has now proceeded far enough to determine that the engine will operate satisfactorily, but not far enough to determine whether it offers an appreciable improvement over the standard pulse jet engine. Fig. 6 shows the combustion chamber assembly of this engine with one cover plate removed. A number of runs have been made with different types of flappers at various tailpipe lengths. Study of high speed pictures and the test results collected to date indicated that attention should be directed to reducing the mass of the flapper to at least one quarter of its present value, and this is now being done.

H. IDEALIZED PULSEJET ENGINES. (NYU-6R1)

Submitted by: J. Lemelson, New York University.

No data on the operations of the glass-walled pulse jet have been collected during this quarter. Work on improved observational techniques (reported under 8R4) has led to the development of an interferometer that is expected to be used in this study.

Due to anomalies that have been observed during the study of gas jet formation (7R1) and large amplitude gas vibration (7R5), it was felt that an investigation should be made of the effect of resonant chambers on the operation of a pulse jet engine. The chambers tested consisted of resonating chambers of lengths of various sized tubing coupled to the combustion chamber at right angles to the axis of the basic engine. The effective length of each tube could be changed at will by adjusting the position of a piston within it.

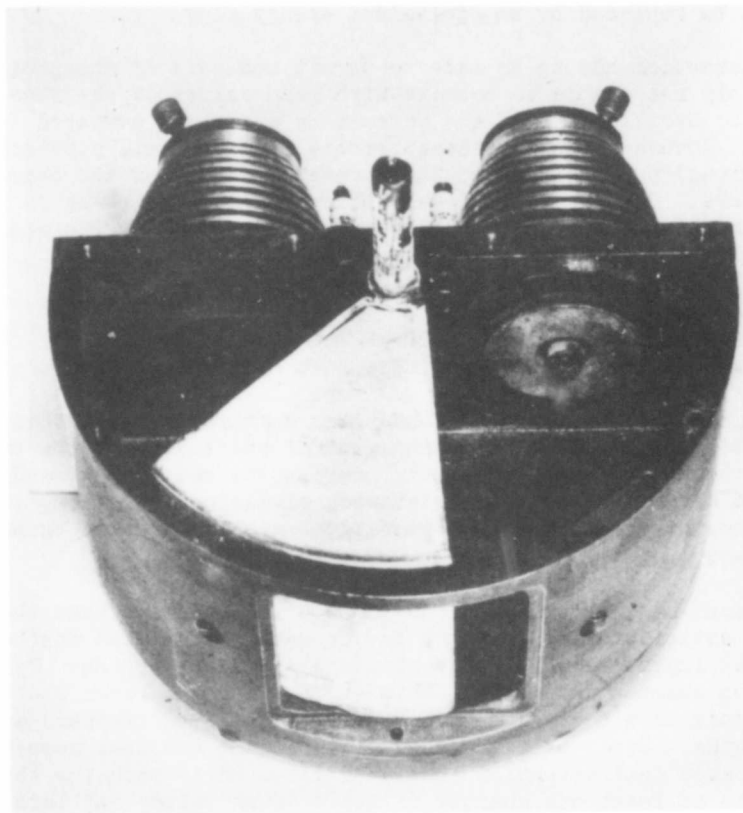


Figure 6 View of combustion chamber of oscillating piston engine with top cover plate removed. The tailpipe is connected to the opening.

The results obtained, though not yet analyzed in detail, and confined to two engine configurations, indicate that there is a marked variation in thrust and fuel flow as the resonating chamber length is changed. So far, maximum thrust has not been increased above that of the normal engine.

With a $5/8$ " I.C. tube, the maximum thrust rose from 2.0 lbs. at 1" to 2.2 lbs. at 4" - 8", gradually decreasing to 1.0 lbs. at 19". Between 20" and 22", the engine would not run; but above 23" the thrust increased from 1.0 lbs. to 2.2 lbs. at 34", remaining relatively constant from there to 46".

With the $7/8$ " diameter tube, the readings were started at 4" tube length where the thrust was 2.4 lbs. As the tube length increased, thrust dropped to approximately .9 lbs. at 24". At tube lengths greater than 26", the engine could not be started, or kept running, as the piston was withdrawn until the configuration of the engine was changed. These data have not yet been analyzed.

With a $1-1/2$ " I.C. tube, the thrust was 2.7 lbs. with the piston at the tube opening, gradually dropping to 2.5 lbs. at 10", and then swiftly dropping to 1.2 lbs. at 17". Above this length it was once again impossible to start the engine, or to keep it running, as the piston was withdrawn.

II. FLUID MECHANICS**A. PROPAGATION AND STABILITY OF SHOCK WAVES IN SUPERSONIC DIFFUSERS.(CAL-IR6)**
Submitted by: J.V. Foa and G. Rudinger, Cornell Aeronautical Laboratory.

The manuscript covering the previously reported¹ experimental work on the propagation and stability of shock waves in small supersonic diffusers was completed and submitted for editorial review. No further work with the larger models was carried out during this Quarter.

B. LARGE AMPLITUDE GAS VIBRATION SOURCE. (NYU-7R5)
Submitted by: R.P. Shaw and J. L. Neuringer, New York University.

A talk on an improved version of the theory outlined in the last Quarterly Progress Report, 1 April 1950, was presented at the meeting of the Fluid Dynamics Section of the American Physical Society on May 13, 1950, and a technical paper is in preparation.

Briefly, this analysis reveals the structure underlying one-dimensional compressible fluid flow to such an extent that the method applies not only to interaction of general simple waves, but, with slight modifications, to more general problems. The ultimate aim is, of course, the analysis of large amplitude periodic oscillations, which can be represented by solutions of the same general character as those already obtained for simpler problems. Another step in this direction has been taken by obtaining explicit representations of reflections of simple compression and rarefaction waves from the open end of a tube, using the conventional boundary condition requiring pressure to remain constant at the open end.

In applying the theory of such large amplitude gas vibrations to jet propulsion devices, the theory of the production, maintenance and propagation of sound in gaseous regions containing local heat sources is extremely important. However, even the simplest example of this sort found in the literature, the Rijke tube, has not as yet been quantitatively resolved. It is felt at NYU that a better understanding of the relatively simple phenomenon of the Rijke tube is, therefore, essential before headway can be made toward the understanding of the more complicated process of large amplitude vibrations with local heat sources inside jet devices.

1. Project SQUID, Quarterly Progress Report, 1 April 1950, Div.II,Sec.A.

The Rijke effect is as follows: A loud tone is produced when a piece of wire gauze, placed in the lower half of a tube held in a vertical position, is strongly heated. Experiments at N.Y.U. have verified the supposition that if gravitational convection be replaced by forced convection, the tone will be produced, even if the tube is horizontal. It is with this arrangement of horizontal tube and forced convection that the mathematical analysis described below is concerned.

Consider a tube of uniform cross-section of length L , and open at both ends. Inside the tube and perpendicular to the axis is placed a fine wire gauze or grid which is heated electrically. The grid is assumed to be placed initially at any point in the tube, say at a distance L' from one end. Air is then forced into this end by blower action with velocity U' , at density D' and pressure P' . We now wish to determine the aerothermodynamic processes inside the tube, and the air column vibration that can exist in such a tube, i.e., the theory of sound production or decay.

One can begin by setting up the most general aerothermodynamic equations, but they are non-linear, and at present too difficult to solve. Therefore, the assumption is made that the zero order effects are independent of position, except for a discontinuity at the heated region; viz., that a layer of gas with parameters (U', P', D') is heated uniformly by the gauze, emerging on the other side with parameters (U'', P'', D'') . This assumption is borne out quite well by the experiments of Lehman.²

Since gas oscillations are superimposed on the uniform flow, the instantaneous total velocity, pressure and density in region I are designated by u_1, p_1, ρ_1 , and the values in region II by u_2, p_2, ρ_2 . If continuity of mass, and conservation of momentum and energy is required across the heated interface, and if Q be the heat added to the layer of gas per unit area per unit time, one has at the heated gauze

- (1) Continuity $\rho_1 u_1 = \rho_2 u_2$
- (2) Momentum $-(p_2 - p_1) dt = \rho_1 u_1 dt (u_2 - u_1) + f dt$
- (3) Energy $p_1 u_1 dt - p_2 u_2 dt + Q dt = \frac{1}{\gamma - 1} (-p_1 u_1 dt + p_2 u_2 dt) + \frac{1}{2} \rho_1 u_1 (u_2^2 - u_1^2) dt$

where the parameters may be functions of time and f is the effective pressure exerted on the gas by the gauze obstruction. For convenience, this latter effect was assumed to be a first order effect.

2. Uber die Theorie der Netztone, "Analen Der. Physik", July 1937, Vol. 29, p. 539.

It is, of course, difficult to ascertain the exact functional relationship of Q in terms of the dynamical variables but, fortunately, in the case of convective cooling of a heated cylinder immersed in a moving media, King³ has derived a theoretical formula for the rate of loss of energy by convection. King's formula is well established and is the starting point of conventional hot wire anemometer analyses. Furthermore, Langmuir⁴ has shown that the heat transfer is just to the thin layer of gas which surrounds the cylinder. Hence, it is a good approximation to assume that the heat is not conducted up or down the tube by conduction from layer to layer, but is given up only to the layer which is in immediate contact with the cylinder.

If l units of length of wire, each heated uniformly to the same temperature, are exposed to the gas, and A is the cross-section of a layer of gas, King's formula becomes

$$(4) \quad \dot{Q} = \frac{l}{A} \left[K + \sqrt{2K C_v K \rho_1 u_1 d} \right] (T_g - T')$$

where K = coefficient of thermal conductivity of the gas

C_v = specific heat at constant volume

ρ_1 = density of gas

u_1 = velocity of gas

d = diameter of cylinder

T_g = temperature of cylinder

T' = temperature of gas.

With each variable in each region assumed to consist of a uniform part plus a small perturbation, e.g.,

$$(5) \quad A_1 = D^I + \rho^I, \quad \rho_2 = D^{II} + \rho^{II}, \text{ etc.,}$$

we substitute (5) into (1), (2) and (3), and collect zero and first order terms. The zero order equations thus obtained make it possible to solve for the 0-order parameters in region II in terms of the known parameters of region I. The first order equations act as boundary conditions at the wire heater which must be satisfied by the first order solution of the acoustic wave equation.

3. King, "Philos. Trans. of Royal Society", Vol. 214, 1914.

4. I. Langmuir, "Convection and Conduction of Heat in Gases", Physical Reviews, Vol. 34, 1912.

The first order wave equation in velocity takes the form in region I

$$(6) \quad (c^2 - U^2) \frac{\partial^2 u^I}{\partial x^2} - 2U \frac{\partial^2 u^I}{\partial x \partial t} = \frac{\partial^2 u^I}{\partial t^2}$$

and in region II

$$(7) \quad (c'' - U''^2) \frac{\partial^2 u''}{\partial x^2} - 2U'' \frac{\partial^2 u''}{\partial x \partial t} = \frac{\partial^2 u''}{\partial t^2}$$

Now, in addition to the conditions determined at the interface, it is assumed that pressure nodes exist at both ends of the tube. This assumption confines the oscillations within the tube (no radiation) and one may possibly obtain an increase of oscillation amplitude with time. If so, the value of the frequency is a complex number, whose imaginary part must be negative in order to obtain sound production.

The wave equations, together with the conditions at the gauze and at the ends, enable one to solve for the complex frequency.

At the present time, the wave solutions for the oscillations have been obtained and the possible frequencies in the tube have been calculated in terms of the convective velocity, position of the wire gauze with respect to the input end, and energy input to the oscillations.

So far, the theory checks with all existing experimental results, and has even led to certain predicted phenomena apparently not heretofore mentioned in the literature. The following has been verified:

1. For a grid temperature of 800° C, it was predicted that gas coming in at 0° C would emerge on the other side of the grid at temperature about 160° C. This was found to agree with Lehman's experimental results.
2. For each of several convective velocities, it was predicted that the principal frequency would increase by amounts varying between 3.5 to 4.2 per cent as the grid temperature was raised from 800° C to 1200° C. This is in agreement with Lehman's results, who estimated the change at 3 per cent in one of his experiments.
3. It was predicted that the principal note would be sounded at a grid position of about .43L and could not be obtained for grid positions beyond .5L. This agrees with the description by Rayleigh.⁵
4. It was predicted that notes of higher frequency than the principal note could be excited by moving the grid closer to the blower end. Though this was not mentioned by Rayleigh, it has been verified experimentally both by Lehman and by the writer.

5. Rayleigh, Theory of Sound, Vol. 2, p. 233.

5. It was predicted that if the heater be replaced by a sink or cold source, then the principal note would be sounded at a grid position greater than $L/2$. This was verified by the experiments of Boscher and Riess⁶ in 1859.

6. While Rayleigh states that the principal note cannot be sounded for a gauze position greater than $.5L$, both Rayleigh and Lehman never mention the possibility of exciting notes of higher frequency for such gauze positions. The theory, however, predicts the excitation of these notes which have subsequently been observed experimentally at N.Y.U. The grid positions predicted agreed closely with those calculated.

Further theoretical and experimental investigations of other cases are being planned in which there are different acoustic impedances at the ends of the tube, and higher air stream velocities. It is believed that the periodic structure of the velocity affects the temperature of the gauze in some periodic manner, thereby providing the "feedback" necessary for spontaneous oscillations. It is with this "feedback" mechanism that we will also be concerned.

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 research during this period was devoted primarily to Leray's concept of "turbulent" solutions of Navier-Stokes equations. The role played by Lebesgue's integral in this theory has been studied carefully. The introduction of Reynolds number from the Navier-Stokes equations has apparently shown (in previous work) that the passage of this number beyond certain limits leads to the possibility of irregular (i.e., turbulent) solutions. This has suggested an attempt to establish a correspondence between the occurrence of Leray's irregular solutions and the passage of Reynolds number beyond some critical value. The consideration of vortex field led us to go back to the equations we gave for such a field.⁷ We are now about to extend Lichtenstein's Theory.⁸ A paper, which will describe this work, is in preparation.

6. Boscher and Riess, "Pogg. Ann.", Vol. CVII, p.342, 1859.

7. Comptes Rendus, Vol. 223, 1946, p.1095.

8. Math. Zeitschrift, Vol. 23, 1925, pp.89-159.

D. FLOW OSCILLATIONS IN RAMJETS. (CAL-5R1)

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

The purpose of this study is to acquire an understanding of the various types of nonsteady flow phenomena which are frequently observed in the operation of ramjets, to determine the causes of these flow fluctuations and to establish criteria for their control or elimination.

Work on this phase was started on May 15, 1950 with a thorough survey of the available literature on "rough burning," cold flow oscillations in ramjets and related phenomena in other fields.

There is nothing to report at the present time.

III. H E A T T R A N S F E R**A. THEORY OF NON-LINEAR HEAT CONDUCTION IN SOLIDS. (NYU 7R9)**

Submitted by M. L. Storm, New York University.

Analytical work on this problem has been completed, and the paper is being written.

B. EXPERIMENTAL STUDY OF LIQUID INJECTION INTO A GAS STREAM WITH REFERENCE TO TRANSPARATION COOLING OF ROCKET MOTORS. (PRF-7R10)

Submitted by: Eldon L. Knuth, Purdue University.

The object of this problem is to determine the feasibility of cooling rocket motor nozzles (and walls) by transpiration cooling through spaced parallel disks. However, before film cooling can be utilized effectively, the factors governing the stability of the coolant film under different flow conditions must be known at least generally. The determination of these factors and the relative importance of each is the purpose of the immediate investigation.

The general plan of attack is to inject, in various manners, liquids having different physical properties into a moving air stream and to observe the effects of different variables upon the magnitude of the critical velocity of injection; the latter velocity is defined as "the mean velocity of the coolant flowing through the injection slot corresponding to the maximum rate of coolant flow obtainable without visible separation of the coolant film from the test section wall."

In conducting the experiments, the airstream into which the liquid was injected flowed through a $1\frac{1}{2}$ -by 5-inch duct while the liquid was injected through a slot located in the bottom of the test section of the duct. The air density, air viscosity, slot length, and test section width were held substantially constant, and the following parameters were investigated over the ranges indicated:

- (1) air velocities from 40 to 340 ft/sec,
- (2) slot widths from 0.004 to 0.007 in.,
- (3) surface tensions from 0.0020 to 0.0051 lb/ft,
- (4) coolant densities from 1.94 to 3.34 slugs/cu ft,
- (5) coolant viscosities from 0.000724 to 0.00785 lb/ft-sec,
- (6) angles of injection from 0 to 60 degrees, (0 degrees is perpendicular to main stream flow)
- (7) test section heights from 3.5 to 5.0 inches, and
- (8) two injector heights.

The experiments conducted so far show that the critical velocity of injection is increased when

- (1) the air velocity is increased,
- (2) the coolant viscosity is increased,
- (3) the angle of injection is increased,
- (4) the slot width is decreased, and
- (5) the liquid density is decreased.

The critical velocity of injection is independent of the dimensions of the air stream duct, the attitude of the injector, and the surface tension of the liquid. An empirical equation was derived relating the critical coolant velocity with the coolant density, coolant viscosity, slot width, and air velocity.

Plans for the future work include the following studies:

- (1) the effects of the viscosity of the main stream gases, the density of the main stream gases, a thin film of oil on the injection slot blocks, round slot block exit edges, and main stream air velocities greater than 340 ft/sec;

- (2) measurement of the thickness of the liquid film downstream to the injection slot; and

- (3) the design and test of an experimental rocket motor employing film cooling through parallel disks.

C. VISUAL STUDY OF HEAT TRANSFER FROM A VERTICAL CHANNEL TO A GAS WITH FREE AND FORCED CONVECTION. (DEL. 1R2)

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

The apparatus, testing and photographic techniques have been further improved. The blower first installed to supply the counter-flow air has been replaced by a larger one in order to get a greater variation in flow rates of the counter-flow air.

The schlieren set-up had problems inherent in any photographic apparatus, such as the determination of the focal lengths of mirrors, the optimum position of the knife edge, the type of film to use, and exposure times. After many trial runs with various photographic films and exposure times, a photographic technique for obtaining unblurred and printable negatives has been developed. The photographic film that is being used is Kodak Super-XX Panchromatic 8" x 10" safety film. The exposure time is one-two hundredth of a second.

Temperature profiles between the two heated plates are now nearly symmetrical. To obtain these symmetrical profiles the thermocouples were bent to a 90° angle about one inch from the junction so that one inch of the thermocouple tube lies in a substantially isothermal zone, thus reducing heat conduction along the thermocouple assembly. However, that such heat conduction has not yet been completely eliminated becomes evident from the fact that temperatures measured near the plate through which the thermocouples protrude are from 3°C . to 5°C . higher than the temperatures near the opposing plate. It has been noted during high counter-flow air rates that the temperature profile recorded by the thermocouple traversing the distance between the tops of the two heated plates is not symmetric, this may be due to uneven air flow through the calming section despite screens placed ahead of it. It is expected to learn more about the character of the flow at this section when the heat transfer unit is lowered and schlieren pictures of the upper half of the unit are taken. The flow seems to be more uniform by the time it reaches the middle of the heated plates.

Runs with constant plate temperatures and varied counter-flow air rates have been made. Plate temperatures used were 75°C ., 100°C ., 150°C ., 200°C ., with twelve different counter-flow air rates at each temperature. Since the mirrors used in the schlieren system are eight-inch mirrors whereas the heated plates are 12" high, it is possible to photograph only half of the heated section at a time. In these runs only the bottom halves of the plates have been photographed. When these runs are completed, the test section will be lowered and photographs of the upper half will be taken.

A detailed study of experimental data has not yet been carried out, but some observations of the flow pattern and film thickness have been made. For illustration, the following are observations based on pictures of flow patterns with a plate temperature of 150°C . and an air supply average temperature of 45°C .

The film thickness due to natural convection without counter-flow (Figure 1a) seems to be much thicker than that with superimposed counter-flow (Figures 1b-1f). Figure 1a shows clearly the laminar layer next to the heated plates (white on the right, black on the left). It also shows that, under the test conditions, the flow is substantially laminar. Figures 1b, 1c, 1d, show flow patterns with counter-flow air average velocities of 0.36, 0.72, and 1.32 ft/sec., respectively. Under these conditions, the counter-flow was unsteady and took place in surges. Figure 1b shows the condition just before the counter flowing air forced its way through the rising air caused by natural convection. Figure 1c indicates the flow pattern between surges, while Figure 1d shows clearly two surges of counter-flow air. Figure 1e shows the flow pattern when the counter-flow air has a velocity of 1.47 ft/sec., sufficient to maintain steady downward flow. The wave-like flow of the laminar layer is, also, noticeable. Figure 1f, for an air velocity of 1.59 ft/sec., shows a thinner laminar layer with more turbulence in the main stream.

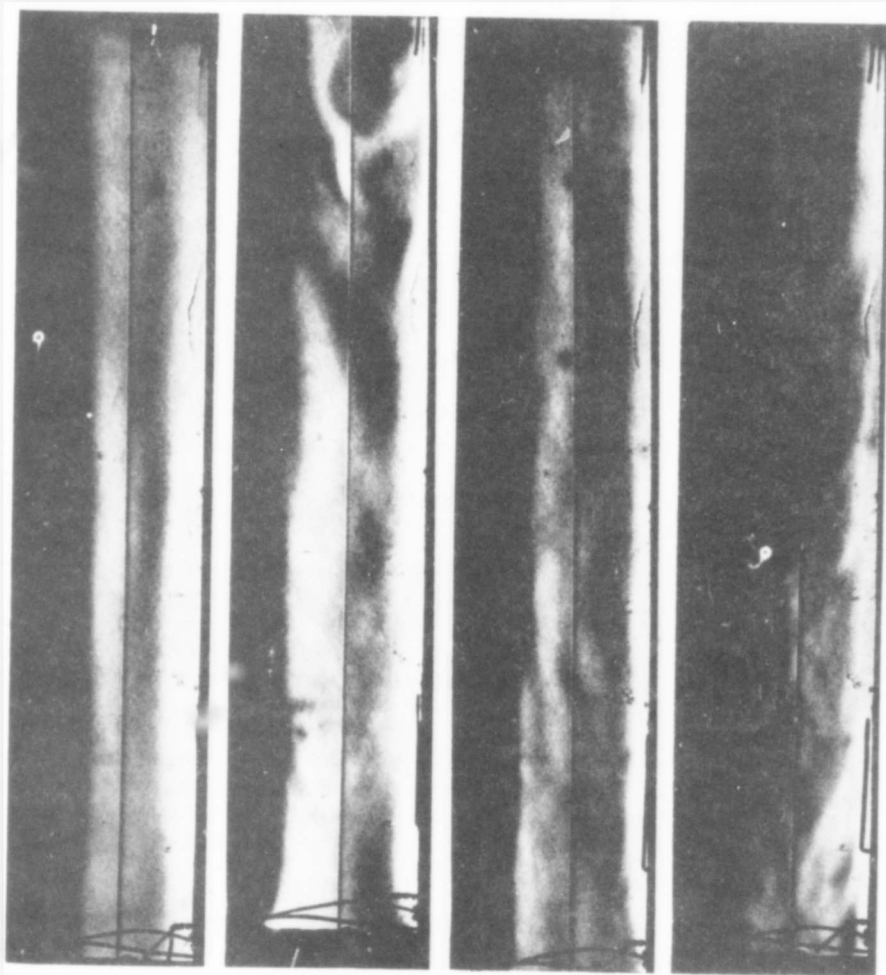


Fig. 1 a.
0 ft/sec.

Fig. 1 b.
0.36 ft/sec.

Fig. 1 c.
0.72 ft/sec.

Fig. 1 d.
1.32 ft/sec.

Fig. 1 SCHLIEREN PHOTOGRAPHS OF AIR FLOW

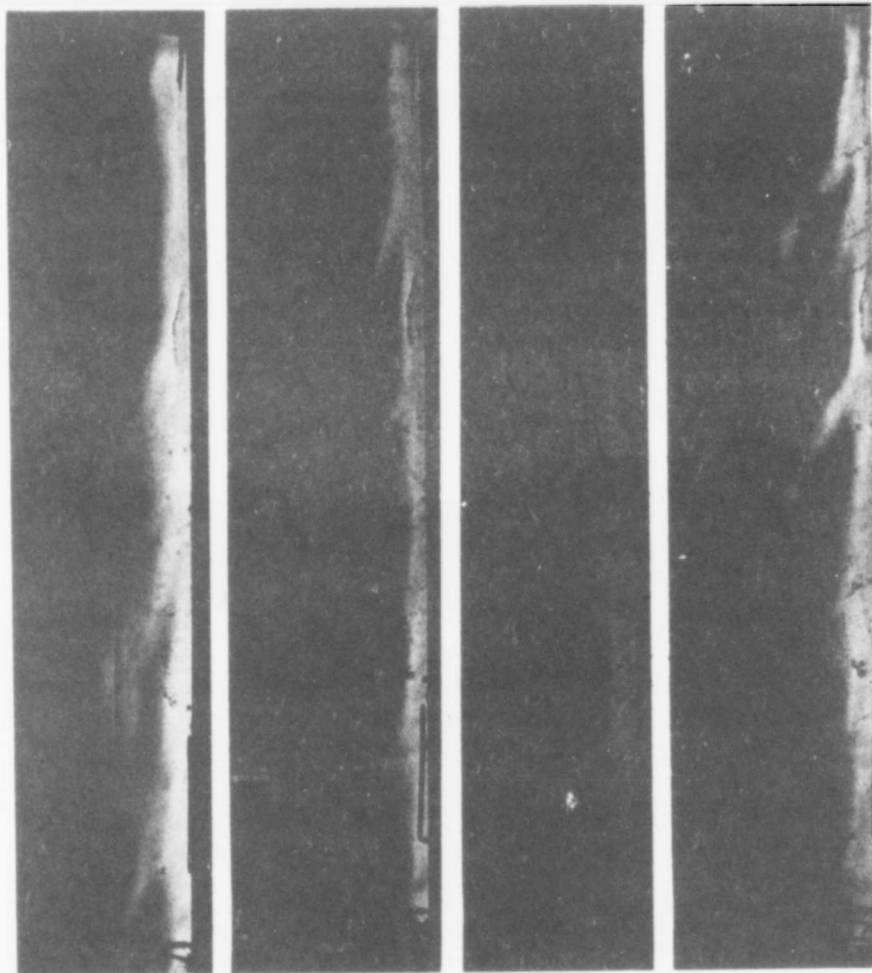


Fig. 1 e.
1.47 ft/sec.

