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UNITED STATES NAVY

PROJECT SQUID

FIELD SURVEY REPORT

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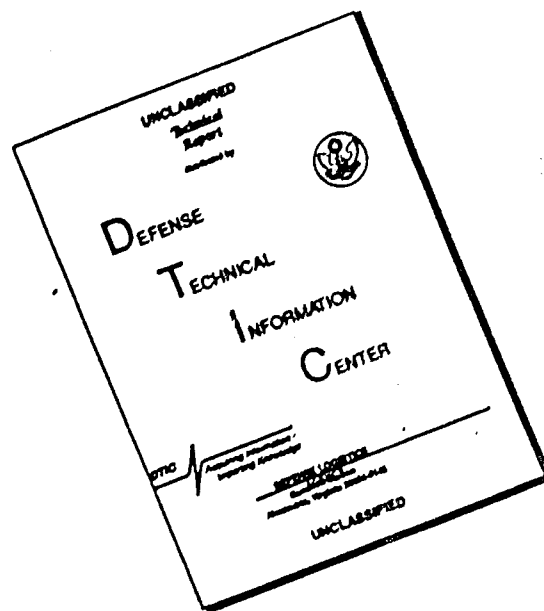
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FIELD SURVEY REPORT

Volume I: RESEARCH

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- Part 2. Fuels A. W. Sloan
- Part 3. Materials R. C. Bryant
- Part 4. Fluid Mechanics J. H. Wakelin
- Part 5. Heat Transfer and Cooling George Vaux
- Part 6. Instrumentation J. W. Fitzgerald

Volume II: DEVELOPMENT:

- Part 1. Pulse Jet Engines F. A. Parker

PROJECT SQUID

COMBUSTION

Field Survey Report

Volume I, Part 1

by

ROYAL C. BRYANT AND ARTHUR W. SLOAN

Engineering Research Associates, Inc.

Washington, D. C.

30 June 1947



Princeton University, the central management organization of Project SQUID, arranged for the preparation of the *Field Survey Report* under Contract N6ori-105, Task Order III, with the Office of Naval Research, Navy Department.

This report was prepared by the Technical Survey Group of Project SQUID as a cooperative effort of Princeton University and Engineering Research Associates, Inc. Engineering Research Associates was given primary responsibility for the preparation of these reports in accordance with the provisions of Task Order II under Purchase Order Number 08451 with Princeton University.

TECHNICAL SURVEY GROUP

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FOREWORD

The *Field Survey Report* on liquid propellant rockets and pulse jet engines was prepared at the suggestion of the Policy Committee, in order that the fundamental research in Project SQUID might be related to other projects and programs of research in this field, and to problems arising in the development of rocket and pulse jet engine equipment.

In order to fulfill this purpose the *Field Survey Report* had to be more than a brief outline of the work of each contractor, but time did not permit it to be prepared as a monograph in each branch of the field of propulsion. The choice of presentation of the work in each volume of the report was governed in part by the amount of available information, and by its relation to the research now being sponsored by Project SQUID.

The Policy Committee will use the *Field Survey Report* as a basis for adjustments in the research program of Project SQUID, in order to ensure a more effective attack on the fundamental problems in the field of propulsion. The Policy Committee hopes that this report may also be useful to scientists conducting research and development in fields relating to propulsion, and to members of government organizations responsible for the planning and integration of research programs in propulsion.

HUGH S. TAYLOR, Chairman
Policy Committee, Project SQUID

P R E F A C E

The Field Survey Report was prepared by the Technical Survey Group, Project SQUID, under the direction of Engineering Research Associates, Inc.

The assembly of the material and the preparation of each part of the report was undertaken as a group effort, to which the staffs of both Princeton University and Engineering Research Associates, Inc., have contributed. Mr. F. A. Parker, Project Organizer, and Mr. W. C. House, Chief Technical Aide, of the central administrative staff of Project SQUID at Princeton served as members of the Technical Survey Group and prepared Volume II. In addition, Prof. J. V. Charyk of the Aeronautical Engineering Department at Princeton visited the California Institute of Technology and furnished basic information concerning the research program there. He also offered many helpful suggestions with regard to several parts of Volume I.

In the preparation of this report the members of the Technical Survey Group have received the assistance, counsel and cooperation of representatives of the War and Navy Departments and other Government agencies, and of representatives of academic and industrial laboratories who are under contract to the government for research and development in this field.

The authors are indebted to a number of scientists who have reviewed each part of the report and have offered much constructive criticism. The authors also wish to express their appreciation for the assistance which was so generously given by representatives of the Office of Naval Research and of the Bureau of Aeronautics.

THE TECHNICAL SURVEY GROUP

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I. SUMMARY

This report summarizes the research work on combustion being carried on under government sponsorship. In addition, a few projects under private sponsorship are included, the information having been made public. Brief discussions of the status of knowledge in fields of research important to combustion are given, to indicate the relation between the outstanding problems and the present research program.

The quantitative description of the combustion process in terms of the detailed mechanisms involved is possible at present only in principle. Before this can be achieved, formidable mathematical difficulties remain to be solved, and the separate phenomena which are part of the general combustion process must be investigated experimentally. The present research program on chemical kinetics, effect of turbulence on

combustion, and chemical reactions in flowing streams should be particularly important in this regard.

The research on ignition of combustible mixtures, normal flame velocity, conditions for maintaining stable flames in laminar and turbulent flow, and combustion in liquid sprays, is described. It appears likely that equations can be developed relating normal flame velocity to other observed flame phenomena, important from both the practical and theoretical points of view.

The acoustic vibrations caused by flames and the possibility of using acoustic fields in the study of flame phenomena are discussed.

Some of the combustion work being carried on in connection with the design of jet power plants is described to indicate the type and scope of the problems in combustion engineering.

II. RECOMMENDATIONS

It is believed that the program described in this report covers rather well the most significant and necessary projects in the field, though it is quite evident that more people should be working on such projects. It is also felt that some elaboration of the program should be made in the following specific instances:

- A. Investigations of the mechanisms and the rates of reactions must be extended to include the propellant systems now being used in jet power plants and those proposed for future use. Metals, metal alkyls, metal hydrides, and hydrazine and their reactions with the usual oxidants need to be investigated. Similar information for the reactions of fluorine and its derivatives with fuels is pressingly required. Considerable work is being done on developing new techniques for studying the mechanism of combustion reactions but there is still a need for studying propellant systems, particularly liquid systems, using any techniques which may be available.
- B. Chemical equilibria should be studied at high temperatures and pressures in static and flowing systems to determine the concentrations of the components at equilibrium, the time required

for the establishment of equilibrium, and thermodynamic properties as a function of time. Studies of reactions in which some of the products are solid and the others gaseous are needed. This information, which is not available, is necessary for the accurate computation of rocket performance.

- C. The thermodynamic properties of fuels and products of combustion should be determined at high temperatures over a range of pressures to give data for combustion calculations and for checking theory with experiment. Calculations and measurements are being made of some of these properties for some of the compounds, but the program needs to be extended.
- D. Basic studies of combustion at high and at low pressures should be extended. Liquid propellant rockets operate presently at 300-400 pounds per square inch pressure, solid rockets up to 2000 pounds per square inch. Investigations of the reactions of fuels with oxidizers at pressures at least up to 200 atmospheres (3000 pounds per square inch) are necessary. Determination of the mechanism of combustion may be more practicable at low pressures than at atmospheric

pressure, and valuable information may be obtained although the reactions may not be the same at low pressures as at atmospheric pressure.

- E. Investigations of the effect of turbulence on combustion are of prime importance, and it appears that further development of the theory of turbulence and of techniques for measuring turbulence will be necessary in this connection. Turbulence is discussed in more detail in Part 4 of this Volume, "Fluid Mechanics."
- F. The development of techniques for measuring the pressure, temperature, and velocity of moving gas streams should be emphasized here, although it will be mentioned again under Part 6 on "Instrumentation." Instrumentation is one of the most difficult problems in combustion work.
- G. More attention should be given to basic studies of ignition phenomena. Little is known about the energy requirements or about methods of reducing ignition delay.
- H. Many combustion investigations have had too limited objectives. The studies have been carried out to learn what happens under specified experimental conditions with too little consideration of possible contributions to the understand-

ing of the basic factors involved. Wherever possible, even in essentially development programs, experiments should be performed under simple, well-defined, and accurately measured conditions, so chosen that the results can be interpreted in terms of fundamental parameters. The immediate objective of combustion research is to develop quantitative relations between appropriate variables. The ultimate objective is to explain combustion in terms of the detailed mechanisms involved. These objectives can be attained only if suitable experimental data are available to check and guide theory.

It is possible that it should be made to coordinate the efforts of different groups working toward solutions of the same problem. Such coordination appears particularly desirable for studies described in this report under the headings: Chemical Kinetics, Turbulence, Flame Velocity and Stability, and Combustion in High Speed Gas Streams. These difficult and important problems, requiring the efforts of several groups, can be solved only if there is a free exchange of information on results, procedures, and experimental difficulties at the technical as well as the administrative level.

III. INTRODUCTION

The importance of the study of combustion arises from the fact that present knowledge is inadequate to provide a theoretical basis for the design of jet power plants. The characteristics and efficiency of the combustion in a power plant depend on factors such as the following: fuel injection; mixing; ignition; fuel oxidant ratio; pressure, temperature, and velocity of fuel and oxidant; size and shape of the combustion chamber; nature of the flow; and the physical and chemical properties of the fuel and oxidizer. The present state of knowledge is such that design is largely a matter of trial and error, based on the results of a large number of experiments in which one component of the chamber after another, or one of the above factors, has been slightly altered and the effect on the combustion observed. The main objective of combustion research is to obtain a basic understanding of each of the above factors and of the combustion process as a whole. Without this understanding, it will not be possible to achieve the most effective design of jet power plants, particularly for large units.

In practical installations, a non-homogeneous mixture of fuel and oxidant in turbulent flow is burned. Because such a system is too complicated to study in any but an empirical way, subdivision is necessary so that simpler components can be investigated separately. Accordingly, the research program on combustion may be considered to involve the following general investigations: (a) an investigation of non-homogeneous systems, with and without burning, including particularly the impinging of liquid streams, formation of liquid sprays, evaporation, and mixing; (b) an investigation of turbulent flow and the mutual interaction between turbulent flow and the chemical reaction of combustion; and (c) a theoretical and experimental investigation of all phases of flame phenomena without the complications of non-homogeneity and turbulence.

The problems of non-homogeneous mixtures and turbulent flow belong essentially to fluid mechanics and are discussed in Part 4 of this Volume. Research projects on the influence of these factors on combus-

tion, however, will be reviewed here. The instrumentation problems of combustion and a discussion of the physical and chemical aspects of combustion which influence measurement and measurement techniques are given in Part 1 of this Volume. The thermodynamic properties of chemical compounds and certain other problems common to a discussion of fuels and of com-

bus-tion are given in Part 2 of this Volume. The main concerns of this Part are the theoretical and experimental investigations of flame phenomena. A brief review of some of the development work connected with combustion will be given in order to indicate the scope of the problems which have to be solved in combustion engineering.

IV. SURVEY OF RESEARCH PROJECTS

An attempt has been made to group the projects discussed below according to the objectives of the research. However, because many of the projects include an investigation of the effects of several parameters on flame phenomena, it is impossible to achieve a completely logical classification and at the same time give an adequate description of the overall research program of a given institution. Therefore, wherever it appeared desirable, a compromise has been adopted in which work may be described under a heading which does not include all phases of the research.

A. Basic Flame Studies

1. SURVEYS. A group at Brown University¹ is reviewing all of the German information and literature bearing on the subject of compressibility of gases and compressible flow. In certain cases, information from American and British sources will be included in addition to the German. The results of this work will be available in the form of monographs on the following subjects: (a) Compressible Flow, a digest of all available literature; (b) Non-Stationary Flow; (c) Combustion; (d) Shock Waves; (e) Stability in Compressible Flow.

Cornell Aeronautical Laboratory² is preparing a series of reports in the nature of textbooks, the first of which treats the theory of flame propagation. This report reviews the older thermal theory, the new theory of Zeldovich, and recent work on the influence of turbulence. The report has been written and will shortly be issued (19). A second report has just been started which will cover the experimental phases of flame propagation.

A report giving a brief discussion of turbulence and of the effect of turbulence on combustion phenom-

ena has been prepared by Experiment, Inc.³ A bibliography of 169 references is included (2).

A conference on combustion was held at the Applied Physics Laboratory of Johns Hopkins University on March 17-18, 1947. The technical papers and descriptions of the research at various institutions which were presented at this meeting are given in reference (11).

2. THEORETICAL STUDIES. In principle it is possible to derive a set of equations which will describe the combustion process. In addition to the equations of fluid dynamics, the following factors must be considered for the general case: the heat of reaction; the conduction of heat; the molecular diffusion of the particles taking part in and formed by the reactions; the effect of any mass flow or turbulent condition which may influence the transportation of energy and matter; the specific chemical reactions taking place, and their velocities; the effect of radiation; and the energy associated with elastic wave propagation. These factors must be known as functions of temperature, of course. It is to be noted that the study of chemical reactions in flowing streams is important and is different from the static case in that consideration of time, distance, and condition of flow must be introduced. The general case has not been solved, because of formidable mathematical difficulties, lack of convincing theoretical and experimental treatment of the separate phenomena which must be combined to give the general case, and lack of exact knowledge of the physical and chemical conditions which exist in a flame. Because of these difficulties, it may be more practicable to treat combustion phenomena in aerodynamic and combustion terms than to introduce the detailed mechanisms involved.

Quantitative treatments of combustion phenomena have been given for cases in which the process is controlled by one or two relatively well-known factors.

¹Brown University, Providence, Rhode Island; John Marchant; AAF Contract W-33-038-ac-15004 (13651); *Restricted*.

²Cornell Aeronautical Laboratory, Ithaca, N. Y.; J. H. Seely; Subcontract with Curtiss-Wright Corporation, Airplane Division, BuOrd Contract NOrd 8993; *Confidential*.

³Experiment, Inc., Richmond, Virginia; J. W. Mullen, II; BuOrd Contract NOrd 9756; *Confidential*.

For example, the combustion velocity of the laminar diffusion flame (a laminar jet of combustible gas burning in an oxidizing medium) is determined by the molecular diffusion process, and flame parameters can be calculated with relatively good agreement with experiment (4, 13). If the reaction rate in a combustible mixture is sufficiently great, ignition of the mixture may result in a detonation that is controlled by fluid dynamic factors rather than by the reaction rate. Thus Lewis and Friauf have been able to calculate, from thermodynamic and fluid dynamic considerations, the detonation velocities of mixtures of hydrogen and oxygen with varying amounts of argon, helium, or nitrogen added (17). The calculated results have shown excellent agreement with observations.

