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PROJECT SQUID

FIELD SURVEY REPORT

INSTRUMENTATION

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Volume I, Part 6

30 June 1947

ENGINEERING RESEARCH ASSOCIATES, INC.

INSTRUMENTATION

FIELD SURVEY REPORT

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by

JAMES W. FITZGERALD

Engineering Research Associates, Inc.

Washington, D. C.

30 June 1947

[redacted]

Princeton University, the central management organization of Project SQUID, arranged for the preparation of the *Field Survey Report* under Contract Number 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

PREFACE

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

On the thesis that high temperatures and high gas velocities are from the standpoint of instrumentation the two most characteristic conditions of the liquid-rocket pulse jet fields, the emphasis in this report is on measurement of parameters of systems involving combustion processes.

The actual survey material is preceded by two review sections. In the first of these the principal experimental conditions under which measurements are made are discussed. Included are power plants, diffusion flames, stationary flames, moving flames, closed chambers, and soap bubbles. The instrumentation requirements for each condition are pointed out as well as some of the major difficulties. The three basic difficulties are (1) effects of the system on the instrument, (2) effects of the instrument on the system, and (3) fluctuations in the system.

In the second review section the basic mechanisms of operation of some of the principal instruments and methods are discussed. These include techniques for measuring pressure, temperature, gas velocity, turbulence, flow patterns, flame propagation velocity, and others. Limitations and errors are discussed in relation to measurements in combustion systems.

The survey section treats the information on measurement methods contractor by contractor. No attempt is made to associate a given instrument development with a given contract for in most cases this cannot be done. Since only meager and incidental material was available in many instances, the instrumentation material is incomplete. The result is a kind of a montage of techniques and methods throughout the country. It is hoped that this will furnish some stimulus for exchange of information between laboratories.

Some general conclusions and recommendations arising from this study are given in Section II

II. CONCLUSIONS AND RECOMMENDATIONS

The most significant conclusion apparent from a review of work on instrumentation related to pulse jets and liquid rockets is that there is an insufficiency of dissemination of experimental methods and measurement techniques. This results in much duplication, wasted effort, and lost time. Often the main aim in an investigation is neglected while effort is spent on developing an instrument already in use elsewhere. There is a great need for a consolidation of methods already available and an integration of effort in methods being developed.

Another factor evident from this study has its origin in the diversity of schemes of measuring the same physical parameter. This results in difficulty in interpreting data from various sources. Standard methods, where possible, would be helpful, and a refererence laboratory is desirable.

And finally, the rather obvious conclusion is that in many cases no acceptable methods exist for measurement of required parameters under relevant physical conditions, and in other cases the methods are only moderately successful. The investigation of new techniques should be continued under an integrated program.

With these factors in mind, the following recommendations are made:

1. Instrumentation Committee. A central committee should be formed for the purpose of consolidating, disseminating, and integrating measurement methods for jets, rockets, and associated basic research. This should be on a *nationwide* basis with cooperation from universities, armed forces, government laboratories, industrial laboratories, and scientific societies.

2. Instrumentation Symposia. Under the direction of the Committee, a series of symposia on measurement and calibration methods and instrumentation should be held.

3. Instrumentation Bulletin. A regular bulletin relating to experimental techniques should be issued by the Committee. This would be based on contributions from the various cooperating laboratories.

4. Instrumentation Handbook. A practical handbook on methods should be edited and published by the Committee. It would include sections by various experts in the field.

5. Reference Laboratory. A reference laboratory should be established under the direction of the Committee for the purpose of setting up standard methods and designs. Other laboratories throughout the country might be utilized for part of the program.

III. INTRODUCTION

The rapid growth of the field of jet and rocket propulsion has brought with it problems in measurement techniques and instrumentation of exceeding complexity and difficulty. In some instances acceptable instruments and methods have been evolved; in other cases the solution seems practically hopeless. Between these two extremes are many methods capable of more or less successful application.

The importance of instrumentation scarcely needs mentioning, but it should be pointed out that more is involved than simply development of means of measuring the operating characteristics of pulse jet and liquid rocket units. In many instances further evolution of theoretical understanding of basic processes awaits methods of measuring some of the physical parameters involved.

It is scarcely possible to describe or even list all the instruments and methods used in a field as broad as is covered in this survey. This is especially true in the research phases, since almost the whole realm of physical science is involved in one way or another. Moreover, even the classification of instruments is difficult, since many units can be used for measuring a number of different physical quantities and others are only modifications of basic forms.

One useful method of classification is based on experimental conditions. Nearly all the work covered in this survey falls into one of the following classifications: (1) investigations of combustion phenomena, (2) studies of aerodynamics, (3) properties of materials, and (4) properties of fuels. The emphasis in this report will be on measurement of physical parameters of systems involving combustion processes. This, from an instrumentation standpoint, will include the two most characteristic environmental conditions of the jet and rocket field, i.e. high temperatures and high gas velocities.

In order to achieve a semblance of unity, the material on instrumentation at the various contractors has been prefaced first by a section describing the physical-chemical environments to which instruments are subjected, and second by a section briefly reviewing the basis for some of the measurement methods. The survey is based on information which was gathered incidentally in compiling other portions of this series and is, therefore, incomplete. It is hoped, however, that this report will be some stimulus to exchange of information on measurement techniques between various workers in the liquid rocket and pulse jet fields.

IV. MEASUREMENT ENVIRONMENTS

Although primarily concerned with instruments, we cannot ignore experimental conditions under which measurements are made, for these conditions often impose such severe limitations on the instrument that the indicated reading may bear only remote relation to the physical parameter supposedly being measured. There are, in general, three essentially different effects that tend to render effective measurement difficult if not impossible. The first of these is the effect of the system being measured on the instrument. For example, the extreme high temperatures associated with combustion processes (upwards of 5000°F) impose severe limitations on materials used in instruments. The second difficulty is just the reverse—the effect of the instrument on the system being studied. Thus the introduction of a thermocouple into a combustion system may so alter the turbulence and combustion processes locally that the temperature around the couple may be considerably different from that existing at the same point before the introduction of the couple. And finally, the third effect is one of failure of the instrument to follow rapid fluctuations of the system under investigation. All this contributes to the formidable difficulties in obtaining accurate and reliable values of physical parameters.

A discussion of combustion and the work in progress on combustion at the various places covered by this survey will be found in Volume 1, Part 1 of this series. We will be concerned here only with those aspects that effect measurement of the various physical quantities desired. Most of the experimental work on combustion falls into one of the following headings: (1) power plants, (2) diffusion flames, (3) stationary flames, (4) moving flames, (5) closed chambers, and (6) soap bubbles. Following are brief descriptions of these six aspects.

A. Power Plants

In this classification we are concerned with performance tests of power plants, prototypes, and models.

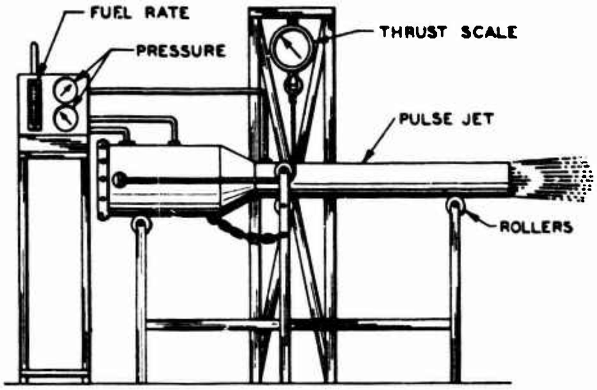

Figure 1. Pulse jet test stand.

In the main this includes only liquid rockets and pulse jets, but where certain fundamental aspects of ramjet studies yield basic information on combustion, they are included. The usual experimental setup consists of some sort of test stand for holding the unit under test, fuel tanks, blower for ram pressure when necessary, and assorted instruments for obtaining performance data. Due regard for the safety of operating personnel is important, so that remote recording instruments are preferable. Figure 1 shows a typical test stand setup.

In most cases no fundamental information is sought, but rather operational characteristics of the particular unit under test. Thrust and fuel rate are determined as well as operating life. In some tests temperature and pressure at various points are also determined.

From the instrumentation standpoint, the most distinctive feature of the study of power plants is that it is the only field of study in which thrust is of importance. Another point of importance is that the installation of instruments is somewhat more difficult since the experimental conditions are determined by an engineering design and cannot be tailored to the quantities being sought. And finally, since operating characteristics are the aim, the instrumentation must not interfere with the normal operation of the jet or rocket.

B. Diffusion Flames

In combustion processes of gases not mixed before combustion, the combustion velocity is not predominately determined by the reaction velocity (8). Instead, diffusion and turbulent mixing at the interface between the gas and air are the limiting processes. Examples of this kind of combustion are the candle flame, illuminating-gas flame, and the outer ring of the Bunsen flame.

Experimental burners such as shown in Fig. 2a are sometimes used. The gas and air are introduced side by side and mix from the contact surface on. The zones in the burning jet are shown in Fig. 2b (after Rummel). This type of combustion is not very important in pulse jet and liquid rocket research, although certain information on diffusion and mixing can be obtained. In connection with burner studies, flame holders, and pilot flames, studies along these lines may be of interest.

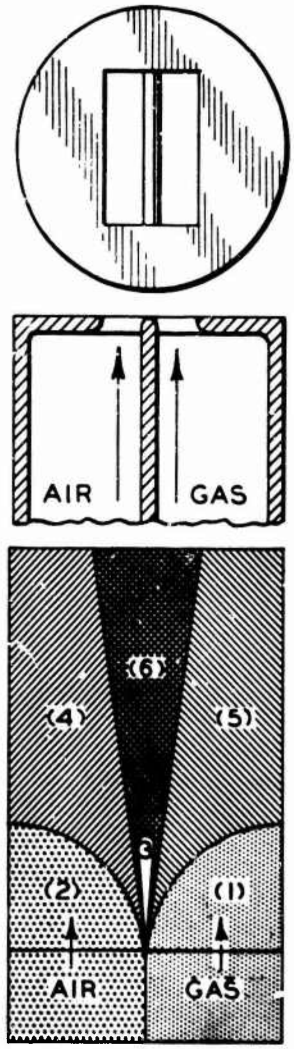

Figure 2. Unmixed combustion.

Usually information as to gas and air velocities, temperatures in the various zones, etc., are obtained. The temperatures are not particularly high and the velocity is relatively low, with a steady flame being the normal condition. This means that the instrumentation problems are relatively straightforward.

C. Stationary Flames

A far more common experimental condition is combustion of pre-mixed gases. Here combustion processes

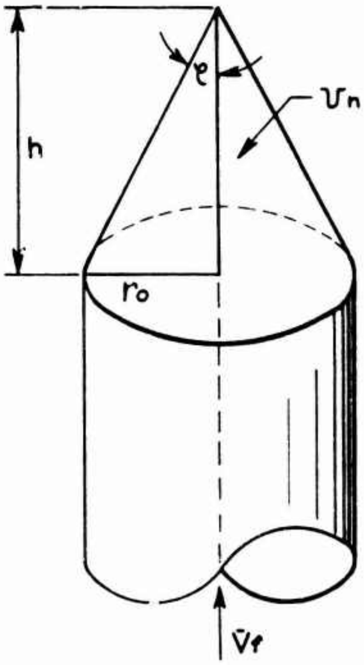

Figure 3. Bunsen burner.

are initiated at some point (ignition) and are propagated more or less explosively to the other portions of the mixture by chain reacting and branching processes.

There are three commonly used means of holding the flame front stationary. The first method is that of the inner flame of the ordinary Bunsen burner. The simple theory, due to Gouy (8), assumes the inner flame to be conical (see Fig. 3), and leads to the relation $V_f = \bar{V}_m \sin \theta$; where V_f is the normal combustion velocity, V_m is the average rate of flow of combustible mixture, and θ is the cone angle as indicated.

In the second method, combustion takes place in a tube with the gas-air mixture flowing down the tube at a velocity such that the flame front is stationary (Fig. 4a). If the burning surface is assumed to be a plane, then $V_o = V_f$. If V_o, ρ_o, T_o are the velocity, density, and absolute temperature of the fresh mixture flowing from the right and V_e, ρ_e, T_e are similar quantities for the exhaust gas, it follows from the principle of continuity that:

$$V_e = V_o \frac{\rho_o}{\rho_e} = V_n \frac{\rho_o}{\rho_e} \qquad (1)$$

If the reaction takes place without change of mol-number

$$\frac{\rho_o}{\rho_e} = \frac{T_e}{T_o} \qquad (2)$$

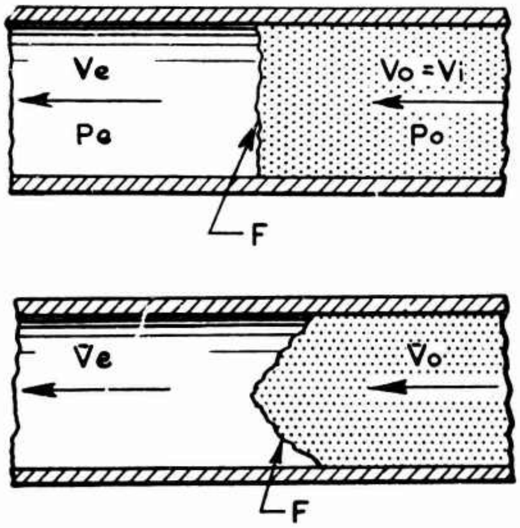

Figure 4. Stationary flame in tube.