Fig. 1 f.
1.59 ft/sec.

Fig. 1 g.
1.92 ft/sec.

Fig. 1 h.
2.27 ft/sec.

Fig. 1-SCHLIEREN PHOTOGRAPHS OF AIR FLOW

Figure 1g air velocity of 1.92 ft/sec., shows this condition a little more clearly but with the laminar layer thickness apparently increasing. Figure 1h for a flow rate of 2.27 ft/sec., shows more turbulence in the main stream. Figures 1i, 1j, 1k, 1l for air velocities of 2.43, 2.76, 3.34, and 3.75 ft/sec., respectively, show well-developed turbulence with the thickness of the laminar layer decreasing with increasing air velocity.

There are some indications that the direction of flow of the laminar layer is reversed as the counter-flow air velocity is increased above 2.3 ft/sec. The next series of runs will make the determination of the point of reversal of this layer one of the major objectives.

It is, also, planned to complete the series of constant plate temperature runs with the last run at a plate temperature of 240°C. The test section will then be lowered and schlieren photographs of the top six inches of the heating plates will be made at 75°C., 100°C., 150°C., 200°C., 240°C., with twelve different counter-flow air rates. After the above work is finished, high speed motion pictures of the more interesting conditions encountered in the experimental work will be made.

D. EXPERIMENTAL STUDY OF HEAT TRANSFER FROM A VERTICAL TUBE TO A LIQUID WITH FREE CONVECTION. (Del-1R2)

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

During the last quarter, the specific heat of the oil which is being used as the heat transfer medium has been determined over a temperature range of 100°F. to 250°F. These data have been correlated by the equation:

$$C_p = 0.000596t - 0.4064$$

where C_p is the specific heat of the oil in BTU/(lb.) (°F.) and t is the temperature in °F. The average per cent deviation of the experimental results from the above equation was less than 2%. This equation gives values of specific heat which agree with those from the literature with an average per cent deviation of 0.9%. On the basis of these results it is evident that literature values of the specific heat of the heating oil may be used in heat balances.

A constant temperature bath of the stirred-liquid type was assembled and used to calibrate the thermocouples against a standardized platinum resistance thermometer. The temperature of the bath was well controlled and no evidence of change of temperature with time could be noted at the null point with the aid of a sensitive galvanometer. This calibration is estimated to be within 1/20°F.

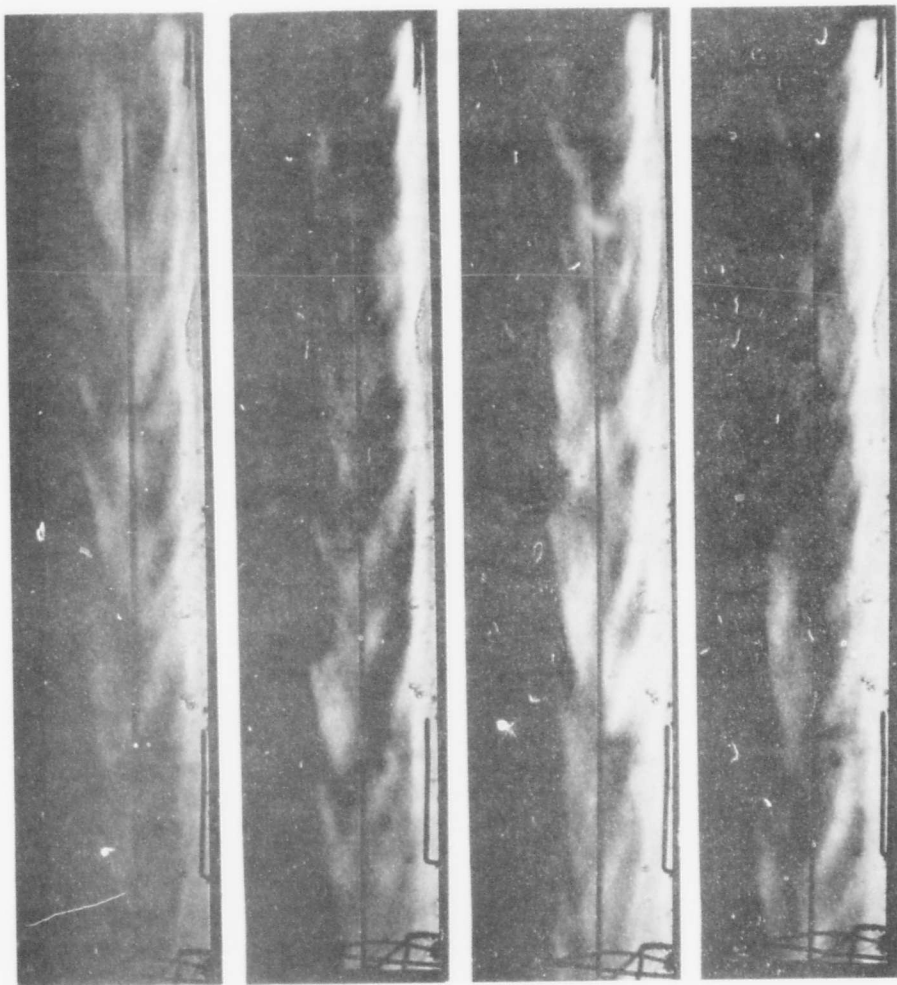


Fig. 1 i.
2.43 ft/sec.

Fig. 1 j.
2.76 ft/sec.

Fig. 1 k.
3.34 ft/sec

Fig. 1 l.
3.75 ft/sec.

Fig.1 SCHLIEREN PHOTOGRAPHS OF AIR FLOW

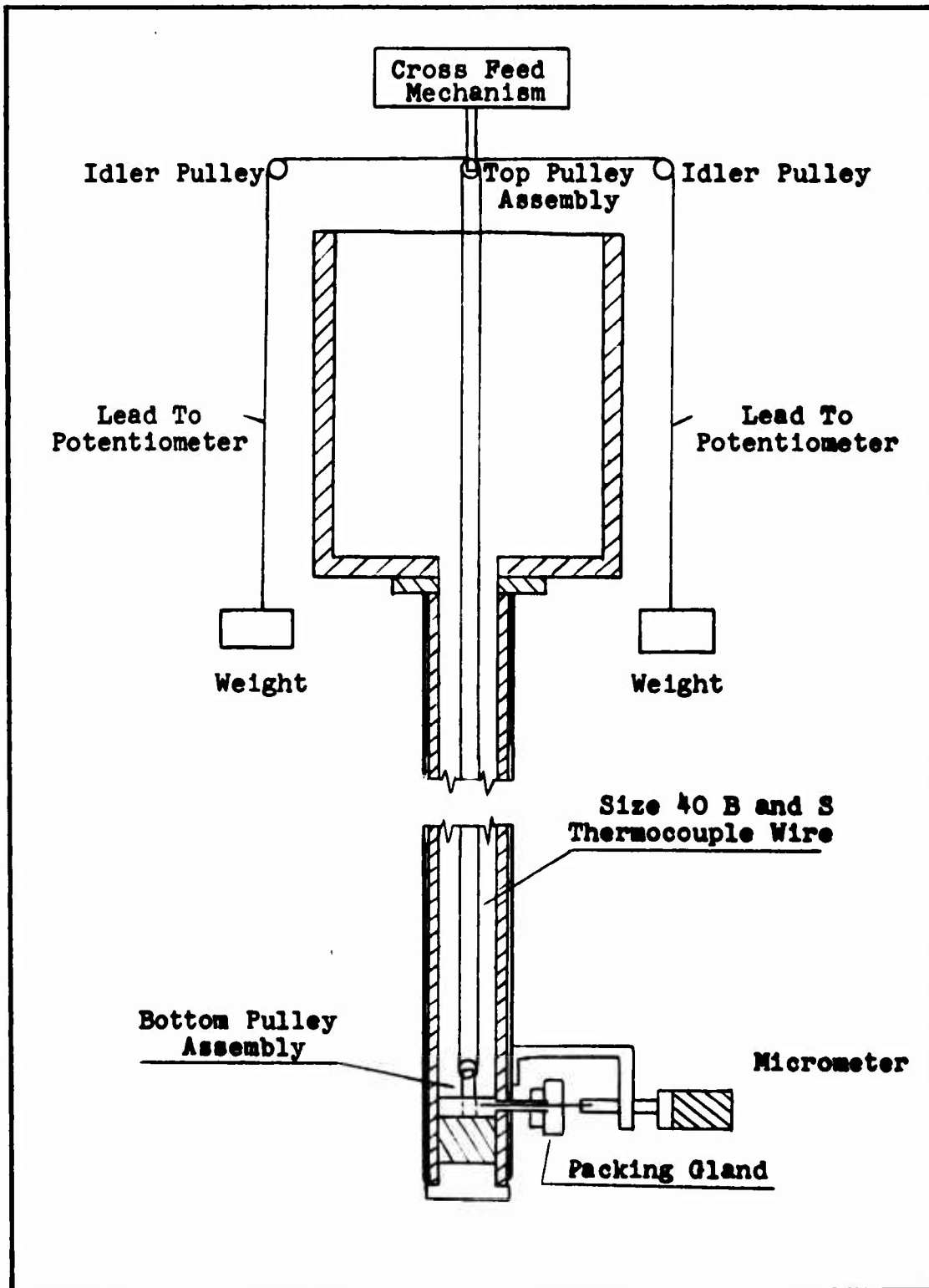


Fig. 2 REVISED TRAVELING THERMOCOUPLE ASSEMBLY

After several modifications and trials, the original traveling thermocouples which entered the vertical tube from the side to determine the temperature profile horizontally across the tube diameter were discarded and a new arrangement was built. This arrangement, which is shown schematically in Figure 2, consists of a pair of pulley assemblies which are placed at the top and bottom of the vertical test section. The top pulley is carried by a cross-feed mechanism from a lathe and the bottom pulley is mounted on a rider which is fastened in turn through a packing gland in the wall of the tube to a micrometer mounted on the outside of the tube. A traveling thermocouple constructed with No. 40B and S copper and constantan wires butt-welded together to form the junction is threaded around the two pulleys and is thus suspended inside the vertical tube parallel to the walls of the tube. By moving the lathe mechanism and the micrometer simultaneously, the junction of the traveling thermocouple can be traversed across the diameter of the test section at any desired height above the bottom of the tube. By placing the traveling thermocouple in a vertical position in the tube, i.e., in a nearly isothermal zone when near the wall, and using a wire of small diameter, conduction along the thermocouple wire is reduced to a minimum and the accuracy of the measurement of the point temperature is improved. However, the small size of the thermocouple junction causes the junction to attain the temperature of the fluid around it almost instantaneously. Hence, at some points in the tube, particularly in the central core and in the upper section where turbulent conditions exist and temperature varies erratically with time, the true average temperature cannot be ascertained accurately because of the rapid random fluctuations of the sensitive galvanometer used to determine the null point.

In a preliminary trial of this arrangement, temperature traverses taken at intervals across a diameter of the tube gave temperature profiles which were symmetric about the long axis of the tube.

The results of two runs, one using air as a test fluid, the other a light oil, and with the bottom of the tube closed are shown in Figure 3. The temperature profiles at various depths and for positions on one side of the center line of the tube are shown and can be compared for the two fluids. The curves do not include temperatures taken less than 0.025 inch from the wall since there was some uncertainty in those values. For the air run, temperature profiles were taken at one, two, three, five, and ten inches from the top of the tube. For the light oil, temperature profiles were taken at the same levels as for the air run and also at fifteen and eighteen inches below the top of the tube. Tube wall temperatures were 57.0°C. and 53.2°C. for the air run and the oil run, respectively. A Grashof number, using as a length term the effective heating length of the tube which was taken as three inches for the air run and fifteen inches for the oil run, fluid properties evaluated at an average film temperature, and temperature difference based on an estimated average central core temperature and wall temperature, was 3.1×10^5 for the air run and 10^9 for the oil run.

Referring to the temperature profiles for air, a definite trend in the temperature gradients is apparent as the horizontal temperature profiles are taken lower in the tube. At a distance of one inch below the top of the tube the temperature gradient is quite steep but decreases rapidly with distance from the wall. At the two and three-inch levels, the temperature gradient appears to be constant but with a lower value for the three-inch depth. At five inches and below, the temperature gradient is quite small but reversed in sign. At this time, no logical explanation can be made for this change of sign in the gradient but it may be due to errors in the temperature measuring technique. Further work should clarify this question.

In the case of the oil runs, the shape of the temperature curves down to a distance of fifteen inches below the top of the tube is generally the same as that for air at the one-inch level. However, the laminar layer near the wall as indicated by the temperature profiles is much more clearly defined for the oil than for the air, and the gradient is much steeper.

As can be seen, the curves for both air and oil flatten out with increasing depth and finally give core temperatures which approach wall temperatures. These results show that below a certain level, which is dependent upon the tube diameter, the nature of the test fluid and other factors, a stagnation condition existed. Thus, only a fraction of the tube area was transferring heat by convection; the remaining tube area was transferring heat by conduction, into and through the fluid medium, and was, therefore, substantially ineffective for the purpose of practical heat transfer. Further work on this unit will include the measuring of temperature profiles, stagnation depth and heat transfer rates at various temperature levels and temperature differences with fluids which will give a wide range of Grashof numbers.

Qualitatively, the results given here seem to confirm the predictions made in the Quarterly Progress Report in April, 1949, p.68, that below a certain level the tube becomes inoperative. In the application of these findings to the cooling of turbine blades with blind passages, the use of large, shallow passages rather than small, narrow passages is indicated. Thus, a hollow blade should be better than a blade with several small holes or passages.

A visual apparatus for the study of the effect of the aspect ratio is being built and should be in operation in the next quarter.

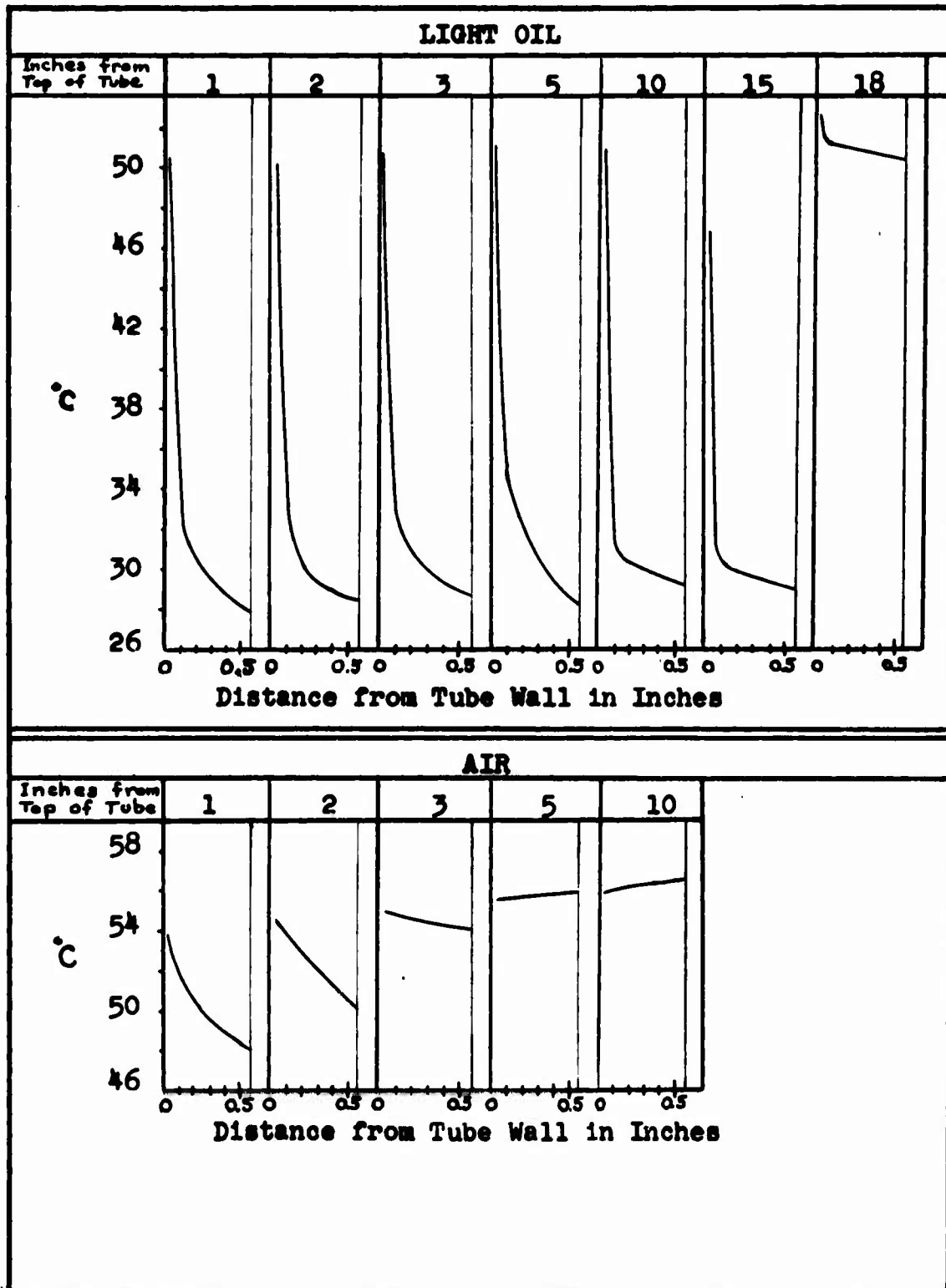


Fig. 3 TEMPERATURE PROFILES FOR LIGHT OIL AND AIR AT VARIOUS DEPTHS

E. A THEORETICAL INVESTIGATION OF THE TEMPERATURE FIELD IN 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. A method for predicting the thickness of the laminar sublayer in turbulent flow is being developed. In this connection the instability of the laminar sublayer is being studied.

From Reynolds' analogy between momentum transfer and heat transfer, the relation between heat flow rate and shearing stress is established at the boundary of the laminar sublayer. This can be calculated from the results of the investigation of the laminar sublayer along a flat plate. A relation between the wall temperature and the mass coolant flow is then obtained, provided the temperature in the hot stream and the coolant, the Reynolds' number, and the measured turbulent friction coefficient are known.

A preliminary investigation of heat transfer in a laminar compressible boundary layer on a flat plate with tangential fluid injection along the wall has been completed. The results show that a much greater quantity of coolant is needed to cool the wall to a given temperature in the case of tangential fluid injection than in that of the vertical fluid injection. On the other hand the thickness of the laminar boundary layer is much less for the case of tangential fluid injection than that of the vertical fluid injection. This phenomenon indicates that a more stable laminar boundary layer exists in the flow with tangential fluid injection along the wall.

The complete results will be presented in a technical memorandum at a later date.

For the investigation of characteristics of laminar compressible boundary layers in an axial pressure gradient with heat transfer at the wall, numerical calculations have been started, and are continuing, for the case of a linearly diminishing potential velocity distribution. The Runge-Kutta method is being used, and the accuracy of results thereby obtained has been checked by comparing such results for zero Mach number with the known exact solution to the corresponding differential equation.

The main parameters which are at present being varied are the Mach number and the ratio of wall temperature to free-stream temperature. The emphasis has been placed on determination of skin-friction, heat transfer, and separation point. Results obtained thus far indicate downstream movement of the separation point with decrease in the ratio of wall temperature to potential flow temperature.

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

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

The past quarter has been spent making plans and preparations to conduct further tests of airflow over the surface of a porous plate at room temperature, as mentioned in the previous Quarterly Report. To ensure an initially laminar flow over the surface of a porous bronze plate, it was decided to mount the plate as close to the entrance of the PIBAL turbulence channel as possible, with a surface of the plate coinciding with one of the channel walls. Provision is being made to inject air through the porous plate into the air stream.

The bronze plate will be 5 feet long, 14 inches wide, and $1/8$ of an inch thick. It will be mounted in a plywood panel whose inner surface, coincident with the channel wall, is mahogany veneer. Since the turbulence channel is 2 inches wide and 28 inches high, the plate will be mounted with its lengthwise centerline halfway between the top and bottom of the channel. To eliminate roughness and to introduce air into the channel as nearly parallel to the walls as possible, a new entrance bell has been fabricated and installed. A copper bell, semi-circular in cross section is under construction and will be mounted on the outside of the porous plate to provide a reservoir for injected air, which will be supplied by a supercharger with appropriate transition fittings.

Boundary layer velocity profiles over the surface of the porous plate will be determined by means of hot wire anemometers. It is planned to make surveys at frequent chordwise stations and at several ratios of free stream velocity to injection velocity.

The air quantity flowing through the porous plate for various pressure drops across the plate will be determined by a flowmeter.

An unavoidable delay in the delivery of the porous plate has been caused by the breakdown of facilities at the manufacturing plant. However, the plate has recently been completed and is now enroute. The plywood panel and mounting hardware are on hand and ready for assembly upon arrival of the bronze plate. Wires have been mounted on all available hot wire probes, and these are being calibrated.

The design of the high temperature channel is continuing. This channel will be used in fundamental studies of the characteristics of laminar and turbulent boundary layers on porous plates being cooled by fluid injection. The design conditions are (1) a maximum temperature of 1600°F ., (2) a maximum free stream velocity of 200 feet per second; (3) a maximum velocity of injected air of one foot per second; (4) a maximum Reynolds number of 10^6 at high temperatures and of 10^7 at room temperatures; and (5) an inlet cross section of 2x16 inches.

Figure 4 is a layout sketch of this channel. The air entering the channel from the contraction cone originates from two sources. Air is brought from outside the building and forced into the furnace by the main air blower. This room temperature air mixes in the furnace with a second flow, namely, the products of a lean mixture combustion of city gas and air, which are pressurized by a gas booster and blower, respectively. By varying the proportions of the total air originating from the two sources, the velocity and temperature of the flow in the channel can be independently controlled. Careful design of the corner vanes and of the contraction cone, and installation of fine mesh screens at the furnace exit and contraction cone inlet sections will permit uniformity of temperature and velocity at the channel inlet to be achieved.

The test channel will be rectangular in cross section, sixteen inches high and from two to five inches wide. The major portion of one wall will be formed by a porous plate, 14 inches x 8 feet, while the opposite wall will be adjustable so that the pressure gradient due to skin friction and mass addition can be effectively controlled, and, indeed, can be made negligible when comparison between theory and experiment for the flat plate case is to be investigated. The injection air, which will cool the porous plate, will be pressurized by a blower and distributed uniformly over the porous plate by an injection bell. After passing the test section the mixture of high temperature and injected air will be quenched by a water spray and discharged outside the building.

Measurements will be made of the temperature and velocity profiles in the boundary layer over the porous wall. Total head tubes and shielded thermocouples will be mounted on micrometer barrels supported on the adjustable wall. Thermocouples embedded in the porous plate close to the heated surface will provide the wall temperatures necessary for heat transfer calculations. These measurements will permit comparison between the experimental laminar boundary layer theory of S.W. Yuan developed in problem and assignment 3R2, and will, also, provide the fundamental data necessary for the analysis of turbulent boundary layers with fluid injection. They will further permit comparison between laminar boundary layer transition and theoretical laminar boundary layer stability limits with fluid injection.

During the past quarter the orders for the blowers and furnace have been placed. The detail design, which involves many problems, is now underway. It has been decided to fabricate the uncooled ducting from stainless steel shielded from the room by Refrasil, a high temperature fiberglass insulation which will be formed into removable mats.