The normal combustion of premixed gases, however, is the case of general interest, the first treatment of which was given by Mallard and LeChatelier from heat conduction considerations alone (18). They assumed that the gas is heated to the ignition temperature by conduction from the burning zone and that after ignition the reaction takes place at a constant rate independent of temperature. Diffusion and change in concentration of reactants during burning are neglected. It is assumed that the temperature gradient in the burning zone is constant and that average values of the specific heat and thermal conductivity may be used. With these conditions postulated, the following equation was derived:

$$V_N = \frac{\lambda}{c_p \rho d} \frac{(T_1 - T_i)}{(T_1 - T_0)} \quad (1)$$

In this equation V_N is the normal velocity of flame propagation, λ the (constant) thermal conductivity, c_p the (constant) specific heat, ρ the density of the unburned gas, d the thickness of the combustion zone, T_1 the final temperature, T_i the ignition temperature, and T_0 the initial temperature of the unburned gas. This equation has obvious limitations because of the nature of the assumptions used in its derivation. Nevertheless, it has recently been used by Danköehler

for an estimate of the thickness of the combustion zone (8), and it is felt by Lewis that its possibilities have never been fully explored (11). The concept of ignition temperature in the Mallard-LeChatelier equation being a property of a gas mixture independent of combustion conditions has been criticized.

An extension of the Mallard-LeChatelier equation to include effects of the decrease in concentration of the reactants during burning has been made by various authors, making use of the original assumptions, and introducing others concerning the reaction velocity. Several equations so developed may be put essentially in the form (13):

$$V_N = \sqrt{\frac{\lambda}{c_p \rho} f (T_1 - T_0)} \quad (2)$$

where f depends on the (constant) reaction velocity and the other symbols have the same meanings as in equation (1). In a different treatment of this same situation, the following equation has been proposed (28):

$$\frac{T_1 - T_0}{T_1 - T_i} = \frac{1 - e^{-b}}{b} \quad (3)$$

$$\text{where } b = \frac{V_N^2}{\lambda} c_p \rho f$$

and the other symbols have the same meanings as in equations (1) and (2). Equations (2) and (3) may be criticized, of course, on the same grounds as equation (1), because the same assumptions were used, and hence they can be expected to have only a limited application.

An attempt has been made to remove some of the restrictions imposed on the above equations by an analysis which considers molecular diffusion and the effects of temperature on reaction rate, thermal conductivity, and specific heat. For details, references (28, 50) should be consulted. For bimolecular reactions, an approximate solution of the equation is:

$$V_N = \sqrt{\frac{2 \lambda^* (k a_0)}{L^3} \left(\frac{T_0}{T_1}\right)^2 \left(\frac{\Lambda}{B}\right)^2 \left(\frac{n_1}{n_2}\right)^2 \left(\frac{RT_1^2}{E}\right)^3 e^{-\frac{E}{RT_1}}} \quad (4)$$

In the derivation of this equation, it has been assumed that the rate of reaction, W , is given by

$$W = k a^2 e^{-\frac{E}{RT}}$$

where k is a constant, a is the number of molecules per unit volume of the combustible, E is the activation energy, R is the gas constant, and T is the temperature. The other symbols in equation (4) are defined as follows:

- λ^* - thermal conductivity at temperature T_1 .
- a_0 - the number of molecules per unit volume of the combustible in the initial cold mixture.
- ρ - density of the original mixture.
- L - heat of combustion of 1 gram of the initial mixture.
- T_0 - initial temperature.
- T_1 - final temperature.
- $\frac{A}{B}$ - ratio of λ c_p to Dz , D the diffusion coefficient.
- n_1 - ratio of the number of molecules before the reaction to the number after the reaction.

Calculations of the combustion velocity of glycol-dinitrate and of carbon monoxide according to Equation (4) have given satisfactory agreement with observed values. It should be noted that such expressions as Equation (4), if proven valid, offer a means of determining the reaction rates of very fast reactions by measurements of flame velocities.

Important factors which remain to be considered in combustion theory are the specific effects of the active particles in chain reactions and the mutual interaction between chemical reaction and turbulent flow. Little is known about these factors, and they will have to be investigated before they can be introduced into the theory. In fact, this brief review of some of the early theoretical developments in combustion theory indicates the importance of experimental combustion research under conditions such that the results can be interpreted in terms of the significant parameters.

A group at New York University⁴ is developing the mathematical theory of gaseous viscosity, thermal conduction, and diffusion for non-uniform gases for systems without chemical reactions and for systems with chemical reactions. It is important, if the theory is to furnish useful results, that certain characteristics of chemical reactions be explained by theory rather than introduced as hypotheses. A careful study of a variety of models is going on with a gradual reduction in the number of assumptions which are necessary. Some equations have been devised, but due to their complexity, analytic solutions seem feasible only under very special conditions.

Theoretical calculations are being made by New

⁴New York University, New York, N. Y.; J. K. L. MacDonald; ONR Contract N6-ori-11, T.O. -2, *Unclassified*.

York University on transient velocities and pressures in semi-open flame tubes using one-dimensionalized thermo-aerodynamical equations. Calculations for pressure, temperature, and flame front positions as a function of time have been made in terms of the parameters: rate of release of energy per unit mass, velocity, and acceleration of the flame front with respect to the gas. The theoretical work is closely correlated with the experimental work described elsewhere in this Part. The calculations have been made to fit data on flame propagation in a four-foot tube and may easily be adapted to fit the data which will shortly be obtained with an eight-foot tube. Extension of the theory has been made to include a definite zone of burning, about two or three feet long, in the eight-foot tube. A formal report on these theoretical considerations will shortly be prepared by New York University.

An extensive theoretical and experimental research program on the fundamentals of combustion is planned at the University of Wisconsin.⁵ The general objective of the project is to bridge the gap between chemical kinetics in static systems on the one hand and the performance of practical burner systems on the other. It is planned to calculate the thermodynamic properties of air from 0° K to 5000° K and the specific impulse and flame temperatures of hydrocarbon fuels. The theory of turbulence will be adapted to conditions within the flame zone. In order to make a theoretical study of flame propagation, it will be necessary to develop aerodynamical equations for a compressible fluid in which chemical reactions are taking place. In addition, it will be necessary to develop the theory of chemical kinetics in flow systems, taking into account radiation, turbulence, heat conduction, and viscosity. It is expected that the theoretical treatment will result in complicated equations, which may be very difficult to solve accurately. However, attempts will be made to get approximate solutions in closed form in order to determine the natural grouping of the constants. Initial work seems to indicate that the Chapman-Cowling treatment of non-uniform gases may not be the best approach to the problem, and other theoretical methods will be tried. An experimental program, described elsewhere in this Part, will be carried out to check and to guide the theoretical work.

3. TURBULENCE. It has long been known that motion of a combustible mixture increases the rate at which the mixture will burn. If the usual assumption is made that the normal flame velocity is a constant

⁵University of Wisconsin, Madison, Wisconsin; J. O. Hirschfelder; BuOrd Contract NOrd 9938; *Restricted*.

characteristic of a given combustible mixture, then the effect of motion must be ascribed to an increase in flame area, and it has been proved for many cases that flame areas do account for observed variations in rate of burning. Recently, equations have been proposed giving turbulent flame velocity in terms of normal flame velocity and other parameters, but more experimental work is needed to confirm these relations.

There have been only a few theoretical or experimental investigations of the effect of turbulence on flame propagation (8, 11, 29, 30), because suitable theoretical and experimental techniques have been developed only in the last few years. This work has recently been reviewed by Barr (2).

Danköehler (8) considers that for turbulence whose scale is much larger than the thickness of the flame front, the area of the flame surface will increase and that the turbulent flame velocity will be proportional to the intensity of turbulence. For turbulent flow in which the scale is smaller than the thickness of the reaction zone, he proposes the following relation:

$$\frac{V_T}{V_N} = \sqrt{1 + \frac{K}{\nu}}$$

where V_T is the turbulent flame velocity, V_N is the normal flame velocity, K is the coefficient of turbulent exchange, and ν is the kinematic viscosity. Calculated velocities of the turbulent flame were 30% higher than the maximum observed flame velocities. This was attributed to the presence of both large and small scale turbulence. According to the above expression, the turbulent flame velocity will approach zero, not the normal flame velocity, as the coefficient of turbulent exchange decreases.

Three cases have been considered in another study (29):

- (a) If the scale of turbulence is less than the width of the reaction zone, the following relation is proposed:

$$\frac{V_T}{V_N} = \sqrt{1 + \frac{K}{\lambda}}$$

where V_T is the turbulent flame velocity, V_N is the normal flame velocity, K is the coefficient of turbulent exchange, and λ is the thermal conductivity.

- (b) If the scale of turbulence is of the same order as the width of the reaction zone, the reaction time will be determined by the speed of mixing and not by the speed of reaction.

- (c) If the scale of turbulence is large compared to the width of the reaction zone, the expression for turbulent flame velocity is found to be:

$$\frac{V_T}{V_N} = \sqrt{1 + B \left(\frac{v'}{V_N} \right)^2}$$

where V_T is the turbulent flame velocity, V_N is the normal flame velocity, v' is the root mean square value of the velocity fluctuations, and B is a constant.

An accurate check of the theory has not been made, but the theory appears to be in qualitative agreement with observations of flame speeds in engines.

The above discussion shows that quantitative investigations of the effect of turbulence on flame phenomena are in their very early stages. The effect of turbulence is believed by some workers to be the most important single factor in the design of combustion systems for jet power plants, and it is necessary that a better understanding of the phenomena involved be obtained.

A review of the studies of the effect of turbulence on combustion is given below. For discussions of turbulent flow as such and of instrumentation problems, see Part 4, "Fluid Mechanics," and Part 6, "Instrumentation," of this Volume.

A program to study mixing phenomena and to develop experimental techniques for the study of combustion in a rocket motor has been started at Battelle Memorial Institute.⁶ A survey of the past and the current research in the field will be carried out first. Preliminary plans for the experimental part of the program include an investigation of the fundamentals of mixing of liquid-liquid, liquid-gas, and gas-gas systems. In connection with this study, techniques for the sampling and analysis of products of combustion from the rocket nozzle and from within the rocket motor will be developed. Methods of measuring the temperature of the gas at the nozzle and in the combustion chamber will be studied.

The Cornell Aeronautical Laboratory⁷ has started an investigation of the influence of different parameters, in particular turbulence, on the velocity of flame propagation, under controlled conditions of temperature, air-fuel ratio, and pressure (7). A cylin-

⁶Battelle Memorial Institute, Columbus, Ohio; R. A. Sherman; Materials, Fuels, and Combustion Project, Project RAND; Confidential.

⁷Cornell Aeronautical Laboratory, Buffalo, N. Y.; J. L. Beal; Confidential; not to be distributed outside the Laboratory; not classified.

drical pyrex combustion chamber, two feet long and six inches in diameter, is provided with a series of spark gaps along the tube. The gaps are sparked successively at a known rate, and the flame front is photographed. The angle of the flame front and the known ignition rate along the tube are used to determine the flame velocity. The effect of turbulent motion of the gas in the combustion chamber on the flame velocity will be investigated.

The University of Delaware⁸ is studying mixing and turbulence using the shadowgraph technique. The mixing of streams of carbon dioxide and air has been investigated as a function of flow velocity, size, and angle of the stream. Best mixing is obtained by opposed jets, as would be expected. Shadowgraphs of turbulent jets show a mottled effect, the size of the irregularities increasing down the jet. This suggests the possibility of determination of the scale of turbulence from the photographs, which cannot be done until means are developed to interpret the shadowgraph quantitatively. Experiments will be carried out on simple systems, for which the diffusion of one gas into another can be calculated, to clarify the interpretation.

Research on turbulent diffusion flames at the University of Delaware has recently been reported (11). Flame heights were measured as functions of average flow velocity, tube diameter, and coefficient of turbulent exchange in order to correlate observed functional relationships with the expressions calculated from turbulence theories. Preliminary indications are that present theories do not account for the observations.

From work on the action of flame holders in high velocity air streams, it is concluded that the nature of the flow around an igniter has a great deal to do with the type of combustion. Experiment, Inc.⁹ plans to investigate turbulence phenomena in the region of the pilot flame, with direct measurements of the transport of heat and matter through the reaction zone. Fluorescent materials or radioactive isotopes may be introduced into the gas stream to measure the mixing directly. The possibility of making measurements of the temperature, pressure, turbulence, and composition throughout the reaction zone will also be investigated. The application of the theory of turbulence to simple, easily evaluated experiments is to be the subject of future work.

The Applied Physics Laboratory of Johns Hopkins

⁸University of Delaware, Newark, Delaware; Kurt Wohl; Subcontract with United Aircraft Corporation, East Hartford, Connecticut; BuOrd Contract NOrd 9845; *Confidential*.

⁹Experiment, Inc., Richmond, Virginia; J. W. Mullen, II; BuOrd Contract NOrd 9756; *Confidential*.

University¹⁰ is undertaking the experimental determination of the effects of turbulence on flame propagation (12). The apparatus includes a rectangular combustion chamber 2 inches on a side and 2 feet long, through which a homogeneous mixture of air and propane flows with velocities from 0 to 50 feet per second. A horizontal rod $\frac{1}{8}$ inch in diameter is used as a flame holder. Visual and photographic observations can be made through a quartz window in the combustion chamber. Turbulence is created in the gas stream by the introduction of screens or perforated plates upstream from the flame holder, so located that isotropic turbulence is produced at the flame holder. The scale and intensity of the turbulence is measured by a hot wire method, using a Wollaston wire about 1 millimeter long and a few ten thousandths of an inch in diameter. The apparatus is calibrated by oscillating a wire in a non-turbulent stream. The hot wire method cannot be used in the flame and therefore it will be necessary to determine, by other methods, the turbulence in the flame as a function of the turbulence in the gas stream without a flame.

The velocity and direction of flow is determined by the standard method of introducing aluminum flakes and illuminating them intermittently from the side. The initial results with this method have been quite satisfactory and have shown that the stream lines are crowded toward the boundary, giving a large velocity increase in this region.

The preliminary phases of this work at the Applied Physics Laboratory on the effect of turbulence are nearly completed. The apparatus has been constructed and the experimental techniques have been worked out.

A study of the effect of turbulence on flame stabilization is being carried out by the Massachusetts Institute of Technology¹¹ (20). Two-dimensional flames formed around geometrical objects will be studied in a rectangular duct with glass sides by photographic and visual observation. The duct is fed with compressed air and gas through straightening vanes, resulting in flow through the working section of very low turbulence. Turbulence producing screens can be introduced at the entrance to the working section and arrangements are made for determining the scale of turbulence upstream and downstream from the flame holder. Various simple two-dimensional flame

¹⁰Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland; H. M. Nicholson; BuOrd Contract NOrd 7580 (BY MIDDLEBURY); *Confidential*.

¹¹Massachusetts Institute of Technology, Cambridge, Mass.; H. C. Hottel; Joint Sponsorship of the Bureau of Ordnance and the Bureau of Aeronautics under Contracts NOrd 9661, *Confidential* and NOa(s) 8632, *Restricted*.

holders will be studied, such as cylinders and gutters. Initial results indicate that the apparent flame velocities are not a function of the turbulence of the stream in the range 0 to 2.7% but are proportional to the velocity of flow. This has been attributed to eddies shed from the rod (3).

The Massachusetts Institute of Technology¹² is studying flame propagation velocities with very lean and very rich mixtures of gas and air. For these conditions, the flame speeds are very low. Measurements of the turbulence, without combustion, were made with a hot wire anemometer at various points along the axis of the tube, with and without various turbulence producing discs placed upstream. Inlet velocities vary from 10 to 20 feet per second. The mixture is ignited on the axis downstream from the turbulence discs and photographs made of the flame front. It was hoped that from the known inlet velocity and the angle of the flame front the flame speed could be calculated. However, the flame front was so irregular that no propagation velocity could be determined. The next step will be the use of propane or other fuel with a lower flame speed.