Actually, the flame front departs radically from the assumed plane and may look more like Fig. 4b. No simple relations such as given above then hold.

A third method introduces the combustible gas mixture into the tube at a velocity exceeding that of normal combustion and the mixture is kept continuously ignited by one means or another. This corresponds to conditions in a ram jet. Pilot flames, flame holders, etc. are some of the methods used for continuous ignition. In a highly idealized form, the combustible gas (see Figure 5) mixture is introduced at velocity V_o (greater than the flame velocity) and is ignited continuously at the plane F_o. If we consider a slab of gas as it travels down the tube, it is evident that its velocity will be V_o before it reaches the ignition plane but will increase beyond F_o. The slab continues burning as it passes along the tube to some point F_1 where combustion is complete. It has then attained the velocity V_e and is exhaust gas. The net result is a combustion zone of length l with essentially steady-state conditions. Actual combustion often departs considerably from the above and in cases of rough burning can no longer be considered steady-state.

In the foregoing cases the measurements required are made under essentially static conditions and lag

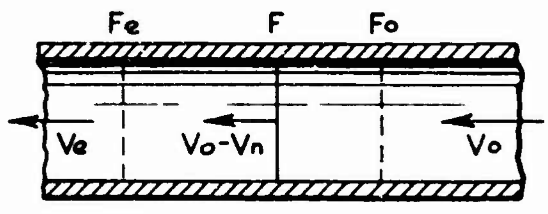

Figure 5. Idealized ramjet combustion.

characteristics of given instruments are not important (except for rough burning). This is a tremendous simplification. The temperatures and velocities involved, however, still impose difficult conditions.

D. Moving Flames

In addition to conditions imposed by temperature and velocity, this type of combustion is characterized by requirements of time response of instruments. Usually low lag in an instrument is contrary to strength requirements of drag at high velocities as well as cooling requirements due to high temperatures. Thus, instruments for measurements of transient conditions associated with moving flames in tubes are, at best, a compromise.

Here again there are three basic experimental setups. In the first, the combustible mixture is introduced into the tube and allowed to reach static conditions and then ignited at either a closed or open end (i.e. opened just before ignition), and the progress of the flame front is observed along with pressure, temperature, etc. Various turbulence-producing grids are often introduced in order to observe effects of turbulence on flame speeds. In many cases the flame speeds are high enough so that no appreciable heating of an instrument results as the flame front passes over. This means that, for some instruments at least, no special cooling system is required.

The second type of moving flame often used is similar to the foregoing but with the combustion repeated cyclically in the manner of a pulse jet. Included are all the various glass-sided self-ignition and timed ignition systems used in studying pulse jet operation. With the repeated explosion, the heating problem is severe and some means of cooling of instruments are usually required.

In a third method for observing a moving flame front, the combustible mixture is introduced into the tube at a velocity either greater or less than the flame speed, and the flame front travels respectively downstream or upstream at a more or less controlled speed. Sometimes flame holders are introduced. This experimental setup is not often used.

E. Closed Chambers

Combustion in closed chambers is complicated by changes in pressure. This means that the combustion velocity is continually changing due to the pressure and temperature changes so that the whole process is much more complicated.

In the first of the two methods used, the mixture is ignited in a static condition from one end of a closed tube. The initial combustion compresses the combustible mixture ahead of the flame front and combustion proceeds at increasing pressures. This compression is essentially adiabatic so that considerable heating of the fresh mixture also results. Behind the flame front, expansion takes place along with some cooling. In addition to the effects of compression, the combustion is further complicated by reflected shock waves. This affects both the flame speed and the shape of the flame front, often resulting in oscillating flame fronts.

Usual investigations of combustion in closed tubes are carried out in glass-walled containers, and Schlieren photographs of shock wave propagation are correlated with high-speed photographs of the luminous flame. Temperatures and pressures are also measured.

The other type of closed chamber combustion is that of the ordinary spherical bomb. The mixture is ignited at the center from a static condition and combustion proceeds spherically to the outer periphery. Effects of compression and shock waves are also present here with the pressure time function as shown in Fig. 6.

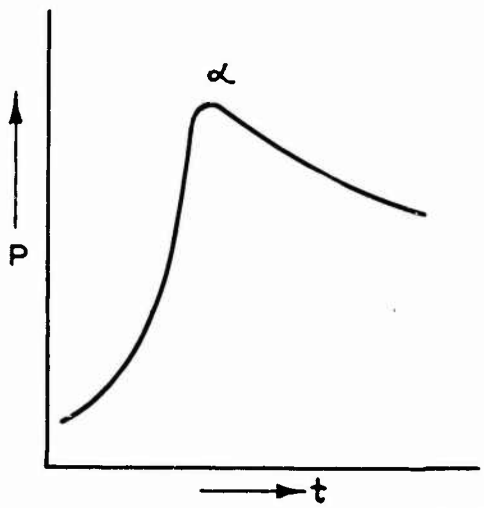

Figure 6. Pressure-time curve for combustion bomb.

The point marked a corresponds to the instant that the flame front reaches the wall of the bomb (8). From maximum pressure in the bomb and known heats of reaction, the average specific heats of reaction products or maximum temperatures can be computed. Equilibrium constants of dissociation must be taken into account.

From the instrumentation standpoint, measurements in closed chambers are transient, and low response times are necessary. Moreover, the gauges are subjected to relatively high temperatures (though not nearly so high as those in the stationary flames) and some cooling may be necessary. In the bomb experiments particularly, probe type instruments are seldom of importance.

F. Soap Bubbles

Combustion at practically constant pressure has ingeniously been accomplished by Stevens and later developed by Fiock and Marvin by means of the well-known soap bubble technique (8). Here the combustible mixture is enclosed in a soap bubble and ignited at the center. High-speed photographic techniques give the flame velocity and the ratio of initial to final radii of the burning sphere. From this the so-called normal combustion velocity can be computed as:

$$V_n = \frac{\rho_e}{\rho_o} = V_f = \frac{r_o^3}{r_e^3} \qquad (3)$$

where:

V_n = normal combustion velocity
V_f = flame speed
r_o = initial radius of bubble
r_e = final radius of burning mixture.

Account must be taken of the water-vapor pressure for exact work. Usually temperatures and pressures have not been measured though there is no inherent reason why they could not be.

V. MEASUREMENT METHODS

Because of the variety of individual designs of instruments, it is not possible within the scope of this report to do little more than list the basic methods and point out some of their advantages and disadvantages. It is felt, however, that the following brief compilation will help in tying together the somewhat disjointed field of instrumentation pertaining to rockets and jets. No claim to completeness is made. Some of the leading references will be found at the end of the report.

The experimental conditions that instruments are subjected to in investigations of combustion phenomena have been described in Section IV, and the general conditions that make measurements difficult have been discussed there. In what follows, some of the effects of these conditions on specific instruments will be pointed out.

A. Pressure

The measurement of pressure in a region in the interior of a gas is usually accomplished by introducing the instrument into the fluid (16). For static conditions this presents no particular problems and the pressure measured is an average over a small area determined by the finite dimensions of the gauge. With the gas in motion, however, the insertion of the instrument disturbs the flow and the velocity and pressure in the neighborhood of the instrument are altered. For subacoustic velocities there will be (under approximately incompressible steady flow conditions) a stagnation point on the unit when the pressure will be in excess of the undisturbed pressure by $\rho u^2/2$ where u is the undisturbed velocity. Superacoustic velocities result in even more difficulties since shock waves will form on the instrument, and in this case pressure measurements are difficult. Calculations upstream through the shock wave are required. Conditions are further complicated since the disturbances of flow in the vicinity of the pressure measuring element can alter the local combustion process, causing a further deviation from the undisturbed pressure.

Measurement of pressure at a solid wall along which the fluid flows is relatively simple, since the introduction of a foreign body is not necessary. However, pulsating pressures impose additional complications on pressure measurements, and instruments must be designed to minimize lag. Moreover, it is important that the instruments be calibrated under conditions corresponding to the pulsations encountered in use in order that the readings mean something.

There are several essentially different phenomena that can be used to measure pressures. Some of the more common methods in use and of possible use are presented here.

1. Manometers. The manometer is the most common type of pressure measuring element. It depends, for operation, on the supporting of a height of a liquid column of known density by the fluid pressure. In its usual form, it consists of a U-shaped tube partly filled with the working liquid (Fig. 7). One end is open (subject only to atmospheric pressure) and the other end is connected to the chamber under study. The difference in height of the liquid columns is a measure of the chamber pressure. Without optical attachments, a level difference of 0.004 inch can ordinarily be read with mercury. Because of capillary phenomena, the best that can be done with water is about 0.04 inch (16).

Since the indication of a manometer is dependent on the movement of a mass of fluid to establish equilibrium between fluid pressure and the weight of a column differential, it is not adaptable to measuring fluctuating pressures, but it does give a true time average and can be used for measuring under high-temperature conditions by cooling the static or the

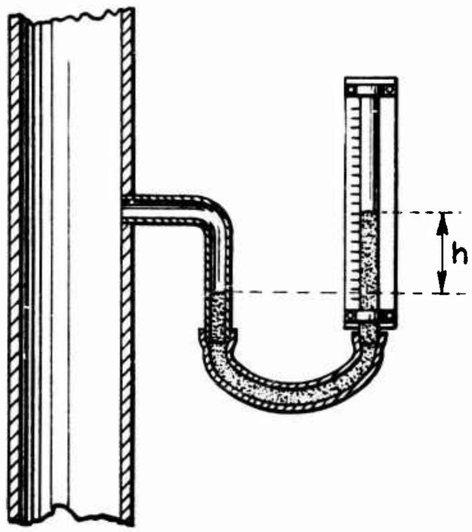

Figure 7. Mercury manometer.

Pitot tube that is inserted in the test chamber. As previously pointed out, however, the pressure-sampling tube may alter local combustion conditions so that the pressure at the tube entrance is no longer that of the undisturbed combustion.

2. Dead Weight Gauge. The liquid manometer depends on balancing the pressure against the gravitational force on a known mass; i.e. a liquid column of known density. Another form in which the pressure supports a weight upon a small piston is known as a dead-weight gauge (Fig. 8). The gas pressure is transmitted to the piston through an oil.

The principal use of the dead weight gauge is for calibration of Bourdon and other types. It is obviously not suited to fluctuating pressures.

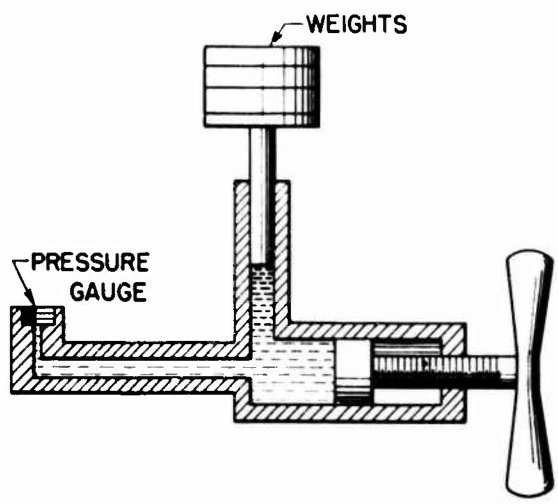

Figure 8. Dead weight gauge.

3. Bourdon Gauge. In the Bourdon gauge a hollow tube of metal having an elliptical cross-section is bent into an arc (over 180°). One end is closed and the other is open to the pressure being measured (Fig. 9). When the pressure increases, the tube tends to straighten out; when the chamber pressure decreases, the tube becomes more curved. The movement of the free end of tube is transmitted through a rack and pinion (or linkage) arrangement to a pointer and serves to indicate the pressure. The Bourdon gauge cannot be used for very rapidly fluctuating pressures because of errors introduced by lag and phase shifts.

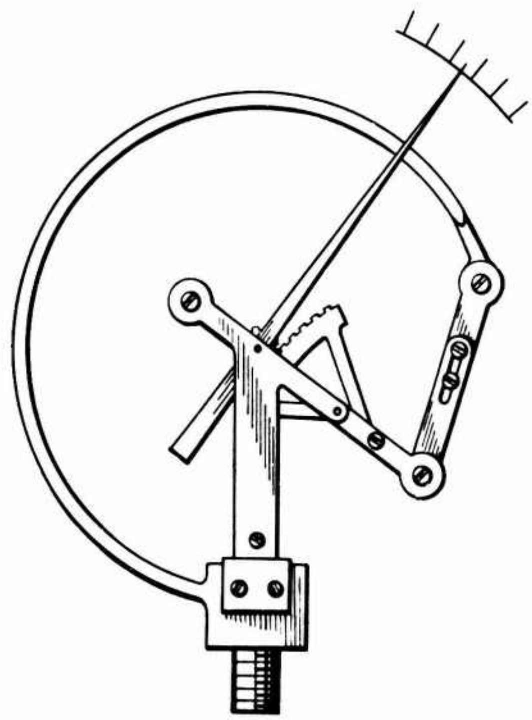

Figure 9. Bourdon gauge.

4. Diaphragm Deflection Methods. Some of the most useful instrumentation for measuring pressure is based on the elastic deflection of a diaphragm. The various modifications amount to different methods of measuring the deflection; the most common of these are by such means as variation of capacitance, inductance, and resistance (18). There are also useful optical techniques. In all cases, calibration with standard instruments is necessary.