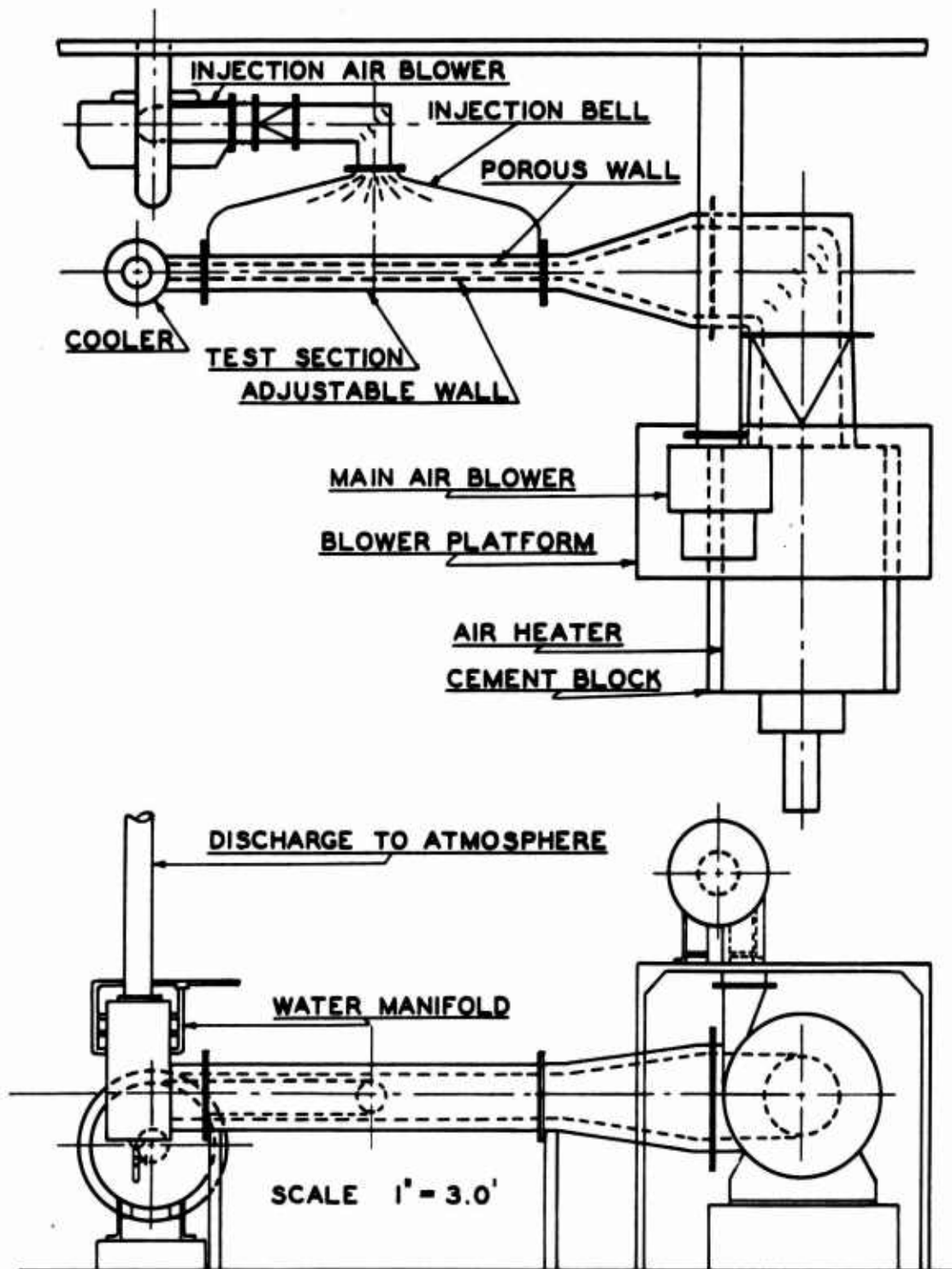


Fig. 4 LAYOUT OF HIGH TEMPERATURE CHANNEL

G. CONVECTIVE HEAT TRANSFER IN HIGH TEMPERATURE GASSES. (PRF-5R1, PRF-5R2).

Submitted by: Dr. J. M. Smith, Professor of Chemical Engineering, Purdue University.

Wall thermocouples have been installed on the test section wall and calibrated. Preliminary tests have been made. Calculations based on the test runs indicated the need for cooling the probe fitting. This modification has been completed and the equipment is being fully insulated. It is anticipated that measurement of convective heat transfer coefficients will be accomplished in the coming quarter.

Preliminary test runs were accomplished to establish heat balances. These runs indicated thermal conduction through the probe section fitting into the water jacket. A falling film cooler was placed on the probe section to reduce the axial tube wall temperature gradient and thus the conduction.

Preliminary runs indicate a symmetrical temperature profile at the test section entrance. This will facilitate the calculation of bulk mean temperatures. The wall temperature axial gradient appears relatively uniform. At 1000°F. the mean temperature drop from the gas stream to the wall is of the magnitude of 400°F.

During the test runs, difficulty was encountered with the wall thermocouples due to shorting. This required modification of the thermocouple packing glands. During the modification the number of tube wall thermocouples was increased to twelve.

The effect of velocity on the bulk mean temperature of the gas stream is being investigated.

It is anticipated that within the month delivery of recording and indicating-type potentiometers should be realized. Their use will facilitate the measurement of convective heat transfer coefficients which will be undertaken in the coming quarter.

IV. C H A R A C T E R I S T I C S O F F L A M E S

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

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

The preparation of a technical memorandum on the work on cellular flames has been continued. In addition, a paper covering both experimental and theoretical work on flame front stability in slightly condensed form has been prepared.¹

An interesting relation was found upon replotting on logarithmic scales the data on the pressure dependence of average cell size d in butane-air-nitrogen flames previously presented.² Figure 1 and Table 1 show that with exception of the values for the lowest pressures, the data fit the expression

$$(1) \quad p^{3/4} \cdot d = \text{Const. remarkably well.}$$

The theory of flame front stability, on the other hand, yields, under certain reasonable assumptions, the relation

$$(2) \quad d \cdot p \cdot S_u = \text{Const.}$$

where S_u is the burning velocity. From (1) and (2) there follows

$$(3) \quad S_u \cdot p^{1/4} = \text{Const.}$$

This pressure dependence of burning velocity has been theoretically predicted³ and experimentally verified for various hydrocarbons.^{4&5} It should not be overlooked, however, that a general validity of (3) cannot be justified.⁶ Furthermore, work on burning velocities of butane-air mixtures at various pressures⁷ gave results which differed from (3) and depended critically on fuel concentration; therefore, no definite conclusions can, as yet, be drawn from relation (1).

1. G. H. Markstein, "Experimental and Theoretical Studies of Flame Front Stability." Presented at the Heat Transfer and Fluid Mechanics Institute, Los Angeles, Calif., June, 1950.

2. Project SQUID Annual Program Report, 1 Jan., '50, p.101.

3. C. Tanford & R. N. Pease, "Theory of Burning Velocity II. The Square-Root Law for Burning Velocity." J. Chem. Phys. 15, 861, (1947).

4. E. J. Badin, J. G. Stuart & R. N. Pease, "Burning Velocities of Butadiene 1,3 with Nitrogen-Oxygen & Helium-Oxygen Mixtures." J. Chem. Phys. 17, 314 (1949).

5. F. H. Garner, G. K. Ashford and R. Long, "Effect of Pressure on Burning Velocity." Nature 164, 884 (1949).

6. C. Tanford & R. N. Pease, op. cit. 884 (1949). A. G. Gaydon & H. G. Wolfhard, "Low Pressure Flames and Flame Propagation." Fuel 29, 15 (1950).

7. K. Wohl and N. M. Kapp, "Flame Stability at Variable Pressures." Meteor Report UAC-42, Univ. of Delaware (1949).

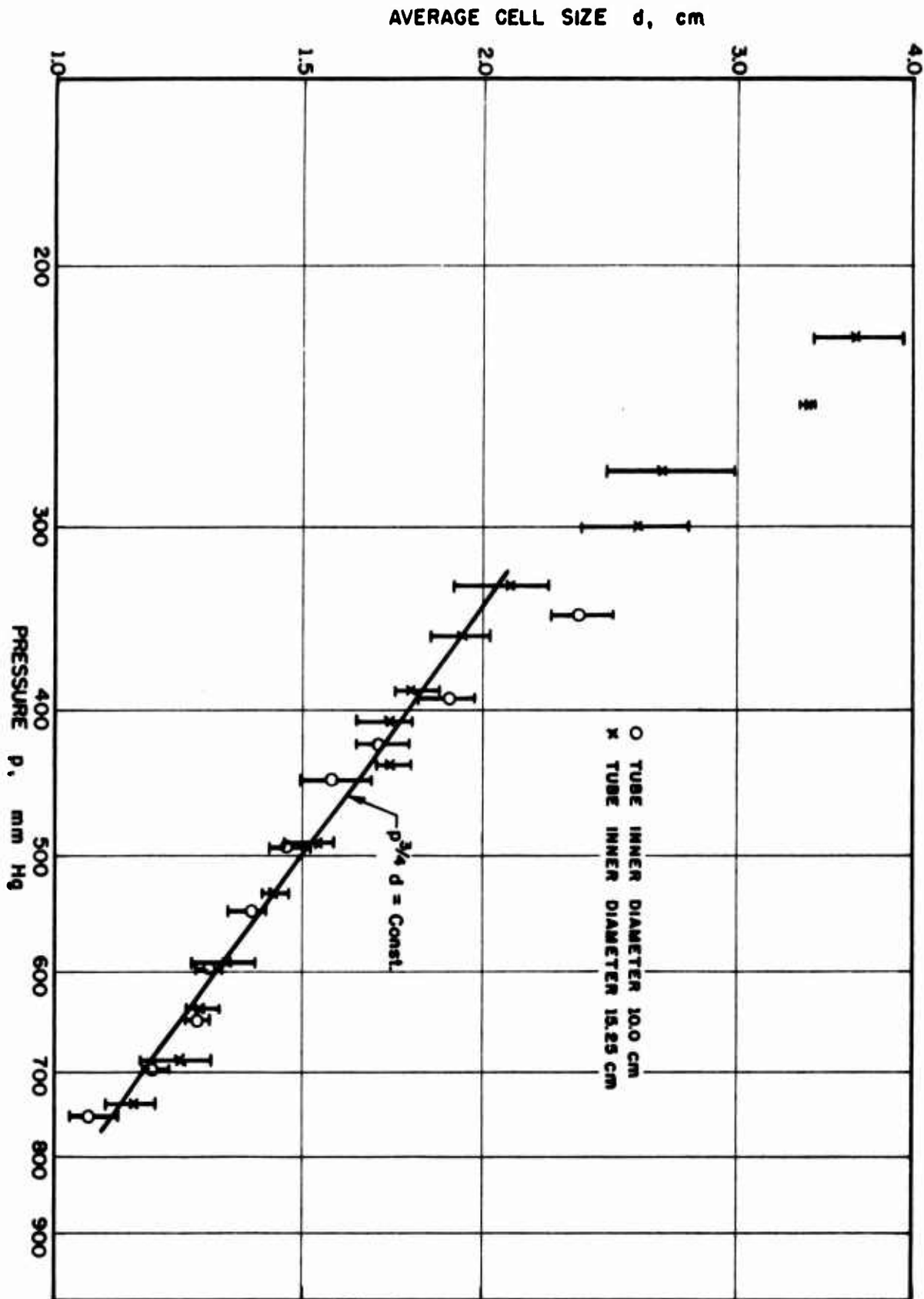


Fig. 1

Average cell size of butane-air-nitrogen flames vs. pressure. (The circles and crosses are mean values determined from at least five flame photographs; the vertical lines indicate the spread of values from individual photographs.)

Table 1

Average cell-size of n-butane-air-nitrogen flames at various pressures

15.25 cm I.D. Tube			10.0 cm I.D. Tube		
Pressure p mm Hg	average cell size d cm	$p^{3/4} \cdot d$	Pressure p mm Hg	Avg cell size d cm	$p^{3/4} \cdot d$
739	1.14	162	750	1.06	153
690	1.23	165	698	1.18	162
638	1.27	161	647	1.26	162
593	1.33	160	597	1.29	155
531	1.43	158	546	1.37	155
492	1.52	159	494	1.46	153
435	1.72	163	446	1.56	151
407	1.72	156	422	1.69	157
388	1.78	156	393	1.89	167
357	1.94	159	345	2.33	186
330	2.09	162			
301	2.57	185			
276	2.67	181			
249	2.37	215			
224	3.65	216			

In order to carry out plans to study the effect of a fourth mixture component, notably of hydrogen, on flame structure, additional flow meters were acquired and are being calibrated. The study of cellular flames will be resumed as soon as this auxiliary work is finished.

The work on vibratory flame motion was, for some time, hampered by faulty operation of the condenser-type pressure pickups. These difficulties were finally eliminated when it was found that they were partly due to cracked insulators in the condenser heads and partly to microphonics of the receiver. After these conditions were remedied, very good agreement between simultaneous records obtained with the condenser gage and with a Statham pressure gage, both connected to the flame tube near the closed end, was obtained.

Subsequently, simultaneous records were taken with the condenser pickup remaining near the closed end and the Statham gage connected at various positions along the tube. These records have not yet been evaluated; it is hoped that it may be possible to construct from them empirical wave diagrams which should yield some information on the interaction of the pressure waves with the flame front. As in previous work, the approximate positions of the flame front during its travel from the open to the closed end of the tube were marked on the records as intensity pips by means of the ionization flame timer.⁸

8. Project SQUID Annual Program Report, 1 January 1948, p.106.

In order to investigate the effect of gravity on vibratory flame motion, two series of pressure records were taken with downward and upward propagation, respectively, under otherwise equal conditions, i.e., propagation from the open toward the closed end in butane-air mixtures of various compositions. These records are shown in Fig. 2 and Fig. 3. Upward propagation is seen to differ from downward propagation mainly by slightly increased average flame speeds (the flames reach the closed end of the tube at the point where the low-frequency oscillation stops). Reproducibility was somewhat inferior for upward propagation, as evident from the irregular dependence of flame speed on composition. While one would expect this behavior, since the effect of gravity should be unstabilizing for upward, and stabilizing for downward, propagation, it may seem at first surprising that the records are otherwise quite similar. In particular, the range of compositions over which the first harmonic of the tube was excited was the same in both cases. (It should be noted that this range coincides with the range of pronounced cellular structure.) One must thus conclude that the influence of gravity in flame front stability is not of great importance. Furthermore, if the hypothesis is accepted that vibratory flame motion is caused by the effect of acceleration on flame front stability, the oscillatory accelerations would have to be large compared with gravity acceleration. This condition is, however, fulfilled even for small amplitudes: for an amplitude of only 1 mm and a frequency of 200 cycles/sec. the peak acceleration is about 1.5×10^5 cm/sec², i.e., more than two orders of magnitude larger than gravity.

In connection with the work on vibratory flame propagation in tubes, it would be very desirable to be able to measure instantaneous rate of burning or at least some quantity proportional to it. The possibility of doing this by radiation measurements has been contemplated and preliminary work gave promising results. A photomultiplier circuit for this and similar applications is under construction.

Schlieren high-speed motion picture studies of vibratory flame motion in a tube of rectangular cross-section have been continued. The new method of recording pressure (or any other variable) on the movie by means of a mirror galvanometer⁹ was found to operate very satisfactorily. The movies have not yet been evaluated; it seems likely, however, that it will be possible to obtain information not only about motion and structure of the flame front, but also about motion in the burned gas, since density gradients remained visible long after passage of the flame front.

9. Project SQUID Quarterly Progress Report, Cornell Aeronautical Laboratory, Phase IIA, 1 April 1950.

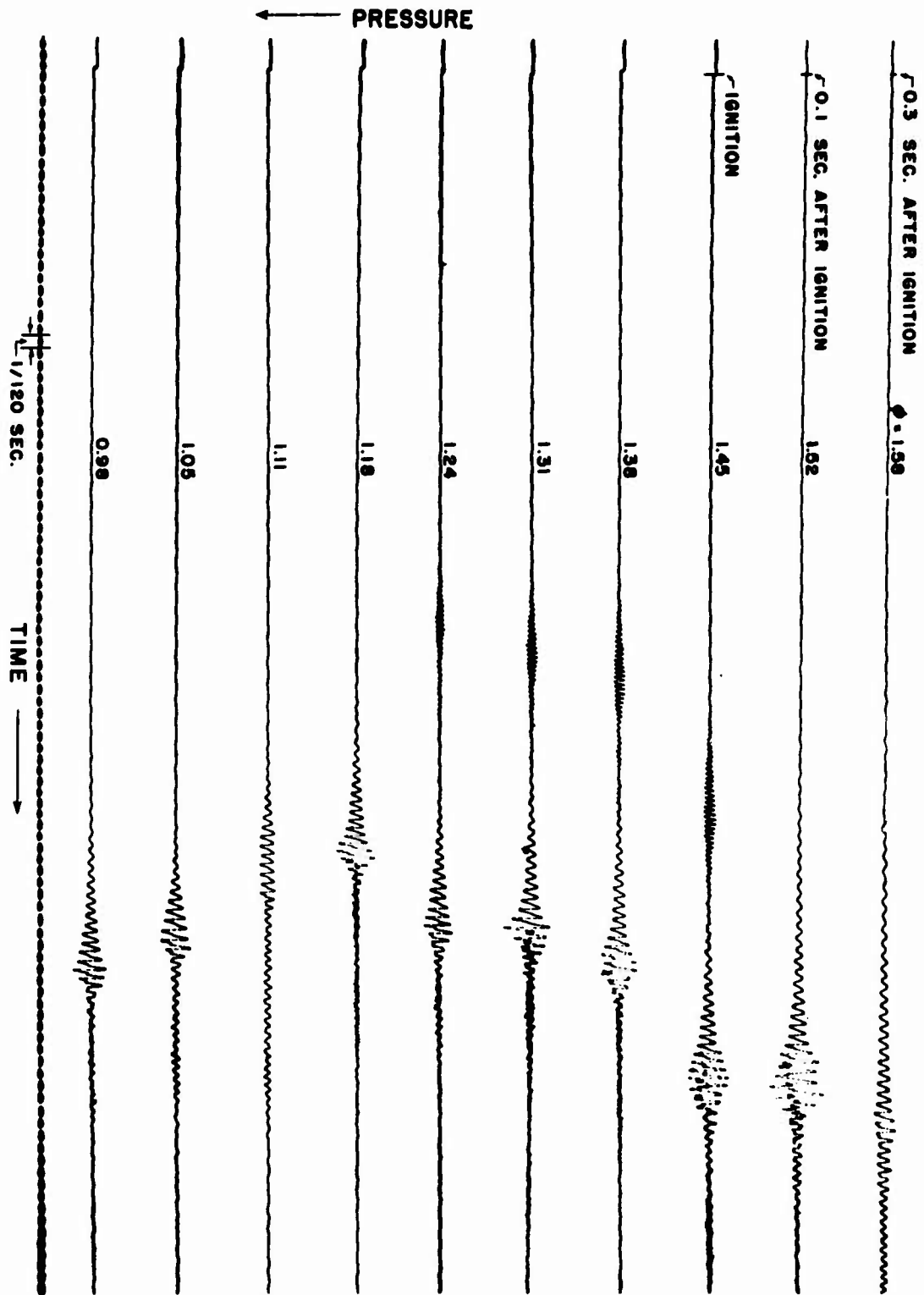


Fig. 2 Pressure records of vibratory flame motion. Downward propagation from open to closed end, 8.4 cm I.D. tube of 120 cm length. Butane-air mixtures, ϕ = fuel concentration/ stoichiometric fuel concentration.

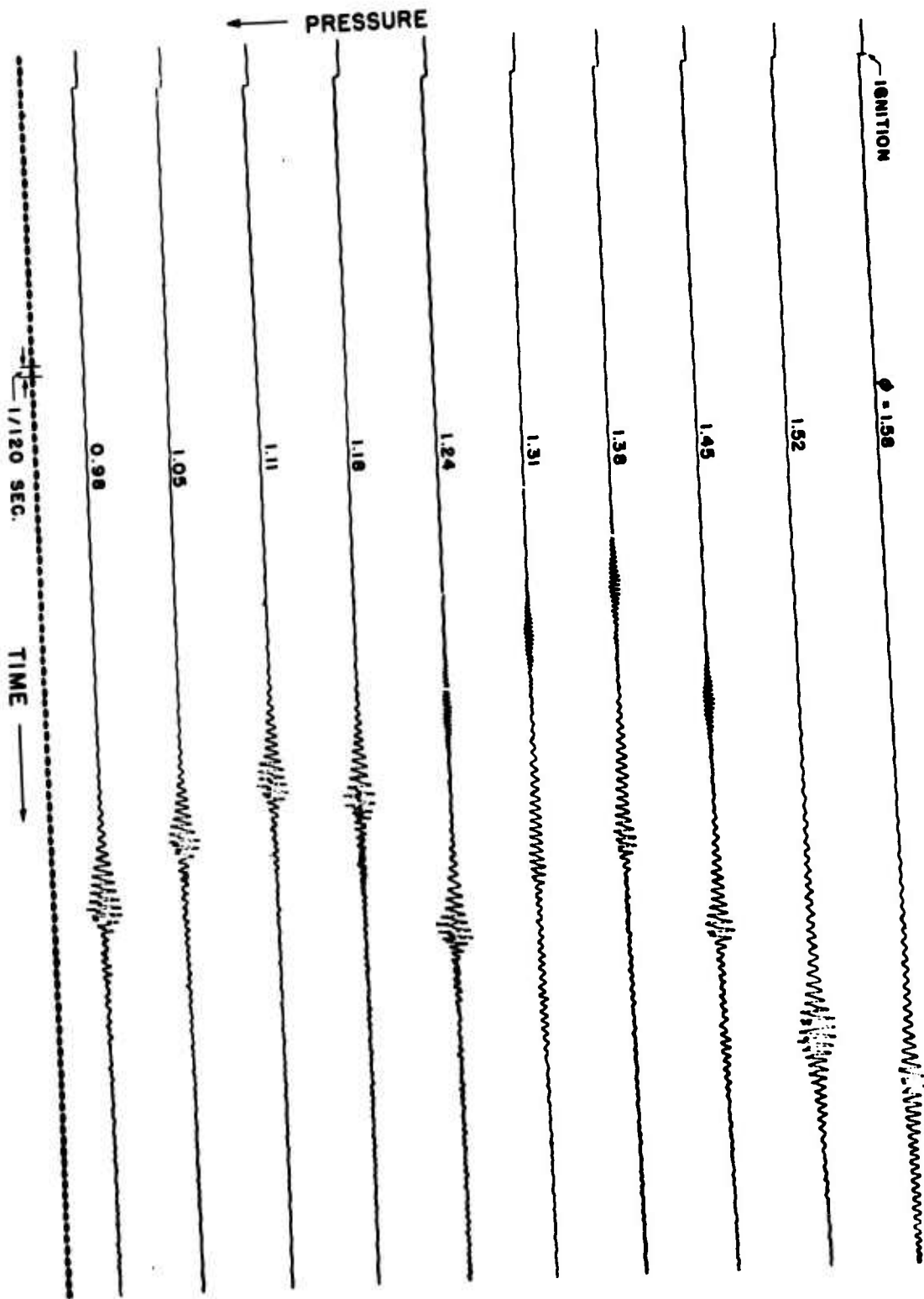


Fig. 3 Pressure records of vibratory flame motion. Upward propagation, otherwise the same conditions as for fig. 2.

Theoretical work on flame front stability and on vibratory flame motion is continuing. Among other problems now under study, an attempt is underway to evaluate the effect of viscosity on flame front stability.

B. FLASH-BACK STABILITY OF BURNER FLAMES. (CAL-2R6).

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

During the work on cellular flames, which was performed with compositions for which the flames just entered the tubes from the top, i.e., flash-back compositions, it was found that these compositions were almost independent of flow velocity and tube diameter. This deviation from the theory of flash-back stability¹⁰ appeared interesting enough to warrant a more extensive study. The results so far obtained have confirmed the previous findings in the case of butane-air-nitrogen mixtures, but not for methane-air-nitrogen flames. Thus, for the large tube diameters and low flow velocities employed, the flow disturbances present in the cellular butane flames seem to modify the flow conditions near the tube wall in such a way that flash-back occurs always at practically the same compositions. This possible connection of flame structure with flash-back may be of practical importance since certain forms of "rough burning" in which the flame propagates upstream from a flame holder may be related to flash-back stability. It is planned to extend the work on flash-back to other fuels.

Work on the visualization of flow in burner flames by means of smoke tracers is continuing.

C. A 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.

The behavior of high velocity flames depends, to a certain degree, on the flow patterns and the characteristics of turbulence and other types of fluctuation in the unignited gas stream. In order to study these relations a hot-wire anemometer has been built which is of the constant resistance type and makes use of the push-pull amplifier circuit described by Ossofsky.¹¹ It is planned to study the fluctuations in the ignited gas stream at a later stage of this work by using the hot-wire anemometer as an indicator of temperature fluctuations. At present the instrument has been developed to the point that turbulence measurements in the cold gas stream can be made, and during the next months the problems mentioned above will be actively attacked.