Dr. D. T. Williams has recently reviewed the work at the University of Michigan¹³ on combustion (11). The effect of turbulence on flame velocity is being investigated, using an inverted flame held in a jet by a disc-shaped flame holder. It is hoped that it will be possible to correlate the angle of the flame with the scale and intensity of turbulence produced by the introduction of screens in the jet. The scale and intensity of the turbulence will be measured by a hot wire anemometer. A study of the inverted flame technique will be necessary to establish a relation connecting flame velocity with the angle of the inverted flame. The apparatus for this work has been set up and some preliminary results have been obtained. It was found in past work that turbulent flame velocity is proportional to laminar flame velocity for identical fuel-air mixtures and that the ratio of the turbulent flame speed to the laminar flame speed gives a straight line when plotted against the square root of the Reynolds number.

A study of the effect of turbulence (21) on the combustion of premixed gases in cylindrical combustion chambers has been carried out at the Flight Propulsion Research Laboratory¹⁴. In one series of tests,

a mixture of air and pre-evaporated gasoline was used, the fuel/air ratios varying from 0.05 to 0.10. The air velocities varied from 60 feet per second to 110 feet per second. The air inlet temperature was either 90 F or 225 F. The turbulence was created by the introduction of flat plates, perforated by holes of various sizes, or by a cone shaped obstruction with a perforated wall, with the apex upstream, or by cylindrically shaped obstructions with no holes in the upstream cap of the cylinder but with holes in the wall. The turbulence creating device covered the whole cross-section of the combustion chamber. It was found that the cone shaped obstruction would permit the combustion of leaner mixtures and combustion at higher velocities than the flat plate or the cylinder. Increasing the inlet temperature from 90 F to 225 F increased the air velocity at which combustion can be maintained and decreased the minimum fuel/air ratio. With the temperature of the combustible mixture at 200 F, and using the flat plates, it was possible to increase the air velocity from 80 feet per second to 105 feet per second by increasing the area of the holes in the plate from 17.2% of the total area to 21.9% of the total area. The size of the hole in the range from $\frac{1}{4}$ inches diameter to $\frac{3}{4}$ inches diameter was of little significance as long as the total hole area was kept constant. Larger holes, however, were less effective in creating turbulence, and one large hole was less effective than an equal area of smaller holes. In tests using propane as a fuel instead of gasoline, it appeared that it was possible to obtain combustion with smaller values of the fuel/air ratio with the cylindrical perforated wall turbulator than with the flat plate or the cone turbulator.

A study of flow patterns in turbojet combustion chambers is being carried out at the Flight Propulsion Research Laboratory by Schlieren techniques.

New York University¹⁵ is investigating the rate of flame propagation in tubes with controlled initial turbulence (22). In the first experiments, the tube was a pyrex cylinder four feet long and four inches in diameter, flame speeds being determined by high speed photography. A 7% mixture of propane in air was used for a fuel. To produce turbulence, a screen was placed in the tube four inches below the igniter. The average flame speed in tubes which contained no grids was found to be about 38 feet per second. With the grid in place, the flame speed between the igniter

¹²Massachusetts Institute of Technology, Cambridge, Mass.; H. C. Hottel; Joint Sponsorship of the Bureau of Ordnance and the Bureau of Aeronautics under Contracts NOrd 9661; Confidential, and NOn(s) 8632, Restricted.

¹³The University of Michigan, Ann Arbor, Michigan; D. T. Williams.

¹⁴National Advisory Committee for Aeronautics, Flight Propulsion Research Laboratory, Cleveland, Ohio; A. M. Rothrock.

¹⁵New York University, New York, N. Y.; J. K. L. MacDonald; ONR Contract N6 ori-11, T.O.2; Unclassified.

and the grid appeared to be between 30 and 70 feet per second, but after the flame had proceeded through the grid, a sharp acceleration was observed and velocities as high as 800 feet per second were observed near the end of the tube. It is possible that the high speed flames were produced by jet-like motions through the grid caused by the pressure built up behind the grid. This was checked by experiments with flame tubes which had latex or tissue paper sections designed as pressure release devices. These experiments were not conclusive but indications are that the relief of pressure behind the grid decreases the turbulence so that the very high speed flames are no longer observed. Further study of this phenomenon is being carried out in a new pyrex combustion tube 8 feet long.

A study of turbulent diffusion in high temperature gases is being carried out at New York University by investigating the diffusion pattern from a glass bead held in a burner flame. Theoretical considerations show that measurements of the geometrical characteristics of the diffusion pattern and of the velocity of flow of the gas enable both the turbulent intensity and the scale of turbulence to be calculated. This project is still in the early stages. The diffusion pattern will be observed photographically. Several methods of determining the rate of flow of the gases are under consideration, one of which is to withdraw the bead suddenly from the flame and to record the upward motion of the sodium vapor produced. Also under investigation is a method of measuring the flow velocities by photographing the reflected light from very fine silica or aluminum particles. It is planned to study the flame using the Schlieren technique and both still- and motion-picture photography.

4. CHEMICAL KINETICS. While much has been written on the chemical kinetics of combustion reactions, speculation has played a large part in the conclusions, necessarily so because the reactions are so numerous that our limited analytical tools cannot give a proper indication of what is taking place. There is, of course, no reason to believe that in a reaction whose totality is



all 12 molecules must collide simultaneously to produce the end result. There is necessarily a sequence of reactions involving molecules, atoms, and free radicals, and the problem is to identify each reaction, determine its rate, and the conditions under which it will take place. Then there is the problem of determining what influences can be brought to bear to vary their rates, particularly to speed up the slower, rate-

controlling steps. There is reason to believe that all of the reactions are either monomolecular, bimolecular, or trimolecular. Higher orders of reaction must be statistically unimportant. But this limitation is not enough to make the actual kinetic picture simple.

In the reaction of hydrogen with oxygen, Jost (13) has reviewed in detail twenty-three possible reactions, which have been suggested by himself and others, that may take place in the course of the overall reaction. Of these, there is experimental proof for one, favorable evidence for four others, and spectroscopic evidence of the presence of particles which demand the postulation of other reactions which cannot further be surely identified. Similarly, Lewis and von Elbe (9, 15) have discussed the hydrogen-oxygen reaction, and on the basis of such evidence as the upper and lower explosion limits, reactor size, effect of packing, etc., they have presented twelve reactions which they believe are necessary to explain the experimental evidence. There is no doubt that a chain reaction is involved and that it propagates by chain branching. Both double and triple collisions are involved, and among the intermediates are not only atomic O and H, but also OH, HO₂, H₂O₂, O₃, and activated O₃.

The carbon monoxide-oxygen system has been rather extensively investigated but not in as much detail as hydrogen-oxygen. In the carbon monoxide-oxygen system the outstanding observation is the sensitivity of the reaction to small amounts of hydrogen or water vapor or even to small amounts of organic compounds containing hydrogen. Mixtures of completely dry CO and O₂ will not explode when an attempt is made to ignite them with an ordinary spark. The accelerated combustion in the presence of moisture or hydrogen suggests that a chain reaction is taking place, and that probably OH radicals and atomic H enter into the chain. The presence of the former has actually been established spectroscopically. The elementary reactions which on the basis of the accumulated data have been postulated to explain the overall reaction of CO with O₂ are again numerous, but yet there is no direct experimental evidence proving their existence.

Less studied than either of the above reactions is the high temperature combustion of hydrocarbons, the fuels of particular interest in the consideration of jet motors. It must be pointed out, of course, that investigations of hydrocarbon burning have benefited greatly from the researches on the other two systems, and it is reasonable to suppose that an explanation of what happens to H₂ and CO will have an important

bearing on the explanations of what happens to hydrocarbons.

There is no longer any doubt that in the high temperature combustion of hydrocarbons, certain radicals and atomic hydrogen must play important roles. The presence of the radicals OH, CH, C₂, and CHO has been substantiated by spectral analysis. The manner of their appearance and disappearance, however, is still not at all certain and other fragments may be present which have not yet been identified. Although the explosive combustion of hydrocarbons is known to be a chain reaction propagated by a chain branching mechanism, the reaction mechanism has not been proved, and the rate-controlling step, or steps, is not known.

Of the energy-rich particles which enter into hydrocarbon combustion, it is quite probable that both OH radicals and atomic H play significant parts, for both can attack the hydrocarbon molecule even at low temperatures. It has long been known that many of the lower hydrocarbons (except methane), including both saturated and unsaturated types, react with atomic H to split the C-C bonds, giving lower saturated or unsaturated hydrocarbons. Atomic deuterium is likewise known to react with hydrocarbons, producing both an exchange of D for H, and the molecule HD.

Atomic O also will react with hydrocarbons, most readily with methane, and, as would be expected, requires even less activation energy than the atomic H reaction. Spectroscopic evidence has shown the presence during the reaction of OH, CH, and C^{*} (the latter from acetylene and benzene). Since OH₂ is present in the oxidation of H₂, it is probably also present in the oxidation of hydrocarbons. These reactions can certainly take place at flame temperatures as well as at low temperatures and therefore may take part in the combustion of hydrocarbons unless even faster, but unidentified reactions supersede them.

It is known that the formation of hydrocarbon radicals can result in chain reactions which are of importance in the propagation of combustion at low temperatures. At high temperatures such as those encountered in jets and rockets, hydrocarbon radicals are thought to be important in initiating combustion and perhaps even in spreading the flame front rapidly. In the reaction zone, however, hydrocarbon radicals, although present, may not take part in the reaction to the same extent as at lower temperatures because of the high thermal energy of all particles at the elevated temperatures involved.

There is much evidence to show that ions as well as radicals form in the combustion zone, but it is be-

lieved that they are not of great importance in combustion studies and they are not necessary to the mechanism of burning. The formation of radicals is much more important and requires only $\frac{1}{3}$ to $\frac{1}{4}$ the energy necessary for the formation of ions.

The systems discussed briefly above, hydrogen-oxygen, carbon monoxide-oxygen, and gaseous hydrocarbon-oxygen are the only reactions of interest in connection with combustion in jet power plants which have been studied extensively from the point of view of chemical kinetics. An extension of the work in this field to include investigations of the liquid propellant systems now in use and those being considered for use is highly desirable. Studies of the kinetics of combustion reactions involving the halogens (particularly fluorine), metals, metal alkyls, and metal hydrides are particularly important.

In summary, it may be said that excellent fragmentary evidence has been obtained showing that atoms, active radicals, and peroxides are formed in the course of combustion reactions; that the sequence of reactions involves a chain mechanism, which includes chain branching and chain breaking; that the wall of the reactor, and various packings play an important part in what takes place; that the presence of "inert" gases is significant in ways entirely different from the effects of dilution (24); and that the oxidation reactions are frequently characterized by induction periods, the times of which are susceptible to modification by temperature, pressure, and the presence of "additives." The detailed treatment of the reaction kinetics, however, is not possible from what is known at the present time. Not only must the experimentation be continued, but new methods of approach must be sought. Particularly required are optical methods which will assist in the identification of the intermediates in the reactions, or sampling techniques which will at the same time "freeze" a particular reaction without interfering with it up to the time the sample is taken.

a. Chain Reaction Mechanisms in Combustion.

The Bureau of Mines¹⁶ plans to continue work on the chemical kinetics of combustion reactions using the techniques which proved successful in studying the reaction between hydrogen and oxygen (9). A simple hydrocarbon such as methane or normal propane will probably be chosen for investigation. The combustion of hydrocarbons may also be investigated in a spherical combustion chamber using a central spark for ignition. The pressures and temperatures will be recorded. Calculations using the data ob-

¹⁶Bureau of Mines, Pittsburgh, Pa.; Bernard Lewis; ONR Order ONR-2747; *Unclassified*.

tained should indicate the completeness of the reaction and give some clue as to what has taken place in the flame front.

Arthur D. Little Co., Inc.¹⁷ has made a survey of about 3000 references to unclassified literature on combustion for the years 1936 to 1946 (1). Over 600 of these were examined closely because they referred to experimental methods of detecting radicals and of determining radical concentrations. The report has mainly to do with the chemical kinetics of the oxidation of hydrogen, carbon monoxide, and hydrocarbons. There is no discussion of the physical aspects of combustion, but there are a few literature references to such topics as: Ignition, Flame Propagation, Detonation, Burner Flames, Diffusion Effects, Shock Waves, Turbulence and Mixing, Energy in Flames, and Flame Temperature Measurements.

b. Mass Spectrometer.

The mass spectrometer and the velocity spectrometer are considered by some to offer considerable promise of providing basic information about the mechanism of combustion reactions (1). Not all, however, hold the point of view that the mass spectrograph is a very useful tool, in its present state of development, for studying the chemical reactions in flame fronts. The attempt to identify molecules, or particles, or radicals present in or near the flame front by physical sampling methods such as are required for the mass spectrograph will be very difficult, for the sampling methods change the conditions in the flame to an important degree. Some of the fragments will not exist long enough even when chilled. While identification of the products of recombination may aid in speculation on what was present at the high temperature, the lack of knowledge of the rates of formation of the radicals, and the concentration of the radicals present, will still not permit a determination of the rate-controlling step in the reaction.

Although recognizing the difficulties inherent in the method, a number of research groups have mass spectrometric equipment and are attempting to develop it as a tool for the study of reaction mechanisms.

Battelle Memorial Institute¹⁸, for example, is carrying out an investigation of the chemical reactions occurring during the combustion of a gas or vaporized liquid hydrocarbon, and have built a mass spectrometer to assist them. Preliminary tests have been made. It was found that the pressure in the ionization

head could be maintained at 10^{-4} millimeters of mercury when the pressure in the reaction vessel was 5 millimeters of mercury.

Johns Hopkins University APL¹⁹ is studying the kinetics of oxidation reactions as a part of the combustion program of the laboratory (12). The mass spectrometer will be used to evaluate bond energies, to analyze the components of the reacting mixtures, and to detect and to measure the energy of formation of free radicals. This work is in the relatively early stages. The apparatus for introducing the gas samples into the spectrometer is being designed and constructed. The mass spectrometer has been assembled and is in operating condition. The accuracy and sensitivity of the instruments have been tested in preliminary experiments with air samples. The evaluation of the possibilities of the instrument is continuing with the analysis of gas samples for which accurate data are available in the literature.

In addition to the work on turbojet and ramjet combustion, the National Advisory Committee for Aeronautics²⁰ has started a project to study the molecular species present in a chemical reaction by mass spectrometer techniques.

Ohio State University²¹ is planning to carry on a study of reaction kinetics of oxidation, including the influence of pressure and of homogeneous catalysis. The mass spectrograph will be used to measure appearance potentials and for the detection and analysis of intermediate reaction products. Hydrogen as an additive will be studied.

c. Spectroscopic Studies.

Emission and absorption spectra have been used successfully in detecting and identifying some of the molecular fragments which are important in combustion reactions, and several present studies of combustion include the use of spectroscopic methods. These techniques have the important advantage of not disturbing the reaction. However, further development of spectroscopic methods is desirable, particularly to devise ways of determining concentrations quantitatively.

Spectroscopic techniques are being extensively used to measure temperatures in flames. For a discussion of the work in this field see Part 6 of this volume, "Instrumentation."

