ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Interim Report

METHODS FOR MEASURING AMBIENT-AIR TEMPERATURES FROM HIGH-SPEED AIRCRAFT

A Preliminary Investigation

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Project 2523

DEPARTMENT OF THE AIR FORCE
WRIGHT AIR DEVELOPMENT CENTER
WRIGHT-PATTERSON AIR FORCE BASE, OHIO
CONTRACT NO. AF 33(616)-3630

November 1956

ACKNOWLEDGMENT

Several persons at The University of Michigan have been very helpful throughout this study. In particular, the following have given consultation in regard to one or more parts of this report.

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ABSTRACT

This report considers several methods which might conceivably be used to measure the true free-stream air temperature from a vehicle operating between 0.3 and 3.0 flight Mach number and between sea level and 150,000-ft altitude.

Techniques employing either vortex thermometers or a combination of stagnation temperature and flight Mach number have been specifically excluded from this study.

The main methods discussed have been considered in terms of their expected capability of producing accurate indication of the static air temperature under most expected flight conditions. Several of the methods discussed are considered to be worthy of further study.

OBJECTIVE

The development of a technique for measuring true free-stream air temperature from aircraft at flight Mach numbers from 0.3 to 3.0 and at all altitudes up to 150,000 ft.

INTRODUCTION

This is an interim report covering the preliminary phase of Air Force Contract No. AF 33(616)-3630. This study is under the direction of Mr. C. J. Jolley (WCLCI-1) of Wright Air Development Center and has as its purpose the development of a technique for measuring true free-stream (i.e., ambient) air temperature from aircraft at flight Mach numbers from 0.3 to 3.0 and at all altitudes up to 150,000 ft.

Knowledge of ambient-air temperature has become more vital as flight speeds have increased. However, the difficulties encountered in measuring free-stream static temperature have also increased with flight speed.

Considerable work has been done in developing instruments for measuring free-stream total temperature and relatively satisfactory techniques have been developed for that measurement. Some work has been done in an attempt to develop satisfactory techniques to measure the static temperature, but this effort has not been as successful as have the total-temperature studies. The most workable system developed thus far for determining static temperature (for normal aircraft usage) requires total-temperature measurement, flight Mach number measurement, and a computer to derive static temperature. Since this method has inherent limitations, it is desirable that a more direct method of ambient-temperature measurement be developed for high-speed aircraft.

GENERAL DISCUSSION

Maxwell has given a definition of temperature which says that "The temperature of a body is its thermal state considered with reference to its ability to communicate heat to other bodies" (Ref. 1).* With this definition in mind, it is apparent that there is no such thing as direct measurement of temperature. In fact, the International Temperature Scale is defined between -182.97°C and 630.50°C in terms of the resistance of a standard platinum resistance thermometer (Ref. 2). The ice point (0.00°C) or the triple point of water (.01°C) and the steam point (100°C) are reference points for this definition.

*References for all sections of this report are listed in the Appendix.

The temperature of an ideal gas is proportional to the average translational energy of the molecules [i.e., $T \propto 1/2\ m(V_m^2)_{avg}$]. A relatively direct method of obtaining an indication of the temperature of any given ideal gas would therefore be the measurement of the average of the square of the molecular translational velocity $(V_m^2)_{avg}$. Here again, however, the means of direct measurement is not apparent.

The temperature of a gas is obtained by what is usually considered "direct measurement" when a body immersed in the gas is at thermal equilibrium with the gas and some property of the body which has a known relation to temperature is measured. The immersed body is at thermal equilibrium with the surrounding gas when there is no net heat flow between the two. When it is desired that the thermal state of a moving gas be obtained by "direct measurement" it is necessary that either (1) the immersed body move with the gas or (2) the effect of the relative ordered motion between the gas and the immersed body can be eliminated or counteracted. This is precisely the problem at hand.

Where so-called "direct measurement" is not feasible, other methods of obtaining indications of temperature must be considered, even though they involve devious approaches to the temperature.