10. B. Lewis and G. von Elbe, "Stability and Structure of Burner Flames." J. Chem. Phys. 11, 75 (1943).

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

The Wheatstone bridge arrangement for the hot wire and its operation with the amplifier have been tested successfully. Three arms of the bridge were made from fine straight constantan wires- the fourth arm is formed by the hot wire, consisting of platinum or tungsten. The purpose of the test is to assure that the hot-wire anemometer will operate stably, i.e., that no oscillations will occur when the feedback loop from the output of the amplifier is connected to the bridge. In order to achieve this, care has to be taken that if an in-phase signal is applied the output of the amplifier is less than the input. It has been shown in the previous quarterly report that the amplifier alone satisfies these requirements. It is found now that this favorable result can be obtained with the system bridge-amplifier up to 2 megacycles.

The tests are carried out in such a way that the hot-wire is kept in still air and DC current is supplied to the bridge from a battery that raises the resistance of the hot-wire until the bridge becomes balanced for DC current (as indicated by a galvanometer). In addition, a signal generator producing a sine wave is connected across the bridge. Conditions are varied until, at a state of DC balance, the amplitude of the AC signal from the output of the amplifier as observed on an oscilloscope is less than the input AC signal across the bridge. In order to achieve this, the wires have to be mounted in such a manner as to reduce capacitance effects to negligible proportions. Two methods of mounting of the resistance wires have proved suitable; one in which the wires are soldered next to iron plates, and another in which the wires are fastened to a plastic plate using silver conducting paint. As another precaution, the slight inductance of the probe and its leads must be compensated for by placing a coil (5 to 30 turns of 3/8-inch diameter, made of No. 18 copper wire) in series with its matching resistance in the bridge.

After these preliminary tests, the feedback loop from the output of the amplifier was connected to the bridge, and the hot-wire was placed into an air stream to test its response to mean velocity and velocity fluctuations. The first successful operation of the instrument was obtained with short leads from the bridge to the amplifier and short leads from the bridge to the probe. At present, it has been found possible to operate with lead lengths from the amplifier to the bridge of six feet, and with a probe length of 21 inches.

Although the frequency response of the amplifier alone is flat up to frequencies above 70 kilocycles, the frequency response of the hot-wire amplifier combination is less perfect, due to the thermal lag of the wire. Usually, one is interested in exploring frequencies of turbulence up to 20 kilocycles. An electrical test of the frequency characteristics of this combination can be made by the introduction of an AC signal of constant amplitude and variable frequency across the bridge, while the feedback circuit is operating.

The frequency response is conveniently described by the 3 db point, i.e. by the frequency at which the response has dropped by 30%. The deviations from flat response decrease rapidly with decreasing frequency: For example, if the 3 db point is at 30 kilocycles, the deviation at 15 kilocycles is about 10%, and at 6 kilocycles about 2%. Tests have been made with a platinum wire of 0.0003-inch diameter and 1/8-inch length in a bridge requiring 1.5 times the cold resistance at equilibrium conditions of operation. At zero air velocity 55 milliamp. are required for this purpose. At this condition the 3 db point lies at 10 kilocycles. If put into an air stream which requires a current of 101.5 milliamp. for the establishment of equilibrium conditions, the 3 db point shifts in a favorable direction up to 30 kilocycles. In future operations it is expected to use 0.0002-inch diameter platinum or 0.000125-inch diameter tungsten wire with the equilibrium resistance twice the cold resistance, and expect to have a 3 db point of the wire-amplifier combination above 20 kilocycles at zero velocity.

Mean velocity measurements made with the instrument show agreement with King's equation

$$I^2 R = a - b\sqrt{V}$$

where I is the current through the wire, R its equilibrium resistance, and V the velocity past the wire. Since R is constant, plots of I^2 vs. \sqrt{V} should be linear. In Fig. 4 two runs made with painted bridges are shown.

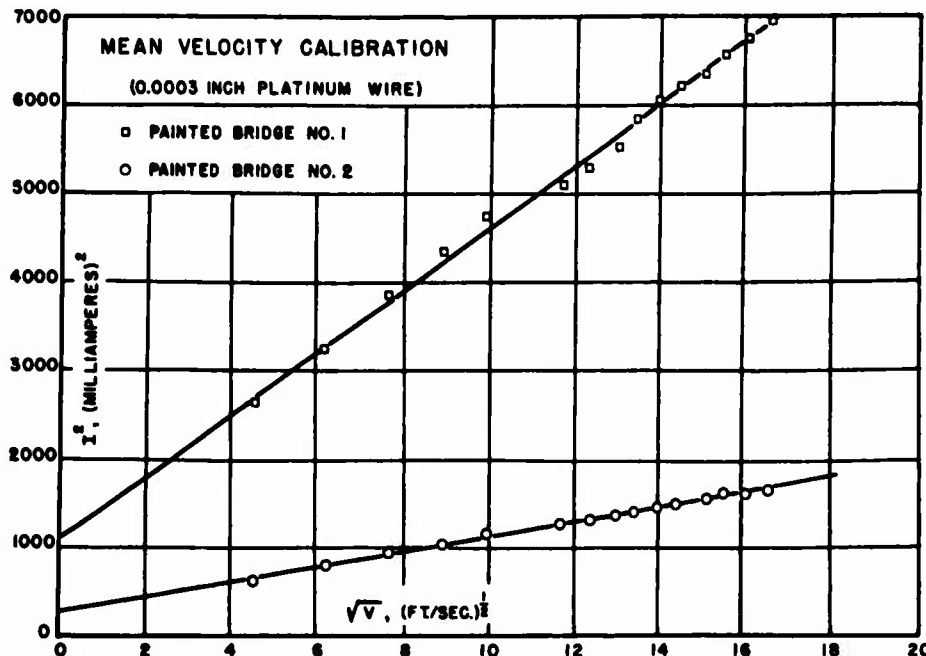


Fig. 4 Calibration of constant resistance hot-wire anemometer with respect to mean velocity of air stream.

The hot wire in both bridges is platinum wire, 0.0003-inch thick and 3/8-inch long. The fixed resistor opposite to the hot wire is smaller for bridge No. 2 than for bridge No. 1, so that bridge No. 2 requires a smaller current for the equilibrium condition than bridge No. 1. This explains the difference between the two curves. Both comply satisfactorily with the linearity condition.

Some preliminary measurements of the intensity of turbulence in an air stream have been carried out. The final procedure for such measurements will be as follows: One observes the root mean square AC current in the feedback loop caused by the velocity fluctuations, with the help of a thermomilliammeter and output amplifier of known sensitivity. From a calibration as shown in Fig. 1, the air stream velocity can be ascertained which corresponds to a given value of current, whether AC or DC, at equilibrium condition of the bridge. Consequently, the velocity change can be determined which corresponds to the root mean square current mentioned above. This velocity change is the intensity of turbulence. So far the degree of turbulence has only been measured approximately by judging the average height of the signal on an oscilloscope screen. As the oscilloscope is calibrated with respect to voltage and as the bridge resistance is known, the same procedure is possible which just has been described, except for the fact that the conversion of average AC current into DC current depends on the wave form. For the present preliminary estimations a sine wave form has been assumed. The instrument has been used to study the turbulence in a cold-air jet emerging from a 1.5 inches x 2.0 inches converging nozzle with an average velocity of 45 ft/sec. at the nozzle exit. The results were, at least qualitatively, as might be expected from the literature. Turbulence was less than 1% at the center of the nozzle exit and increased along the axis (giving 12% turbulence at a distance of 6 inches from the nozzle exit.) A traverse through the jet at 3 inches distant from the nozzle showed a very strong increase of turbulence when moving from the axis towards the jet boundaries (8% turbulence in the axis, 70% in the boundary).

Preliminary experiments have also been conducted on the frequency spectrum of turbulence. For this purpose a General Radio Wave Analyzer was used in conjunction with the amplifier. The turbulence field behind a 20 mesh screen at an air velocity of 45 ft/sec. was chosen for exploration. In the immediate vicinity of the screen, frequencies were observed up to 16 kilocycles while 4 inches behind the screen the upper limit was 2 kilocycles.

During the next months, work will concentrate on the measurement of the intensity of turbulence in relation to flame behavior.

D. THEORY OF FLAME SPEEDS; LOW PRESSURE BURNER STUDIES. (Pr-2R1).
Submitted by: Dr. R. N. Pease, Princeton University.

It is planned to re-activate this problem. Flame speeds and stability limits are to be determined for mixtures of methane and oxygen with helium and argon. The principal aim will be to obtain data on the effects of pressure and of diluents on flame speeds with a view to testing the hydrogen atom diffusion theory.

V. C H E M I C A L R E A C T I O N K I N E T I C S**A. KINETICS OF COMBUSTION OF GASEOUS BORON COMPOUNDS. (Pr-2R2)**

Submitted by: R. N. Pease, Princeton University.

Diborane (B₂H₆). The system - diborane, hydrogen, oxygen - is being studied. It has been found that small amounts of dry air (5-10 mm) are without effect on diborane (100 mm) at 100°C. Somewhat greater additions of air (15-30 mm) lead to explosive decomposition. Hydrogen alone (50-200 mm) partially suppresses the decomposition, probably due to the quasi-reversibility of the decomposition reaction. It is now proposed to determine explosion limits of hydrogen-oxygen mixtures when small amounts of diborane are added.

A paper entitled "A Preliminary Study of the Kinetics of Pyrolysis of Diborane" has been submitted for publication.

Aluminum Borohydride (Al(BH₄)₃). This substance in small amounts (e.g., 0.46 mm) will ignite a dry ethylene-oxygen mixture (1 C₂H₄ + 3 O₂) at 100 mm. and 20° C. after an induction period (18 to 800 seconds). It has been found that borohydride first reacts with ethylene yielding boron tri-ethyl (B(C₂H₅)₃) among other things. Since the latter compound in small amounts is itself an igniter for ethylene-oxygen mixtures without measurable induction period, it is assumed that the effect of borohydride is essentially due to this initial process. A further characteristic of the process is that the formation of boron triethyl is itself accelerated by small additions of oxygen.

It should be added that aluminum borohydride will not ignite a mixture of a paraffin hydrocarbon (e.g., propane) and oxygen at room temperature unless there is moisture present.

This work is summarized in Technical Paper No. 48 entitled "The Effect of Traces of Oxygen on the Reaction of Aluminum Borohydride with Ethylene" by R.S. Brokaw.

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

Submitted by: R. N. Pease, Princeton University.

This problem is inactive at present. However, in this general field the low-pressure interaction of oxygen atoms from a discharge with hydrazine is being studied. Preliminary data indicate a rather low collision efficiency with an activation energy of about 3000 calories per mole, as judged from the temperature coefficient.

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

Submitted by: R. N. Pease, Princeton University.

Experiments in a constant volume apparatus at reduced pressure have confirmed the flow experiments at 1 atm. in revealing partial inhibition by ammonia. However, the total pressure change does not correspond always to formation of nitrogen and water vapor. Experiments are being conducted on the effect of varying the partial pressures of ammonia and oxygen, and of additions of water vapor, nitric oxide, and nitrous oxide.

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

Submitted by: R. N. Pease, Princeton University.

Hydrogen-chlorine mixtures may be exploded by means of a photo-flash bulb (e.g., G.E. Synchro-Press No. 11 or No. 22). Relative intensities of illumination are judged by the distance from flash bulb to reaction vessel, such distances being of the order of a meter or less. It is found that pre-illumination of the chlorine is helpful in achieving reproducibility.

Preliminary data indicate that small amounts of oxygen inhibit the explosion as expected (greater light intensity required). It also appears that excess of hydrogen is unfavorable when oxygen is present but is favorable in its absence - a result that is not immediately clear.

An appreciable amount of reaction (20-40%) occurs in the region just short of explosion. Since this would be sufficient to raise the temperature very considerably, it would appear that the explosion itself is essentially due to the incidence of the thermal reaction.

E. PHOTOIGNITION OF OXYGEN-PROPANE-AZOMETHANE MIXTURES. (NYU-7R7)

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

A study is being made of the effect of methyl radicals upon the oxidation of propane by oxygen in the temperature range 35°C - 200°C. The methyl radicals are produced within propane-oxygen-azomethane mixtures by photolysis of the azomethane.

During the past quarter, more data were gathered at 35°C and several runs were made at 85°C and 135°C. In this temperature range, using 40 per cent C₃H₈, 50 per cent O₂ and 10 per cent azomethane, there does not seem to be any significant temperature coefficient for the overall reaction. It was found that 10-15 per cent of the propane-oxygen mixture reacted, while approximately 50 per cent of the azomethane was photolyzed.

A test has been performed to determine the nature of the condensible products obtained in the reaction. The results indicate that these products are water and reducing compounds (probably aldehydes). The test was performed by placing a small crystal of anhydrous copper sulfate in a freezing trap, and transferring the condensible material to the trap. The copper sulfate crystal then turned blue ($\text{Cu}^{++} \cdot 5\text{H}_2\text{O}$). After standing a while, the crystal turned green ($\text{Cu}^{+}_2 \cdot \text{hydrate}$), indicating the presence of a reducing agent.

There appears to be a large effect upon the overall reaction rate (moles reacting per unit time) at both 35°C and 85°C , when the total pressure of the mixture is changed, the rate increasing with increasing pressure. This effect will be utilized to increase the amount of propane which reacts at any given temperature per unit time. The highest total pressure used to date has been 163 mm. of mercury, but the addition of a vertical manometer with a pressure range of 0 - 875 mm. of mercury to the apparatus will make possible a series of experiments at higher pressures. It is felt that by gradually increasing the total pressure, a point will be reached at which the oxidation process will be sufficiently rapid to produce cool flames.

During the next quarter, the experiments will be extended to include the pressure range 200 - 600 mm. of mercury.

F. 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 effects of selected variables upon the ignition lag of several hypergolic liquid rocket propellants. The variables to be investigated are:

- (1) temperature of propellants prior to mixing (mixing temperature),
- (2) mixture ratio,
- (3) manner of mixing, and
- (4) additives to either the oxidizer or the fuel.

For the purpose of this investigation, ignition lag is defined as the time interval between the instant of contact of the propellants and the instant of emission of visible light from the reaction as indicated by a photoelectric cell.

An investigation to determine the effect of mixing temperature upon the ignition lag of the bipropellant system, white fuming nitric acid and furfuryl alcohol, has been completed. The results of this investigation are shown graphically in Figure 1. The significant feature demonstrated by the Ignition Lag vs Temperature curve is the asymptotic increase in ignition lag as the mixing temperature approaches the freezing temperature of the furfuryl alcohol.

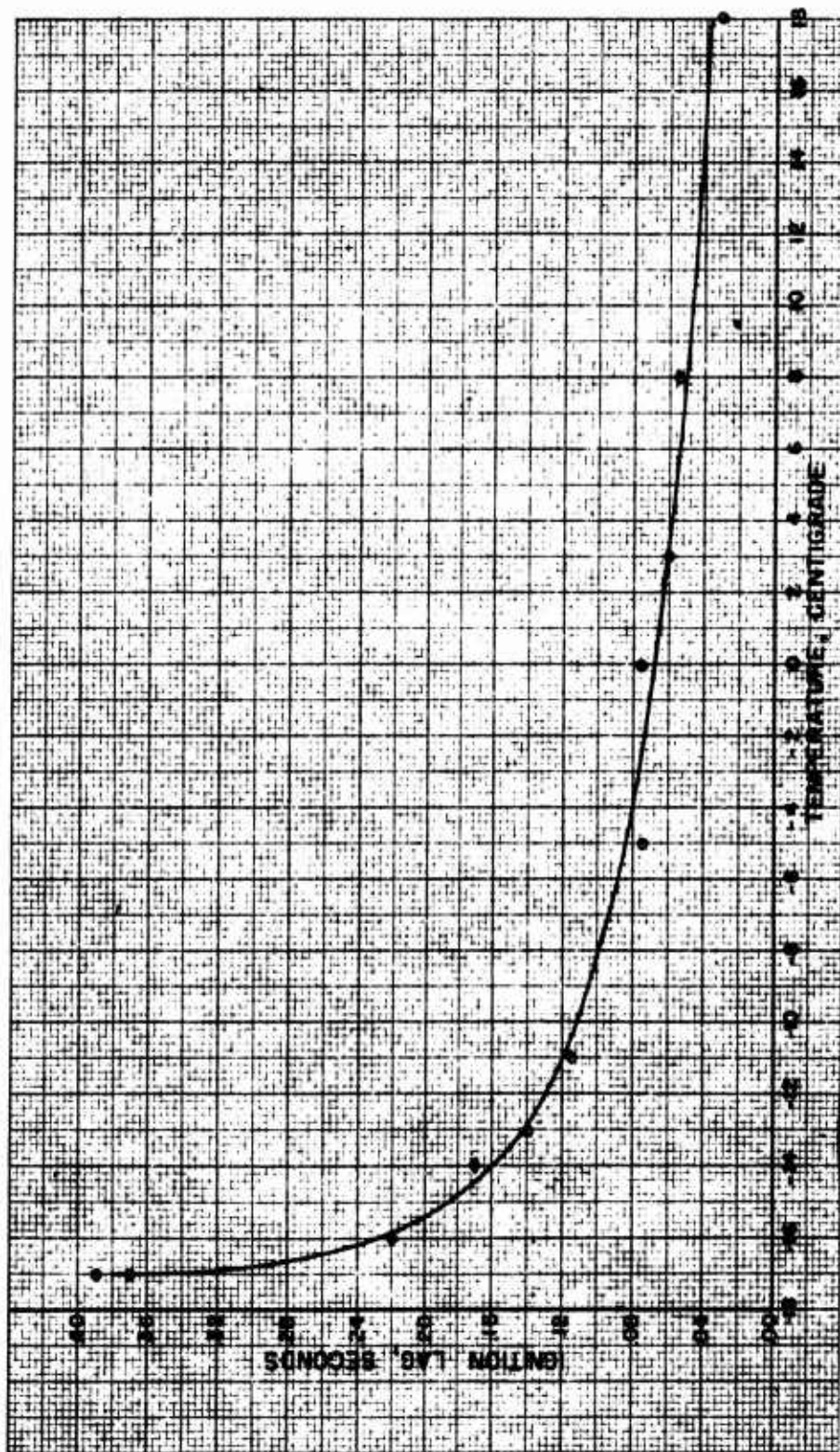


Figure 1 The effect of mixing temperature upon the ignition lag of the Rocket Bipropellant System, White Fuming Nitric Acid and Furfuryl Alcohol.

The causes of this phenomenon, at present, appear to be the reduction in molecular activity with decreasing mixing temperature and the poor mixing resulting from the marked increase in viscosity of the furfuryl alcohol at low temperatures.

An investigation has been undertaken to determine the effects, upon the ignition lag of 80% furfuryl alcohol-20% aniline (by weight) oxidized by white fuming nitric acid, of additions of partially dehydrated ferric nitrate $\text{Fe}(\text{NO}_3)_3$, anhydrous ferric chloride FeCl_3 , and pure iron to the acid.

The investigations to be undertaken next include the effect of mixing temperature upon the ignition lag of 80% furfuryl alcohol-20% aniline (by weight) oxidized by

- (1) technical white fuming nitric acid,
- (2) anhydrous nitric acid, and
- (3) anhydrous nitric acid to which known amounts of water have been added.

G. CATALYSIS OF THE REACTIONS OF NON-HYPERGOLIC PROPELLANTS. (PRF-7R5)
Submitted by: Charles H. Trent and Charles M. Ehresman, Purdue Univ.

This problem 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 main problem has been subdivided into three parts:

1. Measurement of the temperature history for the reactions between liquid hydrocarbons and liquid WFNA.
2. Research on the chemical and physical behavior of hydrocarbons with the gases produced by boiling WFNA.
3. The determination of the chemical species formed as the result of the reaction between AN-F-58 jet engine fuel and WFNA.

Measurement of the temperature history for the reactions between liquid hydrocarbons and liquid WFNA. The determination of the temperature history for the reaction between fuels hypergolic with WFNA has been continued. The construction of a second apparatus¹ for measuring rates of temperature change for chemical reactions was completed. This apparatus consisted essentially of a 50-ml Dewar flask rotated in a direction opposite to a mechanically driven stirrer immersed in the partially filled flask. The amount of mixing of the liquids could be

1. Project SQUID, Quarterly Progress Report, PRF-7R5, 1 April '50.

varied by changing the speed of rotation of both the Dewar flask and the stirrer. A platinum-platinum-10%-rhodium thermocouple in conjunction with a recording oscillograph was utilized to record the temperature changes.

The reaction between concentrated sodium hydroxide solutions and concentrated hydrochloric acid (37% by weight) was employed to determine the reproducibility possibilities of the new equipment. When 8 ml of a 25 per cent aqueous sodium hydroxide solution were introduced into 10 ml of concentrated hydrochloric acid contained in the Dewar flask and stirred at 1800 rpm, the maximum temperature reached (99°C) could be reproduced within less than one per cent. However, the time-rate of change of temperature could not be measured with a precision exceeding 4.5%. The apparatus, thus far, has been considered as unsatisfactory.

Experiments with the aforementioned apparatus have shown that thus far the reproducibility obtained was best at a stirring speed of 1800 rpm and that probably higher stirring speeds will give better reproducibility. Therefore, further experiments are to be performed using larger quantities of reactants and employing stirring speeds as high as 10,000 rpm.

Methods for determining a correction for thermocouple lag were investigated^{2,3,4}. In order to define the lag of a thermometric element properly, the actual time-rate of temperature change of the system being measured must be known. Since the actual rates of temperature rise for reactions between WFNA and rocket fuels are as yet unknown, any attempt to make corrections for thermocouple lag would introduce further uncertainty into the final measurement of temperature.

The characteristic time for a platinum-platinum-10% rhodium thermocouple, about 0.001 inches in diameter, was determined by suddenly immersing it into a bath of water at 100°C and measuring the time interval to 63.2 per cent of the original temperature difference. The response rate of this thermocouple was found to be faster than the measured rate of temperature rise for the reaction between aniline and WFNA. Since the aforementioned apparatus is to be employed for comparing the relative reactivities of hydrocarbon compounds with WFNA, the problem of thermocouple lag becomes of secondary importance and will henceforth be neglected.

2. Rhodes, "Industrial Instruments for Measurement and Control." McGraw-Hill Book Co., 1st Edition, 1941, p.113.

3. A. I. Dahl and E.F. Flock, "Rates of Response of Thermocouples from Shielded Thermocouples for Gas Turbines," Trans. A.S.M.E., Vol. 71, 1949, p.153.

4. Harnfeck, "Response Characteristics of Thermometer Elements," Trans. A.S.M.E., Vol. 71, 1949, pp. 121-133.

During the latter half of this quarter, very little experimental work has been accomplished because the chemical laboratory at the Rocket Laboratory is being moved to larger quarters.

Research on the behavior of liquid hydrocarbons with 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 of the reaction apparatus has been completed and parts for its construction are being ordered. As reported previously,⁵ in taking the photographs stroboscopic light is to be employed. A series of tests in which the droplet was allowed to fall in air indicate that stroboscopic light photography should be satisfactory.

Upon completion of the test apparatus, the following factors will be investigated:

- (1) the minimum ignition temperature,
- (2) the effect of acid vapor temperature on ignition delay,
- (3) the physical behavior of the fuel droplet during the period prior to combustion.

The initial investigation will be made on AN-F-58 jet engine fuel, n-decane, and 1-decene.

H. OXIDATION KINETICS, CORROSION OF HEAT-RESISTANT ALLOYS. (PRF-3R1).
Submitted by: Dr. H. J. Yearian, Purdue University.

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

Precision analysis of the X-ray diffraction patterns of the oxide scale formed on chromium steels when oxidized in air have been completed for 20-hour oxidations at temperatures of 775°, 825°, 900°, and 925°C, and partially completed for a 1000°C. run. The general trends established by visual analysis have been reported previously.⁶ The precision measurements verify that the α -Fe₂O₃ phase, which occurs under nearly all conditions, contains not more than 5% Cr₂O₃ in solid solution, and that the Cr₂O₃ phase, which occurs under low rate of attack conditions, contains not more than 5% α -Fe₂O₃ in solution.

5. Project SQUID, Quarterly Progress Report, PRF-7R5, 1 April 1950.

6. Project SQUID, Annual Program Report, 1 January 1950.

The lattice parameters found for the two types of spinel phase, discussed previously,⁷ are listed in Table 1. The spinels which occur

Temp. (°C)	Time (hrs)	Per Cent Cr in Alloy				
		5	11	13	17	26
775	20	8.381		?	8.425	8.427
825	20	8.386		8.449 .01	8.431	8.431
	5	8.390		?	?	8.436
900	20	8.384		8.388	8.43 .01	8.425 .01
	100	8.382		8.388		8.42 .01
925	20	8.385	8.382	?	8.38 .01	8.435
	5				8.380	8.437
1000	10				8.39 .01	8.427 .01
	18				8.38 .01	.005

Table 1 Lattice Parameter in KXU of Spinel Phase of Scale Formed on Chromium Steels in Dry Air - 1 KXU = 1.00202×10^{-8} cm. Estimated limit of error 0.005 KXU except as noted - spinel not present.

under high rate of attack conditions have parameters within the range $8.385 \pm .005$ KXU, and for those present under lower rate of attack conditions the range is $8.435 \pm .01$ KXU. As in the corresponding results for oxidation in one atmosphere of oxygen⁸ there is indication of a trend for the parameter of both types of spinel to decrease as the time or temperature is increased, but in this case the variations are within the limits of error. Work is in progress to complete the high temperature data.