¹⁷Arthur D. Little Co., Inc., Cambridge, Mass.; W. H. Avery; Subcontract with Applied Physics Laboratory, Johns Hopkins University, BuOrd Contract NOrd 7386 (BUMBLEBEE); *Confidential*.

¹⁸Battelle Memorial Institute, Columbus, Ohio; J. F. Foster; AAF-AMC Contract W-33-038-ac-14202; *Confidential*.

¹⁹Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland; A. Kossiakoff; BuOrd Contract NOrd 7386 (BUMBLEBEE); *Confidential*.

²⁰National Advisory Committee for Aeronautics, Flight Propulsion Research Laboratory, Cleveland, Ohio; A. M. Rothrock.

²¹Ohio State University, Columbus, Ohio; H. L. Johnston; AAF-AMC Contract W-33-038-ac-14794 (16243); *Restricted*.

Battelle Memorial Institute²² is planning to make spectroscopic studies of flames under pressures greater than atmospheric.

California Institute of Technology²³ is planning to study molecular fragments such as OH and NO in the exhaust gases of a rocket motor with spectrographic techniques in order to obtain information concerning the maintenance of equilibrium during expansion through the nozzle. In addition, studies of molecular fragments such as CH, C₂, and CN, which should be detectable, may give an indication of the completeness of combustion within the chamber. Experiments are planned to observe the effects of various catalysts on the concentration of the above molecular fragments.

Cornell Aeronautical Laboratory²⁴ will investigate the possibility of studying the mechanism of combustion of hydrocarbons by spectrographic means. This program is in the early planning stages. The first step in the experimental program will be a study of the effect of combustion variables on the emission spectra to be observed in the combustion of a simple hydrocarbon such as methane.

The radiation emitted by non-luminous flames is being studied at the University of Delaware²⁵ by a technique which allows the recording of the relative intensities of the radiation from different parts of the flame on an oscilloscope. This technique is in the late development stage and most of the results obtained have been qualitative. The sensitivity of the apparatus is such that the radiation from one square millimeter of the non-luminous flame can be recorded on the oscilloscope. Filters are used to cut out certain regions of the spectrum. Zones of chemical reaction can be distinguished from zones of high temperature where reaction is completed, and regions of good mixing can be distinguished from regions in which the mixing is poor.

It has been found that the C₂ radical dies out only near the top of the flame. It is planned to replace the filters now used with a spectrophotometer. It will then be possible to exhibit on the oscilloscope a trace

of the relative concentration of any given radical as the concentration varies across the flame. By using a standard light source, it may be possible to determine absolute radical concentration. If the range of the spectrophotometer can be extended into the infra-red, it may be possible to measure lower temperatures, by observing the H₂O bands, than can be measured by using the sodium D-line reversal method.

Johns Hopkins University APL²⁶ is carrying out a spectroscopic study of the carbon monoxide-oxygen system (11). Previous work has been done on this system, but the results obtained have not been conclusive. It is planned to obtain the emission spectra of flames out into the infra-red using a high resolving power. Preliminary observations have already been made and the data are now being interpreted. In this initial work exposures of 7 hours were required but it may be necessary to go to exposures as long as 30 hours. The emphasis of the work will be on the study of emission spectra, but an investigation of absorption spectra may also be necessary in order to obtain the information desired.

The Standard Oil Development Company, Esso Laboratories²⁷ is making flame studies of various volatile hydrocarbons in horizontal glass tubes, with the objective of obtaining information on the fundamental aspects of combustion which will permit a scientific approach to the design and development of combustion systems for jet engines. The effects of molecular weight and structure, turbulence of the gases, and inlet temperatures of the gases on the rate and temperature of burning have been investigated. Spectrographic examinations of the flame fronts in Bunsen and in diffusion types of flame are being made to detect the presence of molecular fragments such as C₂, CH, CHO, etc. The results obtained so far are not of a quantitative nature but will be made so later.

d. Sampling Techniques in Combustion.

California Institute of Technology²³ intends to investigate the water gas equilibrium over a range of temperatures from 900 F to 1800 F. It is hoped that this work will give some information on the validity of sampling techniques by indicating the rapidity with which combustion gases must be cooled in order for the method to be satisfactory. From this experiment, it may be possible to determine whether equilibria are

²²Battelle Memorial Institute, Columbus, Ohio; J. F. Foster; AAF-AMC Contract W-33-038-ac-14202; *Confidential*.

²³California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California; L. G. Dunn; AAF Contract W-33-038-ac-4320 (12847); *Restricted*.

²⁴Cornell Aeronautical Laboratory, Ithaca, N. Y.; *Confidential*. ONR Contract N6-ori-119, T.O.-1, Phase 2 (SQUID); *Unclassified*.

²⁵University of Delaware, Newark, Delaware; Kurt Wohl; Subcontract with United Aircraft Corporation, East Hartford, Connecticut; BuOrd Contract NOrd 9845; *Confidential*.

²⁶Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland; S. Silverman; BuOrd Contract NOrd 7386 (BUMBLEBEE); *Confidential*.

²⁷Standard Oil Development Company, Esso Laboratories, Elizabeth, N. J.; W. P. Lakin; ONR Contract N6-ori-109, T.O. -1; *Unclassified*.

frozen or maintained during the quenching, at least for the water gas equilibrium under the particular conditions used in this work.

The quantitative estimation of the products of combustion by sampling technique is being studied at the Cornell Aeronautical Laboratory²⁸. Preliminary calculations have been made of the rate of cooling to be expected under given experimental conditions. Samples were taken from a stream of carbon dioxide passing through an electric arc, and the amount of carbon monoxide and of oxygen present were in approximate agreement with the decomposition to be expected at the probable temperature of the arc. In the case of samples removed from an oxygen-gas flame, the analysis showed amounts of carbon monoxide, hydrogen, and oxygen which corresponded to equilibrium at a lower temperature than the calculated flame temperature. Using a three-inch diameter combustion tube, and burning pre-mixed air and "notoxalin", samples of the combustion gases were taken at four ports downstream at one foot intervals, and analyzed for carbon monoxide, carbon dioxide, and oxygen. The results of several experiments were not entirely consistent, but it appeared that the concentration of carbon monoxide decreased as the gases progressed downstream. The highest wall temperature observed was 1680 F. Analyses of samples taken across the diameter of the tube were not identical but showed no consistent trend.

A project is under way at Purdue University²⁹ to study temperatures, pressures, and concentrations of reactants for various oxidation reactions of materials that may be of value as fuels for jet engines (25). An extensive literature search has not revealed a good way of quenching the reaction, and it appears that the desired information concerning the concentration of the reactants cannot be readily obtained by the method of sampling and analysis. However, it might be possible to obtain significant data from a study of the slow oxidation reactions which take place at low temperatures. At present, laboratory equipment is being designed and constructed to determine qualitatively the rate of cooling when a hot gas and a cold inert gas such as helium or argon are mixed in a zone of turbulent flow. The data obtained should indicate the order of magnitude of time required to quench a hot gas stream, and the future course of this project will depend on these results.

²⁸Cornell Aeronautical Laboratory, Buffalo, N. Y.; J. L. Beal; ONR Contract N6 ori-119, T.O.-1, Phase 2 (SQUID); *Unclassified*.

²⁹Purdue University, Lafayette, Indiana; D. E. Holcomb; ONR Contract N6 ori 104, T.O. -1, Phase 4; *Unclassified*.

Picatinny Arsenal³⁰ is making a study of the temperatures of spontaneous ignition of hydrogen-carbon monoxide mixtures in air as affected by various catalysts (11). Reaction rate measurements will be made at various temperatures and pressures in order to get information concerning temperature coefficients of the reaction. The data will be checked by a study of the water gas equilibrium. This investigation has been undertaken because of its bearing on the problem of flash and smoke in gun firing and of the burning characteristics of propellants.

e. Catalytic Influence of Combustion Chamber Wall.

A series of tests is being planned by Cornell Aeronautical Laboratory²⁸ to investigate the possible influence of wall materials on combustion. If combustion proceeds more rapidly on certain surfaces, the effect might be sufficiently great to influence the amount of heat which can be liberated per unit volume of the combustion chamber. The apparatus for this investigation is nearly completed and the first results should be obtained in the near future.

f. Low Temperature Combustion.

California Institute of Technology JPL³¹ has constructed apparatus for the study of the slow combustion of fuels at relatively low temperatures. These experiments involve passing mixtures of various fuels and air through a furnace maintained at a fixed temperature. From the measured flow rate and an analysis of the combustion products, it is hoped to learn something of the mechanism of the initial stages of combustion. A knowledge of the intermediate products of combustion may suggest proper choices of additives to accelerate the rate of burning and to permit operation over wider limits of air-fuel ratios.

g. Atomic Hydrogen in Flames.

An attempt was made at Battelle Memorial Institute³² to determine the effect of adding atomic hydrogen to the fuel-air mixture on the flame propagation velocity of a Bunsen burner. It was found that no atomic hydrogen was actually introduced into the fuel-air mixture with the particular experimental arrangement used and that the maximum life of atomic hydrogen under these conditions could not have been more than 0.04 seconds.

³⁰Picatinny Arsenal, Dover, New Jersey; C. G. Dunkie.

³¹California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California; L. G. Dunn; AAF Contract W 33 038 ac-4320 (12817); *Restricted*.

³²Battelle Memorial Institute, Columbus, Ohio; J. F. Foster; AAF-AMC Contract W 33 038 ac 14202; *Confidential*.

Princeton University³³ is particularly interested in determining the effects of hydrogen atoms on the combustion process. It appears that the diffusion of hydrogen atoms from the flame front back into the unburned gaseous hydrocarbon-air mixture reacts in some way to bring the mixture up to the burning temperature in the flame front. It is known, for instance, that when the nitrogen in air is replaced by helium the burning rate of butane is increased by a factor of three. This is perhaps due partly to an increase in diffusion constants for hydrogen atoms at the higher temperature and partly to the formation of more hydrogen atoms at the higher temperature. One cannot be certain yet that the diffusion of hydrogen atoms into the unburned gas is the important factor in the rate of flame propagation, but present evidence favors this point of view, and further evidence needs to be obtained. In preliminary work to clarify some of these points, an apparatus was constructed similar to that used at Johns Hopkins University in which hydrogen molecules under a pressure of 0.1 millimeters of mercury in a Wood discharge tube could be converted to atomic hydrogen. The atomic hydrogen was mixed with oxygen at an equally low pressure and led directly into a flask cooled with liquid nitrogen. As observed at Johns Hopkins University, solid hydrogen peroxide was formed on the walls of the flask. Since the product was hydrogen peroxide, rather than the radical HO₂ or water, and since no product whatsoever could be trapped in a flask cooled with solid carbon dioxide, further investigation of the chemistry of the reaction is necessary.

h. Combustion of Metal Alkyls and Metal Hydrides.

Princeton University³³ is also working on the rates of combustion of volatile metallic compounds such as zinc dimethyl, nickel carbonyl, and boron triethyl. Boron triethyl, for example, explodes at 5 millimeters of mercury partial pressure, and when added to a mixture of butane and oxygen, it will cause the mixture to explode without a measurable induction period. Thus boron triethyl might serve as a useful additive to gasoline and other hydrocarbons to make them self-igniting. Experiments with these reactive materials are being continued. As soon as aluminum borohydride, diborane, and hydrazine can be made available, Princeton University will investigate them with regard to their reaction kinetics.

5. FLAME VELOCITY AND STABILITY. Flame velocity and stability are important considerations for jet power plants. According to present theoretical and experimental evidence, flame velocity increases with reaction rate and the values of flame velocities may be used to compare reaction rates when no other experimental technique is available. Reaction rate, in turn, is one of the factors determining the design of combustion chambers for maximum efficiency. Combustion in a power plant must proceed not only rapidly but smoothly over a range of fuel oxidant ratios and fuel-oxidant inlet velocities, a factor of particular importance in motors using air as the oxidant. For these reasons, investigations of the velocity and stability of flames may have a direct influence on the performance of jet engines.

The normal flame velocity has been defined as "the velocity with which the flame front advances into the unburned charge in a direction normal to the flame front" (11), which is equivalent to the ratio of the volume of gas burned per second per unit area of the flame front to the density of the gas. This quantity has been assumed to be constant for a given combustible mixture. Numerical values of the normal flame velocity are unusually in the range between 1 foot per second and 50 feet per second, although the flame front itself, with respect to the stationary container, may travel more than 10 times as fast. Detonations, which occur under the right conditions, may have velocities of more than 1 mile per second. Several methods have been devised for measuring the normal flame velocity, two of which are frequently used in the research projects discussed below. The rate of propagation of a flame front in a stationary or moving combustible mixture may be directly determined by electric or photographic techniques, the observed velocity being corrected for mass flow of the gases and change in area of the flame front to obtain the normal flame velocity. A stationary flame, such as the Bunsen burner, may also be used, the normal flame velocity being determined from the rate of flow of the gas and the dimensions of the inner cone.

Stability studies are concerned with the conditions under which a stationary flame can no longer be maintained. As the rate of flow of the gas is increased, a stationary flame will first "lift" and remain above the burner. At still higher velocities it will proceed downstream, a phenomenon called "blow-off" or "blow-out." At a flow rate less than that required for "lift", the flame will "drop-back." If the flow rate is decreased enough the flame will travel down the tube as a "flash-back." As a part of stability investigations, flame velocities and the critical flow rates for "lift"

³³Princeton University, Princeton, New Jersey; R. N. Pease; ONR Contract No. 49-107, 747; formerly under BuOrd Contract 7920).

off" and "flash-back" are studied as functions of pressure, temperature, fuel oxidant ratios, burner dimensions, and flow conditions.

Extensive investigations of flame velocity and stability have been made at the Bureau of Mines by Lewis and von Elbe. They have shown that the flow rates for blow-off and flash-back for laminar flames are determined by the velocity gradient at the burner wall and that the critical gradients are independent of tube diameter over a wide range (10,16). In recent work (11), Lewis has proposed a more thorough investigation of the Mallard-LeChatelier equation which was discussed in the section on "Theoretical Studies." He indicates that it is possible to correlate the temperature gradient in a flame front, calculated from measurements of normal flame velocity by the Mallard-LeChatelier equation, with average reaction rate, quenching distance, and the minimum energy required for ignition. In this way normal flame velocity can be connected with other easily observable flame phenomena.

The Bureau of Mines³⁴ is just starting a program of research continuing and extending the work described in the previous paragraph. The propagation of combustion waves in fuel gas-air (or oxygen) mixtures is being studied under conditions of laminar flow. Normal flame velocity, width of reaction zone, and temperature gradient in the flame front will be measured. Similar studies will be made under various turbulent flow conditions. The work on flame stability is also continuing with investigations of velocity gradients and normal flame velocities at the stream boundaries in laminar and turbulent flow. The velocity gradients will be provided by changing the shapes of the flow channels to produce regions of retarded, or even counter-current, gas flow or by artificially affecting them by putting the boundary wall in motion.

A group at the University of California at Los Angeles³⁵ is planning to continue a program of research on combustion which was started before the war (11). The blow-off and flash-back characteristics of methane and air mixtures will be measured at room temperature and pressure. The temperature distribution in flames will be investigated by the use of spectral-line reversal and other techniques and the radiant energy of flames by the use of thermopile radiometers. Particle velocities in flames will also be measured. Flame characteristics will be determined over a range of pressures from below atmospheric pressure to above atmos-

pheric pressure, using several fuels, unspecified as yet.