It is often necessary to protect the diaphragm from the high temperature of the combustion process. This can be accomplished as shown in Fig. 10. Water is circulated through a ducted chamber to cool the hot

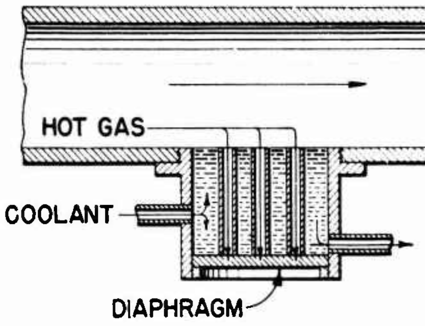

Figure 10. Cooling cell.

gases before they contact the diaphragm (3). For pulsating pressures, it is important that the length of gas ducts leading to the diaphragm be small compared to the acoustic wavelength to assure no phase changes and that an experimental check be made to assure no adverse effects due to the cooling chamber are introduced. The cooling liquid must not be in contact with the diaphragm, since considerable lag will be introduced. Mechanical vibration of the cooling chamber components also is a source of trouble.

a. Capacitance Gauge. In the capacitance gauge the pressure sensitive diaphragm is made one plate of a condenser (Fig. 11) and deflections of the diaphragm results in changes of capacitance. These capacitances changes can be detected in a variety of ways that will not be discussed in detail here. Associated electric circuits are used to convert the change of capacitance into a change in voltage, current, or frequency and to indicate or record the changes. Of the two most common methods, the first utilizes the capacitance of the gauging element in a resonant electric circuit in such a manner that a change of capacitance causes a change in the resonant frequency of the circuit and a corresponding change in either a frequency or a current. The second method introduces the condenser gauging element as a reactance in a bridge circuit. The unbalanced output from the bridge is a measure of the diaphragm deflection, and therefore the pressure (18).

Pressure pickups of this type can be made very sensitive, stable, and accurate but are subject to errors due to thermal expansion. They will respond from static pressure (depending on the nature of the associated electric circuit) to frequencies limited only by the natural frequency of the diaphragm.

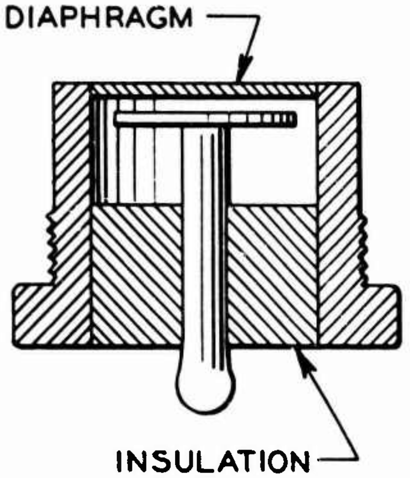

Figure 11. Capacitance gauge.

b. Resistance Strain Gauge. The ordinary resistance strain gauge can also be used to measure the diaphragm deflection, and hence the pressure. The resistance unit can be cemented directly to the diaphragm or to a connected compression or tension member. Its operation depends on the change of resistance of a fine wire with elongation; this resistance change being directly proportional to the product of the initial resistance of the gauge and the unit longitudinal strain.

The strain-gauge is usually incorporated in a leg of a Wheatstone bridge and the resulting measured change of resistance gives a measure of the pressure (18). Considerable care must be taken in the cementing and difficulty is often encountered at high temperatures due to failure of the bond. Temperature compensation is required and the gauges are usable from static deflection up to 5000-10,000 kc. sec.

c. Electromagnetic Gauge. Unlike the two preceding methods that depend on the displacement of a diaphragm, electromagnetic gauges operate by virtue of the time derivative of the diaphragm displacement velocity). There are two basic types of electromagnetic converters. In the moving diaphragm type (Fig. 12a), the diaphragm is of magnetic material and forms part of the magnetic circuit. Movement of the diaphragm due to pressure changes results in a change in the number of lines of force cutting the pickup coil and hence a voltage is generated. In the moving coil type (Fig. 12b), a movement of the diaphragm moves the pickup coil through the magnetic field and a voltage is generated (14).

Since the voltage generated depends on the time rate of displacement, the sensitivity falls off for low frequencies and the method is not usable for static pressures. The upper frequency response depends on the proper design of the mechanical elements (low mass, etc.) and frequencies of 10,000 c.p.s. are easily obtained.

d. Magnetic Reluctance Gauge. Either of the preceding two units can be used as elements in an AC

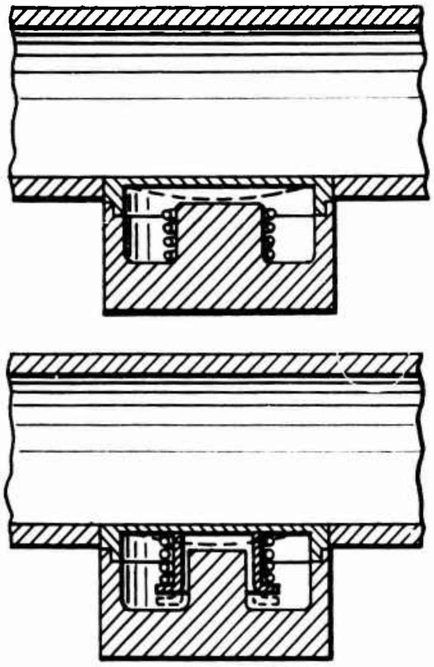

Figure 12. Electromagnetic gauge.

bridge so that static response can be obtained. Displacement of the diaphragm changes the magnetic reluctance of the unit and hence its impedance. This changes the bridge balance and the resulting output can be used as a measure of pressure.

e. Optical Technique. An optical technique for determining the displacement of the diaphragm is shown in Fig. 13. Light from a source is made plane by a lens and allowed to fall on a polished diaphragm.

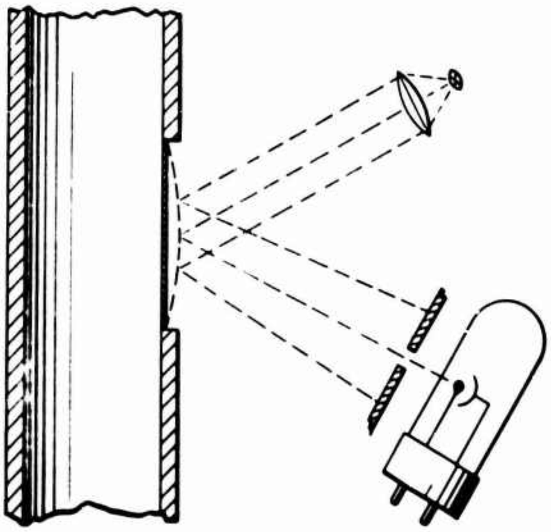

Figure 13. Optical gauge.

The light reflected by the diaphragm passes through an aperture and is focused on a photo-tube. The output from the tube is amplified and read on an output meter or recorded. Pressure changes result in a change of curvature of the diaphragm, and hence the intensity of the light reaching the photo-tube.

As in the case of the condenser gauge, there is no mass loading of the diaphragm and high frequency response can be obtained. With proper design of the amplifier, this gauge can be used down to static pressures. Some difficulty in maintaining calibration due to discoloration of the diaphragm at high temperatures is encountered, but cooling obviates this disadvantage. In general, this method is useful for only rather high pressure changes as in internal combustion engines, if heating effects are not to blanket pressure effects.

f. Balanced Diaphragm. The use of contact-closing devices provides a useful technique for a step-wise determination of pressures. In the balanced diaphragm indicator, the diaphragm is normally held against a contact by the unknown pressure being measured. Compressed air is applied to the opposite side until the contact is just broken. At this point the measured air pressure is equal to the unknown pressure. A series of such diaphragms, set for different pressure, can be used to obtain a recording of transient pressures.

5. Piezoelectric Methods. Certain asymmetrical crystalline substances develop electric polarization when subjected to mechanical strain (4). This is known as *the direct piezoelectric effect* and the polarization is proportional to the strain. The *converse effect* is a closely related phenomena whereby an electric polarization in the crystal produces a proportional strain. Among such materials are, notably, quartz, tourmaline, Rochelle salt, and ammonium dihydrogen phosphate (ADP).

The piezoelectric effect is associated with the crystalline structure and depends on the direction of application relative to the various crystal axis. Plates are cut from the mother crystal with an orientation emphasizing desired piezoelectric properties. Thus, for example, the type of quartz most often used as a transducer is the X-cut with the electrode faces perpendicular to the electric axis and including the optical and mechanical axes of the crystal.

A common form of piezoelectric pressure gauge is shown in Fig. 14a. One electrode is grounded and the other leads directly to the associated amplifier circuit. For combustion studies, quartz may be cooled by the method shown in Fig. 14b. In this instance it is permissible to allow the cooling fluid to contact the

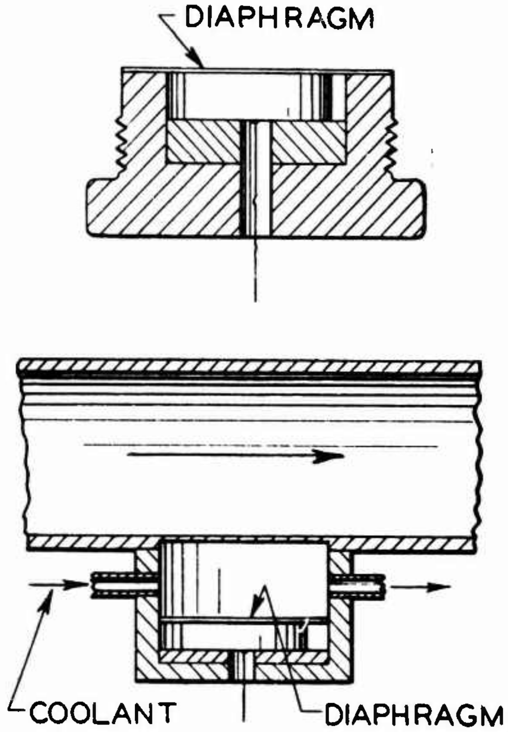

Figure 14. Piezoelectric gauge.

measuring element directly, since quartz is a pressure-sensing element and does not depend on displacement as in the case of a diaphragm. It is important in the design to eliminate inertia effects of the cooling fluid and to make the thickness of cooling fluid small compared to the acoustic wavelength in the fluid.

The upper frequency response of quartz pressure gauges is practically without limit (being well over 1000 megacycles sec.), but the low frequency response is effectively limited by electrical leakage of the mounting and input circuit, and it is difficult to measure as low as 10 c.p.s. Other problems arise in change of capacity of connecting cables, temperature effects, etc., but careful design can minimize these.

6. Magnetostriction Method. Ferromagnetic materials exhibit appreciable change in length when placed in a magnetic field (3). This effect is known as "magnetostriction" and is reversible, i.e. a strain in the material causes a change in the magnetic field. This converse effect can be used as a pressure gauge in the manner shown in Fig. 15. The pressure on the end of a magnetostrictive rod results in a change in the magnetic field through the pickup coil (5).

As in the cases of the electromagnetic and reluctance gauges, the magnetic change can be used to generate a voltage in the pickup coil or to change its

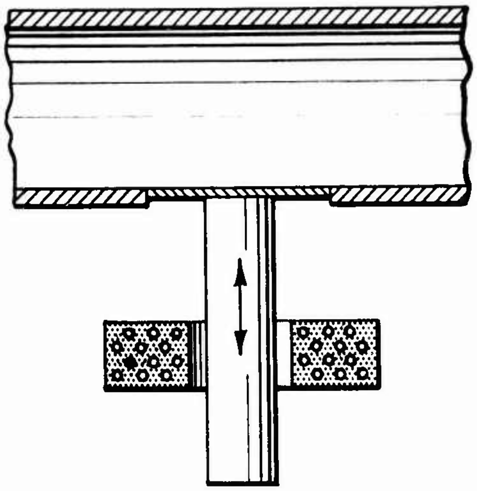

Figure 15. Magnetostriction gauge.

impedance. In the first method the sensitivity decreases in the low frequency range while the second method is usable down to static pressures. The upper frequency response obtainable is from 50 to 100 kc. sec.

Some of the principal magnetostrictive materials (3) that have been used are nickel, nickel-iron alloys, alloys of chromium, nickel, and iron (nichrome, monel, etc.), nickel copper alloys, and cobalt-iron alloys. The change in length is different for different materials, in some cases being an increase and some cases a decrease. In fact some materials show a reversal in strain as the flux density is increased. In all cases the change in length is independent of the direction of the field so that a vibration frequency of twice the applied electric field is obtained. This is overcome by applying a polarizing field. As with piezoelectric crystals, cooling fluid may be used in contact with the magnetostrictive rods.

7. The RCA Vibrotron. The plate impedance and grid-plate transfer characteristics of electron tubes depend, among other things, on the inter-electrode spacings. With proper design, the electode spacing may be varied by some external effect such as pressure. A commercial form of such a tube is shown in Fig. 16. The anode is attached to a stiff rod which passes through a flexible diaphragm sealed across the end of the envelope. Movement of the rod changes the electrode spacing (18). This effect, with associated electrical circuits, can be used for pressure measurement.