The X-ray diffraction analysis of the oxides formed on a series of Ni-Cr-steels has been virtually completed. These samples (kindly furnished by Mr. Howard S. Avery, American Brake Shoe Company) are selected members of a large group for which extensive studies of high temperature mechanical properties and oxidation resistance have been published.^{9&10}

7. Project SQUID, Annual Program Report, 1 January 1950.

8. Project SQUID, Quarterly Progress Report, April 1950

9. Howard S. Avery and A. Mathews, Trans. of the ASM, (1947) 38, 957 .

10. Anton DeS. Brasunas, James T. Gow, and Oscar E. Harder, Proceedings A.S.T.M. (1946), 46, 129.

The exposure conditions duplicate those of the latter tests, namely; exposure for 100 hours at temperatures of 1600°, 1800°, 2000°, and 2200°F. in air saturated with water at a temperature of 90°F. The air was pre-heated and supplied at a rate of 200 cc/min. Partial semi-quantitative results were discussed in an earlier report;¹¹ the more complete data are given in Table 2.

%Ni	Per cent Cr:	10-11	15-16	21	25-26
	1600°F.			W 8.435 X 10 Xc	
8	1800 F.			W 8.322 X 10 - M 8.348	
	2000 F.			X25 Xc	
	2200 F.			X45 Xc	
	1600 F.				M 8.317 X10 Xc
11-12	1800 F.				M 8.31(8.42) X12 Xc
	2000 F.				MS 8.340 X40 Xc
	2200 F.				X40 Xc
	1600 F.				W 8.429 X10 Xc
19-20	1800 F.				M 8.37(8.41) X25 Xc
	2000 F.				M 8.332 X20 Xc
	2200 F.				VW 8.332 - Xc
	1600 F.		W 8.43 X7 Xc		W 8.439 Xc
35-36	1800 F.		M 8.33(8.42) X15 Xc		W 8.412 - Xc
	2000 F.		S 8.325 - Xc		VS 8.329 - Xc
	2200 F.		W 8.321 - Xc		- - Xc
	1600 F.	S 8.329 - Xc			
63	1800 F.	MS 8.318 - Xc			
	2000 F.	8.320 NiO			
	2200 F.	M 8.318 - Xc			

TABLE 2

11. Project SQUID, Annual Program Report, 1 January 1949.

Oxide Structures Formed on Ni-Cr-Steels in Moist Air for 100 Hours

Number entered is lattice parameter of spinel phase in KXU (0.005 KXU) 1 KXU = 1.00202×10^{-8} cm. S.M.W.VW = strong, medium, weak, very weak, spinel pattern relative to other phases. Xn = n % of Cr_2O_3 in solid solution with Fe_2O_3 . Xc = X100 = Cr_2O_3 with less than 5% Fe_2O_3 in solid solution. () = sometimes found.

The first entry in each box of the table is the lattice parameter of the spinel, in KXU and the symbols S.M.W.VW, indicate the strength of this pattern relative to that of the Fe_2O_3 - Cr_2O_3 phases.

There are, in general, three phases present. Cr_2O_3 is always found except on the 63 Ni - 10 Cr alloy at 2000°F.; this is also exceptional in that it is the only case for which NiO is found. Pure α Fe_2O_3 is never found, but a solid solution with 7 to 50 per cent Cr_2O_3 is usually present; a high Ni content and the higher temperatures preclude the formation of this solution.

The third phase is a spinel which falls into one of three classes according to lattice parameter. At the lower temperatures the parameter is approximately 8.43 and therefore similar to the high parameter spinel of controversial composition¹² found on the simple chromium steels. As with the latter spinel, the temperature above which this oxide disappears increases with chromium content of the alloy. Comparison of Tables 1 and 2 indicates that Ni in the alloy tends to reduce this, limiting temperature somewhat. At the highest temperatures, and for higher Ni and lower Cr content of the alloys, a spinel of lower parameter is found. In only one case (19 Ni - 25 Cr at 1800°F.) is this parameter high enough, 8.37, to be ascribed to Fe_3O_4 . The spinel of parameter 8.348 occurring on the alloy of lowest Ni content probably corresponds to $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ and the values $8.33 \pm .01$ otherwise present require $\text{NiO} \cdot \text{Cr}_2\text{O}_3$ to conform to the lower limit, and this oxide with some $\text{FeO} \cdot \text{Cr}_2\text{O}_3$, $\text{NiO} \cdot \text{Fe}_2\text{O}_3$, or Fe_3O_4 , in solution at the upper limit.

It has been possible to remove the scale and reveal a temper color oxide film on the 13 and 26 per cent alloys oxidized for 20 hours in air at 925°C. referred to in Table 1. These films have been stripped electrolytically. Electron micrographs show that the film on the 13 per cent alloy consists of irregular agglomerates ranging in size up to approximately 0.1μ , whereas that on the 26 per cent alloy is a much more uniform one of crystallites less than 0.05μ in size overlaid by smoothly bounded and uniformly thick patches of material which is nearly opaque to the electrons (0.2 to 0.5μ thick). Transmission electron diffraction patterns of these films give a best fit with a high chrome Fe_2O_3 - Cr_2O_3 type of structure (75 to 100 per cent Cr_2O_3); this result applies only to the thin portions of the films. A technique has been developed by which such films may be wound up on a glass fiber to make

12. Project SQUID, Annual Program Report, 1 January 1950.

specimens suitable for the Debye-Scherrer method of X-ray analysis. The amount of material is minimal, but weak patterns are obtained. In the present case there can be no doubt that the bulk of the samples is α - Fe_2O_3 . Since all the parts of the sample are penetrated by the X-rays and contribute to the diffraction pattern according to their volumes, this result characterizes the thicker portions of the films. Thus the thinner parts seem to be richer in Cr_2O_3 than are the thicker parts. In contrast with this, the X-ray analysis of the scale which had been removed from the film gave strong Fe_2O_3 and weak Cr_2O_3 for the 13 per cent alloy and no Fe_2O_3 , strong Cr_2O_3 , and strong high parameter spinel for the 26 per cent alloy.

Further investigation of the transition from thin film to incipient scale has been made. Samples of 5 to 26 per cent chromium steel were oxidized for 20 hours at 500°C and at 600°C . No scale was formed at these temperatures except on the 5 per cent alloy at 600°C . These films were stripped and examined. Those formed at the higher temperature were too thick for electron penetration except at isolated spots—the lower temperature gave thin films made up of crystallites which decrease in size with increase of chromium content of the alloy¹³ and superposed by heavier agglomerates which frequently conform to the scratches of the original 3/0 polish. Transmission electron diffraction and Debye-Scherrer X-ray patterns were obtained successfully in all cases (except the 20 per cent alloy at 500°C), with the same results as described above for higher temperature sub-scale films.

The formation of the films on these alloys in short times of oxidation at 500°C in air has continued. The data for 15 minutes oxidation is complete and similar to those obtained for 5 minutes.¹⁴ Surface replica electron micrographs show that the exposed oxide has a flat matte surface with projections, the size and frequency of which increase with decreasing chromium content of the alloy. The projections are isolated and more or less rounded in shape except those on the 5 per cent alloy which form a continuous vein-like network of ridges approximately 0.2μ wide and high. Electron diffraction patterns obtained in reflection from these surfaces and in transmission after stripping, all conform to a low chrome Fe_2O_3 structure. This result, it will be noted, is contrary to that obtained from films formed in longer times which indicated a high chrome phase. An X-ray pattern was obtained only from the 5 per cent alloy film; this corresponded to α - Fe_2O_3 . Some indication of such a difference in the chrome content of films formed in long and short times is evident in earlier data.¹⁵ Additional experiments to clarify this point are in progress.

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13. Project SQUID, Annual Program Report, 1 January 1950.
 14. Project SQUID, Quarterly Progress Report, 1 April 1950.
 15. Project SQUID, Annual Program Report, 1 January 1950.

To assist in the investigation of thin film and oxide scale composition, a scheme of micro-colorimetric analysis for Fe and Cr has been set up and tested. It is now believed that approximately 5 per cent accuracy can be attained for samples containing 0.1 mg of metal/sq cm when 1 sq cm of film is available, and correspondingly greater sensitivity for larger samples. In order to analyze for oxygen by difference, a microbalance has been constructed and is being tested. The indicated sensitivity is approximately 1 microgram.

Plans for the next quarter include the extension of the X-ray diffraction studies to higher temperature, oxidations in air and in oxygen at reduced pressures, and the correlation of the diffraction studies 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.

I. 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.

To make preliminary studies of rocket motor performance under certain conditions with a view to gaining an 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.

A stainless steel porous plug injector has been inserted downstream of a standard injector in a rocket body to provide a pre-mixing chamber for fuel (methane) and oxidizer (gaseous oxygen). While several rocket bodies were being fabricated, a dummy pre-mixing chamber, exhausting at atmospheric pressure, was made by inserting a piece of this porous material between flanges, with a spark plug downstream beyond the chamber. This dummy was run for five seconds at an upstream propellant pressure of 600 p.s.i., and the flame did not travel back into the pre-mixing chamber.

In a second run under these same conditions, apparently the flame flashed back into the premixing chamber. Although the premixing chamber was not ruptured, a detonation in a 3/16 inch copper line leading to the oxygen pressure gauge shattered the line in five places. The line is rated at 15,000 p.s.i.

Four firings of a rocket motor with premixing have been made. One of short duration was successful- the other three failed through burnout, but with no explosion in the premixing chamber. It appears that this method of premixing propellants will be satisfactory after the mechanical difficulties have been overcome and operating procedure established.

A new motor design is being made to incorporate the porous plug in the head and eliminate welding.

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

Submitted by- L. Schoen, New York University.

As described in the January 1950 Annual Report, comparison of the flame spectrum of a deuterated hydrocarbon with that for the normal molecule is expected to yield data leading to the identification of the emitter of the hydrocarbon flame bands.

Satisfactory photographs of these bands have been obtained with acetylene and atomic oxygen, using a Jarrell-Ash grating spectrograph, having a dispersion of $10.9 \text{ \AA}^\circ/\text{mm}$. in the first order.

At present, the apparatus for the generation of deuterio-acetylene by the reaction between calcium carbide of high purity and deuterium oxide is undergoing revision, in order to improve the yield of acetylene per mole of deuterium oxide.

It is anticipated that a recording of the deuterio-acetylene-atomic oxygen flame will be carried out in the near future.

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

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

Burner studies of the effect of pressure on the intensity of the OH, CH, and C_2 bands of the methane-oxygen flame burning at low pressure have been continued. The maximum pressure thus far attained has been about 80 mm. When higher pressures were tried in the burner mantle, the flame became unstable and it was not possible to obtain satisfactory spectrographic plates. The spectrographic data which were obtained below the upper limit are being analyzed to determine the influence of pressure on the relative intensity of the bands.

Various optical arrangements between the burner and the spectrograph were studied to investigate the possibility of sectioning the flame, so that the relative intensity of the bands in question could be studied as a function of point of origin in the flame structure. None of the methods considered was adequate.

The calculation of the effective rotational temperatures of the 3064 \AA OH band and the 3900 \AA CH band has been continued.

The structure of the bands has been analyzed and K-values have been assigned. The J-values are now being calculated. The relative intensities of the resolved lines for the various branches of the above bands have been determined.

As a result of the complete identification of the lines in the region of the 3064\AA OH band, the presence of the 3142\AA CH band was established in these spectra of the methane-oxygen flame burning at low pressure. The intensity of this band was weak in comparison with the other bands under investigation.

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

Submitted by- Kurt Wohl, University of Delaware

In the last three months, work has been concentrated on the study of the radiation of non-luminous butane air flames in the near infra-red. It was confirmed that the radiation in this spectral region is thermal in nature in all zones of the flames including the primary burning zone. This has led to the development of a method of measuring flame temperatures which applies to all flame zones.

1. Instrumentation. A few features of the instrumentation and experimental approach will be briefly reviewed below - A spectro-photometric apparatus has been constructed which can be used 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 recorded on a Brown Electronik strip chart recorder. Absolute spectral intensities may be measured by comparing the flame spectral intensity to that of a calibrated tungsten-in-quartz standard lamp. Standard lamp intensities are recorded on the same chart as the flame radiation.

The object of study is a two-dimensional inverted flame. A cross-section through this flame is shown in Figure 1. The flame burns between two quartz plates of 3.4 cm. distance. The side walls are cooled. The specific feature of the flame is that it has a truly flat primary burning surface. The burner can be tilted so that the burning surface is parallel to the slit of the spectroscope. The flame zone which is under observation at any instant has at present an average width of 0.27 mm and a height of 3 mm.

Since the last report the upper limit of the wave lengths open to investigation has been extended from 2.5 to $3.2\ \mu$ by the acquisition of a lithium fluoride prism and a "Cetron" lead sulphide photoconductive cell manufactured by the Continental Electric Company of Geneva, Illinois. These modifications have made it possible to include the strong water bands around $2.7\ \mu$ in our studies.

The instrument was calibrated using known mercury emission lines, and ammonia, benzene, and carbon dioxide absorption bands. The bands observed are practically completely due to water vapor with the possible exception of the band at 2.7μ to which carbon dioxide may slightly contribute.¹ Four of the seven principle band heads observed were found to overlap with absorption bands due to the room air moisture present in the optical path of the instrument. For this reason, quantitative studies were confined to those which are practically free of this disturbance, i.e., to the 1.346, 1.819, and 2.505μ bands. A sample of the spectrum emitted by the combustion gases downstream of the primary burning zone of a 3.88% butane-air flame is given in Figure 2. The standard lamp spectrum which is included in the figure shows a number of absorption bands due to moisture in the room.

2. The Principle of the Method Used for Temperature Measurement.

The normal way of obtaining temperatures of flame gases by measurements in the infra-red spectral region is to determine the emission and absorption at a given wave length. This method requires an absorptivity which can be measured with a certain degree of accuracy. Within the wave length range accessible to our instrument, only the 2.7μ band has a sufficiently large coefficient of absorption to open the possibility for using this method without applying a very long absorbing path. But even for this wave length the present set-up is not entirely adequate. The electronic detection circuits are being revised in order to obtain the required accuracy.

The method for measuring temperatures which is being employed at present is an application of the two-color method to flame gases, i.e., to non-gray bodies with a low absorptivity. It presupposes that the radiation at the chosen wave lengths is thermal, and the development of the method provides a check for this being or not being the case. A general application of the method would require that the wave lengths chosen are all emitted by the same substance, in our case water vapor. The description of the method may start with Planck's radiation formula:

$$(1) E_{\lambda} = \epsilon_{\lambda} c d \left(\frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} \right)$$

E_{λ} = brightness at wave length λ

ϵ_{λ} = molecular absorption coefficient at wave length λ

d = length of emitting path

c = concentration of water

c_1 and c_2 = constants

T = temperature $^{\circ}\text{K}$.

1. G. Herzberg, Molecular Spectra and Molecular Structure, Vol. II (1950). E. K. Plyler and C. J. Humphreys, "Infra-red Emission Spectra of Flames," Nat. Bur. of Standards, Res. Paper, RP 1890, 1948.

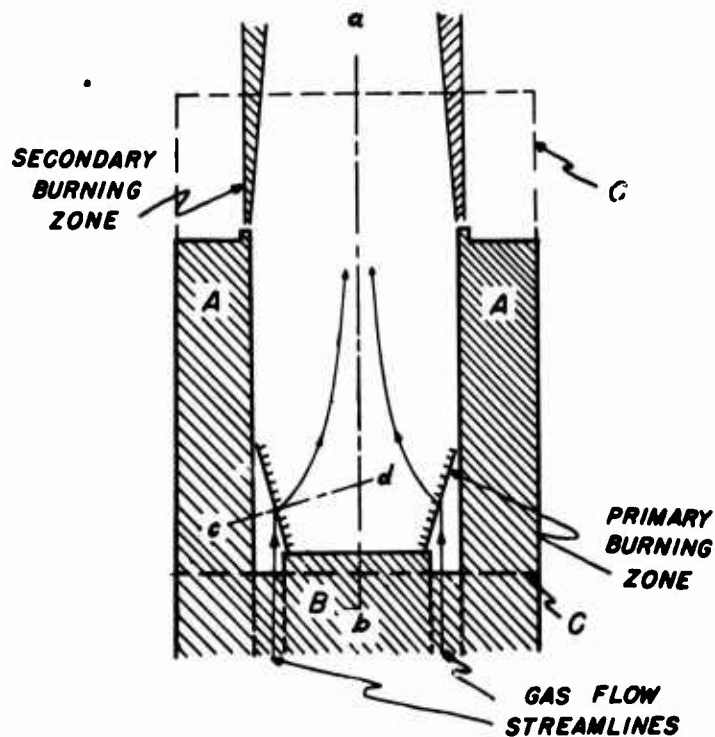


Figure 1 End View of Two-Dimensional Burner

- A. Water Jackets
- B. Flame Holder
- C. Quartz End Plates

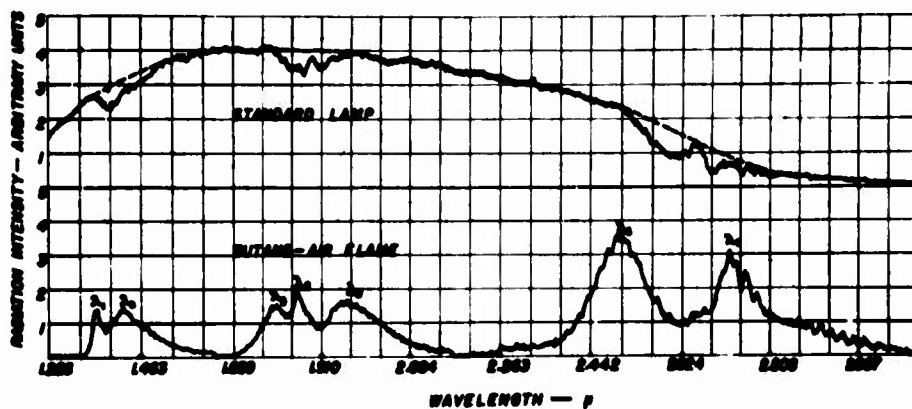


Figure 2 Infra-Red Spectrum of Butane-Air Flame with 3.88% Butane (80.1% of Stoichiometric Air)

- $\lambda_1 = 1.346 \mu$
- $\lambda_2 = 1.422 \mu$
- $\lambda_3 = 1.819 \mu$
- $\lambda_4 = 1.876 \mu$
- $\lambda_5 = 1.960 \mu$
- $\lambda_6 = 2.505 \mu$
- $\lambda_7 = 2.700 \mu$

By taking a ratio of the light intensities at two wave lengths λ and λ' , the term (c d) cancels out.

$$(2) \frac{E_{\lambda}}{E_{\lambda'}} = \left(\frac{E_{\lambda}}{E_{\lambda'}} \right) \left(\frac{\lambda'}{\lambda} \right)^5 \frac{e^{c_2/\lambda'T} - 1}{e^{c_2/\lambda T} - 1}$$

A similar equation may be written for the ratio of the light intensities at the above wave length λ and a third wave length - λ'' , (or if this is preferred, at λ' and λ''). It is desirable to make the difference between the three wave lengths as large as possible. The three wave lengths mentioned above comply with this condition. Measurement of light intensity at three wave lengths now provides two equations of the type of equation (2) with the three unknowns

$$E_{\lambda}/E_{\lambda'}, E_{\lambda}/E_{\lambda''} \text{ and } T.$$

Since water is the emitter of all the three wave lengths, the ratios of the absorption coefficients are unique functions of the temperature.

$$(3) \frac{E_{\lambda}}{E_{\lambda'}} = f'(T) \text{ and } \left(\frac{E_{\lambda}}{E_{\lambda''}} \right) = f''(T)$$

If now the form of the functions $f'(T)$ and $f''(T)$ is postulated, it is possible to determine all the unknowns involved including T by repeating the measurement of light intensity at the three wave lengths for a number of different temperature points. If, e.g., it is assumed that each of the E -ratios is a constant, independent of temperature, the measurement at two temperature points would provide four equations for observed intensity ratios with the four unknowns $\frac{E_{\lambda}}{E_{\lambda'}}$, $\frac{E_{\lambda}}{E_{\lambda''}}$, T_1 and T_2 .

If it is assumed that the E -ratios are linear functions of temperature, four temperature points are necessary to make the number of equations equal to the number of unknowns so that all the four temperatures can be calculated. Though this procedure is not an inviting one, it is possible, in principle, to make it safe by using any number of different flames and temperature points as a check, so that the consistency and accuracy of the numerical equations for the E -ratios, as well as for the temperatures, can be assured. Once this has been achieved, i.e once, e.g., $E_{\lambda}/E_{\lambda''} = f''(T)$ is well-known, the temperature at any point of the flame can be ascertained by just measuring for this point the ratio of light intensities for the two wave lengths λ and λ'' . This can be done by plotting the ratio of measured light intensities directly as a function of temperature and taking the temperature for any measured point from this curve. If any doubt on the validity of this temperature should arise, the light intensity ratio for another pair of wave lengths may be used as a check,

3. The Procedure Adopted for Temperature Measurements. In order to avoid the involved mathematical manipulations which are necessary for the determination of the ϵ -ratios as a function of temperature, the sodium line-reversal method has been used to determine preliminary temperature values. For the purpose the apparatus has been employed, which was described in the previous Quarterly Report. The sodium line-reversal temperature was obtained along the center line of the burner (line a - b of Figure 1) for five different butane-air flames of 2.64%, 3.13%, 3.45%, 3.88%, and 4.80% butane, respectively. Figure 3 is such a temperature plot for the 3.88% flame.

Along the same axes flame spectral intensities at the three wave lengths $\lambda_1 = 1.346 \mu$, $\lambda_3 = 1.819 \mu$, and $\lambda_6 = 2.505 \mu$ were measured for the five flames by comparison to the standard lamp. From the measured light intensities and the sodium line reversal temperatures, the ratios of the absorption coefficients $\epsilon_{\lambda_1} / \epsilon_{\lambda_6}$ and $\epsilon_{\lambda_3} / \epsilon_{\lambda_6}$ were determined with the help of equation (2). The ϵ -ratios obtained were then plotted as a function of the sodium line reversal temperature for all the five flames. Figure 4 shows the result. The distribution of points is entirely at random showing that the differences of combustion conditions for the different flames did not affect the radiation except via the temperature which was produced by these combustion processes. Now preliminary straight average lines were drawn through the points (not the lines shown in Figure 4), representing a first approximation of the equation (3) above, and with the help of these functions the ratio of radiation intensities $E_{\lambda_1} / E_{\lambda_6}$ and $E_{\lambda_3} / E_{\lambda_6}$ were plotted as a preliminary function of temperature.

Radiation intensities at the three wavelengths were now determined along traverses perpendicular to the primary burning zones of the five flames (line c - d in Figure 1), and two independent temperatures along the traverses were determined from the curves for $E_{\lambda_1} / E_{\lambda_6}$ and $E_{\lambda_3} / E_{\lambda_6}$. It was found that these two temperatures agreed with each other quite well in any case. As the final step the average lines for the ratios of the absorption coefficients in Figure 4 were now changed within the limit of errors such as to give the best agreement between the two "two-color temperatures" along the traverses through the primary burning zones. The lines used are shown in Figure 4. The two temperatures through the burning zone agree with each other for all the five flames practically completely (within a few degrees centigrade). Three of the temperature curves obtained are shown in Figure 5. It is remarkable that no anomaly can be detected when the curve passes through the burning zone (which is indicated by the vertical zero line). It should be pointed out that the criterion for the position of the final lines in Figure 4 - which refers to the center lines of the flames - has been derived from measurements along the traverses through the burning zones. These lines are therefore independent of the sodium line reversal temperature against which they have been plotted in Figure 4, and can be used to determine independent two-color temperatures along the center lines.

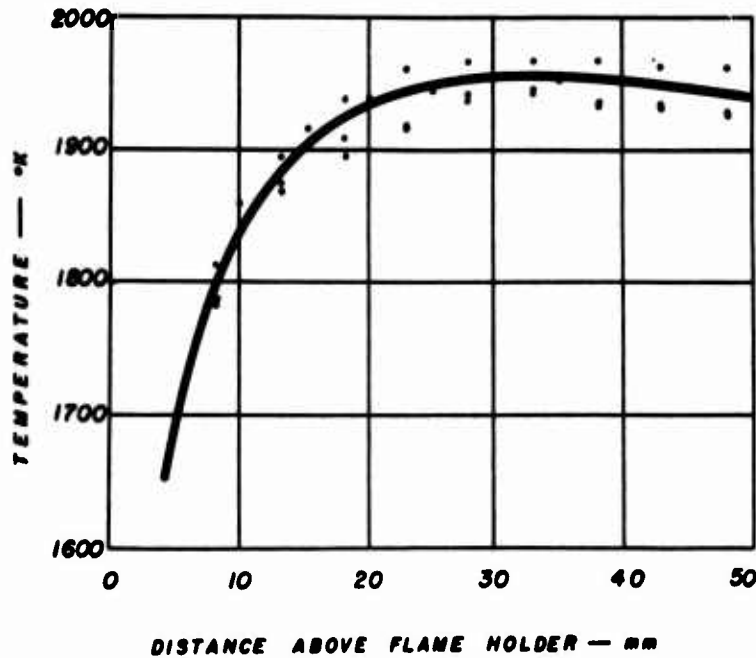


Figure 3 Sodium Line Reversal Temperature along the Center Line of Two-Dimensional 3.88% Butane-Air Flame.