The following conceivable methods of temperature measurement have been listed with the above discussion in mind and with a view toward their possible application to the problem at hand, i.e., measuring the true static free-stream air temperature from flight Mach numbers of 0.3 to 3.0 and at altitudes from sea level to 150,000 ft. These methods are grouped according to the variable being measured and not in order of ease of application or expected accuracy.

Suggested Approaches to the Problem of Measuring True Free-Stream Temperature (Static) from Subsonic and Supersonic Aircraft

Group A - Primarily a function of temperature only (i.e., independent of pressure or density)

1. $(V_m^2)_{avg}$
2. Very small probe (e.g., fine wire)
3. Viscosity
4. Speed of sound
5. Intensity of an emission spectral line (such as the 4.3-micron CO_2 line)
6. Thermal conductivity

Group B - Function of pressure and temperature
(i.e., function of density)

1. Density (or mean free path)
2. Electrical discharge
   (including dielectric of air)
3. Ionizing radiation
   a. collection of ions
   b. absorption of radiation
   c. scatter of beta radiation
4. Index of refraction
5. Absorption of electromagnetic
   waves.

Group C - Miscellaneous

1. Combinations of enthalpy, entropy, and thermodynamic processes
2. Vortex tube
3. Stagnation temperature combined with Mach number
4. True air speed combined with Mach number and/or speed of sound.
5. Two-temperature method.

DISCUSSION OF APPROACHES TO THE PROBLEM OF MEASURING FREE-STREAM TEMPERATURE FROM SUBSONIC AND SUPERSONIC AIRCRAFT*

GROUP A—PRIMARILY A FUNCTION OF TEMPERATURE ONLY

A-1. $(V_m^2)_{avg}$.—Within the range of temperatures encountered between sea level and 150,000 feet (-67°F to approx. 110°F) the temperature of air is directly proportional to the random translational energy of the molecule, i.e., $T \alpha$ kinetic energy = $1/2\ m(V_m^2)_{avg}$, where m = molecular-weight average, V_m = the velocity of any one molecule, and $(V_m^2)_{avg}$ = the average value of the velocity-squared terms. However, there does not appear to be any method yet available for measuring $(V_m^2)_{avg}$ directly.

Conclusion: It would not be profitable to give the parameter $(V_m^2)_{avg}$ any further consideration as regards its direct applicability to this problem.

*It is to be expected that the conclusions stated are subject to revision as additional knowledge and techniques become available.

A-2. Very Small Probe.—Included in this category are any probes of such configurations as to produce areas wherein the static temperature can be measured by immersed bodies. A body immersed in a moving air stream will in most cases assume some temperature between the static and stagnation air temperature. This temperature is usually described in terms of the recovery factor:

$$\text{Recovery Factor} = T_b - T_a / T_t - T_a$$

T_b = temperature of the immersed body
T_a = static or true free-stream ambient temperature
T_t = total or stagnation temperature

Temperature probes have been designed which have recovery factors greater than 0.99 (Ref. C-3-5). This high recovery factor is accomplished primarily by

1. Shielding the probe's temperature-sensing element with good reflectors which are themselves held very near the stagnation temperature, thus practically eliminating radiant heat losses.

2. Minimizing conductive heat losses from the sensing element by proper design of the support points.

3. Designing the air ducting around the sensing element so as to decelerate the air and thus convert most of the kinetic energy of the air to sensible heat before it reaches the element.

The recovery factor of a bare thermocouple wire is on the order of 0.65 (Ref. C-3-7). Although much work has been directed toward increasing the recovery factor, very little information is available regarding the minimum recovery factor practically attainable. Obviously, a probe with a recovery factor of zero would give us immediately the information desired.

The probe scheme sketched in Fig. 1 is suggested as one method of reducing the recovery factor of a temperature-sensitive immersed body. The fine wire is insulated so that the resistance of the wire is measured at all times and hence the temperature of the wire is determinable (Ref. A-2-5). The main body of the probe would be at some temperature near stagnation, but the wire could be essentially independent of this by employing very large length-to-diameter ratio. Radiation to the wire from the support may be a problem, but by the use of platinum wire with its low emissivity ($\therefore$ low absorptivity) this could probably be held very low.