8. Spectral Line Pressure Shift. All of the techniques of pressure measurement discussed above have been "macroscopic" in nature, dependent on averaging kinetic impacts of the gas molecules on an interface such as the surface of a quartz crystal. The

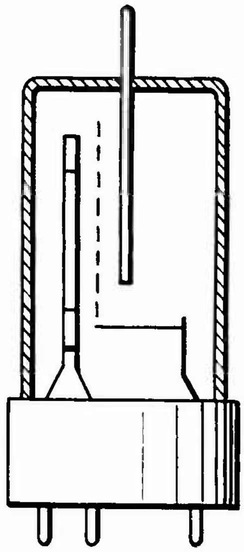

Figure 16. Vibrotron.

phenomena of shift and broadening of spectral lines with pressure seems to be a possible method of determining pressure in the interior of a gas without the introducion of any foreign body (21). Figure 17 shows the effect for the mercury resonance line λ 2537 (after Fuchtbauer, Joos, and Dinkelocker). The cause of the broadening lies in the sudden change in phase of the emitted radiation by collision. This is known as "collision damping" and is pressure dependent for a given gas composition. During collision, the energy levels of the excited atoms are altered due to polarization effects. This results in a shift toward the red.

High-speed photography of such spectral broadening and shifts would afford a means of pressure measurements. Unfortunately the effect depends on the gas composition, reaction products and temperature so that calibration would be required for a given system.

B. Temperature

The structure of the thermal field in combustion processes is exceedingly complex and difficult to measure. The high temperatures, high velocities, turbulence, and irregularities of thermal structure in steady state combustion (such as the ramjet) and additional transient conditions in cyclic combustion (such as the pulse jet) present almost insurmountable problems for measurement. Some of the more common methods for temperature determinations and their limitations are reviewed here.

1. THERMOCOUPLES. If two wires of dissimilar metals are connected at their ends and the two junctions maintained at different temperatures, a current will flow. The magnitude of the small electromotive force causing this current is dependent on the temperature difference between the hot and cold junction. Either a potentiometer or a high resistance galvanometer may be used to measure the thermal e.m.f. and hence the temperature (see Fig. 18).

Various metal and alloy combinations have been used for thermocouples. Among them are iron to constantan (900°C), chromel to alumel (1100°C), and platinum to platinum-10% rhodium (1500°C). For short time service these may be used up to 200-300°C higher than the limits indicated (10). For

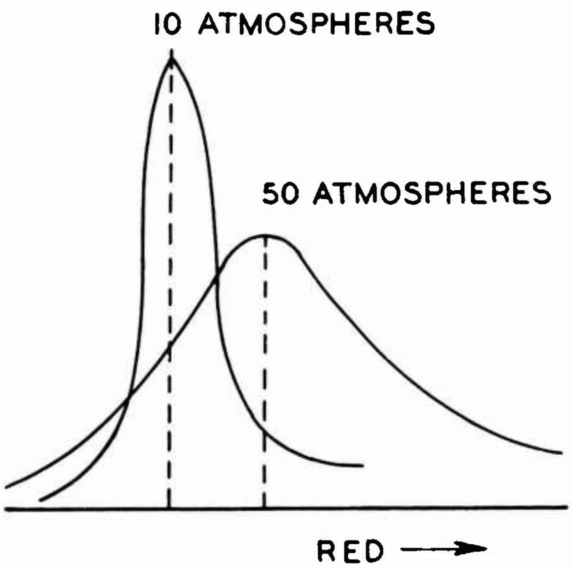

Figure 17. Spectral line pressure shift.

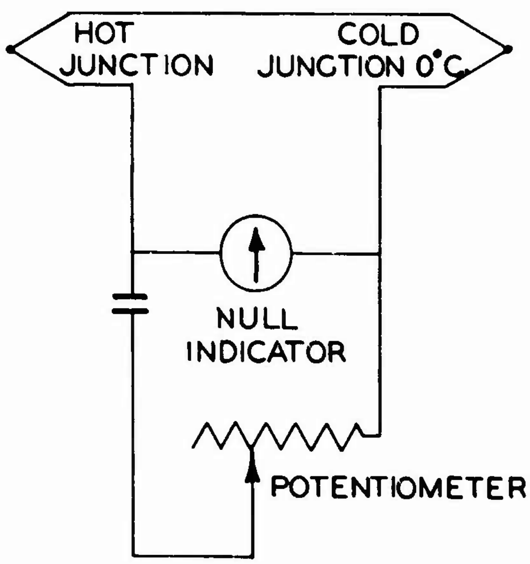

Figure 18. Thermocouple circuit.

higher temperatures Ryan Aeronautical Corporation has developed a carbon to tungsten thermocouple usable up to about 3000°C. Details of this device are discussed in a succeeding section.

Thermocouples are subject to various errors, and care must be taken in interpreting their readings. Among such errors are catalytic heating, stagnation heating, radiation, conduction, and lag due to heat capacity of the couple. Catalytic heating can be eliminated through proper choice of materials or through the use of poisons. Stagnation heating can be minimized by streamlining the couple and is only of consequence in high velocity flow. Radiation shields reduce radiation losses and proper design can reduce errors due to heat conduction to the couple supports. By making the thermocouple wires as small as mechanically feasible, the lag due to heat capacity is minimized. These are but a few of the considerations required when using thermocouples.

Although very useful for many applications, thermocouples are generally not completely satisfactory for flame and combustion studies.

2. Sodium D-Line Reversal. By far the most popular method of measuring temperatures in nonluminous combustion studies is that of sodium D-line reversal. Essentially the technique consists of matching the brightness of a black body radiating source with the sodium D-line radiation from sodium vapor introduced into the flame being measured (19). The sodium atoms are assumed to be in statistical thermal equilibrium with the gases of the flame and no sodium radiation other than from thermal excitation is postulated. Schematic arrangement for this method is shown in Fig. 19.

With the black body temperature below the flame temperature, the sodium radiation as seen in the spectroscope appears as a bright line against a darker background radiation from the black body through the flame. With the black body at a higher temperature radiating through the flame, the sodium D-line is dark against a brighter background. Just at the "reversal" temperature, the black body and flame are at the same temperatures so that from the known temperature of the black body the temperature of the flame is determined. The reversal occurs over a rather narrow temperature range and measurements to within 3°C are not difficult.

Ordinarily a reference source such as a tungsten filament lamp is used and its apparent temperature must be corrected for departure from true black body radiation. If a lens is used between the lamp and flame, a correction for its reflection and absorption must be made. If the flame temperature is not steady, a well defined reversal temperature cannot be obtained. Other spectral lines can also be used but sodium is the most common. The method is not adaptable to continuous measurement or recording.

3. Two Color Method. The radiation from an ordinary luminous flame departs considerably from black body radiation but by measurement of intensity at two wave-lengths the true flame temperature can be obtained (20). The basis of the method can be understood by referring to Fig. 20, which is a graphical representation of Wien's law, giving the intensity of radiation J_λ as a function of wavelength λ, and absolute temperature T. The solid curve T is for a black body at the true flame temperature T, and the dotted curve F is the actual radiation from the flame. Intensity measurements on the flame at wavelengths λ_1 and λ_2 yield apparent temperatures $T_{\lambda 1}$ and $T_{\lambda 2}$ corresponding to black body radiation at these temperatures. From the known wavelengths λ_1 and λ_2, the measured apparent temperatures $T_{\lambda 1}$ and $T_{\lambda 2}$, and two other constants that can be evaluated for a given flame and wavelength, the true flame temperature can be readily calculated.

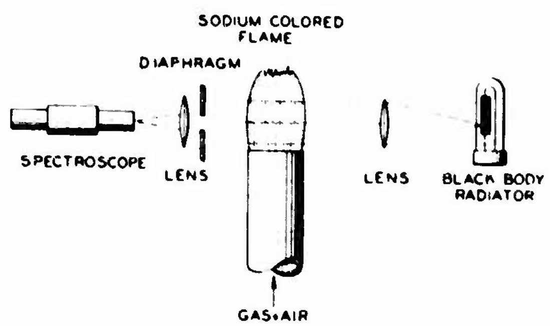

Figure 19. Sodium D-line reversal apparatus.

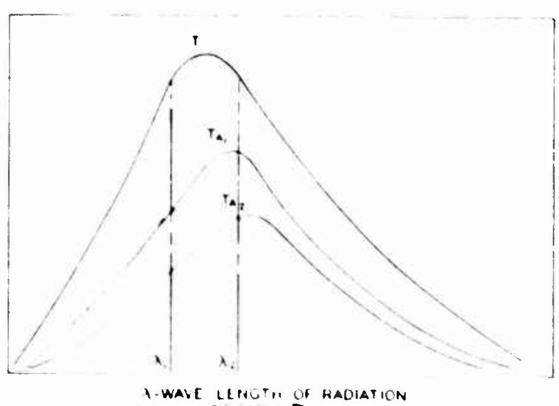

Figure 20. Two-color method.

A variant of this method at the University of Wisconsin (20) has led to the development of an electro-optical pyrometer which is instantaneous in response to flame-temperature variations and will determine the temperature-time cycle for an internal combustion cycle. The final representation is on a cathode ray oscilloscope whose sweep is synchronized with the crank position. The application of the method to the study of the pulse jet is obvious and should prove of importance. In this case a pressure pickup could be used to trigger the oscilloscope sweep.

4. Radiation Pyrometer. If the radiation from the combustion process under investigation is not far from black body radiation, or if the departure from black body radiation is known, the ordinary radiation pyrometer may be used to measure temperature (10). It consists of a means of focusing (usually a quartz lens) the radiant energy of all wavelengths upon the hot junction of a thermopile, thereby developing an e.m.f. which can be measured by a potentiometer or indicated directly with a millivoltmeter. In practice the indicating meter or recording instrument is calibrated to read temperature directly. Mirrors are sometimes used for focusing and vacuum thermocouples for detectors.

Care must be taken that the source is large enough to "fill" completely the opening to the pyrometer. When sighting into combustion chambers through viewing ports, the pyrometer is quite reliable, since such radiation closely approximates that of a black body, but the corrections for open flames are not well-known and such readings are not good.

A variation of this method measures the monochromatic radiation from sodium introduced in sufficient concentration into the flame.

5. Optical Pyrometer. The disappearing-filament optical pyrometer is somewhat analogous to the line reversal method, but essentially black body radiation from the flame is required. The common form of the instrument is shown in Fig. 21.

The filament of a small electric light is located at the focal points of the objective and ocular lenses of the pyrometer and serves to superimpose an image of the filament on the radiation field as viewed through the pyrometer telescope. The filament current and hence its temperature is varied until the image disappears in the background radiation. Filters just in front of the eyepiece make the radiation essentially monochromatic so that at the disappearance point the filament can be said to be at the temperature of the flame. The filament current can be calibrated directly in temperature (10).

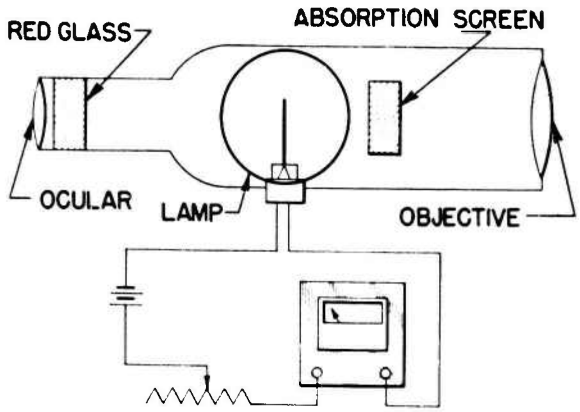

Figure 21. Optical pyrometer.

Ordinarily the lamp should not be operated higher than 1500°C because of deterioration of the tungsten filament. However the range of the instrument can be extended by an absorption glass in front of the lamp as shown. The same precautions required with the radiation pyrometer apply to the optical pyrometer.

6. Heated Wire Method. Consider a tungsten wire heated by an electrical current and engulfed in a non-luminous flame whose temperature is unknown. If the current is varied and the temperature of the wire is measured by an optical pyrometer, a curve such as shown in Fig. 22 (marked "flame") will be obtained. At wire temperatures below the flame temperature, the energy loss due to radiation from the wire will be balanced by the sum of the electrical energy input to the wire (I^2R) and the conduction-convection heating of the wire by the hot gases. At wire temperatures above the flame temperature, the electrical energy input will be balanced by the sum of the radiation loss and the cooling of the wire by conduction-

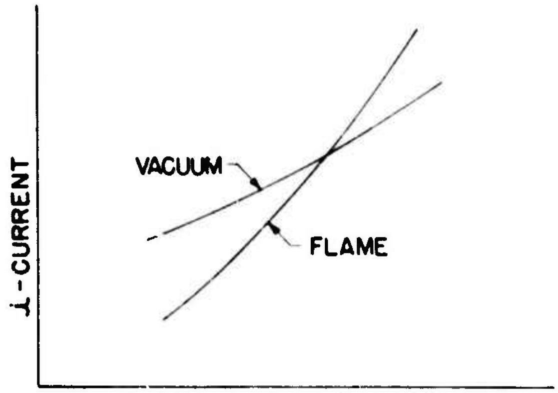

Figure 22. Heated wire method.

convection to the gases. When the wire is at the precise temperature T_f of the flame, the radiant energy is just equal to the electrical energy. This point can be found by obtaining the current-temperature curve of the same wire in a vacuum. In this case the radiant energy from the wire is always equal to the electrical input. Obviously the point at which the "vacuum" curve crosses the "flame" curve determines the flame temperature (8).

One source of error in this method arises from the fact that the wire in the flame "sees" its surroundings through a blanket of hot gases, while in the vacuum it "sees" its surroundings through a bell jar. Except for highly absorptive gases the error is small, however. Other disadvantages are possible catalytic effects of the wire, possible change in electrical resistance of the wire due to contamination, problems involved with the strength of the wire in high velocity streams, stagnation heating, etc.