The Jet Propulsion Laboratory of California Institute of Technology³⁶ is investigating the rate of propagation of flames through a vertical tube as a function of the fuel-air ratio and pressure. The effect of adding small amounts of various chemical compounds to the fuel is being studied.

An experimental program has been planned at the Cornell Aeronautical Laboratory³⁷ to investigate how restrictions or wall disturbances in a combustion tube produce very high burning velocities and how these high burning velocities can be maintained. The combustion chamber is a steel tube 12 feet long and 2 1/2 inches in diameter, made up of sections 2 feet long to permit variations in experimental conditions. A number of small gaps between two insulated wires have been mounted along the tube. The passage of the flame across the gaps, ionizing them, will be recorded on an oscilloscope. Work is continuing on the experimental set-up, and no measurements of flame velocity have been made as yet.

Experimental work has been carried out at the Cornell Aeronautical Laboratory³⁸ on the measurement of flame velocities with different fuels at varying gas velocities. The apparatus consists of a pyrex tube 12 feet long and 1 5/8 inches inside diameter. The mixture is ignited at the downstream end, and the flame velocity at various air-fuel ratios is measured by the starting and stopping of a clock actuated by the burning out of two fine wires in the tube which are 90 inches apart. In this test, the flame velocity of propylene oxide was 70% greater than that of hexane. This observation may have a relation to the observed superior burning qualities of propylene oxide in jets. The use of fuel additives, such as magnesium diacetylacetonate, acetaldehyde, acetylacetone, ethyl isothiocyanate, increased the flame speed only 4% to 8% at lower gas velocities but had no effect at high velocities. In these experiments the rate of gas flow had to be carefully controlled in order to obtain reproducible results.

The University of Delaware³⁹ is carrying out an extensive research program on the fundamentals of combustion to obtain data to lead to the development

³⁴Bureau of Mines, Pittsburgh, Pa.; Bernard Lewis; ONR Order ONR 27-47; *Unclassified*.

³⁵University of California, Los Angeles, California; R. J. Morrin.

³⁶California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California; L. G. Dunn; AAF Contract W 33 038 ac 4320 (12847); *Restricted*.

³⁷Cornell Aeronautical Laboratory, Buffalo, N. Y.; J. L. Beal; ONR Contract N6 ori 119, T.O.-1, Phase 2 (SQUID); *Unclassified*.

³⁸Cornell Aeronautical Laboratory, Buffalo, N. Y.; J. L. Beal; Subcontract with Curtiss-Wright Corporation, Airplane Division, BuOrd Contract NOrd 8993; *Confidential*.

³⁹University of Delaware, Newark, Delaware; Kurt Wohl; BuOrd Contract NOrd 9845; *Confidential*.

of new theories of flame phenomena or to the interpretation of existing theories. A summary of significant results from recent work is given on pages 36 to 39 of reference (11). The present research program may be described as follows:

a. Flame Stability.

The study of the stability of flames (blow-out, lift, drop-back, flash-back) as a function of the air-fuel ratio, tube diameter and flow rate in laminar and turbulent flow, will be continued. The state of turbulence will be varied by the introduction of grids. Such studies have already led to the conclusion that stability depends on the velocity gradient at the walls of the tube for both laminar and turbulent flow. This dependence has previously been reported for laminar flow by Lewis and von Elbe (16).

Flames will be studied under varying conditions of temperature and pressure in apparatus now being constructed. The apparatus is essentially a large box with inlet pipes at the bottom for fuel and air and an outlet pipe at the top. The rate of flow through these pipes will be adjusted until the flame is burning in a medium of the desired pressure.

b. Physical and Chemical Conditions in Flames.

The temperature distribution throughout laminar and turbulent flames will be measured by the sodium D-line reversal technique, in connection with a study of flow distribution and distribution of radiation.

Flames will be studied by direct photography and by shadowgraph photography. These two techniques do not give the same results, because a shadowgraph of a non-luminous Bunsen flame shows the boundaries of the inner cone and of the heated sheath of air surrounding the cone whereas a direct photograph shows the boundaries of the inner and outer cones. Theoretical and experimental studies of the shadowgraph technique will be made to develop a method of obtaining quantitative data from the photographs.

The lines of flow through a flame will be studied by the powder method. At present, silica gel of specific gravity 0.3, free from dust, is used. Silica gel, because of its lightness, follows changes in direction and velocity better than metallic powders, but has the disadvantage that it increases in density in passing through the combustion zone.

A special method for introducing salts into a flame has been developed, and it has been found that salts of copper and manganese are particularly effective in disclosing oxidizing and reducing regions of the flame because of a difference in color of the light emitted. Salts have been introduced into a special burner, an adaptation of the Meeker burner in which the orifices

are parallel narrow slots. For certain air-fuel ratios, the flame is uniformly colored and for others an inner cone is revealed by its diffuse color. Under these conditions, observations show that the flow in the flame is laminar and that mixing is not complete in the flame.

c. Enclosed Flames.

Butane flames in a pyrex tube will be studied. A systematic investigation of stability conditions and of the action of flame holders in mixed and unmixed gases in turbulent flow will be made. Flame holders ignite the gas and cause the flame to propagate. It is hoped to separate these two functions in the experimental work.

Two rectangular combustion chambers with glass sides are available, but no work is now being done with these chambers because of lack of personnel.

d. Flame Heights.

Several theoretical expressions have been derived for the height of a flame which are relatively easy to prove or disprove experimentally (11). Previous experimental results on city gas and on butane have not agreed with these expressions, which has led to the development of other unpublished theoretical relations. This work will continue and the experimental program will be extended to include octane vapor.

Princeton University¹⁰ is studying flames at low pressures under laminar flow conditions. Butane, butadiene, butylene, propylene, and ethylene have been used as fuels. It has been found that butadiene-air mixtures will burn at pressures down to 100 millimeters of mercury and that butadiene-oxygen mixtures will burn at pressures down to 5 millimeters of mercury if the burner port is large enough. As the pressure decreases, the flame velocity of a given mixture increases, sometimes as much as 50%, to a maximum and then decreases until at sufficiently low pressures the flame goes out. Of particular interest in connection with the combustion at low pressures is the possibility of inserting probes to withdraw gas samples at low pressure from the pre-combustion region of the flame front for analytical purposes. At these pressures, it might be possible to withdraw samples sufficiently rapidly and with sufficiently rapid cooling so that some of the fragments could be identified before they have disappeared as a result of further reaction. Measurements of the normal flame velocities with the above fuels in a Bunsen burner at a pressure of 1 atmosphere confirmed other work with regard to the effect of chemical structure, mixture flow rate, and size of the port on burning velocity.

¹⁰Princeton University, Princeton, New Jersey; R. N. Pease; ONR Contract N6-ori-105, T.O.-3; *Unclassified*. (Formerly under BuOrd Contract 7920).

Work is under way at Princeton University on the measurement of the rate of flame travel in quiescent pre-mixed gases. Combustion is initiated with a spark at the top of a vertical tube five feet long. The tube initially is closed at both ends, but it is opened at the top end at the time of ignition so that the pressure does not develop in the tube during combustion. In the experiments conducted, the top end of the tube is connected by a large stop cock to a large capacity container maintained at the same initial low pressure. It appears now that it may be necessary to devise a way of avoiding the disturbing influence of reflected pressure waves. Flame speeds are being detected by a new method which does not require electrodes or other objects within the tube (5). Pulses in two tank coils wound around the tube, caused by the ionization of the flame, actuate a chronoscope circuit. It has been observed that the velocity of propagation of the flame can be more than doubled by imposing on it a direct current field of the order of 1000 volts per centimeter. The reason for this increase has not yet been discovered.

The Esso Laboratories¹¹ have been studying flame propagation in pre-mixed fuel-air mixtures in apparatus consisting essentially of horizontal sections of pyrex pipe $1\frac{1}{2}$ inches in diameter and 7 to 8 feet long, together with the necessary gas metering and flame timing devices. The fuel-air mixture under investigation is fed into one end of the tube and ignited at the other end by means of a spark gap. The rate of flame propagation is determined photo-electrically by timing the flame travel through the desired portion of the tube. A method for preheating the inlet gases has been provided by a gas-fired coil heater which includes means for automatic temperature control.

Studies of the rates of flame propagation in flowing streams of gaseous fuel-air mixtures within horizontal glass tubes have shown that flame velocities increase with: (a) decreasing molecular weight of the fuel; (b) decreasing hydrogen to carbon ratio (increasing unsaturation of the fuel); (c) decreasing branching of the carbon skeleton of the molecule; (d) increasing temperatures of the fuel-air mixture; (e) increasing turbulence.

Almost all of the flame propagation measurements made thus far at the Esso Laboratories have been on flames traveling against a flowing gas stream. Although such data are felt to be of primary interest, some knowledge of the behavior of flames traveling with the gas stream was considered valuable. Tests

have been conducted with $1\frac{1}{2}$ inch pyrex tubes 7 $\frac{1}{2}$ and 22 feet in length. The tubes were fitted at one end with a spark plug for ignition, a gas inlet, and a flap valve held in the closed position by a weight. The valve was installed to provide a means of relieving pressure at the inlet end either by manually opening the valve or allowing it to act as a poppet. This was found to be necessary because the pressure built up high to actuate the timer when the end was blocked off. Observed flame velocities were found to be much greater with propagation traveling in the same direction as the flowing gas.

The impossibility of using thermocouples at the high temperature levels encountered in flame studies has led to the investigation of the sodium-line reversal technique of temperature measurement at the Esso Laboratories. The necessary calibrations and laboratory tests have been made to provide for the use of this method.

Work has started at the Esso Laboratories on the combustion of gaseous hydrocarbons of the methane to pentane series at pressures below atmospheric. Apparatus is being developed for the investigation of combustion efficiencies, flame temperatures, flame shapes and colors, and the effects of diluents. Methods for analyzing combustion zone products will be studied.

The Westinghouse Research Laboratories¹² have studied flame velocities by the Bunsen burner method with the objective of obtaining data on gases and vaporized liquid fuels over a range of temperatures and at pressures below atmospheric (11). The burner used is provided with a nozzle designed to give a uniform velocity distribution. A Schlieren picture of the flame is projected onto a screen by an optical system and the cone angle is measured with a protractor. Flame velocities have been measured at various pressures, temperatures, velocities of flow, and air/fuel ratios. It was found that at an inlet temperature of 900 F a stable flame could be obtained for air/fuel ratios from 8 to 28, while at 137 F stable burning could be obtained for air/fuel ratios from only 13 to 22. Flame velocities measured at flows of from 2.6 feet per second to 5.6 feet per second showed a considerable spread in values, with the slower flow-rate giving the higher flame velocities in the region near the stoichiometric ratio. Measurements have been made at atmospheric pressure, 5 inches of mercury vacuum, 15 inches vacuum, and 20 inches vacuum. Only a few observations could be made at the two lowest pressures because of the difficulty of obtaining a stable flame. In one investigation, the pre-mixed natural gas and air

¹¹Standard Oil Development Company, Esso Laboratories, Elizabeth B, New Jersey; W. P. Lakin; ONR Contract N6-ori-109, T.O.-1; *Unclassified*.

¹²Westinghouse Research Laboratories, East Pittsburgh, Pa.; Stewart Way.

mixture was ionized by exposure to alpha particles just before passing into the nozzle. The ionization caused very little change in the flame velocity. The flame velocity of vaporized gasoline has been obtained at a temperature of 300 F and atmospheric pressure, over a range of fuel air ratios. The maximum normal flame velocity observed was about 2.8 feet per second.

The Westinghouse Research Laboratories are carrying on flame stability studies on simple burners to observe the effects of pressure, temperature, mixture, velocity, and size. In addition, a special burner has been constructed for the study of various primary air admission openings in order to determine satisfactory ways of admitting the primary air and to investigate why one type of admission is better than another. A special combustion tunnel with shielded measuring sections and unshielded test sections is being constructed. Methods of measuring the temperature and pressure of the gases will be investigated and a study of methods of gas analysis will be carried on.

The University of Wisconsin⁴³ is starting experimental work in combustion which is closely correlated with the theoretical program discussed earlier in this Part. Systems whose chemistry is known under static conditions will be studied under carefully controlled flow rates, and the rate of burning will be studied as a function of pressure, temperature, velocity, and velocity gradients. The effect of chemical additives and of the nature of the surfaces will be investigated. The spreading of a gas jet by turbulent mixing and diffusion will be studied by means of Schlieren photography. An attempt will be made to measure the density of the burning gases at every point in the combustion zone by means of interference photography and Schlieren photography. A general study of the interaction of flames and radiation will be undertaken.

A detailed and accurate study of the emission spectra, absorption spectra, and Raman spectra of flames will be made for the purpose of determining the nature of the intermediate and transient combustion products present in the flame. Preliminary theoretical studies indicate that stable flames may be impossible if the chemical reaction occurs in one stage. This indication will be checked experimentally.

This project at the University of Wisconsin is getting under way slowly, primarily because of the lack of laboratory space. A flow system is under construction to be used as a model for equipment to be built later. The nozzle is being designed to give a uniform flow velocity across its mouth. Methods of maintaining and measuring velocities and controlling mixing

⁴³University of Wisconsin, Division of Research, Milwaukee, Wis. AAF-AMC Contract W-33-038-ac-14202; BuOrd Contract NOrd 9338; *Restricted*.

and turbulence with high precision are being developed. This model will be operating in the near future. Schlieren apparatus and a large optical interferometer with nine-inch mirrors have been designed and are being built.

6. COMBUSTION IN HIGH SPEED GAS STREAMS. The investigation of combustion in high speed gas streams involves the usual considerations of combustion efficiency and flame stability as a function of air fuel ratio, pressure, temperature, and velocity. A particularly difficult problem, however, is to obtain smooth, efficient, and reliable ignition. This is ordinarily achieved by placing obstructions in the stream, called flame holders or igniters, of the proper size and shape so that small stable flames can be maintained in the wake of the flame holders to ignite the flowing mixture. It has been found that the size and shape of flame holders are critical, and a great deal of experimental work, some of it described in Subsection B of this Section, has been done in connection with the development of ramjets to improve the design.

In his recent study of the stability of Bunsen burner flames (16), Lewis has stated that a flame remains stationary because of regions in which the gas velocity equals the normal flame velocity which serve to ignite the faster-moving neighboring portions of the stream. The velocity gradient near the burner wall is the determining factor in this case. If similar considerations apply to flame holders, the character of the flow in the region near the boundary between the wake of the obstruction and the main stream of gas would be expected to determine the effectiveness of the flame holder. Little is known as yet about the nature of the flow around flame holders, but the problem is being actively investigated.