The temperature level reached by the wire is further determined by the following:

1. Slip flow - When the characteristic dimension of the immersed body approaches the length of the mean free path of the gas molecules, the assumption

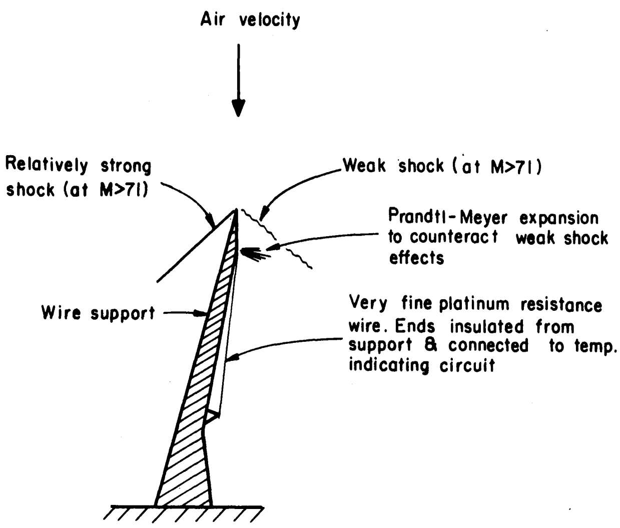

Fig. 1. Fine-wire probe.

that the gas at the surface of the body is at rest relative to the body becomes quite inaccurate. Since the gas at the surface is not at rest, the temperature of the surface gas does not as nearly approach stagnation temperature as it does when the gas comes completely to rest.

2. The heat conducted away from the wire by surrounding air.

3. The expansion of the air (in the supersonic case) before it reaches the temperature-sensitive element. The static temperature will be slightly less than the free-stream static temperature; therefore, with a local recovery factor greater than zero the instrument could still indicate true free-stream static temperature.

The above three effects would all tend to reduce the recovery factor of the probe. There is not, however, sufficient information available at the present time to determine just how low a recovery factor could be reached by such techniques as discussed above.

Unfavorable factors regarding a probe of this type should be mentioned:

1. Because of the wide density range (and, therefore, wide range of mean free paths) encountered by the probe, the extent of the slip effect at the surface will vary.

2. The expansion cooling effect will be quite different for subsonic and supersonic flows.

In spite of these disadvantages and the uncertainties regarding this type of probe, further consideration should be given to it. This technique for obtaining free-stream static temperature is tremendously less complicated than any other method thus far conceived. The basic simplicity of such a scheme might make acceptable less stringent performance characteristics.

Conclusion: The possibilities of such a technique should be pursued by means of at least a few relatively simple tests. The extent of such tests would be determined by the degree of favorableness of initial results.

A-3. Viscosity Measurements.—The temperature relationship of viscosity is

$$\mu/\mu_1 = (T/T_1)^n .$$

Viscosity is a property of a fluid evidenced only where nonisentropic flow exists, that is, where a shearing force and, thus, a conduction of heat exists. The heat generated in any measurement of viscosity at supersonic speeds would, then, seem to militate against determining the free-stream temperature at any point. No method is conceivable which would overcome these difficulties.

Conclusion: Consideration of the use of this parameter in determining free-stream temperature should be discarded.

A-4. Measurement of the Speed of Sound.—The possibility of utilizing the measurement of the speed of sound waves as a means for determining gas temperatures has been the subject of study in several investigations. Some of these studies have resulted in the construction of apparatus for making such measurements in a moving gas stream (Ref. A-4-2,5,28). The utility of the method of course derives from the well-known proportionality of speed of sound to the square root of the absolute temperature of a gaseous medium when the ratios of specific heats and molecular weights are constant. The measurement of the speed of sound must be made in such a way that either the air velocity is known or it does not enter into the equations used for reducing the data. It would seem that the most practical devices designed for the measurement of temperature by sonic means require the use of an emitter and a receiver that are remote from each other. This requirement, at the outset, makes difficult the design of any instrument that would be practical for the vehicle with which we are concerned. On the one hand, the two components would have to be at a great enough distance apart to minimize the effects of heating of the boundary layers near the components. On the other hand, the distance by which the two may be separated would be limited by the increasing effect of the forward speed of the vehicle upon the resultant direction of the sound waves. A two-component system of the type in question may be subject to the additional difficulties introduced by being located on the high-temperature side of flow disturbances. This would depend on the flight Mach number, the design of the supporting structure, and of the vehicle configuration.