7. Thermal Noise. Ordinary thermal noise in an electrical conductor is a possible means of measuring high temperatures (15). The precise mechanism of thermal noise is not well understood, but apparently it has its basis in thermal agitation of electric charges in a conductor. It is assumed that the charges are in thermodynamic equilibrium with the heat motion of the atoms comprising the conductor, which results in a corresponding variation of potential difference at the terminal of the conductor. The frequencies of the voltage charges at the terminals can thus be expected to have a random distribution. From thermodynamical reasoning Nyquist arrived at the following expression for thermal noise:

$$(E^2)_{\Delta f} = 4RkT\Delta f \qquad (4)$$

where:

$E_{\Delta f}$ = r.m.s. thermal noise voltage in frequency band width Δf

R = resistance of conductor giving rise to thermal noise

k = Boltzmann's constant

T = absolute temperature

Δf = frequency band width of receiver.

If the temperature change of resistance is compensated for, then the square of the thermal noise voltage for a given band width is directly proportioned to the absolute temperature.

8. Band Spectra. If thermal equilibrium exists in the combustion process, the temperature may be determined from measurements of relative intensities of lines originating in known energy levels within the atoms or molecules (1). The basis of this method is the relation between relative intensities of the lines J, the Boltzmann factor $e^{-\epsilon/kT}$, transition probability p, and a weight factor α:

$$J = \alpha p e^{-\epsilon/kT} \qquad (5)$$

where

J = relative intensity of a known line

α = a priori weight function

p = transition probability

ϵ = energy level difference of the line in question

k = Boltzmann's constant

T = absolute temperature.

From known atomic and molecular spectral data, various bands may be used such as the λ4216 CN band and the λ4315 CH band. In cases where a suitable spectrum does not exist in the reaction being studied, a "foreign" molecule may be introduced. Line spectra are also usable, especially the alkalies whose transition probabilities are known.

9. Other Methods. The foregoing methods for determining gas temperatures in combustion processes have not, in general, required a specific knowledge of the nature and proportions of the various component molecules, atoms, and fragments present during combustion. There are two additional methods (1) worthy of mention that require some knowledge of the dissociation products.

The first of these is based on the simple fact that for a monatomic gas, or a polyatomic gas below its dissociation temperature, the gas density varies inversely as the absolute temperature. By measurements of density, by X-ray absorption, α-particles, etc., the absolute temperature can be determined. This method has been applied with some success to the measurement of the temperatures in electric arcs up to above 5000° K.

The other method depends on the measurement of sound velocity in the gas mixture. It can be shown that under certain conditions the sound velocity depends on the gas constant, an average molecular weight, the ratio of specific heats, and temperature. It is thus necessary to have specific heat and dissociation data of the system under investigation over the temperature range involved. This method has been also used in arcs up to above 6000 K.

Both of these methods might be used to gain insight into combustion products in conjunction with temperature measurements by other methods.

C. Gas Velocity, Turbulence, Flow Patterns.

Methods for measurement of gas velocity and turbulence and the determination of flow patterns have been extensively developed for fluid mechanical investigations. The application of these methods to combustion flow systems involving high temperatures as well as variable and unknown reaction products cannot be said to be in a very satisfactory state. However, in many cases it proves useful to study the flow conditions for a given combustion chamber in a "cold" condition and interpret the subsequent combustion in the light of these measurements. In some cases the aerodynamic techniques can be used with the combustion process for qualitative results. In some instances techniques specifically applicable to combustion processes have been developed. The basis of several of the methods and some of their limitations are presented here.

1. Pitot Tubes. The velocity in a fluid system in motion is commonly determined by the device shown in Fig. 23. This is the ordinary Pitot tube (7) and is useful in combustion processes if the material comprising the tube can withstand the temperatures involved. Under steady incompressible flow, the total pressure is the sum of the static pressure and the stagnation pressure, or

$$P_t = P_s + \rho \frac{u^2}{2} \qquad (6)$$

Since the static pressure can be obtained by methods discussed previously this serves to determine the velocity.

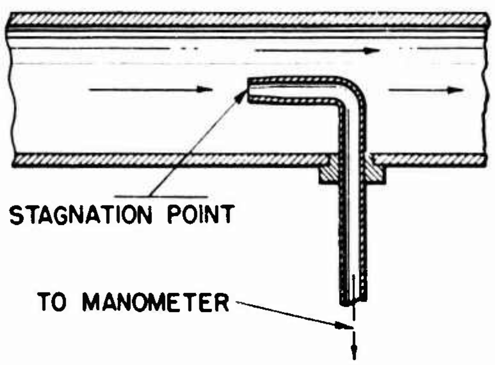

Figure 23. Pitot tube.

There are various modifications of the basic method that measure the total and static head simultaneously, giving the velocity directly. Optimum designs have been evolved to minimize the flow disturbance and sample the static and total head as nearly at the same point as possible.

In combustion studies, of course, there is usually a question as to the value for ρ, and this is a limiting factor in the use of this method. With methods other than the manometer for measuring the pressure, fluctuating velocities can be determined, providing the duct to the pressure-sensing element is not too long.

2. Hot Wire Anemometer. One of the most elegant techniques for velocity and turbulence measurements is based on the fact that an electrically heated wire exposed to the air stream cools off and consequently changes its electric resistance (11). The wire may be used at constant current, in which case the resistance change (or voltage change) is a measure of the velocity change; or it may be used at constant voltage and the current change is a measure of the velocity change. The platinum wires usually employed may be of the order of 0.0001 inch in diameter by 1 mm. long and are mounted on rugged supporting arms. The method is applicable to a wide range of turbulence intensities and velocities (limited by the mechanical failure of the wire at around 300 ft./sec.) and gives a point measurement. Through the use of methods for calculating and compensating for lag, velocity fluctuations as high as 2000/sec. can be measured. Scale of intensity can be obtained by determinations of the correlation coefficients of measurement from two hot wires.

Unfortunately the hot wire anemometer cannot be used in measuring turbulence in flames due simply to the fact that the fine wire will not stand the temperatures. The possibility at once suggests itself that a "cold" wire anemometer might solve the difficulty. A length of fine tubing, cooled by internal liquid flow, would show a change of resistance due to change in heat transfer brought about by a change in velocity. Wollaston's technique, with a core as well as a sheath of silver in conjunction with platinum tubing, could be used for obtaining fine tubing. A proposed form of the instrument is shown in Fig. 24.

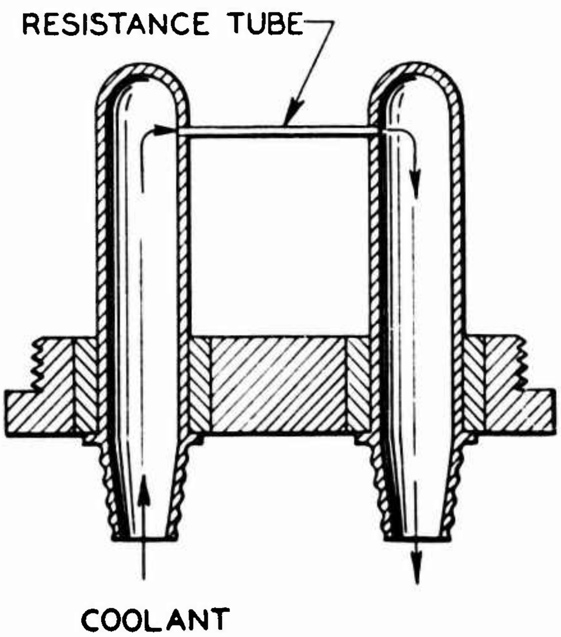

Figure 24. Cold-wire anemometer.

3. Tracer Photography. A very useful method for obtaining local velocity, flow patterns, and a qualitative idea of turbulence is based on the photographing of reflected stroboscopic light from minute tracer particles introduced into the flow system. A typical setup for investigating the Bunsen flame is shown in Fig. 25.

From the known stroboscopic illumination time and measurements of streak lengths of the light reflected from individual particles (from photographs), the velocities at various points are determined. Motion pictures give a qualitative idea of the turbulence present. Silica gel and refractory powders of about 40μ are acceptable particles for the method.

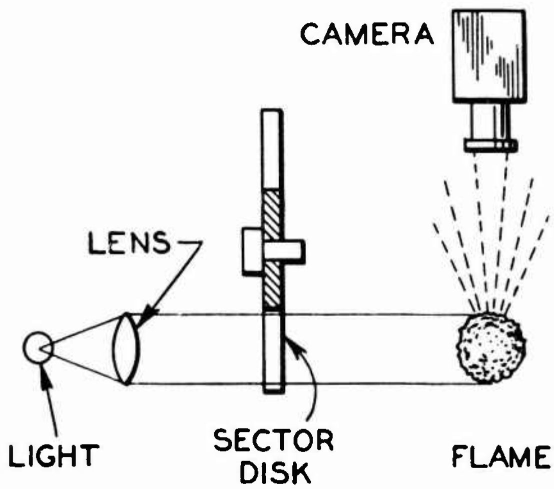

Figure 25. Apparatus for tracer photography.

4. Radioactive Tracers. A pulse of radioactive material can be introduced upstream and its subsequent passage noted by counters spaced down a flame tube. This would serve to measure the average velocity and would be useful when glass sides are not feasible or desirable. The details of this method have not yet been worked out.

5. Schlieren Method. The Schlieren photographic method is much used in the study of air flow and is a valuable tool for investigation of combustion processes (12). One common form of the apparatus is shown in Fig. 26. Light from a bright source is made parallel by a spherical mirror and passes though the system under study to a second spherical mirror. The light reflected from this mirror forms an image on the screen or can be photographed. A knife edge is inserted at the focal point of the second mirror and causes changes in illumination of the image in accordance with density gradients in the test section. If there is no disturbance in the test section, the knife

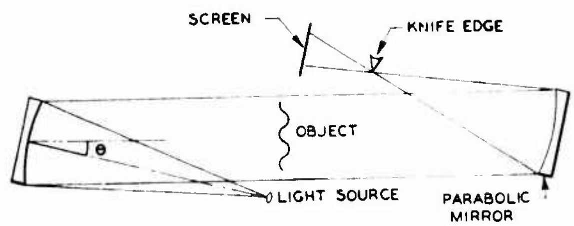

Figure 26. Schlieren apparatus.

edge will cause a uniform darkening of the field on the screen as it is inserted in the light path at the focal point of the second mirror. If, now, a density disturbance takes place in the working section, some of the rays will deflect so as to pass the knife edge and some will deflect so as to be intercepted by the knife edge. The result is a variation of illumination on the screen corresponding to the gradient of density.

There are various other modifications of the Schlieren apparatus involving a single mirror, lenses instead of mirrors, two knife edges, etc. The system is especially adapted to two-dimensional test sections but can be used with three-dimensional flow, though the interpretation is difficult. One point to be kept in mind is that with the knife edge perpendicular to the axis of flow and the direction of the light rays, the pattern will be symmetrical (with respect to light and dark areas) for symmetrical flow; while with the knife edge parallel to the axis of flow, the pattern will be asymmetric for symmetrical flow.

Actually, the basic mechanism for the deflec'ion of the light due to disturbance in the test section is a relation between the index of refraction, the gradient of the index of refraction, and the angle between the gradient and the direction of the light rays. For a given gas or gas mixture this can be resolved into an effect due to the gradient of density, since the index of refraction and the density are related. However, with combustion reactions going on in the test section, this is no longer true and the quantitative interpretation of resulting pat'erns is not possible until more is known about the reaction. The method is nevertheless very useful for flow patterns.

6. Shadow Method. The shadow method is a simple optical system and depends for operation on the derivative of the density gradient (12). The apparatus is shown schematically in Fig. 27. Light from an intense source is made parallel by means of a lens and passes through the test section, falling directly on the screen.

This method is not as sensitive to disturbances as the Schlieren method and is most useful for very

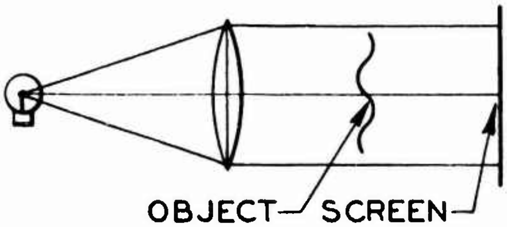

Figure 27. Shadograph apparatus.

abrupt density variations such as occur in shock waves. For combustion processes, the same remarks concerning the density and index of refraction for the Schlieren system apply to the shadow method.

7. Optical Interferometer. Optical interferometers are adaptable to the study of flow patterns and turbulence (12). The method is shown in Fig. 28. Monochromatic light is made parallel and allowed to fall on a half silvered mirror M_1. Half of the light passes through M_1 and, after reflection from fully silvered mirror M_1' and passage through the half silvered mirror M_2', is brought to a focus on the screen. The other half of the light traverses the other path as shown and arrives at the screen, with proper adjustment, in phase with the light from the first path. If a disturbance of the index of refraction S is introduced in one path as shown, the phase relations will be disturbed and an interference pattern will result. The disturbance in index of refraction resolves itself into a disturbance of density which yields a flow and turbulence pattern. For a given gas or gas mixture the method is adaptable to quantitative calculations of density, flow, and turbulence. For combustion processes the patterns are qualitative only.