Part of the University of Wisconsin⁴⁴ is studying the dynamic conditions affecting the blow-off of burners in order to determine the aerodynamic variables that influence the effectiveness of flame holders. The fuel-air mixture enters a chamber to suppress turbulence and is discharged through a one-inch nozzle designed to give uniform flow over the entire discharge area. The flame holder to be studied is mounted in the issuing jet. Horizontal rods, vertical rods, spheres, and discs have been tested. It was not possible to obtain blow-off using holders mounted in the non-turbulent portion of the jet with velocities up to 150 feet per second. Arrangements are being made to obtain higher flow velocities. It is believed that the use of Schlieren techniques will not be feasible because turbulence near

⁴⁴University of Wisconsin, Division of Research, Milwaukee, Wis. AAF-AMC Contract W-33-038-ac-14202; *Confidential*.

the boundary of the jet interferes with the observation of conditions near the flame holder. Photographic observation of the paths and velocities of small particles carried by the gas stream will be used.

Experiment, Inc.¹⁵ is carrying out an extensive research program on combustion in high speed air streams to obtain basic information for ramjet applications. To simplify the experimental conditions, homogeneous gas-or vaporized liquid hydrocarbon-air mixtures are used as fuels. One phase of the work involves an investigation of the influence of pressure, temperature, velocity, and turbulence on the extent of the combustion zone. Photographic and spectrophotometric techniques have been found quite satisfactory for Bunsen burners and for flames in low-velocity streams. For flames in high-velocity streams, however, these methods do not give good results and other techniques are being developed. Measurement of the conductivity between two probes has given satisfactory indication of the relative combustion conditions throughout the combustion zone.

A study of the mechanism of igniter action in ramjet combustion is being carried out at Experiment, Inc. The investigation of pilot flames and obstacles of simple geometric form will be emphasized. The influence of total pilot heat-output, space distribution of velocity and temperature, transport processes in the vicinity of the ignition region, jet and boundary layer phenomena, and the geometry of the components themselves will be investigated. Studies to date show that very small variations in igniter and burner design have a great influence on the combustion. The shape of the igniter and of the struts supporting it are important considerations. The critical zone for initiation, stability, and subsequent propagation of the flame seems to be the point of separation of the flow from the igniter. It is planned to study these phenomena in more detail by a correlation of boundary layer phenomena, turbulence, and wakes with the observed flame properties. A rectangular combustion chamber with two pyrex or quartz sides has been constructed for photographic and Schlieren observation of the flames.

Under certain conditions, detonations occur in high velocity streams of combustible mixtures, known as "rough burning." In connection with the study of the mechanism of igniter action, Experiment, Inc. is investigating the cause of this rough burning. High speed photography shows that the velocity of propagation of the detonation is between 1000 feet per second and 4000 feet per second, and that the combustion

wave travels upstream beyond the igniter. By the injection of water at various points along the inside surface of the flame tube, it has been shown that the origin of the detonation is at the intersection of the ordinary flame with the tube. Further investigations of the cause of rough burning and of the mechanism of the smoothing effect of the introduction of water along the tube are being carried out.

In a study of combustion in ramjet burners at the Flight Propulsion Research Laboratory¹⁶, the effect of air inlet pressure, air inlet temperature, fuel air ratios, and fuel injection methods on flame length and combustion efficiency are being investigated (21). A modified form of the MIT fuel injector and combustor was used. The combustion chamber was an 8 inch diameter water-cooled tube. The length of the chamber could be varied between 22 inches and 96 inches by moving a tube back and forth through the downstream end. On the upstream end of the tube were 8 radial tubes which sprayed a sheet of water transversely across the combustion chamber. This served to quench the flame at any desired chamber length and permitted the exhaust gases to pass on downstream for later collection or examination. By this means, the position at which combustion was complete could be determined quite accurately. Just enough water was used in the spray that it could be all evaporated by the heat of the exhaust gases.

The fuel used in these tests was 62-octane gasoline. It was admitted to the tube through six radially arranged fuel injectors, each of which was provided with a series of small holes, so that the streams were transverse to the long axis of the combustion tube. Immediately downstream from the fuel inlet was a flame holder consisting of seven cones, each about two inches long and about one inch in diameter at the base, with the apex pointed upstream. One cone was at the center and the other six were at the corners of the hexagon around it. The outer six were connected by small V-shaped metal troughs, and three of them were attached to the center cone by similar troughs.

Combustion efficiency was determined by heat balance measurements. The inlet and outlet temperatures and the rate of flow of the water were determined both for the water cooling jacket and for the water sprayed into the tube at the downstream end of the combustion chamber. Fuel air ratios over the range 0.035 to 0.070 were used. The air pressure at the inlet was 40 inches or 55 inches of mercury, and the air inlet temperatures at these pressures were respectively 20° F and 160° F.

¹⁵Experiment, Inc., Richmond, Virginia; J. W. Mullen, II; BuOrd Contract NOrd 9756; *Confidential*.

¹⁶National Advisory Committee for Aeronautics, Flight Propulsion Laboratory, Cleveland, Ohio; A. M. Rothrock.

With the apparatus described above, the combustion efficiency was determined as a function of the fuel-air ratio and the combustion chamber length. The maximum combustion efficiency was obtained with a fuel-air ratio of 0.045. With mixtures richer than this, the combustion was evidently not complete even after a distance of 96 inches. The maximum temperature rise in the burning gases was obtained with a fuel-air ratio of 0.06. The combustion efficiency increases as the inlet air pressure is increased, if the combustion chamber is long enough in each case to give complete combustion. For a given length of combustion chamber, the combustion efficiency decreases as the air inlet velocity increases, and as the air inlet temperature decreases. The combustion efficiency may increase or decrease as the air inlet pressure increases, at constant length of the combustion chamber, depending on the type of injector used, the pressure, and the combustion chamber length. It was found that the flame length in the combustion tube increases as the inlet air velocity increases and as the air inlet temperature decreases.

The importance of the method of fuel injection was indicated in a test in which the fuel injector was changed to a set of Monarch spray nozzles. With the Monarch nozzles, the combustion chamber could be shortened from 96 inches to 40 inches when the air velocity was 40 feet per second, without changing the combustion efficiency. When the air velocity was increased to 120 feet per second, however, the 40 inch combustion tube gave decreased combustion efficiency.

The National Bureau of Standards¹⁷ is also investigating the behavior of flame holders. A four-inch square ramjet with one glass side has been constructed, and it will be possible to observe the holder and the flame visually and photographically. It is planned at first to study high speed streams of homogeneous mixtures of a vaporized hydrocarbon and air. The blowers have a capacity of 1700 cubic feet of air per minute at a pressure of 30 pounds per square inch, giving a velocity of 200 feet per second in the burner. The studies will include the effect of mixture velocity, air-fuel ratio, and type of fuel on action of flame holders. It is hoped that it will be possible to make measurements of the apparent flame speed.

The National Bureau of Standards is also investigating the following: the performance of fuel vaporizers, designed to convert all of the fuel into vapor by the combustion of a small fraction of the fuel; the development of combustion chambers for ramjets; the ignition of ramjets using hydrocarbon fuels contain-

ing additives; and the testing and performance of existing fuel nozzles. Other work at the National Bureau of Standards is discussed in Part 2, "Fuels," and Part 6, "Instrumentation," of this Volume.

Purdue University¹⁸ is studying continuous process combustion, with the objective of defining the effect of combustion chamber type and shape, fuel and oxidizer distribution, and turbulence (25%). A combustion chamber has been designed for use with nozzles up to about 5 inches in diameter which will give a uniform velocity distribution across the jet. It is planned to have an air supply of 240,000 pounds of air per hour at a pressure of 17 pounds per square inch or 100,000 pounds of air per hour at a pressure of 45 pounds per square inch, giving an air flow velocity of 250 feet per second. Approval for the erection of a building to house the necessary equipment has just been received and construction should be finished in a few months. While the arrangements for the large combustion chamber are being completed, work will be carried out with a small combustion chamber which can accommodate nozzles up to 3 inches in diameter. Preliminary tests have been made with this combustion chamber and it is expected that work will be started shortly on studies of the effects of turbulence, of burning length as a function of the mass rate of flow, and of flame holders.

In the work on combustion at Purdue, it is planned to emphasize the effects of turbulence and of scale. In this connection it was thought desirable to carry out some preliminary small-scale experiments. A Bunsen burner has been constructed with a small rod about 1/8 inch in diameter along the axis of the tube with the end of the rod in the plane of the exit of the tube. The rod can be rotated at 9,000 revolutions per minute by a motor, thereby disturbing the flow of the gas stream. If the initial results obtained with this apparatus appear promising the method will be adapted to large-scale work. Methods for evaluating the disturbances created in the flowing gas stream by the rotating rod and of its effects on combustion rate are being investigated.

7. COMBUSTION IN LIQUID SPRAYS. A study of the flame propagation velocity in liquid fuel logs is being carried on at Battelle Memorial Institute.¹⁹ It is planned to use the method of flame propagation and it was found necessary to undertake an extensive investigation of this method in order to get consistent results. Calibration data, obtained with fuel-air mix-

¹⁷Bureau of Standards, Washington, D. C.; E. F. Flock; BuAer Order NAer 00617; *Restricted*.

¹⁸Purdue University, Lafayette, Indiana; H. J. Burmer; OSR Contract N6 ori 104, T.O. 1, Phase 2; *Unclassified*.

¹⁹Battelle Memorial Institute, Columbus, Ohio; J. F. Foster; AAF AMC Contract W 33 038 ac 14202; *Confidential*.

tures whose flame velocity is known from other measurements, are expressed graphically in a plot of the ratio of flame velocity to jet velocity against the observed half-angle of the flame. The factors leading to inconsistent results, such as temperature and turbulence, have been investigated.

The Massachusetts Institute of Technology⁵⁰ is investigating the ignition, combustion, and flame propagation in homogeneous fuel clouds (20). In this work, Diesel fuel under 700 pounds per square inch pressure is sprayed in a combustion chamber and fired by spark ignition. Air is introduced under pressure to study the effect of air velocity on ignition. Ignition was fairly easily accomplished, but some trouble was encountered with fuel accumulating on the electrodes and breaking away as glowing nuclei. These caused erratic burning so that the irregular flame front made flame speed by angle measurements difficult. With high speed photography (1500 frames per second), flame speeds of five to twelve feet per second were observed.

In connection with the development of gas turbines, the Thornton Laboratories (England) of the Shell Oil Company are investigating the influence of fuel properties on the combustion process (11). Of particular interest are the factors which influence the burning of a fuel spray when it has mixed with air, but it has been considered necessary first to study the combustion of the vaporized fuel in order to eliminate the complicating influences of atomization and evaporation. The apparatus for this work consists of a jet of fuel burning in a turbulent air stream in a combustion tube. Using a given vaporized fuel, such as butane, the influences of the following factors are being considered: (a) Air-fuel ratio and air mass flow; (b) Design of fuel nozzles; (c) Fuel and air temperature; (d) Pressure, above and below atmospheric; (e) Additives. In addition, a comparison of different fuels under given experimental conditions will be carried out. After vaporized fuels have been investigated, a study of the combustion of different atomized fuels will be carried out. An accurate method of gas analysis has been developed in order to measure combustion efficiency. Each constituent is estimated by fractional condensation and fractional combustion, and it has been found that combustion losses as small as 0.2% can be detected.

8. ACOUSTIC PHENOMENA IN COMBUSTION. There are two acoustic phenomena which are of interest in

investigations of the combustion process. The first relates to a resonance condition associated with the acoustic geometry of the combustion chamber. In some manner, not too clearly understood, the combustion process sets up and maintains vibrations at a frequency controlled by the dimensions of the system. Examples of this are the well-known singing flame, the pulse jet, and rough burning. The second is concerned with the use of an ultrasonic field as a source of specialized controlled turbulence. The wavelength and amplitude corresponding to the scale and intensity of turbulence, can be varied over a wide range in a known manner. Consequently, combustion phenomena can be studied under specialized, known turbulent conditions rather than under the more general turbulent conditions, produced by grids, which are difficult to control and measure.

The acoustical oscillations which occur in burners are being studied at Battelle Memorial Institute.⁵¹ A blower feeds a Helmholtz resonator to which nozzles of different dimensions can be attached. The flame holder and igniter are mounted in the nozzle. The acoustical frequencies have been analyzed and have been found to be connected with the nozzle dimensions and resonator frequency. In addition, frequencies common to all three nozzles tested were found whose origin is not clear at the moment. A note of frequency about 70 cycles per second, caused by the flame, was discovered. The effect of a change of the resonator volume on the frequency was much less than the calculated value. Under certain experimental conditions, the most prominent acoustic phenomenon consisted of sharp pulses at the natural frequency of the resonator, called "motorboating."

Acoustic studies at Bodine Soundrive Company⁵² have related primarily to the development of acoustic power plant units, and discussions of their work will be found in Part 4 of Volume I as well as Part I of Volume II of this series. From the combustion standpoint, they have recognized the principle, stated by Rayleigh (26), that heat should be communicated to the pulsating gas at the moment of greatest condensation. Their whole approach has been from the theory of acoustics with such measurements as changing acoustic impedance, particle velocity, phase, and radiation pressure being made. The effects of various acoustic impedance terminations of the combustion chamber have been studied.

⁵⁰Massachusetts Institute of Technology, Cambridge, Mass.; H. C. Hottel; Joint Sponsorship of the Bureau of Ordnance and the Bureau of Aeronautics under Contracts NOrd 9661; *Confidential*, and NOA(s) 8632, *Restricted*.

⁵¹Battelle Memorial Institute, Columbus, Ohio; J. F. Foster; AAF AMC Contract W-33 038 ac-14202; *Confidential*.

⁵²Bodine Soundrive Co., Los Angeles 28, California; A. G. Bodine.

The University of Delaware⁵³ is constructing a 750 kilocycle per second ultrasonic generator with a quartz transducer for use in studies of combustion. This work is in the preliminary stages and no results are yet available.

The University of Wisconsin⁵⁴ plans an investigation of acoustic phenomena as a part of the combustion program. The effects of sound on the stability of a Bunsen flame, on normal flame velocity, and on gas flow will be studied as a function of sound frequency, sound intensity, fuel-air ratio, and Reynolds number. The effects of sound on the boundary layer, the wall friction coefficient, and mixing will be considered. This work is in the early design stage.

9. IGNITION. Several rather extensive investigations of ignition phenomena have been made, including the following: (a) ignition by heating the whole mass of gas; (b) ignition by a heated surface; and (c) spark ignition. References (13) and (15) review these studies and give references to the literature. This work has resulted in a qualitative understanding of the factors involved in static systems, but it has not been possible to develop quantitative relations which would be of help to the designer of jet power plants. There is almost no quantitative data on ignition in flowing streams.

The temperature to which a mass of gas must be heated to ignite depends not only on the combustible mixture but also on the exact details of the experiment, the size and shape of the container, the material of which the container is made, and the rate of heating. Measured values of ignition temperatures of the same mixture may differ by several hundred degrees Centigrade under different experimental conditions. Theoretical treatments of this case have been given in which the heat developed by the reaction, the heat lost by conduction, and the decrease in concentration of the reactants due to the reaction are considered. The resulting equations have been successful in explaining observed phenomena in reactions governed by thermal conditions.