Most of the apparatus adaptable for the determination of temperature by sonic means were primarily designed as Mach meters, with temperature seeming to be more or less of incidental consideration. Also many of these systems involve the use of photographic techniques which would make their adaptation for high-speed-aircraft use impractical. A method which seems to hold some promise in the emitter—remote-receiver type of system is the Sonic True Air Speed and Mach Number Indicator - STAMNI - (Ref. A-4-30). This system, having theoretically good possibilities, is subject nonetheless to several practical difficulties. It involves the use of two booms placed several inches apart and leading into the flow of the free air stream. These booms should be in the form of slender half-wedges to minimize flow disturbances, one carrying the emitter and the other carrying the receiver. The emitter should be capable of automatic adjustment of position along the line of flow of the air stream, relative to the receiver or receivers. The Mach number is then directly determined by the ratio of the longitudinal difference of emitter and receiver positions to the distance between the booms, when the components are so positioned that the maximum signal is obtained at the receiver. Temperature would be determined by the acoustic transit time over the normal-incidence system. As stated previously, in any device of this type the two components must be far enough apart so that boundary-layer effects are negligible. For a vehicle flying at Mach 3, this may require booms long enough so that construction would need to be quite rugged to withstand the force of the impinging air stream. It would seem then that in the adaptation of STAMNI or any acoustic system to the problem at hand, it is imperative to investigate the temperature changes brought about by flow disturbances and the noise produced by flow disturbances and vibration.

The above method requires the use of a movable sound receiver. The questionable aspects of this particular system are: the time response, the size, and the complexities of the positioning mechanism.

Another approach to the speed-of-sound method is the use of a pulse technique. One suggested system which eliminates the movable receiver is sketched in Fig. 2.

The arrival of some portion of the sound-wave envelope at the receiver is independent of the forward velocity. The time required for the sound-wave envelope to travel from the plane of the emitters to a parallel plane in which the receiver is located will be measured. The speed of sound, a, will be simply

$$a = \frac{d\text{-ft}}{\Delta\ \text{time-sec}}$$

where d is the distance between the two parallel planes.

It should be noted that the time-measuring circuit will be so constructed as to be active only between the emission of a signal and the arrival of the envelope front at the receiver. Thus, any secondary sound waves will

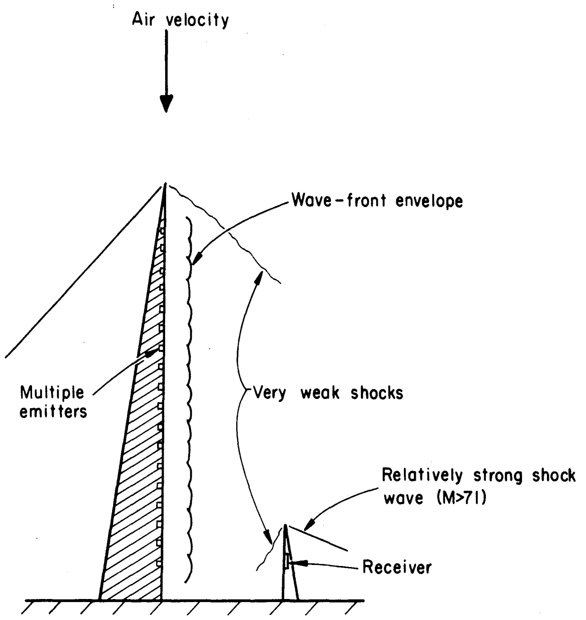

Fig. 2. Acoustic meter.

not affect the time circuit. For a one-foot separation between the two fans, an average traversing time of approximately 1×10^{-3} sec will be required.