It is important to remember that the interferometer method depends on the density ρ; the Schlieren method on the density gradient $\frac{\partial \rho}{\partial x}$; and the shadow method on the second derivative of density $\frac{\partial^2 \rho}{\partial x^2}$.

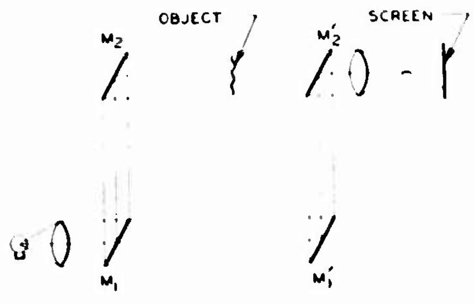

Figure 28. Optical interferometer.

8. Diffusion Method. Both the vorticity and momentum transfer theories of turbulence depend on the mixing length and intensity of the turbulence in predicting diffusion by turbulent motion (7). Measurements of the diffusing power of turbulence are made by exploring the distribution of the diffusable property downstream from a source. For aerodynamics studies, measurements of temperature distribution downstream from a point or line source have been used. In the study of mixing, concentrations of one of the components in the other downstream from an entrance nozzle have been used. Neither of these properties are usable for combustion studies. There is the possibility of using radioactive materials.

D. Flame Propagation Velocity

Flame propagation velocity is of considerable interest in basic studies of combustion and developmental investigations of combustion chambers, burners, etc. Various techniques have been devised for its measurement, and the more common ones will be discussed here. It should be kept in mind that what is measured is the velocity of propagation of an abrupt change in some property associated with the concept of "flame front." Thus the "flame fronts" based on measurements of emitted light, ionization, and temperature may not necessarily be the same.

1. Photographic Method. One of the most direct methods for obtaining flame propagation velocities is by means of high-speed photography. There are two basically different schemes commonly used, both so well known that they are scarcely worth mentioning. In the first, the drum camera, a cylinder of film is rotated at a known speed with the flame front photographed continuously. From the known rotational speed and measured slope of the flame as photographed, the flame speed is obtained. The other method is a high-speed version of the ordinary movie camera, in which successive photographs of the flame as it advances are obtained.

2. Ignition-Angle Measurement. A method proposed by the Cornell Aeronautical Laboratory is shown in Fig. 29. A series of spark gaps spaced along the wall of a combustion chamber are energized in

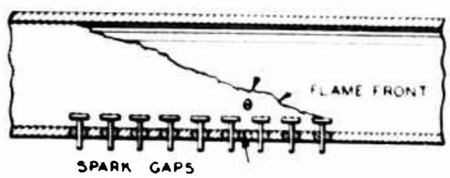

Figure 29. Ignition-angle method.

sequence along the wall at a known rate. This will result in a flame front as shown; and measurement of the angle θ, together with the ignition rate, will give the flame velocity.

3. Flow-Angle Measurement. Consider a combustible mixture flowing down a tube (Fig. 30) at a velocity higher than the flame velocity. If the mixture is ignited at a point on the axis, a conical flame front as shown will result. The flame velocity is obtained from measurements of average velocity of the combustible mixture and the angle of the flame front.

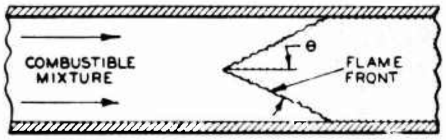

Figure 30. Flow-angle method.

4. Burned-Out Wire Method. A simple method of obtaining an average flame velocity utilizes two fine wires stretched across the combustion tube and spaced a known distance down the tube. The wires are burned out by the flame as it passes and the time interval can be measured by an electronic timer.

5. Ionization Gaps. The breakdown of gaps by the ionization of the flame front can be used in conjunction with a timing circuit to yield average flame velocity.

6. Phototube Method. Two phototubes with an electronic timing circuit can be energized by the light of the flame front and so obtain the average flame velocity.

7. Inductive Flame Detector. Work at the Princeton University has shown that the ionization in the flame will appreciably lower the Q of a coil surrounding the flame (6). For flame velocity measurements two coils are wound around the pyrex combustion tube and each is connected as the plate coil of a conventional tuned plate-tuned grid oscillator. As the flame passes through the first coil, it causes an abrupt dip in the plate current of that oscillator which triggers an electronic timing circuit. Frequencies of 65 and 100 megacycles have been used with the Eccles-Jordan type trigger circuit (5).

Two outstanding features of this method are: (1) no probes or gaps are introduced into the combustion zone, and (2) the pickup coils can be easily moved to any portion of the flame tube without disturbing the setup.

8. Stationary Flame Tube. The stationary flame tube, as described in the preceding section, serves as a method for obtaining flame speed. Under the stationary condition of the flame, the average velocity of flow of the combustible mixture is equal to the average flame velocity. The in-flow velocity can be measured by some of the methods discussed above.

E. Other Measurements

1. Density. The measurement of density in the flame and combustion zone is of much interest but unfortunately no acceptable methods are yet available. The methods of the optical interferometer, absorption of radiation, and acoustic absorption all depend on a knowledge of composition of combustion products and fragments that is still lacking. It appears that such measurements must await further development of combustion kinetics.

2. Thrust. No particular difficulty is encountered in measuring average thrust. There is some interest in measurements of transient thrust for pulse jet studies, but it would seem that piezoelectric or magnetostriction methods are well suited for this. Other schemes for average thrust include use of a weight balance, spring balance, resistance strain gauges mounted on elastic elements, and measurement of hydraulic pressure through a piston arrangement.

3. Fuel Rates. Fuel rates are determined by conventional commercial instruments such as rotometers, before and after weighing of fuel tanks, continuous weighing, float gauges, etc.

4. Air Rates. Air rates can be obtained by any one of a number of methods for measuring gas velocity as discussed above. Since high temperatures are not involved, the instrument problems are relatively simple. If transient rates are wanted, the problem is somewhat more difficult.

VI. INSTRUMENTATION SURVEY

This section contains a brief description of some of the features of instrumentation at the various contractors visited in this survey. The discussion is by no means complete because of the limited time available for the survey, but it is hoped that the details reported are reasonably accurate and that they will be of some service to other workers in the field.

For those contractors and activities that are not included, it means simply that either no information or insufficient information was available to include descriptions of the work in instrumentation. It is hoped that future effort can make this information more complete.

The activities have been grouped according to (a) Institutes and Government Laboratories, (b) University Laboratories, and (c) Industrial Organizations. No attempt has been made to maintain either subject or contractual structure in this presentation, since such an arrangement is virtually impossible.

A. *Institutes and Government Laboratories*

1. BATTELLE MEMORIAL INSTITUTE.[1] A mass spectrograph and known techniques for measuring air velocities and pressures are being used in chemical reaction studies of combustion. For materials study, a high-temperature X-ray diffraction camera is available for phase studies at high temperature as well as equipment for temperature control of samples, stress-strain, recording apparatus, etc.

2. BUREAU OF MINES.[2] In connection with a study of the burning of solid propellants, temperatures will be determined by burying a very fine thermocouple (0.001 inch dia. wire) in a load of the propellants. In due course, the flame will pass over the wire and give a recorded indication of the temperature. Observed temperatures are expected to be within at least 100° C of the actual temperature. Platinum to platinum-rhodium will be used with an expected response time of less than 0.01 seconds. Radiation losses are not expected to be serious.

Combustion in a spherical chamber is being investigated by observing the instantaneous pressure at the wall, the instantaneous temperature throughout the reaction zone (with thermocouples), and the instantaneous volume inside the spherical flame front (by means of a synchronous camera). The difference between the theoretically calculated pressures based on measured temperature and volume and the measured pressure will yield information as to the incompleteness of combustion.

3. NATIONAL BUREAU OF STANDARDS.[3] An effort is being made to develop apparatus suited to the measurement of velocity fluctuations of high frequency and high magnitude, such as occur in turbulent boundary layers, jets and wakes, in turbines, and around propeller blades. Recent work at NBS and elsewhere indicates that present turbulence measuring devices, developed primarily for high sensitivity and low turbulence, are poorly suited to measurements of fluctuations that are a large fraction of the mean speed. Under such conditions hot wires operated at constant current introduce errors because of their response and lag characteristics. Resistance-regulating circuits are being investigated as a possible improvement. Reported German developments of turbulent measuring instruments based on ionic conduction through air at high potentials are to be investigated.

In a development of methods for measuring temperature in gas turbines, radiation losses of thermocouples with cool walls in a hot stream of gas have been evaluated. For a chromel-alumel couple with gas at 1500° F and wall at 1000° F, the radiation error was found to be greater than 25° F. This was reduced to less than 5° F by use of a silver shield. Platinum shields for higher temperatures have been found to give a catalytic chemical action on the surface, which results in an error in indicated temperature. Attempts to poison the catalyst have changed the surface so that it no longer acts as a radiation shield.

The lag of thermocouples is also being investigated in the following manner: with the thermocouple in a steady-state condition in a hot gas stream, a metal cylinder with a cold gas stream is suddenly introduced around the couple and the temperature-time curve is recorded. Approximately 0.01 second is required to change the thermocouple environment from the hot to the cold gas (1000° F to 300° F). Considerable reduction in lag was achieved through the use of couples incorporating four junctions.

Suitable laboratory standard test equipment for establishing specifications for aircraft gas turbine temperature measuring equipment is being developed. Evaluation of thermocouples, thermisters, resistance elements, Flader microwave attenuators, Fairchild gas band analysers, G. E. quartz-nichrome differential expansions, Eclipse Pioneer bolometers, and other instruments will be made.

Flexure, thermal shock, short-time tensile, and creep tests are made on ceramic specimens. X-ray diffraction equipment is available for temperatures up to 1500° C. Attempts will be made to obtain controlled and measurable furnaces above 2000° C with an oxidizing atmosphere and above 3300° C with a neutral or reducing atmosphere for ceramic research. Platinum-rhodium couples are used up to 1600° C and optical pyrometers up to 3000° C.

4. NAVAL AIR MISSILE TEST CENTER (POINT MUGU).[4] The rocket laboratory at Point Mugu has

[1] Battelle Memorial Institute, Columbus, Ohio; J. F. Foster and C. H. Lorig; W-33-038-ac-14202. *Confidential.*

[2] Bureau of Mines, Pittsburgh, Pennsylvania; BuAer Contract NAer 00597; Bernard Lewis.

[3] National Bureau of Standards, Washington, D. C.; G. B. Helms, R. F. Geller, and E. F. Fiock. *Unclassified.*

[4] Naval Air Missile Test Center; Point Mugu, California. *Confidential.*

three test stands set on concrete implacements, with control lines run underground to reinforced concrete block houses. These control houses are equipped with Esterline-Angus pressure and temperature recording apparatus and other gauges and controls.

An elaborate test stand is being built, capable of testing and automatically recording data from high-speed turbo-driven pumps. In addition an Army A-26 airplane has been equipped as a flying test stand for pulse jets. The system contains the necessary apparatus for measuring thrust, drag, fuel flow, and fuel injection pressure at different air speeds and altitudes. Apparatus for measuring skin temperature is being installed.

5. Naval Research Laboratory.[5] In a study of pulse jet parameters, pressure measurements at four points along the pulse jet are recorded and correlated with thrust, specific fuel, combustion chamber geometry, etc. These measurements are made at the Chesapeake Bay Annex of NRL where test stand facilities are available.

Although they have used piezoelectric pressure gauges, NRL has had the most satisfactory experience with the Trimount magnetic gauge. Its response is good to 10 kc./sec., but it was found necessary to develop a cooling cell to protect the diaphragm. The design consisted of a small ducted heat-exchanger that cooled the hot gases before impingement on the diaphragm, and no adverse effect on the response was noted.

Thrust measurements are made by attaching a circular dial spring-scale to the pulse jet through the necessary cables and pulleys for the change in direction required by their particular test stand. This appears to have the decided drawback of widely fluctuating reading due to excitation of resonance conditions in the spring system by the irregular pulsating and detonating thrust of pulse jet.

Fuel is fed from a large vertical drive under compressed air and measured with a rotometer. NRL is only in preliminary stages of temperature measurements.

6. Naval Advisory Committee for Aeronautics.[6] Several test stands are available, equipped with Brown recording pressure, temperature, etc. gauges. Recording is done in a central recording room. Thrust is measured by resistance strain gauges cemented to each side at the steel bar. The bar is loaded in flexure through knife-edges by the jet under test. Average fuel flow is determined by before-and-after weighing of the fuel tank, but it is planned to record this continuously by using strain gauges.

High speed photographic equipment, Schlieren apparatus, and numerous other instrumentation are available.

7. Naval Ordnance Test Station.[7] For determining blast effects and high instantaneous pressures in rockets, strain gauges, oil pressure gauges, and capacitance gauges have been considered. A capacitance gauge has been designed and constructed. The unusual feature is the use of oil to transmit the pressure from the combustion chamber to the diaphragm. The opening to the combustion chamber is a capillary and serves to retain the oil in its cavity. Response as high as 12 kc./sec. is expected. The oil damps out effects due to vibrations and protects the diaphragm from excessive temperatures during the rocket firing. The presentation of the pressure is on an oscilloscope which is photographed for permanent recording.

Average pressures are measured in various parts of rocket chambers by oil-filled Bourdon tubes, with oil lines leading from capillary-cavity arrangements. Lengths up to 25 feet are sometimes used. A mirror mounted on the end of the Bourdon tube and an associated optical system serve to record the deflections on moving photographic film. The response of such a system is not expected to be very high, and various irregularities in the recorded pressure curves probably have their explanation in complex resonance excitations of the oil lines. Pressures up to 5000 p.s.i. have been observed.