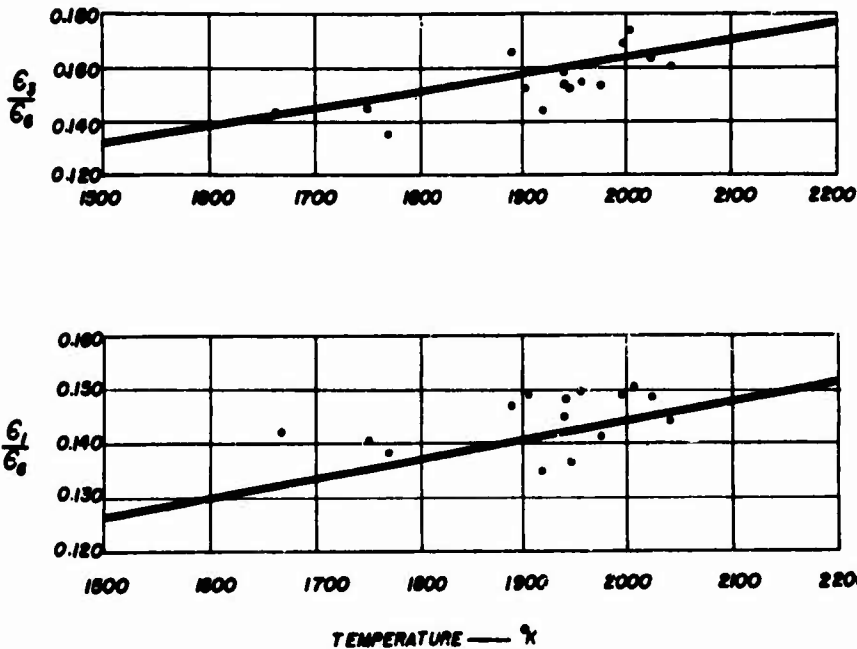


Figure 4 Ratio of Extinction Coefficients of Two Band Head Wavelengths as a function of Sodium Line Reversal Temperatures for Center Line of Five Two-Dimensional Flames. (Butane content ranging from 2.64% to 4.80%)

ϵ_1 - Extinction Coefficient at 1.346 μ
 ϵ_3 - " " " 1.819 μ
 ϵ_6 - " " " 2.505 μ

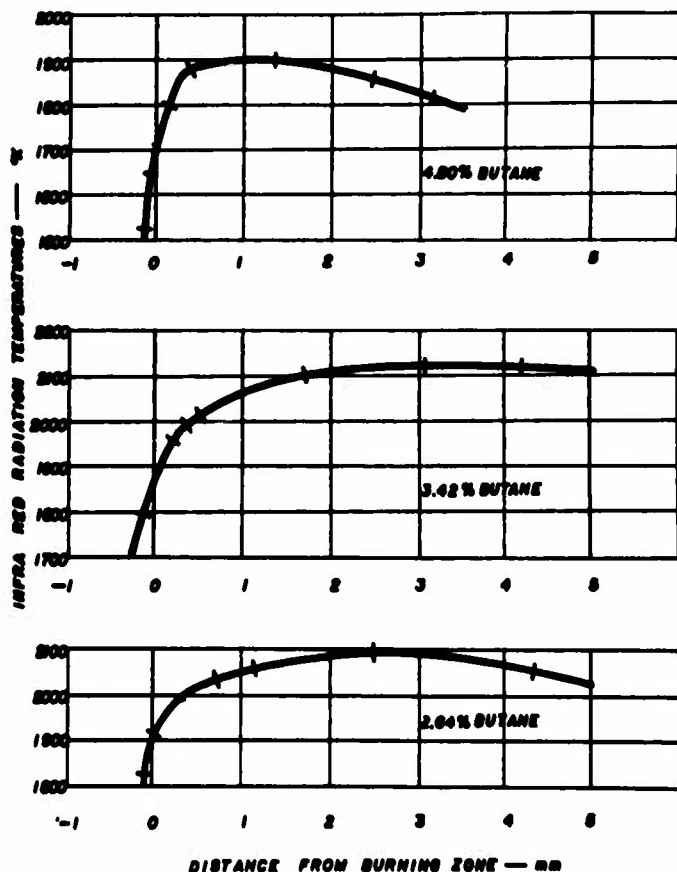


Figure 5 Temperature Traverse Through Primary Burning Zone of Various Butane-Air Flames. The zero line signifies the position of the visible burning zone.

- refers to the side of fresh gas stream.
- + refers to the side of combustion products.

To sum up, the inner agreement of the data obtained for three different wave lengths and five different flames gives evidence that the two-color method described furnishes true temperatures, even within the primary burning zone.

It has to be realized, of course, that the temperature along the optical path through the flame is not uniform so that the temperatures obtained represent some average value. It can be said that, because of the low absorptivity of the flames gases, all layers of the flame contribute equally to this average. For the burning zone and its immediate neighborhood the average temperature should very well agree with the true temperature in the interior of the flame. This is an advantage connected with the use of a two-dimensional flame. Attention should also be drawn to the fact that the absorption coefficients measured are defined only for the instrument and the slit width used as they depend greatly on the wave length range which is transmitted through the exit slit and is incident on the phototube. As long as conditions are kept constant, however, no uncertainty is introduced by this fact.

Once the temperature is known, the product $\epsilon \lambda c d$ (see equation 1) can be calculated from the radiation intensity at one wave length (relative to that of the standard lamp). As d is known and as c can be calculated thermodynamically, at least for the downstream part of the flame in which combustion can be assumed to be complete, the absorption coefficient can be calculated as a function of temperature. This will be done in the near future. Also, it is expected that the absorption-emission method for measuring temperatures will be applied soon. With the help of the extinction coefficients and radiation intensities at known temperatures, the concentrations of water vapor will be calculated in flame regions in which combustion is still incomplete. There this concentration will be an indication of the progress of combustion.

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. TEMPERATURE MEASUREMENT OF ROCKET EXHAUST JETS. (NYU-8R1)
Submitted by- J. B. Gilstein, New York University.

Eight additional records have been obtained of the exhaust temperatures of 3" liquid fuel rockets at the Malta Test Station of the General Electric Company. Temperatures were measured just downstream and just upstream from the tip of the first Mach cone. Spectral Filters used were centered at 6100 A° and 4830 A° - regions which spectrographic studies show are essentially free of line and band structure. These records indicate temperatures which are lower than the average temperatures obtained by the sodium D line method.

Since both the sodium D line method and the N.Y.U. method depend upon equilibrium conditions in the flame, that is, upon a Planckian distribution of energy, some preliminary spectrographic work was done at Malta. These plates are now being reduced at our laboratory. It is probable that more plates will be necessary to increase the accuracy of the determination of the energy distribution.

Spectrographic studies have been made of an additive used in most of the rocket runs. These plates show a continuous background without line structure. Furthermore, these additive studies indicate that the rocket exhaust burns essentially as a rich mixture. This is also confirmed by the presence of Swan bands in the rocket spectra.

The Mach cone of the rockets was also studied, using a Fastax camera at approximately 5000 frames/sec. These pictures show a vast amount of large scale turbulence and large amount of oscillation along the direction of the main axis.

The studies of the rocket exhaust temperatures show large temperature amplitudes of low frequency, approximately 100 cycles/sec. when a normal rocket is shutting down (see Figure 1) and frequencies of the order of 4000-5000 cycles/sec., 50°K. amplitude variation for normal operation.

The present phase of the work at Malta was concluded during this quarter and the apparatus returned to New York. The apparatus was then tested at New York University against standard oxy-acetylene and propane air flames and found to be satisfactory.

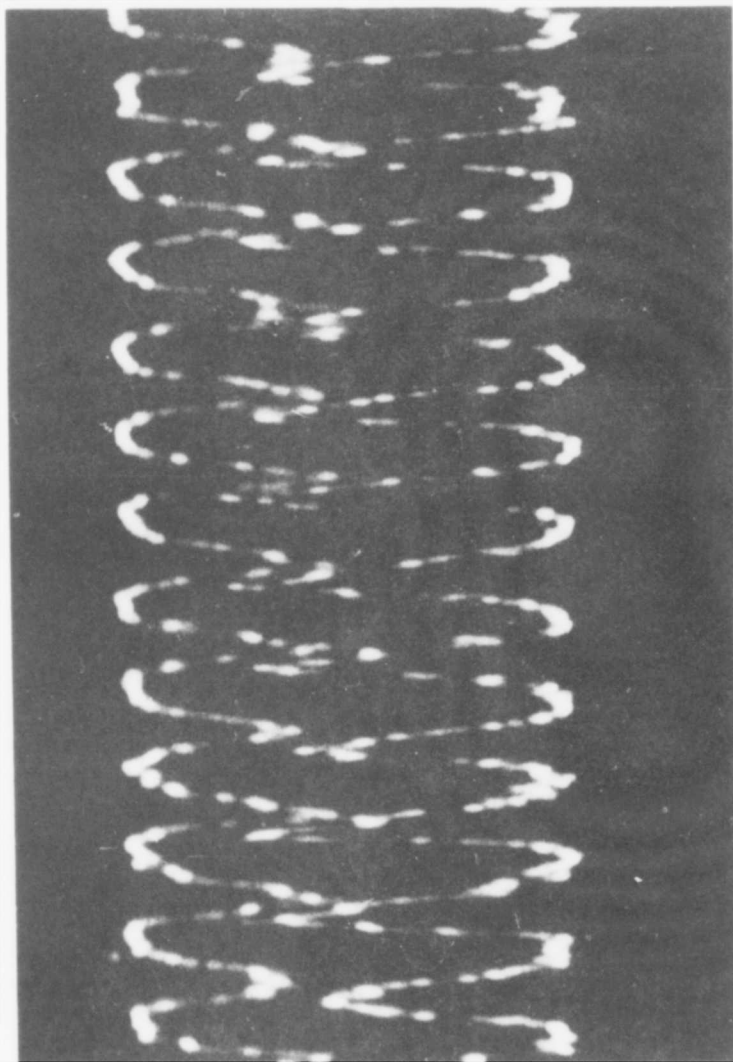


Figure 1 Radiation trace of 3" rocket running at reduced pressure just before shut down. Upper trace is record of single path, and lower trace of double path. The slight displacement of the peaks is due to the internal misalignment of the electron guns of the dual beam cathode ray tube. Frequency of oscillation shown is 100 cycles/sec. The amplitude of the temperature variations shown is about 250°K.

B. EXPERIMENTAL DETERMINATION OF HOT WALL TEMPERATURES BY MEANS OF X-RAY DIFFRACTION TECHNIQUES. (PIB-3R3).

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

In the study of surface temperatures of metal by X-ray diffraction methods, past measurements were made under conditions of zero stress, i.e., the metals were heated and permitted to expand freely. There are, however, many conditions where temperatures of inaccessible surfaces are desired, which surfaces are subject to motion and/or to a variety of stresses. It was, therefore, decided to determine the contribution of various stresses to changes in the diffraction pattern, and, if possible, to separate temperature and stress effects.

Studies were made on a sample of stainless steel AISI No. 347. The specimen, .45" x .187" x 1.5", was mounted in a clamp shown in Figure 2. Stress was applied by turning the screw having a pitch 0.055". Back-reflection X-ray diagrams were taken at every 1/4 turn of the screw, while the specimen remained at room temperature (75°F). Iron K α radiation was used throughout these tests.

Figure 3 shows the result of the applied stress. The specimen was stressed beyond the elastic limit of the material after the screw was moved 0.041 inches (3/4 of a turn). The total line shift of the K α line for one full turn would correspond to a change of approximately 75°F. Such a shift would introduce a considerable error in temperature measurement.

Further studies on the simultaneous effect of compression and temperature have begun. Strain gages will be used to determine the absolute value of the stresses applied. The information sought may help to isolate the effects of temperature and stress on a specimen while applying X-ray diffraction methods in measuring the surface temperature of metal. Construction has begun on the X-ray thermometer incorporating the G-M tube and X-ray spectrometer principles.

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

Submitted by- Leslie S. G. Kovaszny, Johns Hopkins University.

Two different optical techniques are being investigated and compared with the hot-wire technique in a flow field where all density fluctuations are caused by temperature fluctuations alone.

During the period from October to April, shadow and interferometer records were taken in a heated turbulent jet. The velocity being low (30-50 ft/sec.), only the temperature fluctuations are responsible for the density fluctuations recorded by optical techniques. In this case the temperature fluctuations can also be recorded by the hot-wire anemometer if the "hot-wires" are "heated" by very low current (resistance thermometer operation).

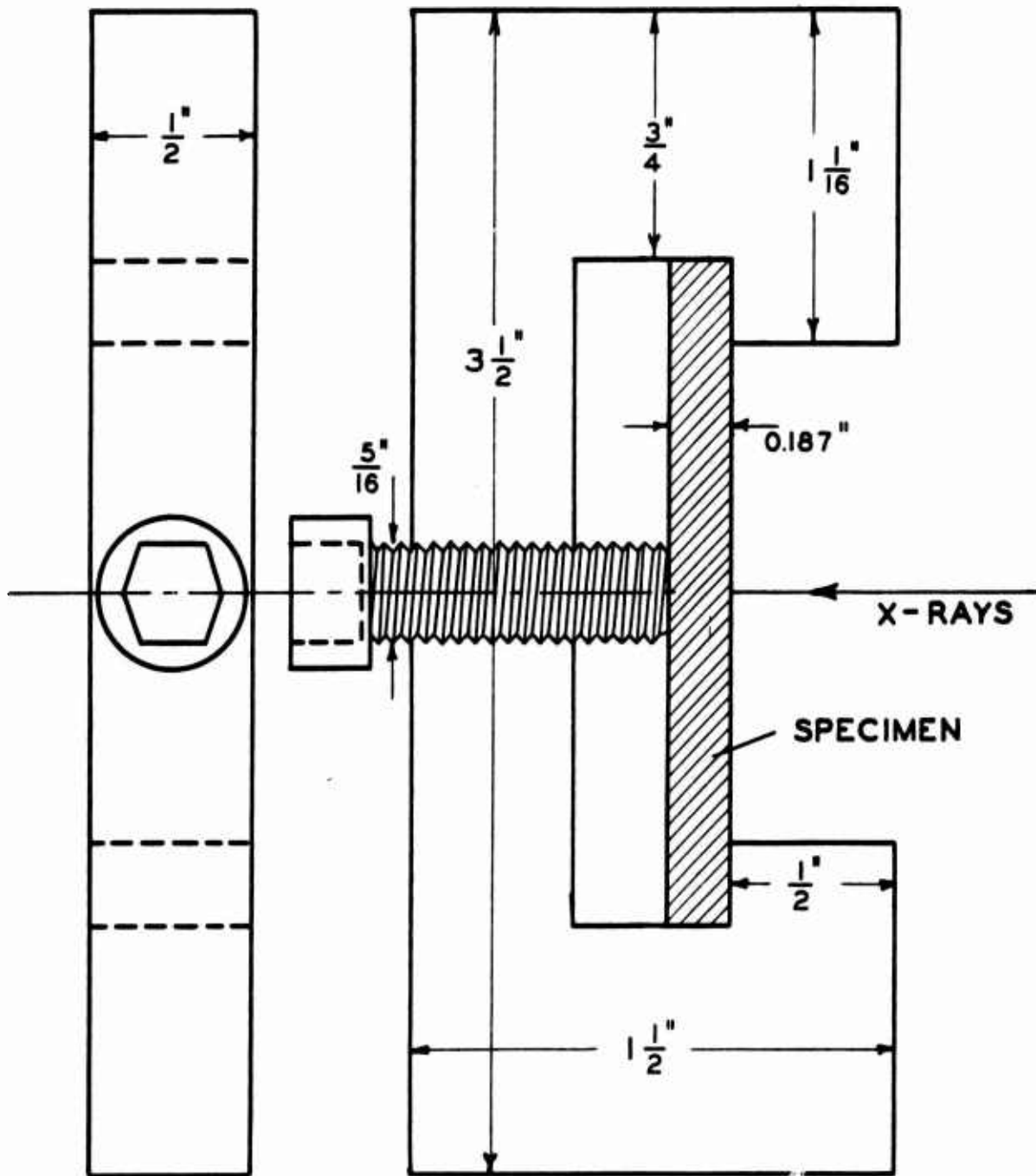
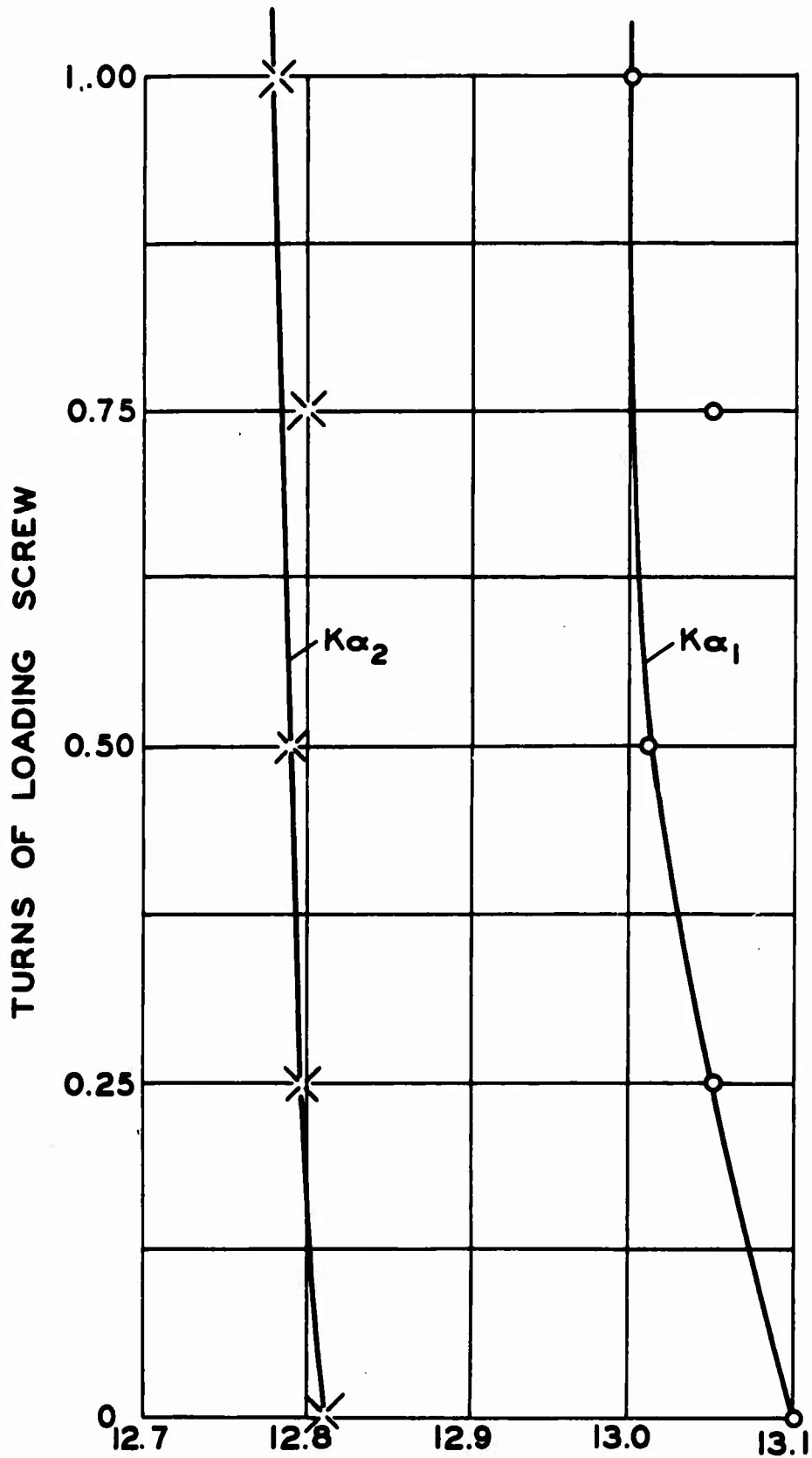


Figure 2 Clamp for Stressing Specimen



Diameter of Diffraction Rings, cm.
 Figure 3 Change in diffraction lines with change in stress at the surface of metal AISI No. 347.

During the last quarter the main emphasis was placed on obtaining statistical data on the turbulent temperature fluctuations by the hot-wire method.

New hot-wire equipment (developed as a cooperative project between The Johns Hopkins University and the National Bureau of Standards) was available for measuring the temperature fluctuations and their energy spectrum in the heated jet.

The hot-wire used was a .00015" Tungsten wire .1" long, and measurements were carried out up to 10,000 c.p.s. These data converted to space coordinates gave resolution down to wave lengths of the order of .05". The temperature fluctuations were of the order of 2.5 - 3° C (r.m.s). A shadow picture of the flow field is given in Figure 4, (slightly larger than the original). The jet emerges from the left and is directed toward the right. The hot-wire is placed 3" downstream (only the two needle prongs are visible).

The previous optical measurements and interferometer records have been taken at 3/4" from the heated grid- therefore, most of the spectra were also measured in this region.

The hot-wire equipment is shown in Figure 5. A converted Hewlett-Packard wave analyser was used for measuring the energy spectrum of the random fluctuations. Even with the rather low r.m.s. temperature fluctuations, the signal-to-noise ratio was above 2.1 at the upper end of the measured frequency range.

Figure 6 shows three temperature spectra taken at three stations across the jet at 3/4" downstream from the heated grid. The general character of the spectra is similar to spectra of the turbulent velocity fluctuations.

The data previously obtained by shadow method and later by interferometer record will be synthesized with the information now obtained by the (more direct) hot-wire method, and during the next few months the different types of information will be converted into a common basis to enable a definite evaluation on the domain of applicability of the various techniques.