Detailed studies of the ignition temperature of given combustible mixtures as a function of the pressure and temperature of the mixture have been made. Such studies have commonly been used to obtain evidence as to the mechanism of the reaction. It is often found for chain-branching reactions that the ignition temperature is high at low pressures, that it first decreases

to a minimum, then increases to a maximum, and then decreases again as the pressure is increased. These phenomena are explained on the basis that a chemical reaction is not simple but involves many separate steps, each with its own rate. The overall rate of the reaction is determined by the relation between the chain-branching and chain-breaking processes, which will be affected by the pressure and temperature change. Furthermore, the induction time, the time for which a given mixture must be maintained at a given pressure and temperature before inflammation occurs, varies with the pressure and temperature. These relations are complicated and complete chemical kinetics may be consulted for details (27). For jet power plants, the value of the ignition temperature is not important, except in starting the motor, because the temperature in the combustion chamber is always adequate. The induction time, however, must be as short as possible, and a detailed knowledge of the ignition process might lead to the discovery of ways to shorten it.

Ignition of a gas by a heated surface, usually a metal wire or strip in the combustible mixture, depends on the temperature, size, and material of the surface. The required ignition temperature is high, partly because of the effect of the high thermal capacity of the metal in reducing the temperature in the nearby regions. In addition, the concentration of the reacting molecules is reduced in the regions of highest temperature, thereby reducing the reaction rate. Equations can be set up describing this ignition process, taking into consideration the heat balance and the change in concentration of the reactants by diffusion and by the chemical reaction. Only numerical solutions or approximate solutions can be obtained, and the theory appears not to have been checked with experiment because of both mathematical and experimental difficulties.

Ignition by a spark depends not only on the total energy introduced but also on the frequency and duration of the discharge. The evidence indicates that the production of active particles is very important but that ionization is ineffective in causing ignition. Landau (14) has investigated ignition theoretically, assuming a chain-branching reaction, and considering heat conduction and the diffusion of active particles. In order to integrate the equation, it was necessary to introduce simplifying assumptions, one of which was that the velocity of reaction is constant. Lack of suitable experimental data has not permitted the equation to be checked experimentally. This work should be extended to remove some of the restrictions imposed by the assumptions.

⁵³University of Delaware, Newark, Delaware; Kurt Wuhl; Subcontract with United Aircraft Corporation, East Hartford, Connecticut; BuOrd Contract NOrd 9845; *Confidential*.

⁵⁴University of Wisconsin, Madison, Wisconsin; J. O. Hirschfelder; BuOrd Contract NOrd 9938; *Restricted*.

All the methods of ignition described above are used in jet power plants, where it is a matter of vital concern to obtain rapid and reliable ignition. Continuation of past work and the extension of ignition studies to flowing streams are obviously desirable.

The Bureau of Mines⁵⁵ has recently made significant progress in the study of the ignition of quiescent gas mixtures by electric sparks. Quantitative relations between the minimum spark energy for ignition, composition and pressure of the mixture, electrode shape, length of spark gap and electric discharge characteristics are being developed. In a recent report (11), Lewis indicated the possibility of relating normal flame velocity and minimum spark energy for ignition and pointed out that such relations, although valuable, are not a substitute for a knowledge of the details of the mechanisms of reactions. The work on ignition at the Bureau of Mines will be extended to include ignition by various means in laminar and turbulent flow.

Massachusetts Institute of Technology⁵⁶ is determining the amount of energy necessary to maintain ignition in a vaporized gasoline-air mixture (20). The fuel-air mixture flows down a 3-inch diameter duct at velocities up to 300 feet per second and is ignited by a thin wire of fuel placed along the diameter of the duct. Such factors as velocity, air-fuel ratio, temperature of the wire, and electrical energy input to the wire are being considered. The first data have been obtained with this apparatus. With a 1/8-inch diameter rod, ignition is obtained by a current flow of 1200 amperes, giving a temperature of about 2000° F.

In connection with a study of re-ignition in a pulse jet, New York University⁵⁷ is investigating ignition by shock waves (22). The apparatus used is divided into three sections: a compression chamber three feet long, an expansion chamber five feet long, and a combustion chamber one foot long. A plane shock wave is sent down the expansion chamber by the bursting of a diaphragm between the compression chamber and the expansion chamber. A fraction of a second before the diaphragm bursts, a sliding plate between the expansion chamber and the combustion chamber is raised in order to allow the shock wave to pass from the expansion chamber into the combustion chamber. The experiments performed in this apparatus so far

have been qualitative in nature and it has not yet been possible to obtain ignition. At present the apparatus is being re-designed so that the combustible gases in the combustion chamber can be pre-heated.

B. Combustion Studies in Jet Power Plants

Some of the experimental work on flames and combustion processes can be done in laboratory apparatus under conditions which permit fairly good control of the variables and more of this type of experimentation should be done. However, the necessity of working with actual power plants before complete information is available on how to design them for greatest efficiency demands combustion experiments in power plants even though the experiments must be of an empirical nature.

The operation of a jet power plant depends upon bringing a fuel and an oxidizer together so that they will react rapidly, or upon bringing a monopropellant into such a thermal condition that it will decompose rapidly, in every case with the generation of large volumes of gas at high temperature.

In a liquid propellant rocket, this means impinging two or three liquid streams in a combustion chamber, or passing a monopropellant over a catalyst, or subjecting it to a heated surface in order to bring about reaction in the shortest possible time. Therefore in rockets, injector nozzle design is a problem that is important, and different for the various fuels and oxidizers. It is recognized too, that although the reaction must go to completion in the shortest possible time, a finite time is required. The chamber must be big enough to permit completion of the reaction before discharge of products through the nozzle, and the shape is important since it influences the rate and efficiency of the reaction. Thus the ratio of chamber volume to exhaust nozzle area (L^*) is not the only factor to be considered.

In other jet power plants, e. g. pulse jets, turbojets and ramjets, where the oxidizer is air taken in during flight, the fuel, which is usually stored in liquid form, such as gasoline, kerosene, or Diesel oil, must be mixed with a large volume of rapidly moving air. The combustion must be initiated and maintained under adverse conditions of fluid flow, and this increases the complexity of the problems to be dealt with. It is also necessary to cope with a variable air supply due to changes in both flight velocity and altitude, and thus provision must be made for a correspondingly variable fuel flow.

These conditions lead one to a study of fuel injectors, the mixing of liquids and gases, or gases and gases, igniters, and flame holders, to accomplish the rapid mixing of the proper ratios of fuel and oxidizer.

⁵⁵Bureau of Mines, Pittsburgh, Pa.; Bernard Lewis; ONR Order ONR-27-47; *Unclassified*.

⁵⁶Massachusetts Institute of Technology, Cambridge, Mass.; H. C. Hottel; Joint Sponsorship of the Bureau of Ordnance and the Bureau of Aeronautics under Contracts NOrd 9061; *Confidential*, and NOa(s) 8632, *Restricted*.

⁵⁷New York University, New York, N. Y.; J. K. L. MacDonald; ONR Contract N6-ori-11, T.O.-2; *Unclassified*.

and the rapid burning of the entire mass. In some cases the fuel is completely vaporized before it enters the combustion chamber. In others, it enters as a liquid, more or less heated, and provision must be made for breaking the liquid streams up into droplets, then evaporating these to form a combustible mixture with the air, since combustion in such cases appears to take place almost entirely in the gaseous phase. Since the air flow through the combustion chamber may be from 50 feet to 250 feet per second and normal flame speeds are more nearly 10 feet to 20 feet per second, it is necessary to use a multiple system of ignition sources to accomplish the necessary rapid burning. The igniters may be separate pilot flames, electric arcs, or a system of flame holders which interrupt the gas flow sufficiently to produce slower moving eddies which can be kept burning. The enforced method of cut and try which is adopted in studying these combustion chambers leads to a large amount of expensive experimentation the results of which are often fruitless.

Most of the present work on these problems is confined to turbojets and ramjets but is reviewed here not only because it has a bearing on the investigation of pulse-jets, but also because it shows the extent of the effort being put forward by engineers in the design and construction of jet power plants, and may indicate the ways in which fundamental research can assist in their better design and more efficient operation. It is not intended that all of the combustion work on jet power plants be reviewed here, for some of it is only incidentally related to combustion.

1. LIQUID PROPELLANT ROCKET MOTORS. The Bell Aircraft Corporation⁵⁸ is investigating the effect of combustion chamber size and shape and of injector design in order to obtain necessary engineering data (20). Recent work has been concentrated on the evaluation of the atomizing characteristics of injectors of various configurations. Plain orifices, impinging jets, annular orifices, centrifugal nozzles, slit nozzles, and lip nozzles have been studied. The spray pattern has been qualitatively observed by visual inspection, but it is planned to use high speed photography in the future. The injectors are tested in rocket motors, and their behavior is characterized by the ratio of the characteristic velocity of the exit gases calculated from test-stand results to the theoretically calculated ideal characteristic velocity. A relatively inefficient nozzle gives a value of about 0.8 for this ratio.

The group at California Institute of Technology⁵⁹ believe that the development of liquid propellant rock-

ets is seriously hampered by lack of knowledge concerning the nature of the combustion process in a motor. Empirical designs have been based on measurements of such parameters as L^* , L/D , c^* , etc., and the validity of the empirical formulae is limited to designs that are similar. They wish to undertake investigations that will give a more general understanding of features such as the distribution of temperatures, velocities, and composition in order to establish more logical methods for guiding combustion chamber design. They will first study hydrogen peroxide monopropellant motors equipped with transparent wall sections, where the temperatures will be low enough to be easily measured. Later they hope to work on hydrogen peroxide-alcohol motors, then nitric acid-aniline, and perhaps nitromethane. If possible, the distribution measurements will be correlated with systematic changes in methods of injection, shapes of combustion chamber, etc. The design of the injector has a marked effect on performance and they are now investigating several aspects of the problem such as droplet size and distribution, spray patterns, and velocity distribution.

2. PULSE-JET MOTORS. New York University⁶⁰ has undertaken to study pulsating jet engines with respect to (a) flame and particle motion, pressures, temperatures, densities, and effects of turbulence; and (b) water stream analogies for gas motions in order to determine characteristics of simple theoretical models. The accumulated information will be used for theoretical treatments of the internal ballistics of jet devices on the basis of justified simple models.

Several models of pulse jets with pyrex side walls and plaster of paris or transite upper and lower walls have been made and tested (22). These were made to provide a way of observing the combustion process visually and photographically. Some models were made with pyrex plate instead of tubing in order to reduce optical distortion. Photographs of the pulsating flame were taken at the rate of 1000 frames per second. A few of these were under satisfactory conditions of true resonance. It was observed that in each combustion cycle, a knot of flame called a "flambeau" was propagated through the tail pipe from the combustion chamber. It was preceded by a region of burning and after a brief interval of no burning, it was followed by a band of flame. This cycle was then repeated. The flame band increased in length as it moved up the tail pipe from the combustion cham-

⁵⁸Bell Aircraft Corporation, Buffalo, N. Y.; Stuart Edleson; BuOrd Contract NOrd 9876; *Confidential*.

⁵⁹California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California; L. G. Dunn; AAF Contract W-33-038-ac-4320 (12847); *Restricted*.

⁶⁰New York University, New York, N. Y.; J. K. L. Mac Donald; ONR Contract N6-ori-11, T.O.-2; *Unclassified*.

ber, then remained constant. Movement through the system had an average velocity of 175 feet per second but superimposed on the gradually accelerated motion was a rapidly fluctuating motion with a definite period indicating a resonant frequency of 154 cycles per second. In one set of measurements illustrating the magnitude of the observed fluctuations, the velocity of the flambeau decreased from 365 feet per second to 40 feet per second in 1.5 milliseconds.

Moving pictures of a later model indicated a resonant frequency of 250 cycles per second, which agrees with the usual estimate given for the Minijet and is a more reliable result than the value 1.4 cycles given above. It was observed that the flambeaux moving down the tail pipe at intervals of about 4 milliseconds hesitated once or twice, and occasionally momentarily reversed their direction. The first hesitation coincided with the initiation of the next cycle. The hesitations were undoubtedly caused by air rushing back in the tail pipe. For this small pulse jet, burning seemed to be more or less continuous, flaring up on each successive compression.

3. TURBOJET COMBUSTION CHAMBERS. The Massachusetts Institute of Technology⁶¹ is determining the combustion efficiency of turbojet burners in order to evaluate the design (20). Temperature measurements at various points in the exhaust gases are made by means of tungsten-molybdenum thermocouples and the results show annular rings of hot and cold regions indicating a persistence of thermal unmixed conditions in the combustion products. Preliminary pilot gas sampling of the product has confirmed this conclusion. That mixing is not more complete as far down the stream as the nozzle is surprising and has led to further fundamental work on the mixing process. The calculated values of the temperature of the exhaust gases do not agree with the temperatures observed by a probe. It is felt that a temperature probe in a gas stream will not give satisfactory results if the chemical reaction is not complete. It is planned to subject the instrument to a chopped stream of hot and cold gases to get some idea of the effect of turbulence.

The condition of the air at the inlet to a turbo jet combustor not only influences engine operation, but also places an altitude limit on the operation of the turbojet engine. Consequently, the National Advisory Committee for Aeronautics⁶² is studying the effect of

the temperature of inlet air, velocity of inlet air, pressure of inlet air, fuel air ratio, combustion chamber pressure, and combustion chamber temperature on the operating performance of the engine and the combustion efficiency (21). In one test with a 19-B engine, whose air compressor operates on a 3:1 compression ratio, a "dead band" at 20,000 feet altitude was found between the air compressor speeds of 6,500 revolutions per minute and 11,300 revolutions per minute. The temperature developed by the engine at 6,500 revolutions per minute drops below 750 F and stays below 700 F until the speed reaches 11,000 revolutions per minute. Within this range, the temperature is not high enough to keep the fuel ignited and of course the engine will not operate. In the 19-XB engine whose compressor operates at a 4:1 compression ratio, the minimum temperature necessary for the smooth operation of the motor is somewhat higher, but except for this its overall operation is much better than that of the 19-B engine.

In other tests, using 100 octane gasoline as a fuel, it was found that the combustion efficiency increases with increase in the speed of the turbine, with increase in the temperature of the entering air, with decrease of the air inlet velocity, and with increased air inlet pressure. At a constant turbine speed of 16,000 revolutions per minute, the combustion efficiency drops from 99% at a simulated altitude of 24,000 feet to 65% at a simulated altitude of 47,500 feet. At a constant simulated altitude of 35,000 feet, the combustion efficiency drops from 78% at 14,000 revolutions per minute to 41% at 10,900 revolutions per minute. In high altitude operation, in addition to the difficulty of maintaining combustion and the impossibility of obtaining high combustion efficiency, there is a further difficulty of vapor-locking in the fuel nozzle, which is also being studied at the Flight Propulsion Research Laboratory.

An extensive study of the effect of combustion chamber geometry on blow-out limits and on combustion efficiency has also been made by the National Advisory Committee for Aeronautics. It is outside the province of this report to discuss the design of turbojet combustion chambers. However, it may be said that combustion chamber design requires a compromise between good burning and good mixing. It is possible to adjust the design parameters of the combustion chamber so that the combustion efficiency will be greater than 40% over the entire range of permissible temperature rise, for given conditions of inlet air pressure and temperature. These efficiencies can not be realized, of course, over the range of altitude at which a combustion chamber must operate.

⁶¹Massachusetts Institute of Technology, Cambridge, Mass.; H. C. Hottel; Joint Sponsorship of the Bureau of Ordnance and the Bureau of Aeronautics under Contracts NOrd 9664; Confidential, and NOn(s) 8632, Restricted.