No direct measurement of temperature in rocket combustion chamber has been attempted here, though plans include the use of optical pyrometers for liquid rockets. For solid propellants, the average temperature can be calculated from the known heat of reaction and the blast interval. Some assumptions must be made regarding heat transfer to the rocket walls, and this is arrived at experimentally. Thermocouples buried at various positions through the rocket wall serve to establish this heat transfer condition. Wall temperatures as high as 1100 F have been obtained.

Various other equipment includes high speed cameras, telemetering apparatus, torpedo launching tracks, etc.

B. University Laboratories

1. Alfred University.[8] In connection with the

[5]Naval Research Laboratory, Washington, D. C. (TED 3401) PU 249-46; L. F. Campbell and T. O. Meyer. *Confidential.*

[6]Naval Advisory Committee for Aeronautics, Cleveland, Ohio. *Confidential.*

[7]Naval Ordnance Test Station, Inyokern, California. *Confidential.*

[8]Alfred University, Alfred, New York; L. I. Shaw. *Unclassified.*

program for studying properties of materials, Alfred University is developing furnaces and instrumentation for testing up to 4000°F and above. Such properties as tensile strength, modulus of rupture, thermal expansion, softening temperatures under stress, and other pertinent properties are sought.

The main experimental difficulties occur in the measurement and control of temperature. The platinum to platinum-rhodium couple will not last long at 1500°C, but it is hoped that a molybdenum-tungsten couple in a reducing atmosphere can be used. The furnace temperature will be controlled by the resistance-temperature change of molybdenum wire.

Structures of various materials being studied will be determined spectrographically and by X-ray diffraction.

2. California Institute of Technology.[9] For a study of starting technique for liquid rockets, an apparatus has been built for measuring ignition delay of spontaneous liquid propellants. A drop of fuel is permitted to fall on a few drops of the oxidizer. The time interval between the passage of the fuel drop past a point just above the oxidizer and the resulting flash is determined by photocells and associated electronic timing circuits.

Determination of densities, specific heats, viscosity, heats of combustion, moisture absorption, melting and boiling points, etc. are being made for various propellant combinations. Ultraviolet and visible absorption spectra of nitromethane containing sensitizing or desensitizing additives are being examined.

Measurements of the rate of flame propagation through a vertical tube with various mixture ratios, additives, and total pressures are being made.

Development of suitable instruments for measurement of high temperatures in rockets is being pursued. An attempt will be made to measure exhaust temperatures from the relative intensities of the two known electronic states of a given species, such as the potassium doublet. In the rocket motor chamber a least reactive metal will be tried as a resistance thermometer. Under conditions where chemical reactions with the resistance element are unavoidable, the results of a high temperature vacuum investigation should prove useful.

Instrumentation with regard to refractories and sintered bodies include methods of measurement of thermal conductivities, coefficients of expansion, and identification of the constituents by X-ray diffraction.

[9]California Institute of Technology, Pasadena, California; Clark Millikan and Louis Dunn. *Confidential.*

3. Carnegie Institute of Technology.[10] In a program for determining the heats of formation, a bomb calorimeter has been designed of low carbon stainless steel (0.2 C, 25 Cr, 12 Hi) that is expected to be accurate to 2 parts per 10,000. Specific heats will be determined by the dropping method.

4. Cornell Aeronautical Laboratory.[11] Three different methods of measuring flame propagation velocities in tubes have been used at Cornell Aeronautical Laboratory. In the first, two fine wires, spaced down a pyrex tube, are burned out as the flame passes over them. This is used to start and stop an electric clock and gives an average flame velocity.

Another method depends on ionization of gaps spaced down the combustion tube. The output of an oscillator is fed to an oscilloscope through a high resistance. Ionization gaps, spaced down the combustion tube, are shunted across the output. The ignition of the combustible mixture is used to trigger the oscilloscope sweep and, as the flame front passes successively over the gaps, their resistance is sharply decreased momentarily. This causes the voltage input to the scope to drop momentarily. The final result is a modulation of the observed wave by the breakdown at the gaps, hence the flame velocity along reflections from the end of the tube, this technique the tube can be determined. However, for cases of reversal of velocity, such as can be caused by acoustic reflections from the end of the tube, this would be confusing.

Flame velocities are also determined by high-speed photographic methods.

For materials studies, various electric furnaces, precision coating equipment, etc. are available. A high-temperature tensile setup has been constructed so that the specimen can be vibrated at elevated temperatures. A high-temperature X-ray diffraction cell has been designed.

5. Cornell University.[12] The structure of various boranes are being determined, using electron diffraction techniques. An electron beam will be sent through the gas and the diffracted beam will be scanned with an electronic pickup. The intensities of the various diffraction orders will be recorded in this manner.

[10]Carnegie Institute of Technology, Pittsburgh, Pennsylvania; N6ori-47, T.O.-7; Harry Seltz. *Unclassified.*

[11]Cornell Aeronautical Laboratory, Buffalo, New York; J. V. Foa.

[12]Cornell University, Ithaca, New York; S. H. Bauer; N6ori-91, T.O.-1. *Unclassified.*

6. MASSACHUSETTS INSTITUTE OF TECHNOLOGY.[13] Hot-wire anemometers are being used to study velocity and turbulence in combustion tubes before ignition. Subsequently, the mixture is ignited and photographed. A dual hot-wire probe is used to obtain scale of turbulence. After a thorough survey of hot-wire techniques, an improved compensating circuit has been developed using a capacitance rather than inductance. This can be expected to be useful over a wider range of frequencies. Platinum Wollaston wires of 0.0001 inch to 0.00005 inch diameter by about 1 to 2 mm. in length are used as the resistance element in the hot-wire probes.

Temperature measurements of turbojet exhaust gases have been made with tungsten-molybdenum thermocouples. Sodium D-line reversal techniques, optical pyrometers, two color methods, heated wire method, etc. have also been used for temperature measurements. The line reversal method was the most successful one for non-luminous flames.

7. NEW YORK UNIVERSITY.[14] Various methods of measuring and recording the pulsating pressures of pulse jets are being developed. Capacitance, magnetostriction, and piezoelectric gauges are being constructed. A water-cooled cell has been developed for protection of the diaphragm. The condenser gauge is used to modulate an FM circuit and a system of preamplifiers at the jet are included to reduce difficulties due to the low level of the output. High-speed photographs of the oscilloscope screen are used for recording. For calibration purposes an adiabatic pressure chamber with a mechanically oscillating diaphragm has been constructed, but some difficulty is being experienced with fatigue at the diaphragm.

A photo-multiplier pickup with amplifying systems has been constructed suitable for measurements of emission intensities of sodium D-line, absorption intensities of sodium D-line, relative intensities of sodium and potassium lines, and intensity of the continuous background from burning flames. A new high resolution spectroscope has been designed and is under construction. This will be employed in sodium D-line reversal methods as well as the "two-color" method for temperature measurement.

In connection with flame tube studies, high-speed photographs of the flame front are used to obtain the flame propagation velocity as affected by various turbulence-producing grids. Another method being considered makes use of a radioactive tracer technique in which a pulse of radioactive material is injected into the tube or engine and its progress observed by means of counters. The same method might be used with a pulse of sodium in a flame. The use of scattered light from small particles will also be investigated. A Schlieren setup with a 16-inch mirror is also available.

8. NORTHWESTERN UNIVERSITY.[15] Several techniques for investigations of mixing and turbulence are being developed. In one case, dye is injected into a stream of water and the concentration gradient downstream determined. For a gas stream, a point source of heat is used and the temperature is measured downstream by thermocouples. It is also planned to introduce different gases and determine the concentration downstream by means of infrared absorption spectra.

In studying transient phenomena accompanying combustion, a sensitive infrared cell and high-speed photography will be used. It is hoped that a camera can be built to take up to 200,000 frames per second.

9. OHIO STATE UNIVERSITY.[16] For studies of reaction kinetics and flames, the mass spectrograph will be used to measure appearance potentials, and for detection and analysis at intermediate reaction products. Flame temperatures will be measured spectroscopically and exhaust velocities by radioactive tracers. Optical pyrometers and line reversal methods will also be used.

10. POLYTECHNIC INSTITUTE OF BROOKLYN.[17] A Henry fatigue machine has been constructed. It consists of a disc about 18 inches in diameter on the axle of a synchronous motor. Ten alnico magnets are mounted around the circumference of the disc. The sample to be tested, $\frac{1}{4}$ inch $\times$ $\frac{1}{8}$ inch $\times$ 5 inches, is clamped at one end so that the free end is over the magnets. When the disc is spun, the sample will vibrate, up to 18,000 cycles/min. are attainable. It is planned to adapt the machine for work at high temperatures up to about 2000° F.

11. PRINCETON UNIVERSITY.[18] Optical means will be used to obtain much of the data from the Princeton

[13] Massachusetts Institute of Technology, Cambridge, Massachusetts; H. C. Hottel and G. C. Williams.

[14] New York University, New York, New York; J. K. L. MacDonald; Project SQUID, N6ori-11, T.O.-2. *Unclassified.*

[15] Northwestern University, Evanston, Illinois; L. F. Stutsman. *Unclassified.*

[16] Ohio State University, Columbus, Ohio; G. A. Bole. *Unclassified.*

[17] Polytechnic Institute of Brooklyn, New York, N. Y.; R. P. Harrington; Project SQUID, N6ori-98, T.O.-2. *Unclassified.*

[18] Princeton University, Princeton, New Jersey; R. N. Pease; Project SQUID, N6ori-105. *Unclassified.*

wind tunnel. A 4-inch Mach-Zehnder interferometer is being built. The specifications call for a final fringe pattern that is straight, parallel, and equidistant to within 1/10 of a fringe. The large tunnel will have a Schlieren system with 12-inch mirrors of 100-inch focal length, and the small tunnel will have 8-inch mirrors with 80-inch focal length. High-pressure mercury arcs will be used, both continuously and in spark operation. Ronchi grating method will also be tried.

An electronic chronoscope for measurement of flame speeds has been developed, based on the Eccles-Jordan trigger circuit. The flame ionization, as it passes a given point, is used as a pulse to start an RC circuit charging. Subsequently the flame passes a second point and stops the charging. The voltage on the RC circuit is measured by means of a vacuum tube voltmeter and serves to measure the flame velocity. Various ranges are available from 4×10^{-3} second to 14 secs. For the spacing used, these correspond to 5700 cm./sec. and 26 cm./sec.

Another unique development has been a new method for detecting ionization in flames utilizing the loading characteristic of a high frequency oscillator. As the flame passes through an oscillator tank coil which is constructed around a combustion tube, the absorption of energy, due to ion formation and increased eddy-current losses in the gas, causes an increase in the plate current of the oscillator which is used to trigger an electronic chronoscope. Two obvious advantages are (1) direct measurement of flame speeds can be made without the introduction of electrodes or screen wires into the tube, and (2) the points in the tube at which measurements are made can be varied at will.

12. PURDUE UNIVERSITY.[19] In determining response of thermocouples, apparatus has been constructed to move the couple mechanically through a Bunsen flame. The d-c voltage developed by the couple is chopped at about 800 cycles/sec. and amplified by a two-stage a-c amplifier. This output is shown on an oscilloscope and photographed. A photocell circuit indexes the camera film when the thermocouple enters and leaves the flame, and a 60-cycle timing signal is also recorded on the film. The deflections of the oscilloscope are calibrated to give temperature.

A high-temperature furnace attachment for the electron diffraction camera has been made. By its use a sample can be oxidized while in the camera, and the surface can be investigated at the temperature of formation without intervening cooling.

The techniques of quenching combustion reactions by rapid dilution of combustion products with cold inert gases are being investigated. Several designs are being constructed.

13. UNIVERSITY OF CALIFORNIA.[20] A device has been built for studying the mechanism of mixing of fluid streams. It consists of a hot wire and a thermocouple on a traversing head downstream.

In a study of spray formations, a small high-pressure oil chamber at 3000 p.s.i. is used with various sizes of hypodermic needles with ends cut perpendicular to the axis. An almost instantaneous means of starting and stopping the movement of the oil through the needle has been achieved. It consists of a magnetically operated valve plunger seated against the rear of the needle. Measurement of particle size and movement is done with the aid of a strong light source and simultaneous photography through a series of microscopes arranged at right angles to the direction of the spray. Curved metal guards protect the lenses from oil deposits.

14. UNIVERSITY OF DELAWARE.[21] A one kilowatt ultrasonic generator is being constructed for the 700 kc./sec. region using quartz crystals as transducers. An attempt will be made to produce finer fuel sprays and better distribution by subjecting the air-fuel mist to an intense ultrasonic field before it reaches the combustion zone. The ultrasonic field will also be used as a means of producing controlled and specialized types of turbulence.

A device for radiation scanning of the Bunsen flame has been developed. The radiation, limited by a 1-mm. square aperature, is picked up by a photo-multiplier tube and after two stages of d-c amplification is shown on a cathode-ray oscilloscope. The aperature scans the flame by means of a synchronous motor which is also synchronized with the oscilloscope sweep. The result is a presentation of the radiation contour of the flame on the screen. This can be observed visually or photographed. Filters can be introduced to limit the wavelength of the radiation, and it is planned to extend the method to infrared as soon as an infrared multiplier tube becomes available.