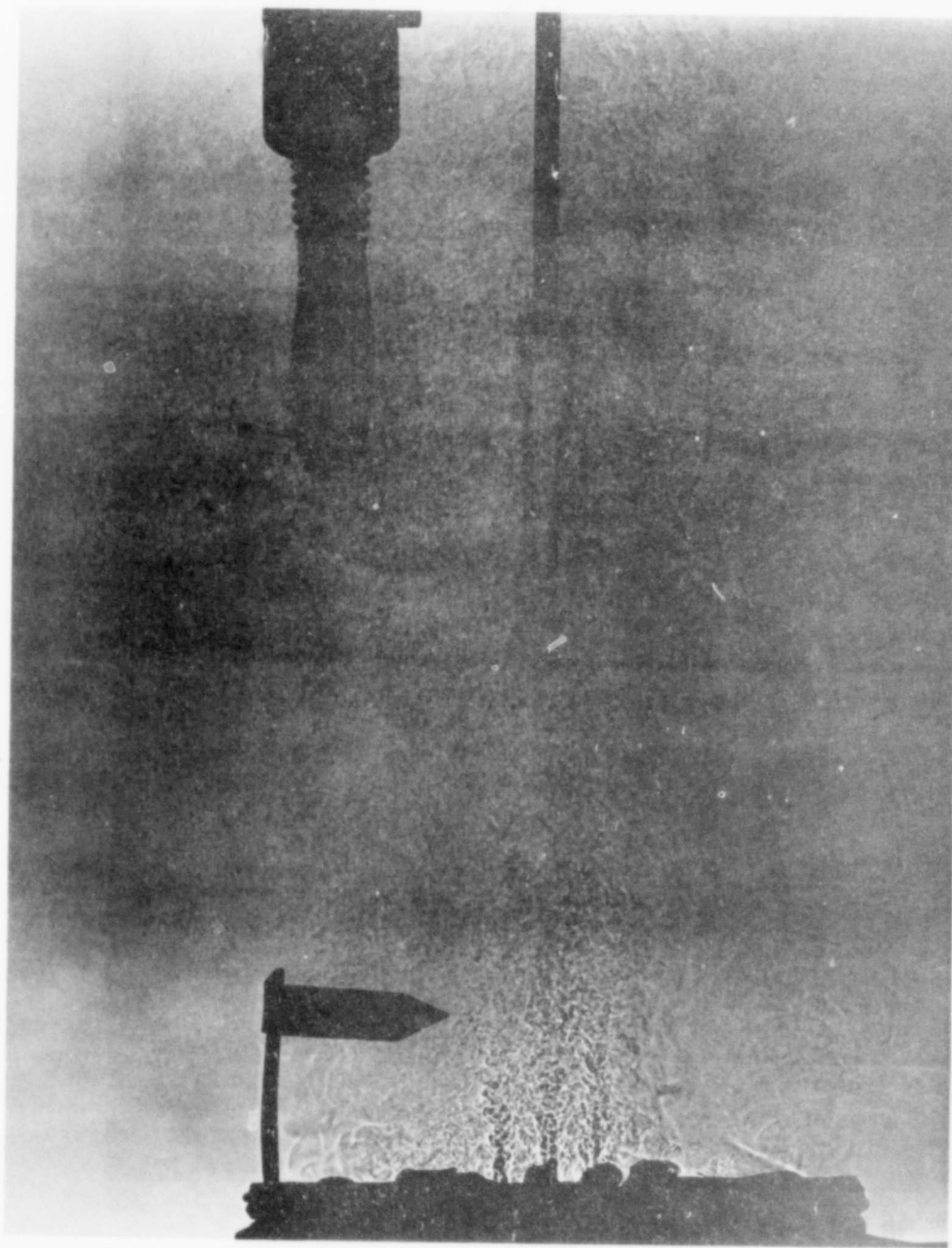


Figure 4 A Shadow Picture of the Flow Field

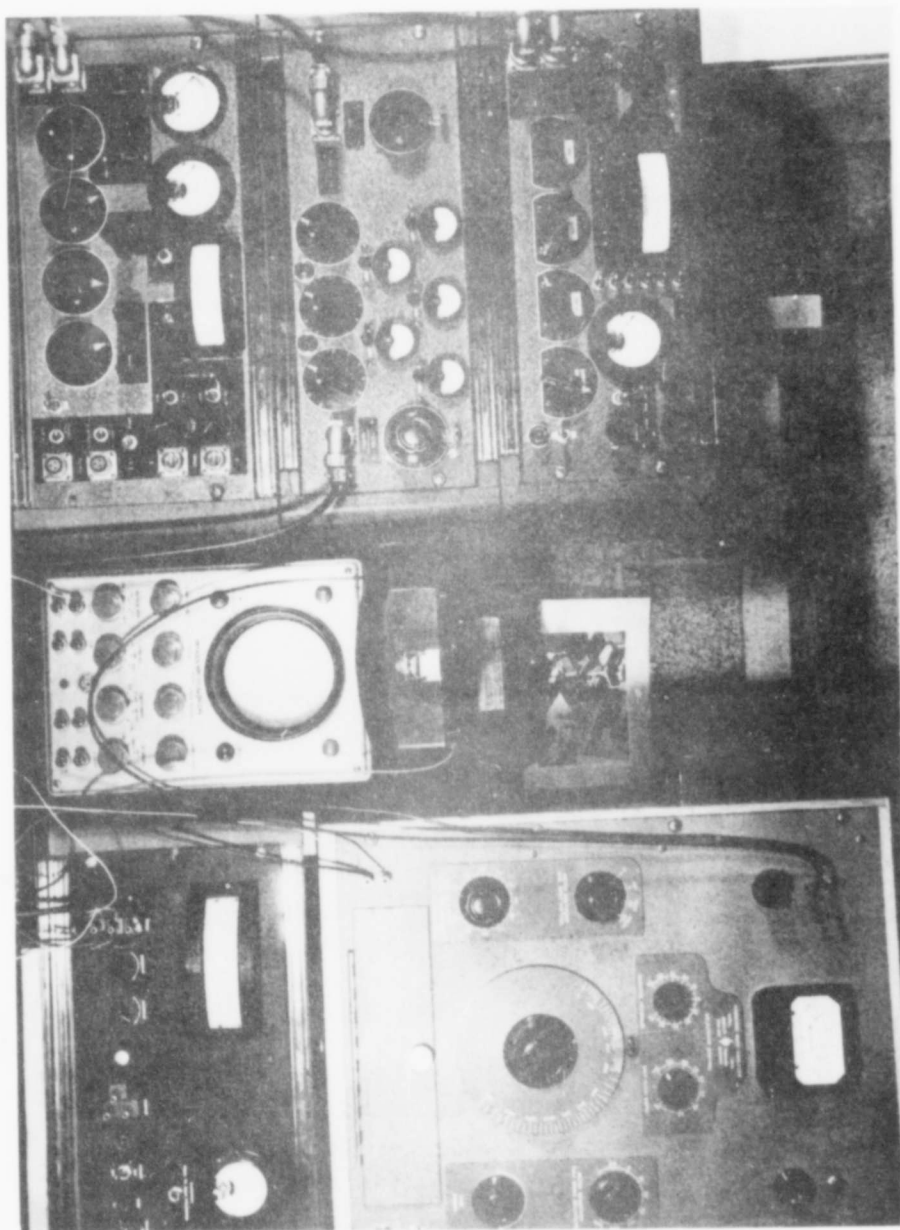


Figure 5 The Hot-Wire Equipment

Spectrum of Temperature Fluctuation
3/4" behind grid

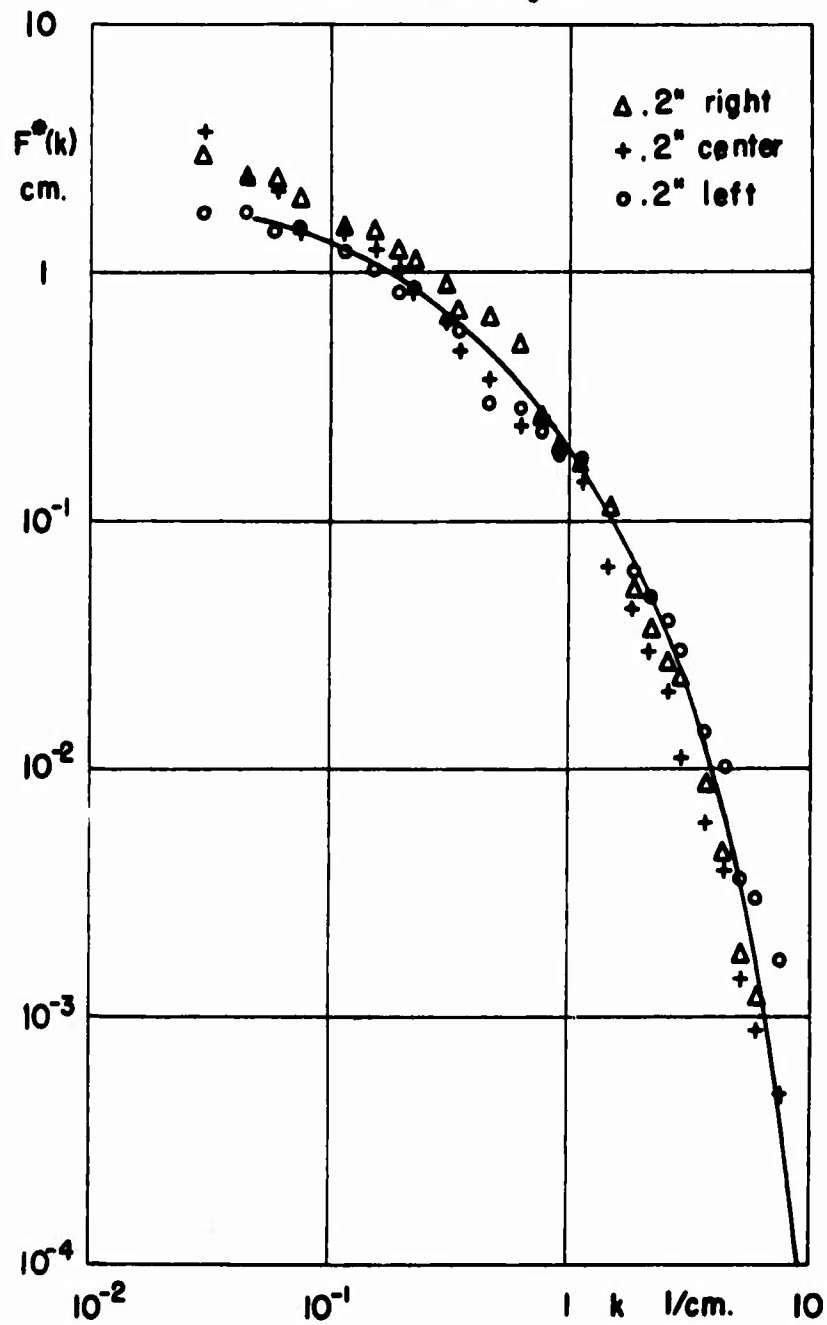


Figure 6

D. THREE-DIMENSIONAL SCHLIEREN APPARATUS. (NYU-8R4)

Submitted by- R. J. Krauschaar, New York University.

The three-dimensional schlieren apparatus, described in the Annual Report of 1 January 1950, has been completed. The Fastax camera has been used to take a series of high speed pictures of gas motions in a large flame tube, with grid and without grid. These film clearly show the third dimension, but have not yet been analyzed.

DEVELOPMENT OF A DIFFRACTION-GRATING INTERFEROMETER.

In the course of earlier experiments on gas jet formation, it was found desirable to study the phenomena quantitatively, and this could not be done very conveniently with an ordinary schlieren system. A simple interferometer was developed on the basis of initial work done with Ronchi systems.

The operation of this interferometer, as described below, is based on the principle that since the orders of diffraction of a diffraction grating are produced by a single source, subsequent division of any pair of the orders into sub-orders may be used to produce interference.

Figure 7 illustrates the field of a 16" mirror with the fringes undisturbed. These fringes consist of two sets in each field image, slightly overlapping at the center of the field, one set being the complement in intensity of the other. By introducing thermal gradients in the atmosphere through which one-half of the light beam passes, typical interference shifts are observed, (Figure 8). Moreover, corresponding shifts appear in each set of fringes. Because of the necessary presence of the two sets of fringes, the useful field is limited in our apparatus to approximately one-third the area of the 16" diameter schlieren mirrors used.

Figure 9 illustrates the original form of the apparatus for a single mirror system, but the operation of the system may be best illustrated with the aid of Figure 10, where, for convenience, reflection gratings are used. If a monochromatic beam of light from a source S is reflected from a diffraction grating G^o , a series of diffracted beams are formed obeying the grating equation $n\lambda = d \sin \theta_n$, where n is the diffraction order, λ the wave length, d the grating constant, and θ_n the angle between the zeroth and the n^{th} order beam. These diffracted beams are produced by the same source, and so if they are recombined, it is possible to produce interference between them. Two of the beams, say the n^{th} and $n+1^{\text{st}}$, are colimated by a mirror M^o , and then refocused by a similar mirror m^o , so that the axes of the converging beams approach one another at an angle equal to the original diffraction angle, $\theta_n + \theta_{n+1}$. If, now, a diffraction grating G'' having the same constant d as the original grating is introduced at or near the conjunction of the converging beams, each beam will in turn be split into a series of diffracted beams. These two series will combine in such a way that the m^{th} order of one series will interfere with the $(m+1)^{\text{st}}$ order of the other, because the grating constant chosen is such that images of the mirrors overlap. Each such combination produces an interferometric pattern covering, with optimum apertures, about one-third the area of the mirrors.

It will be noted that the gratings need not be at the focus of the mirrors, the only requirement being that the image of the first grating be in close proximity to the second. Furthermore, diverging beams are not necessary, a parallel beam of light through the gratings still permitting operation as an interferometer. The light source may even be very broad, as in the Michelson or Mach-Zender interferometer.

A letter to the Editor on this interferometer has been accepted for publication in the Journal of the Optical Society of America.

E. REDUCTION OF TEMPERATURE DEPENDENCE IN PRESSURE GAUGES. (NYU-8R2)

Submitted by- R. W. King, Jr., New York University.

The behavior of bonded bimetallic diaphragms has been studied, and the problem of diaphragm heating is being investigated using various shapes of diaphragms and various coating methods. The experiments on bimetallic diaphragms in which an outer metallic layer is bonded to the standard diaphragm, 1/2" in diameter, with an insulating cement, showed very large values of drift toward negative pressure (bowing outward) for layers of aluminum, stainless steel and invar, .004 to .012" thick. It was found that the amount of drift decreased as the thickness of the bonded layer was reduced, reaching its lowest value upon complete removal of the outer metal layer. The conclusion was drawn that this layer reached an undesirably high temperature because it was insulated by the cement and thereby prevented from transferring its heat to the cooled gauge. Investigation of metal-to-metal bonding of this layer to the gauge diaphragm has not yet been undertaken because other experiments appear more promising, and the construction of such a gauge offers considerable difficulties.

Another test was made in which the gauge diaphragm was covered with a .045" layer of neoprene. This combination showed much less drift than is encountered in the normal gauge when tested with a standard cooling chamber on a small pulse jet engine. The hot gases were found to have no noticeable effect on the neoprene. The frequency response of the gauge was checked in the bursting diaphragm tester and showed no noticeable diminution. Any such effect probably occurs at a frequency above the resonant frequency of the cooling chamber (\sim 5000 cps), which is, at present, the limiting value of the system.

The effect of an insulating layer on temperature drift was confirmed by a similar test using a standard gauge coated with a layer of plastic thermo-setting cement about .020" thick. This unit showed a drift approximately 30 per cent less than the standard gauge unit.

A series of experiments is now being made using diaphragms with curved outer surfaces to see if the forces produced by the thermal gradients can be changed in direction. The experimental set-up consists of an infra-red lamp mounted in front of the gauge whose diaphragm has been painted flat black.

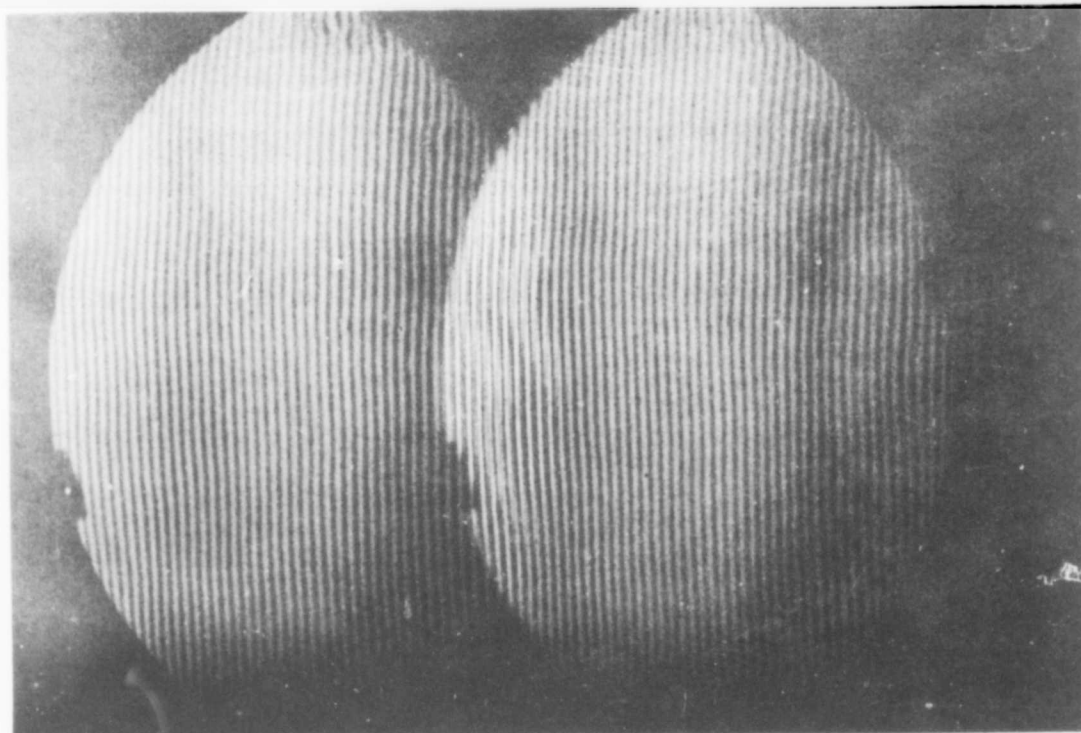


Figure 7 Two images of the undisturbed working area of the diffraction grating interferometer shown in Figure 9. Photograph taken using a 100 Å band-pass filter centered at 6100 Å. Exposure, 1/200 sec. Light source, Zirconium arc.

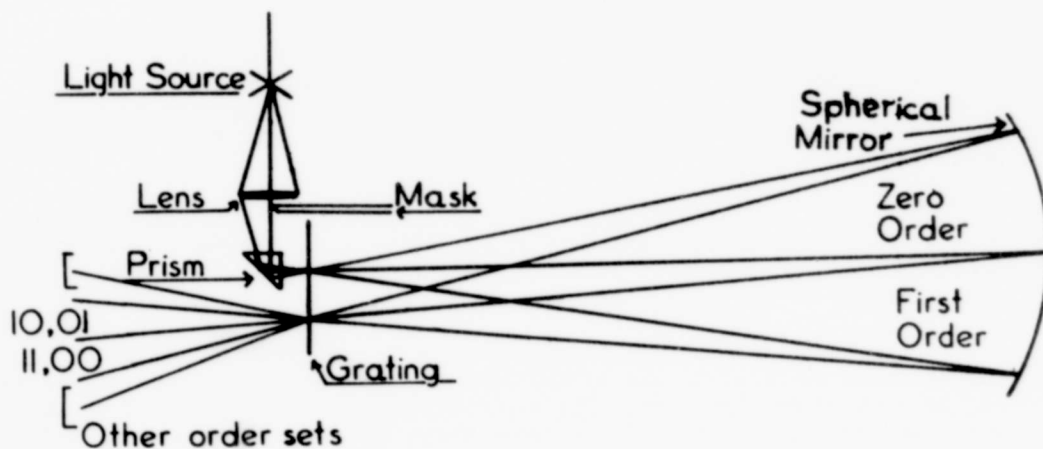


Figure 9 Schematic drawing of NYU single mirror diffraction grating. The spherical mirror used is 16" in diameter, and has a 144" focal length.



Figure 8 Interferometric photograph of heated air rising from a heated metal ring (axial length $1/2$ ", diameter $4-1/2$ ", wall thickness $1/4$ ") taken with system shown in Figure 9.

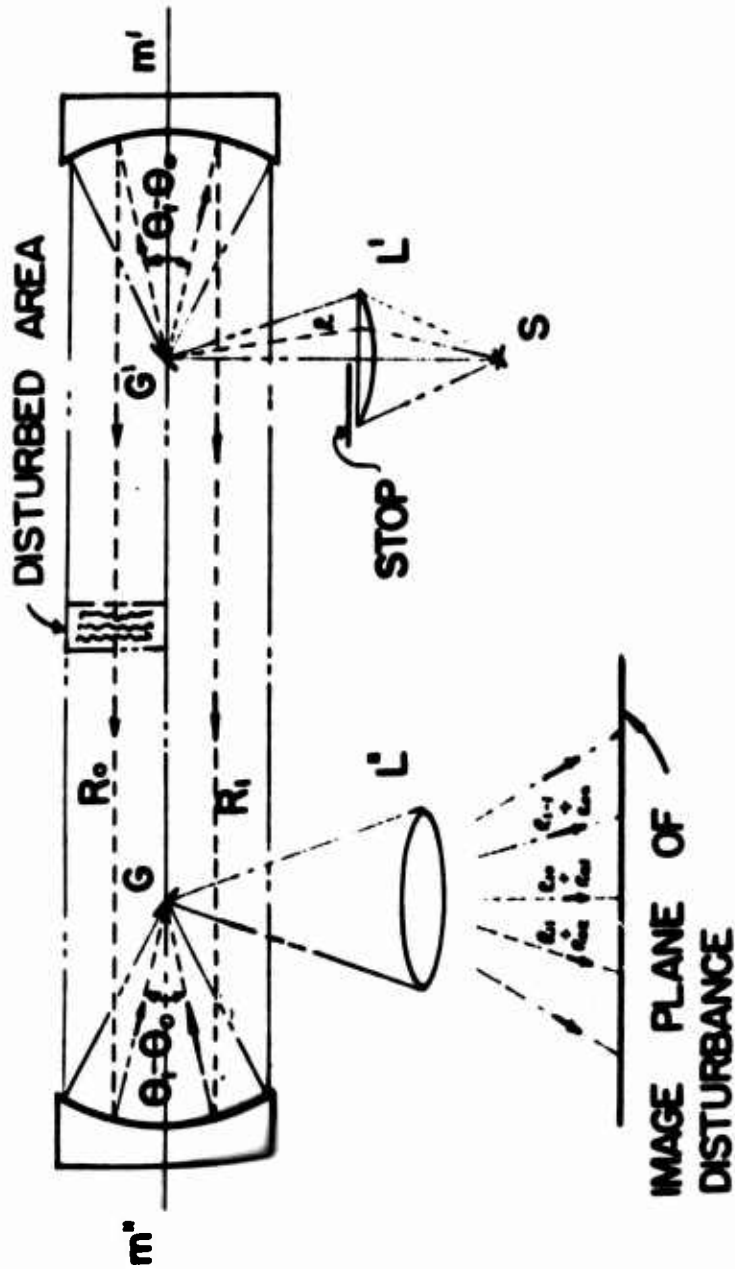


Figure 10 Schematic drawing of double mirror reflectance grating interferometer using parabolic mirrors. In this system now being set up, the light will pass only once through the disturbance.

No cooling chambers are used. The signal from the gauge receiver is recorded on one channel of a Brush recorder. The derivative of this signal is taken electronically, amplified and recorded on the adjacent channel.

Results obtained to date indicate that a standard flat circular diaphragm when exposed to heat bends quickly outwards and then more slowly, but steadily, inwards continuing in this direction as long as heat is applied. Presumably, this drift cannot continue indefinitely, but for runs as long as 20 seconds, the drift rate is steady at values near 0.5 lbs/sec. When the heat source is removed, there is a quick inward deflection just the reverse of the initial outward deflection and then there is a very gradual return to the original rest position (2 min).

The same qualitative result is obtained with a diaphragm whose outer surface is convex with a radius of curvature of 4-1/2".

However, a concave diaphragm of 4.3" radius shows quite different behavior. The initial rapid drift component is reversed in direction, going in the positive direction first. The slower component of drift, though in the same direction as in the previous cases, is of considerably less magnitude and increases slowly during the run. When the heat source is removed, the rapid drift component is negative.

The magnitude of the drifts for all three types of diaphragms seems to depend on experimental conditions and, therefore, the results to date are qualitative.

A new circuit has been designed for the pressure pickup which will simplify the apparatus by eliminating the entire transmitter with its attendant power cable and improve the overall stability by reducing the effect of cable microphonics. A crystal controlled oscillator is used as a frequency source.

The basic principle of operation may be briefly described as follows. A crystal-controlled oscillator feeds a resonant circuit which is coupled by a coaxial cable to a similar circuit at the condenser pickup. Variations in the pickup capacity change the natural frequency of its local circuit and cause a change in the reactive current drawn from the first resonant circuit. This change in reactive current is equivalent to detuning the first resonant circuit slightly and causing a shift in the phase of the circulating current with respect to the applied voltage. This phase shift can be readily measured independently of any amplitude changes by using a 6BN6 tube.¹

1. Electronics, Vol. 23, No. 2, Feb. 1950, pp. 82-85.

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

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

Construction of the extension of the rocket laboratory is nearing completion. A drawing of the extension was included in a previous report.² All major construction has been completed and the new building will be ready for occupancy in approximately one month.

The extension of the power line from the Purdue Airport to the Rocket Laboratory is nearly completed. The power to the Rocket Laboratory has a capacity of 200 KW.

A K-24 Aerial Camera has been installed in the control room and is being employed for photographing the instrument panel for Cell No. 1. A special timing device has been incorporated into the camera so that the number of photographs can be changed at will from three frames per second to one frame every four seconds.

The design of the electrical circuits and the instrumentation of Cell No. 2 have been completed. A bridge-type test circuit for the simultaneous operation of a Brown self-balancing potentiometer, a Consolidated recording oscillograph (type 5-114), and a milliammeter from a single Wiancko pick-up, has been constructed and tested. The circuit was utilized during one rocket test to record the combustion chamber pressure and appears to work satisfactorily.

It is planned to put a 3000 psi torpedo compressor into operation during the next few weeks for supplying pressurizing air to the oxidizer tanks. Two high-pressure gas supply tanks, one for air and one for nitrogen (10 cubic feet capacity) are to be located on the roof of the Rocket Laboratory for storing pressurizing gas. The high pressure will be used for pressurizing the fuel tanks.

All of the components for completing the installation of rocket motor testing apparatus in Cell No. 2 have been ordered. Construction of the thrust stand and of the tank weighing system is in progress.

2. Project SQUID, Annual Program Report, PRF-7R1, 1949, p.165.

VIII. H E A T R E S I S T A N T M A T E R I A L S**A. HIGH TEMPERATURE TENSILE TESTING OF SHEET MATERIALS. (CAL-3R2)**

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

The deformation of iron at high temperatures, as influenced by soluble carbon content, is being investigated. One point of interest in such a study concerns the relationship of interstitially dissolved alloying elements to the mechanism of high temperature creep. Preliminary tests with Armco iron revealed that at 1000°F., a six-fold increase in creep rate was obtained by reducing the original 0.02% carbon content to approximately 0.005%.

Before proceeding with a more systematic series of high temperature creep tests in the 800° to 1200° F. temperature range, procedures have been investigated for protecting the surface of the Armco iron specimen from decarburization and scaling during exposure to the test temperature. It was not possible to achieve specimen protection by maintaining a flow of commercial dry argon through the creep furnace, nor did it seem practical to construct an atmosphere tight creep apparatus in view of the limited magnitude of the project. Trials are currently being made with nickel and chromium plating as a means of surface protection.