⁶²National Advisory Committee for Aeronautics, Flight Propulsion Research Laboratory, Cleveland, Ohio; A. M. Rothrock.

4. RAMJET COMBUSTION CHAMBERS. The ramjet work at Consolidated Vultee Aircraft Corporation, Downey, California⁶³, is largely done under the BUMBLEBEE project. It concerns diffusers, fuel injectors, and flame holders, with the aim of extending the limits of air/fuel ratios for smooth burning and for reignition in case of flame blow-out.

In their 18-inch ramjet, the combustion chamber beyond the igniter is about 5 feet long and 18 inches in diameter. By adding the fuel not through the usual spray system back of the diffuser but through an annular ring which sprays it over the surface of the "spike" at the front end of the diffuser, it has been possible to obtain an operating range of air/fuel ratios (with either gasoline or kerosene) of 7:1 up to 60:1, where the stoichiometric ratio is about 15:1. This design also permits the use of air velocities through the rear of the diffuser ahead of the igniter up to 300 feet per second, whereas previous designs were limited to 160 feet to 200 feet per second. It is believed that at the optimum air/fuel ratio, it may be possible to increase the air velocity up to 600 feet per second and still maintain smooth combustion downstream from the flame holders.

Consolidated Vultee Aircraft Corporation has made a detailed study of the functioning of fuel injectors of various types. This work has involved any or all of the following tests: visual studies, using water in place of gasoline; sampling and analyses of mixtures both upstream and downstream from the igniter without firing the igniter; burning tests with particular attention to air/fuel ratios, flame pressure measured immediately upstream from the igniter, air specific impulse, system pressure on inlet and fuel injector pressure drop; and general behavior of the burning with regard to ease of starting, ease of handling, range between maximum and minimum air/fuel ratios which can be ignited once the flame has been extinguished by use of an improper air/fuel mixture (the "gate"), and the range of air/fuel ratios over which smooth burning can be maintained (the "meadow").

Consolidated Vultee Aircraft Corporation has also worked on several types of fuel injectors other than the annular spray over the spike of the diffuser. One preferred type which has been designed is the recirculating "vortex spray nozzle" which with the aid of a constant-differential fuel pump will give a maximum-minimum fuel ratio delivery of 20:1. This gives, therefore, a 2:1 advantage over what is required at differences in altitude between sea level and 50,000 feet, where the air pressure differential is 10:1. In order to

get basic information for this type of fuel injector, a single-tube, single-opening fuel injector has been studied in a stream of air traveling at 300 feet per second. The injector can be rotated through 360° in the air stream, and the fuel is forced out under 90 psi. By varying the size of the opening, one can determine the fuel jet penetration into the high-velocity air stream at different angles.

Another phase of the burner development work with respect to fuel injection studies is the determination of the percent vaporization of the fuel. This percent evaporation has been calculated from measurement of the temperature drop in a non-burning air stream, assuming that this drop in temperature is caused solely by the latent heat of vaporization. From the practical point of view, more rapid evaporation and more uniform mixing of the fuels in high velocity air streams. Basic studies on these phases of the injector problem would be of considerable assistance in the design of satisfactory fuel injection systems.

In work on flame holders, Consolidated Vultee Aircraft Corporation has investigated the following types: can, rod, catalytic (platinized asbestos), surface combustion (refractory grids), gutter, Cornell Rake, and the spark-ignited pilot. More recently they have been working on a new design of combined "inner-body" igniter and flame holder for a ramjet which is to operate at Mach No. 1.4 up to 2.0. It comprises a perforated cone about 4 feet long with rounded apex pointed upstream just below the diffuser. The base of the cone fills the entire cross-sectional area of the 18-inch ramjet. The fuel is sprayed into the upstream end of the cone, and the perforations, which increase in size toward the cone's base, admit the air from the diffuser. This design will permit an air velocity at the rear end of the diffuser of about 350 feet per second.

At the Consolidated Vultee Aircraft Corporation Lone Star Laboratory⁶⁴ a great deal of work has been done on the design, construction, and testing of injectors and flame holders for an 18-inch ramjet. This has been entirely of an empirical nature, the results with one model being used to suggest changes for the next. The best model of fuel injector which they have tested comprises an annular manifold located outside and around the circumference of the ramjet with a series of radial tubes leading into a corresponding series of tubes inside the ramjet and parallel with the air flow. The downstream ends of the tubes are connected to another annular manifold tube, both the

⁶³Consolidated Vultee Aircraft Corporation, Downey, California; BuOrd Contract NOrd 9028; Restricted.

⁶⁴Consolidated Vultee Aircraft Corporation, Lone Star Laboratory, Daingerfield, Texas; J. E. Arnold; BuOrd Contract NOrd 9028; Restricted.

longitudinal tubes and the inside annular ring being provided with small openings for discharge of the fuel in a large number of places. The best flame holder and igniter, called the Cornell Rake, is one which has ten burning powder charges, which are fired electrically and which burn for 45 seconds. Six of these charges are held in small steel cylinders which have sunflower-shaped fingers at the downstream end, and are arranged radially between the central group of four and the wall of the chamber. The group of four are housed in an extension of the diffuser. The flames burn downstream and ignite the air-fuel mixture which comes from farther upstream. The Lone Star Laboratory is now making a collection of information and photographs of all the types of flame holders and fuel injectors which have been tested, and will include a discussion of about 70 varieties of each.

An igniter to be successful must furnish rapid, smooth, and good ignition over a wide range of air-fuel ratios, and successful re-ignition over a wide range of air-fuel ratios to take care of the frequent conditions in which the flame blows out. In connection with the study of igniters, information is needed concerning the temperature of the exhaust gases during smooth burning versus during rough burning, a method of making point-to-point measurements of the fuel distribution and of the flame distribution, and of the temperature distribution both down the length of the combustion chamber and across its area.

A combination ducted rocket and ramjet power plant is being developed by Consolidated Vultee Aircraft Corporation (Downey, California)⁶⁵ in which the ignition and flame holding is provided by a small 50-pound thrust ethyl alcohol-liquid oxygen rocket located at the center of the upstream end of a ramjet combustion chamber which is 13 inches in diameter. It has been found that placing the rocket inside a duct produces an augmentation of 1.75 times the thrust which can be obtained by the rocket alone, and adding gasoline to the stream of air drawn in by the rocket jet produces an augmentation of 3.0 times the thrust obtained by the rocket alone. The hope is to gain improved fuel economy per pound of thrust, and a higher thrust coefficient, based on burner chamber area, over that which could be obtained by a ramjet of similar cross-sectional area. Further, it is hoped that the ducted rocket will simplify the combustion problem at high velocities, because the rocket will act as a continuous igniter, and the rocket exhaust will increase turbulence in the ramjet and thus produce the so-

burning of the ramjet fuel. It has been found that ignition of the gasoline-air mixture will take place at an air-fuel ratio of 75:1, and satisfactory burning has been carried down to 35:1, the present limit of the air supply equipment. In due course the rocket will be changed over to gasoline-liquid oxygen, and several rockets will be placed in the ramjet, in an attempt to obtain a specific impulse of 186 seconds (about 6000 feet per second gas velocity at the ramjet nozzle).

Very little theoretical work has been done on ducted rockets. It is possible to make performance analyses using the equations for the conservation of momentum, energy, and mass from a gross standpoint, but not from a point-to-point analysis of conditions in the duct.

The Cornell Aeronautical Laboratory⁶⁶ has been carrying on studies of various flame holders, including the Whittle turbojet, airfoil, and inverted cone types. The Whittle type flame holder has good ignition and burning qualities but causes a high pressure loss. By cutting the holder down until it was only a fraction of its original length, the loss was decreased while the other good properties were retained. The airfoil type holder was better than the other types tested with regard to ignition properties and was good with respect to burning properties. In addition, its losses were low. However, since it was attached directly to the chamber wall, it caused warping due to unequal heating of that wall. The cone type flame holder was found to give good ignition and burning and when properly designed, it caused lower loss than the other types. The cone flame holder was therefore chosen for further development. The cone angle and the number of holes for flame exit are critical and must be determined empirically for each specific use.

Experiment, Inc.⁶⁷ has studied and developed several types of igniters for ramjet burners. Some of these have been of the hydrogen-oxygen pilot flame type, but nitric acid-aniline and liquid sodium igniters have also been investigated. Others have been igniters of simple geometric form such as cylinders, spheres, and cones which are heated electrically. They have noted that very small variations in igniter and burner design have great influence on the combustion. Even small irregularities caused by the flame in turning out an igniter may have a noticeable effect. The critical zone for initiation, stability, and the subsequent propagation of the flame seems to be the point of separation

⁶⁵Consolidated Vultee Aircraft Corporation, Downey, California; C. R. Irvine; AAF-AMC Contract W-33-038-ac-14547; *Restricted*.

⁶⁶Cornell Aeronautical Laboratory, Buffalo, N. Y.; J. L. Beal; Subcontract with Curtiss-Wright Corporation, Airplane Division, BuOrd Contract NOrd 8993; *Confidential*.

⁶⁷Experiment, Inc., Richmond, Virginia; J. W. Mullen, II; BuOrd Contract NOrd 9756; *Confidential*.

of the flow from the igniter. They are convinced that the main factors in ignition are aerodynamic not chemical.

The work at the University of Southern California⁶⁸ on subsonic ramjets has been carried on for about two years. Four models have been designed, built, and tested, the fuel in each case being gasoline. Temperatures up to 2800 F in the gas stream have been obtained. They are calculated indirectly by measuring the exit pressure of the exhaust gases. The 20-inch jet should produce a temperature of about 3200 F, but since an air fuel ratio of 20:1 gives only about 85% combustion efficiency, the maximum temperature is not reached.

Much of the work on the subsonic ramjet has been in connection with flame holders, for maintaining combustion has been one of the most serious problems. The present preferred flame holder is a ring with a V-shaped cross-section. Three of these are arranged concentrically with the apex of the V aimed upstream. The apex is punctured with a series of small holes to permit the entrance of the unburned air and fuel. It has been found that the dimension of the open end of the V is critical and that it must be approximately one inch across. Larger and smaller dimensions have failed to maintain continuous combustion. The flame holders are best located a few inches downstream from the diffuser.

The Standard Oil Development Company⁶⁹ is concerned primarily with the development of a satisfactory six-inch ramjet engine and consequently all efforts are directed toward that end (12). Each component has been varied in a cut and try manner to produce the best composite design. The following specific problems have been investigated in connection with combustor development: (a) fuel atomization; (b) air velocity distribution in the diffuser; (c) range of air/fuel ratio for burning; (d) initiation of combustion; (e) maintenance of combustion; (f) effect of varying Mach numbers from 1 to 2; (g) sealing; (h) effects of small departures from design; (i) weight and drag of the combustor; and (j) problems of combustion wall heating. General burner development and improvement is continuing with particular emphasis on efficient feed to the pilot or flame holder stage and on the inclusion of a second baffle or flame holder to aid in the ignition. With regard to the effect of scale, it is felt that a large unit is easier to construct than a

smaller one, not only because it is easier to support combustion with more ignition points but also because certain parts do not have much latitude in size variation and small units carry igniters which are as big as those used in large units.

The Standard Oil Development Company⁷⁰ has put into operation a fuel spray nozzle test stand to study the behavior of nozzles in connection with liquid fuel investigations, since fuel spray characteristics are considered an important variable. A laboratory-scale liner-type burner (functionally similar to the G. E. Type 1-40) has provided for studies at high-output combustion. Reproducible spray distributions have been obtained. Several high output burners have been developed. In one of these burners a heat release of 35 million BTU per hour per cubic foot was obtained.

Further development work is being carried out on liquid fuel burners to provide for studies of fuel type, pressure, and turbulence at high-output conditions. Expanded test facilities will include steam ejectors to create vacuum for low-pressure operation. Studies of spray nozzle performance are being continued, in an attempt to correlate spray characteristics with burner operation. The more fundamental work now in progress includes studies of the effects of combustion promoters, pressure, and diluent gases other than nitrogen, on flame stability.

At the United Aircraft Corporation⁷¹, experimental work on a small pilot burner is planned, to study the fundamental characteristics of this type of burner and to familiarize the personnel with its operation. The effect of various wall temperatures and of various fuels will be studied. Several typical burners designed by other organizations will be tested in the existing density burner stand. This stand consists of a duct 12 feet long connecting a high pressure tank, at an absolute pressure of 100 inches of mercury, and a low pressure tank, whose absolute pressure can be varied down to 8 inches of mercury. The air capacity of the equipment is 9000 pounds per hour. A flame holder and a nozzle can be located in the duct. This study is intended to extend to various altitudes the work on these burners performed by other people.

Wright Aeronautical Corporation⁷² has developed, for combustion studies, in connection with ramjet combustion chamber development, two test cells, one of

⁶⁸University of Southern California, Los Angeles, California; W. T. DeVault; BuAer Contract NOa(s) 7598; *Confidential*.

⁶⁹Standard Oil Development Company, Esso Laboratories, Elizabeth B, New Jersey; J. P. Longwell; BuOrd Contract NOrd 9233; *Confidential*.

⁷⁰Standard Oil Development Company, Esso Laboratories, Elizabeth B, New Jersey; W. P. Lakin; ONR Contract N6-ori-109, T.O.-1; *Unclassified*.

⁷¹United Aircraft Corporation, Dept. 100, Hartford, Connecticut; J. G. Lee; BuOrd Contract NOrd 9845; *Confidential*.

⁷²Wright Aeronautical Corporation, Woolridge, New Jersey; E. Pierce; AAF Contract W-33-038-ac-14145 (15815); *Restricted*.

which has been used for the testing of flame holders and injectors and the other for the study of the operation of combustion chambers as functions of various parameters, such as density and air fuel ratio.

When a new design of flame holder or injector shows promise in the first cell, it is placed in a combustion chamber in the second cell and tested as a complete ramjet.

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ABBREVIATIONS OF GOVERNMENT AGENCIES

AAF	Army Air Forces, War Department Washington 25, D. C.
AAF-AMC	Army Air Forces, Air Materiel Command, Wright Field, Dayton, Ohio.
BuAer	Bureau of Aeronautics, Navy Department, Washington 25, D. C.
BuOrd	Bureau of Ordnance, Navy Department, Washington 25, D. C.
BuShips	Bureau of Ships, Navy Department Washington 25, D. C.
EES	Engineering Experiment Station Annapolis, Maryland.
NACA	National Advisory Committee for Aeronautics, 1724 F Street, N. W., Washington, D. C.
NBS	National Bureau of Standards Washington 25, D. C.
NOL	Naval Ordnance Laboratory White Oak, Maryland.
NOTS	Naval Ordnance Test Station Inyokern, California.
NRL	Naval Research Laboratory Washington 20, D. C.
ONR	Office of Naval Research, Navy Department, Washington 25, D. C.
OSRD	Office of Scientific Research and Development, 1424 16th Street, N. W., Washington, D. C.

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Research on ignition of combustible mixtures, flame velocity, conditions for maintaining flame stability in laminar and turbulent flow, and combustion in liquid spray is discussed. Acoustic vibrations caused by flames and the possibility of using acoustic fields in the study of flame phenomena are determined. A discussion is given of the physical and chemical aspects of combustion which effect measurement. Flame velocities are not a function of the turbulence of the stream in the range from 0 to 2.7%.

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