Shadow pictures are being extensively used for mixing studies as well as for observing turbulence. Both arc and spark (10^{-6} sec.) light sources are used. Stereoscopic shadowgraphs have been made and are

[19] Purdue University, Lafayette, Indiana; H. J. Buttner and G. A. Hawkins; Project SQUID, N6ori-104. *Unclassified.*

[20] University of California, Berkeley, California; C. J. Vogt; Project SQUID.

[21] University of Delaware, Newark, Delaware; Kurt Wohl; NOrd 9845. *Confidential.*

expected to be useful. Correlation between scale of turbulence, as given by shadow pictures, and the hot-wire anemometer is being attempted.

The flow of small particles introduced into a gas stream is useful in determining flow lines and velocity. The apparatus at the University of Delaware consists of a stroboscopic means of illuminating the flame or gas jet and a means of photographing the light scattered from the particles. In the case of flames, photographs of the luminous flame can also be taken. Silica gel at about 40 μ and a density of 0.3 gm./cc. can be used. Smaller particles of lower density would follow the streamlines more successfully.

An elaborate apparatus for line reversal studies is being constructed; this apparatus will make temperature determinations by this method a routine matter. The sodium source, combustion chamber, and spectrometer are all mounted on a rigid channel-iron base. The combustion chamber can be moved horizontally and vertically by means of a micrometer screw, so that different positions of the combustion zone can be measured. Mirrors and a telescope allow for visual observations and location of the region being measured. Introduction of the sodium through a fine jet makes temperature measurement in the interior of the flame possible. The two D-lines of sodium are actually resolved, and a low power microscope has been found useful in determining the reversal point.

A novel technique for introducing coloring salts into flames has been developed. An air jet flows through a mixture of about 80% glycerin and 20% saturated salt solution, small droplets of solution being entrained through small holes in a hood surrounding the jet. This results in a fine mist with about 80% of the droplets in the range at 5-6 μ.

15. University of Pennsylvania.[22] Development of gas analysis methods includes infrared analyzers, dew-point apparatus, ionization potential methods, manometric methods, etc.

16. University of Pittsburgh.[23] For a study of thermodynamic properties of borohydrides, a microcalorimeter is available with a thermopile capable of detecting a few tenths of a microdegree.

17. University of Southern California.[24] This laboratory is equipped to take shadowgraph pictures with a high-power light source and a focal plane shutter camera. An electric arc will also be used. A balance system is being built for use with supersonic free jets to measure lift, drag, and movement. Air velocities ahead of the ramjet are determined by measuring the angle of the shock wave on cones placed in the air streams. Temperatures up to 2800°F in the gas stream have been obtained. These are determined indirectly by measuring the pressure of the exit gases at the nozzle of the ramjet with the aid of a comb of water-cooled Pitot tubes.

18. University of Washington.[25] In connection with shock wave studies, optical instruments for study of shock wave flow characteristics, boundary layer effects, and density gradients with Schlieren apparatus and interferometers will be obtained.

19. University of Wisconsin.[26] A large optical interferometer has been designed and is under construction. Nine-inch mirrors, mounted in vacuum boxes, are used in such a manner that the mirror ensembles can be moved on a rigid track so that the length of working section can be changed.

A Schlieren setup with 12-inch mirrors of 100-inch focal length is being constructed. It is planned to use a grating in conjunction with the knife-edge to get a pattern of contour lines of index of refraction.

C. *Industrial Organizations*

1. Aerojet Engineering Corporation.[27] Test stands are equipped with the usual type of pressure gauges, recorders, and thermocouples for measuring jacket and coolant temperature. Condenser type water-cooled pressure pickups have been built. This development will be continued with a newly designed condenser gauge that decreases temperature effects. Temperature measurement by the sodium D-line reversal method is also being considered, as well as the two-color method. Thrust is measured by the compression of a large spring below the test carriage and indicated remotely by means of Selsyn motors. The wavelengths and intensities of radiation in the infrared region of rocket and pulse jet exhaust flames are to be measured.

2. Aviation Corporation of America (Lycoming Division).[28] Various standard roto-meters, pressure gauges, manometers, and thermocouples are used for

[22]University of Pennsylvania, Philadelphia, Pennsylvania; J. A. Goff; NObs-2477. *Restricted.*

[23]University of Pittsburgh, Pittsburgh, Pennsylvania; Gebhard Stegeman; N6ori-43. *Unclassified.*

[24]University of Southern California, Los Angeles, California; R. T. DeVault. *Confidential.*

[25]University of Washington, Seattle, Washington; F. S. Eastman; N6ori-217. *Unclassified.*

[26]University of Wisconsin, Madison, Wisconsin; J. O. Hirschfelder; NOrd 9938. *Restricted.*

[27]Aerojet Engineering Corporation, Azusa, California; K. F. Mundt.

[28]Aviation Corporation of America (Lycoming Division), Williamsport, Pennsylvania; C. H. Wiegman; NOa(s)-4718. *Restricted.*

routine test work. Cathode-ray oscillographs and amplifiers have been used with pressure gauges for cyclic thrust and pressure.

One test stand consisted of a parallelogram with the motor mounted on the top bar. The whole system is mounted on rollers, so either the parallelogram or the rollers may be used to measure the thrust. The actual thrust unit consists of a piston and cylinder, with thrust being measured by a pressure gauge.

3. Bendix Aviation Corporation.[29] Aircraft instruments for measuring such parameters as pressure, temperature, air velocities, flow, etc. are being developed using flux gate principles. In connection with temperature measurements of ramjet combustion at high altitude, a bolometer sensitive to 5 microvolts/microwatt/cm.^{2} and a reaction time of about 0.005 sec. has been developed.

Fuel metering devices to modulate fuel supply to pulse jet engines are under development.

Various other instrumentation developments are concerned with guidance, telemetering, and other mechanisms associated with complete missiles.

4. Consolidated Vultee Aircraft Corporation.[30] In the operation of the large wind tunnel at Lone Star, Schlieren and spark photographic equipment is available. Most test data are recorded photographically and transcribed to IBM cards, so that computing machines can be used for correlating the data. While the tunnel operates with banks of mercury manometers for determining static and dynamic pressures, burners are equipped with Trimount gauges. These determine transient pressures down the length of the burner tube. A Hathaway 12-channel oscillograph is used. Thrust and drag are measured with resistance strain gauges. Wall temperatures of the burner and the temperature of fuel-air mixtures before combustion are determined with thermocouples and recorded. A Mine Safety Appliance dew-point meter is used. Photographs of all dials, gauges, rotometers, etc. are taken at 1-second intervals, during a test.

An improved dew-point meter that gives continuous recording has been developed. A stainless steel mirror is continuously cooled by a refrigerant, causing condensation to form on its surface. This effects the amount of light reflected from the surface to a photocell, which causes an inductive heater to heat the mirror until the condensation disappears, thus continuously keeping the mirror at the dew-point. A thermocouple measures the temperature of the mirror.

5. Curtiss-Wright Corporation.[31] For test work, a specific impulse indicator that automatically divides the total thrust by the fuel rate is being developed. Thus by varying the mixture ratio manually, the optimum performance can be obtained in one test run.

6. Experiment, Incorporated.[32] Various thermocouple combinations are being investigated, including platinum-platinum rhodium, iridium-iridium rhodium, and silicon-silicon carbide. These combinations are reported to be usable up to 3500°F. Another method for temperature measurement makes use of a bead of carboloy mounted on a water-cooled strut in the ramjet combustion zone or exhausts. An optical pyrometer gives the temperature of the carboloy, and a calculated correction for radiation and conduction gives the temperature of the gas. Line reversal techniques have also been used, and there is some evidence to show that the conductivity between two probes is a satisfactory indication of temperature in a given flame.

Molybdenum water-cooled Pitot tubes have been developed that seem satisfactory for continued use in the hot exhaust gases from a ramjet burner. In one variant, water is forced through the Pitot tube opening, the flow being adjusted to a very slow uniform value. The water pressure is then a measure of the dynamic pressure in the gas stream. Trimount and Esso pressure gauges for fluctuating pressures are used, and some consideration has been given to piezoelectric gauges.

A thorough investigation of turbulence in its relation to combustion is being pursued. Hot-wire anemometers, thermocouples, piezoelectric crystals, flow patterns, etc. are being developed as methods of measuring turbulence. Fluorescent or radioactive materials may be introduced to determine mixing under various flow conditions.

7. General Electric Company.[33] Instrumentation for measuring temperature, pressure, fluid flow, net thrust, and other parameters in testing and developing rocket motors is being developed. An elastic deflection device suitable for measuring pressure, thrust, fuel flow, etc. has been developed. It consists of a balanced pair of iron core inductances, each inserted into a leg of a U-shaped block of aluminum. The inductances form a part of a mutual inductance bridge, and elastic deflection of one arm of the aluminum block unbal-

[29] Bendix Aviation Corporation, Teterboro, New Jersey; Walter Teague.

[30] Consolidated Vultee Aircraft Corporation, Downey, California; C. R. Irvine.

[31] Curtiss-Wright Corporation, Propeller Division, Caldwell, New Jersey; C. W. Chillson.

[32] Experiment, Incorporated, Richmond, Virginia; J. W. Mullen; NOrd 9756, *Confidential*.

[33] General Electric Company, Schenectady, New York; F. P. Bundy.

ances the bridge. The unbalanced output from the bridge is a measure of the deflection of the arm.

A novel means of measuring rocket exhaust gas velocities has been developed. It depends on the Doppler shift of sodium radiation from "diamonds" in the exhaust. An optical system sights upstream and downstream at about 40°, and the resultant shift is measured by means of a Fabry-Perot interferometer.

General Electric is also investigating pressure broadening and pressure shift of spectral lines as a means of pressure measurement. Shifts of 0.022 Å/atmos. towards the red for the sodium D-line have been obtained.

For temperature measurements, the sodium line reversal method is being investigated. By means of a calibrated optical wedge, it is hoped that temperature can be measured directly by matching intensities of the observed D-line and the calibration on the wedge inserted between the source and the flame. The CH band spectrum in the exhaust has also been investigated as a means of temperature measurement. Another technique makes use of microwave transmission through the flame and depends on ionization potentials of salts introduced into the flame.

8. M. W. Kellogg Company.[34] Pressures are measured with recording Bourdon gauges and thrust is determined by means of a hydraulic pickup activating a Bourdon gauge. Thermocouples are used for temperatures and flow meters for fuel.

9. Marquardt Aircraft Corporation.[35] An investigation of fuel spray characteristics is being made with transparent diffusers and nozzles and spark photography. Spray patterns will be determined by shadow photographs and droplet size by high-speed photographs and measurement. An attempt will be made to correlate droplet size and light transmission.

In pulse jet studies wind tunnels are equipped with Schlieren apparatus and high-speed photographing. An 8-inch pulse jet will be run in the tunnel to study flow characteristics into the jet. A hot wire or spark will be installed upstream from the pulse jet in order to make the flow visible. The pressure cycle of the jet will be measured by a strain gauge type of pressure unit.

Several special aerodynamic drag lifts, balance systems, etc. have been developed.

10. Standard Oil Development Company.[36] In connection with fundamental studies of combustion, investigations at Standard Oil have included studies of temperature, turbulence, and flame propagation. Spectrographic studies of various flames have been made to furnish a background for temperature measurement. Sodium D-line reversal techniques are used. Both upstream and downstream flame propagation in tubes is being investigated. Various test stands are available, with flow meters, air compensating thrust gauges, thermocouples, etc.

11. Union Oil Company of California.[37] This Company has a very well equipped general physical-chemical laboratory with such instruments as emission spectrometer, infrared absorption spectrophotometer, ultraviolet absorption spectrophotometer, mass spectrograph, and 12-place electronic calculator for simultaneous equations.

12. United Aircraft Corporation.[38] In conjunction with wind tunnel equipment, this laboratory has extensive optical equipment including spectrographic, shadowgraphic, and Schlieren apparatus. Combustion experiments can be carried out either in the large wind tunnel or in a special pressurized combustion line. Considerable work is being done in recording flight data.

13. Ryan Aeronautical Corporation.[39] A high-temperature thermocouple has been developed, capable of measuring temperatures in excess of 5200 F. It consists of an outer cylinder of graphite and an inner rod of tungsten, with a pressure contact forming the junction at one tip. The response time is rather high because of the size (about 1/4 inch o.d.), but the couple will last in an oxy-acetylene flame for several minutes. A ceramic coating is being developed to protect the carbon from oxidation.

[34] M. W. Kellogg Company, Jersey City, New Jersey; G. H. Messerly.

[35] Marquardt Aircraft Corporation, Venice, California; R. E. Marquardt.

[36] Standard Oil Development Company, Bayway, New Jersey; W. J. Sweeney.

[37] Union Oil Company of California, Wilmington, California; O. L. Polly; W-33-038-ac-13468. *Restricted.*

[38] United Aircraft Corporation, East Hartford, Connecticut; J. G. Lee; NOrd-9845. *Confidential.*

[39] Ryan Aeronautical Corporation, San Diego, California; C. R. Tuttle.

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Parameters of systems involving combustion processes are measured. Principal experimental conditions under which measurements were made are described. Included are power plants, diffusion flames, stationary and moving flames, closed chambers, and soap bubbles. Instrumentation requirements for each condition are pointed out. Three major difficulties are effects of system on instrument, effects of instrument on system, and fluctuations in system. Techniques for measuring pressure temperature, gas velocity, turbulence, flow patterns, flame propagation velocity, etc., are discussed.

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