Creep tests on Armco iron sheet, treated with wet hydrogen to give several carbon contents varying from 0.001 to 0.02 per cent, will be conducted in the 800° to 1200°F. temperature range. The resulting data will be analyzed to indicate comparative creep strengths and activation energies of deformation for the various carbon grades.

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

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

An investigation of the effects of amplitude and frequency of fluctuating stresses on the high temperature creep properties of Armco iron is being conducted.

A complete series of fluctuating load creep tests has been completed at 1000°F. and a mean stress of 6000 p.s.i. The results of these studies are illustrated in Figures 1 and 2. Figure 1 is a semi-log plot of the minimum creep rate values obtained versus amplitude in per cent of the mean stress. Figure 2 is a log-log plot of minimum creep rate values for constant amplitudes as read from figure 1 versus frequency in cycles of stress per minute. The minimizing effect of amplitude on creep rate as frequency increases is illustrated. In Figure 2, the constant amplitude curves indicate that they would probably intersect at the static mean stress creep rate value at a frequency beyond 1725 cycles.

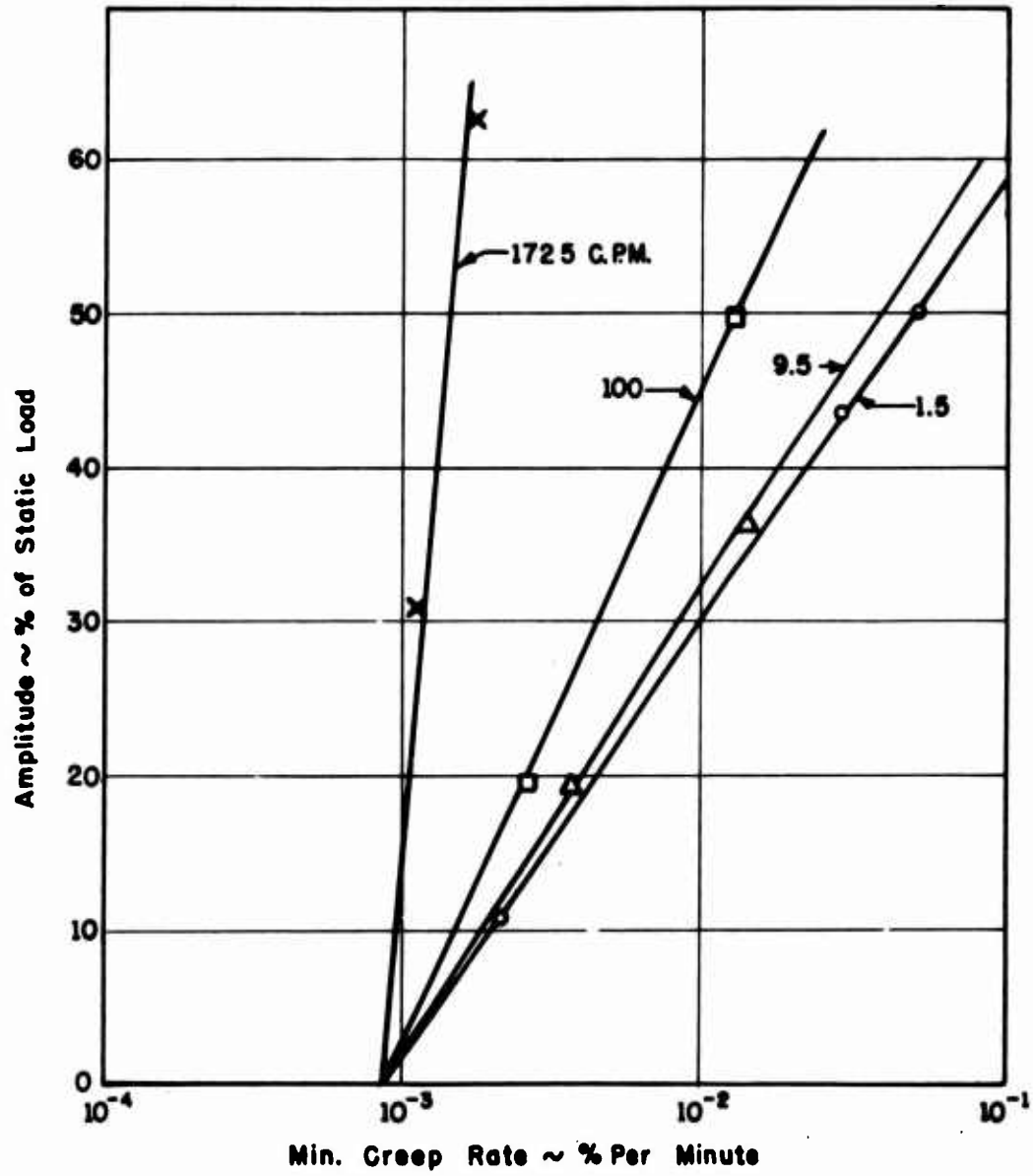


Figure 1 Cyclic Stress Creep Characteristics of Armco Iron 1000°F. 6000 p.s.i. Mean Stress.

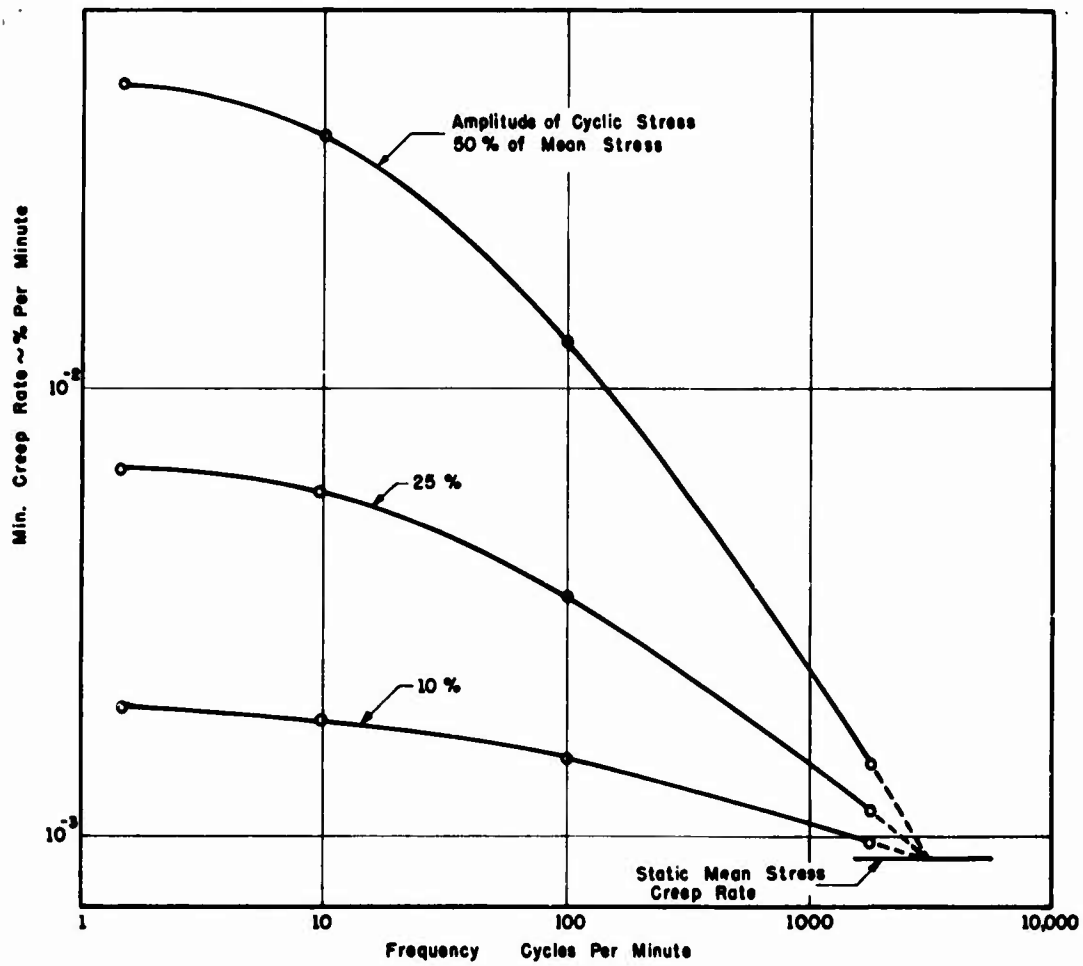


Figure 2 Effect of Frequency of Cyclic Stress on Creep Rate Armco Iron - 1000°F. - 6000 p.s.i. Mean Stress.

Another series of experiments is now in progress at 800°F., 12,000 p.s.i. mean stress and a fluctuating stress at a frequency of 1725 per minute. At this frequency, amplitudes as high as 31% of the mean stress have had a negligible effect on creep rate as compared with the static mean stress creep rate. Additional tests are to be run at this mean stress and temperature but at lower frequencies.

At the lower temperature of 800°F., the frequency, at which the fluctuating component of stress has negligible effect on the mean stress creep rate, appears to be at lower values. In other words, the point of intersection shown in Figure 2 is moved to the left as temperature is decreased. It will be of interest to examine the creep rates obtained under fluctuating stress at frequencies higher than that represented by the intersection of amplitude lines of Figure 2.

C. FATIGUE FAILURE CHARACTERISTICS OF SHEET MATERIALS FOR HIGH TEMPERATURE APPLICATIONS. (CAL-3R4)

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

A paper covering the high temperature fatigue program at CAL was presented at the Project SQUID Conference on High Temperature Fatigue held at Washington on May 24, 1950.

Several general observations can be made as a result of this meeting, which was held to determine the status and the extent of activity in this field of study. The amount of detailed information on high temperature fatigue is very limited. There exists a need for continued investigation into the fundamental mechanism involved. Additional experimental data for theoretical and practical use are necessary. Due to the numerous factors which are involved in the study of high temperature fatigue, and their interrelationship, specialized apparatus to single out the significance of these factors will have to be developed at a reasonable cost and within as short a time as possible.

D. EFFECT OF SIGMA PHASE ON THE STRENGTH OF STAINLESS STEELS. (CAL-3R5)

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

The common occurrence of the sigma phase in the chromium nickel stainless steels, when used or exposed at high temperatures, warrants an understanding of the effect of this constituent on the high temperature strength of these alloys. Little information is available relating sigma bearing alloys with their mechanical properties other than at room temperature. The present series of tests with the 25 chrome - 12 nickel stainless steel are being made to investigate the creep strength properties of this alloy as affected by various sigma contents.

As the result of exploratory aging tests in the 1200° to 1800° F. temperature range, sheet stock of the 309 alloy in both the annealed and

cold worked condition was sigmatized by 1000 hour exposure to 1500°F. Representative microstructures of the material subjected to creep testing are pictured in Figure 3. The microstructures shown represent the initially annealed sigma free condition, with number four austenite grain size, and the two sigmatized structures. Approximately six to eight per cent sigma is present in the specimens aged from the initially annealed condition with austenite grain size unchanged. In the stock originally cold worked 25 per cent, approximately 12 per cent sigma is present with a re-crystallized austenite grain size of about number nine.

A comparison of the creep and fracture strengths at 1200 and 1500°F. in the time range of 1 to 1000 hours is illustrated in Figures 4 and 5 for the three microstructures. At 1200°F. practically no difference exists in the rupture strengths of the three materials, although the stresses, to give one per cent total creep in the time range investigated, show a slight advantage for the sigmatized structures. It is felt that this comparison would be reversed at longer times and lower strain rates. At 1500°F., while the differences in creep strength are not large, the trend is for higher strength in the sigma free structure. The definite inferiority at 1500°F. of the sigma structure produced from the cold work stock is due both to the finer austenite grain size and the finer distribution of the sigma constituent.

Present creep tests are in progress to complete the stress diagrams at times approximating 1000 hour duration. Metallographic study of aged specimens will continue in order to obtain time - temperature - per cent sigma data for the austenitic stainless steels. Although sheet material of 302-B and 316 stainless steel suitable for creep specimens are being sigmatized by aging at 1500°F. for times up to 2500 hours, it is doubtful that creep tests will be made on these alloys in the time available before termination of this project phase.



2000°F. - 30 Min. - Air Cool



2000°F. - 30 Min. - Air Cool
1500°F. - 1025 Hr.



2000°F. - 30 Min. - Air Cool
Cold Worked 25%
1500°F. - 1025 Hr.

Figure 3 Microstructures of Annealed and Sigmatized 25 Cr-12Ni
Stainless Steel. 500X Marbles Etch.

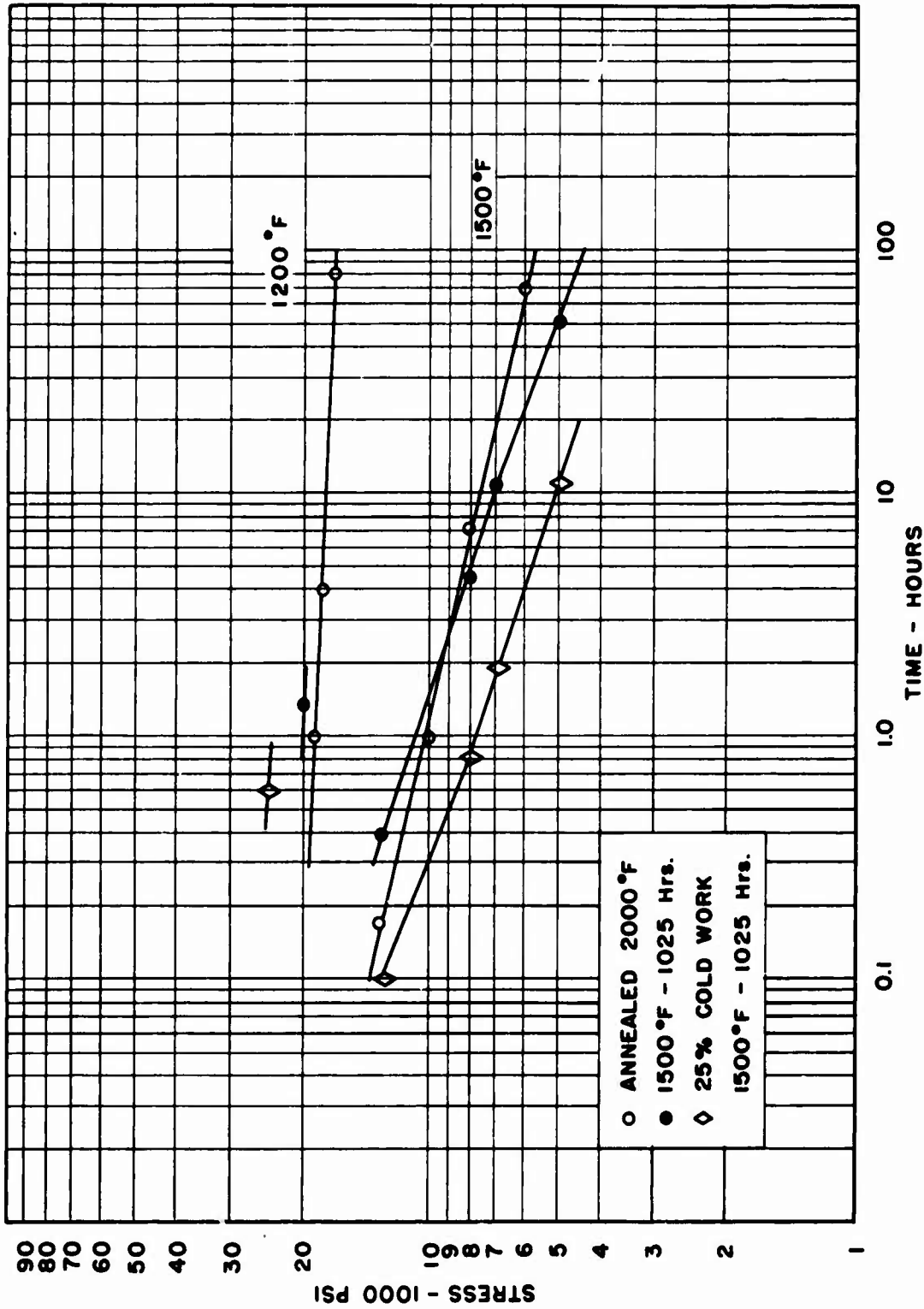


Figure 4 Stress - Time for 1/4 Creep Characteristics of 25Cr - 12Ni Stainless Steel at 1200 and 1500° F.

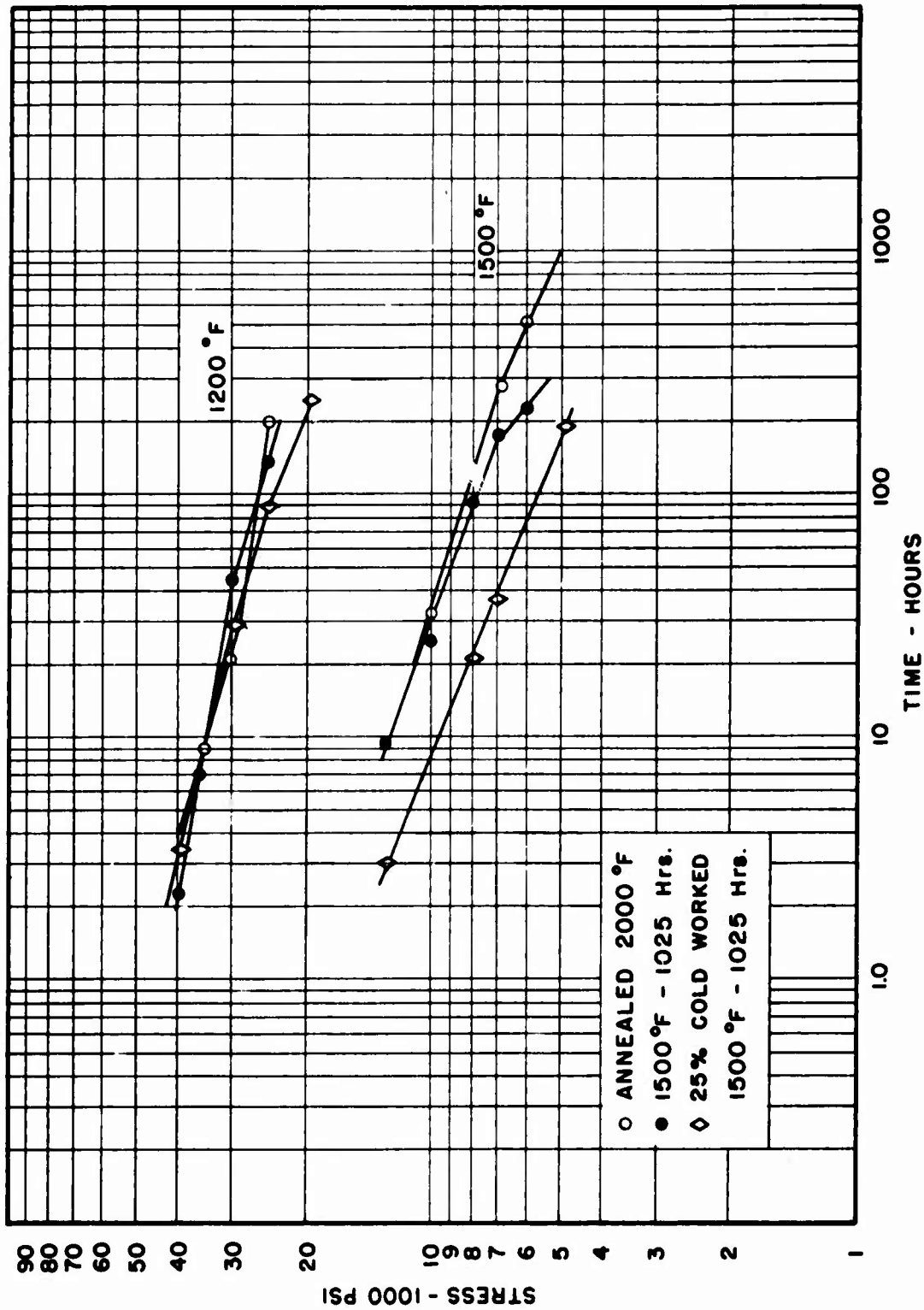


Figure 5 Fracture Stress Characteristics of 25Cr - 12Ni Stainless Steel at 1200 and 1500° F.

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.

	<u>Page</u>
PIB-3R1. An experimental investigation of the stability of the lamina boundary layer above the surface of a porous flat plate with fluid injection.	37
PIB-3R2. A theoretical investigation of the temperature field in the lamina boundary layer (compressible fluid) on a porous flat plate with fluid injection.	36
PIB-3R3. Measurement of pulsejet wall temperatures by X-ray diffraction methods.	79

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-1R1. Study of Pulsejet Operation.	6
CAL-1R6. Propagation and stability of shock waves in supersonic diffusers.	19
CAL-1R7. Investigation of valveless pulsejets.	11
CAL-1R8. Study of the operation of Shrouded Pulsejets.	11

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.

CAL-2R5. Combustion Tube Studies.	41
CAL-2R6. Burner Experiments.	47

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.

CAL-2R9. Investigation of the effect of combustion conditions on the spectra of hydrocarbon flames at low pressures.	67
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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.

	<u>Page</u>
CAL-3R2. High-temperature tensile testing of sheet materials...	93
CAL-3R3. High-temperature short-time creep testing of sheet materials.	93
CAL-3R5. Sigma phase strengthening of high-temperature sheet materials.	96
CAL-3R4. High temperature fatigue testing of sheet materials. .	96

Phase 5
Phase Leader: J. V. Foa

Investigation of transient phenomena contributing to rough burning in ramjets.

CAL-5R1. Study of Flow Oscillations in ramjets.	24
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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.

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.	31
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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.	26
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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.

Page

DEL-2R2. A study of the stability conditions, the fluctuations, and other properties of turbulent flames with the help of the hot-wire anemometer. 47

DEL-2R6. A spectrophotometric study of local flame radiation. . 67

JOHNS HOPKINS UNIVERSITY

Phase 1

Phase Leader: L. S. G. Kovaszney

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. 79

Phase 2

Phase Leader: Ion Cerstiou

To make contributions to the fundamental theory of turbulence with particular emphasis on the case of isotropic turbulence. . . 23

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.	17
NYU-6R2. Oscillating Piston Engine.	15

Phase 7

Phase Leaders: G. E. Hudson and I. Amron
 Associates: R. J. Krauschaar, 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.

NYU-7R6. Large amplitude gas vibration theory.	19
NYU-7R7. Photo-ignition.	14
NYU-7R8. Hydrocarbon Flame Bands.	67
NYU-7R9. Theory of nonlinear conduction in solids.	25

Phase 8

Phase Leader: J. H. Nett
 Associates: R. W. King, J. E. 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.

NYU-8R1. Temperature measurement.	77
NYU-8R2. Effect of temperature on Pressure Gauges.	67
NYU-8R4. Three-dimensional schlieren apparatus.	86

PRINCETON UNIVERSITY

Phase 2¹

Phase Leader: R. N. Pease

To study (1) the characteristics of combustion in high-velocity fueloxidant 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.

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

	<u>Page</u>
PR-2R1. Development of a Low-Pressure Burner.	51
PR-2R2. Kinetics of Combustion of Gaseous Boron Compounds. . .	13
PR-2R4. Interaction of Hydrogen Atoms with Oxygen and Hydrocarbons.	13
PR-2R5. Kinetics of noncatalytic combustion of ammonia. . . .	54
PR-2R6. Photochemical Explosion of Hydrogen-Chlorine Mixtures. .	54

Phase 4
Phase Leader: A. Kahane

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

PR-4R1. Investigation of a Valveless Intermittent-jet Engine... .	4
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Phase 5
Phase Leader: J. V. Cheryk

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. 64

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.	59
--	----

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.	40
---	----

Phase 7

Phase Leader: M. J. Zucrow

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

PRF-7R1. Design, construction and instrumentation of a rocket test facility.	92
PRF-7R3. Investigation of ignition lag of spontaneously ignitable propellants.	55
PRF-7R5. Catalysis of the Reactions of non-hypergolic propellants.	57
PRF-7R8. Experimental investigation of the effect of combustion chamber pressure upon rocket motor performance. . .	1
PRF-7R9. Experimental Investigation of the Effect of Combustion Chamber Pressure upon Heat Transfer in Rocket Motors.	1
PRF-7R10. The Cooling of Rocket-Motor Nozzled by Transpiration cooling through parallel disks.	25

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, DP.
2. R. Courant, New York University.
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**QUARTERLY PROGRESS REPORT - AND APPENDIX
A, by C.F. Warner, C.M. Beighley, J.V. Charyk, and
others. July '50, 109 pp. incl. photos, tables, diags,
graphs, dwgs. UNCLASSIFIED**

A quarterly progress report is presented on Project
Squid. This is a cooperative program of fundamental
research in jet propulsion, with several universities
contributing reports pertaining to jet propulsion en-
gines, fluid mechanics, heat transfer, characteristics
(over)

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