Estimate of the time response required: assuming all errors to be of the same order, an air temperature of 413°R = T, speed of sound of 1000 ft/sec = a, and where

δa = error in speed of sound,
δt = error in time measurement,
δT = error in temperature indicated,
t = time required for second wave to travel from emitter to receiver (sec), and
$a^2 = KT$.

$$(a + \delta a)^2 = K(T+\delta T) = a^2 + 2\delta a \cdot a + (\delta a)^2$$

$$\frac{a^2 + 2\delta a \cdot a + (\delta a)^2}{a^2} = \frac{K(T+\delta T)}{KT} \quad \text{or}$$

$$1 + \frac{2\delta a}{a} + \frac{(\delta a)^2}{a^2} = 1 + \frac{\delta T}{T}.$$

Neglecting $(\delta a)^2$,

$$\frac{\delta a}{a} = \frac{\delta T}{2T} .$$

Also,

$$at = (a + \delta a)(t + \delta t) = at + \delta a \cdot t + a\delta t + (\delta a\ \delta t) \quad .$$

Neglecting the δa δt terms,

$$at = at + \delta a \cdot t + a\delta t \quad \text{or}$$

$$-\frac{\delta t}{t} = +\frac{\delta a}{a} \quad .$$

From above,

$$\frac{\delta a}{a} = \frac{\delta T}{2T} = -\frac{\delta t}{t} \quad .$$

Now, assuming distance between booms, d, is 1 ft and a δT allowable = .5°C or .9°R,

$$t = \frac{d}{a} = 1 \times 10^{-3} \text{ sec}$$

$$\frac{.9}{2 \cdot 413} = \frac{\delta t}{1 \times 10^{-3}}$$

$$\delta t \cong 1.1 \times 10^{-6} \text{ sec} \quad .$$

Thus, an accuracy of 1 microsecond in the timing circuit for a time interval of approximately 1 millisecond is required to give the desired temperature accuracy.

The times involved do not in themselves present any problems that cannot be solved.

The emitter boom with many emitters (the number can be computed for any desired accuracy) presents rather a formidable picture. A type of continuous emitter would be highly desirable. One alternative to many electrical emitters might be a series of holes along the length of the boom. Weak shocks exhausting from all holes simultaneously would provide a wave front traveling at the speed of sound, under proper conditions.

Another interesting method for measuring sonic speeds involves the tracking of sound waves by radar (Ref. A-4-11). The uniqueness of this method results in the elimination of need for a receiver remote from the source. As described in the reference, this method makes use of the dielectric variation in sound waves, which will reflect an electromagnetic wave. The radar waves, however, utilize the optical effect of a sphere and, on this consideration, the effective range over which the propagated sound wave may be tracked depends on the velocity of the vehicle relative to the air. If the range could be sufficiently extended, the system would be a very desirable one, mainly because it does not require a remote receiver.

One other factor which makes questionable the use of radar to track the sound wave is the very low density at high altitudes. The radar depends on a partial reflection of the electromagnetic wave from the surface of the sound wave due to a change in the dielectric of the air. What information the authors have obtained regarding this technique leads us to conclude that the reflected signal from the sound-wave surface at such low densities would not be sufficiently strong for this radar system to be useful.

Any other speed-of-sound technique considered thus far requires a microphone-type receiver, many varieties of which are available. It is anticipated that because of the low pressure existing near 150,000 ft, considerable difficulty will be encountered in obtaining or developing sufficiently sensitive pressure transducers. Present information indicates that this problem can probably be overcome from sea level to altitudes at least as high as 100,000 ft.

Another factor which must be considered in regard to sound technique is the water-vapor content of the air. A few preliminary calculations indicate that the maximum errors due to a variation in relative humidity between 0 and 100% are approximately:

1. ± 3.5°F at sea level, assuming an average temperature of 60°F and speed of sound of 1120 ft per sec.

2. ± 1°F at 10,000 ft, assuming an average temperature of approximately 25°F and speed of sound of 1080 ft per sec.

3. ± .5°F at 20,000 ft, assuming an average temperature of approximately -10°F and speed of sound of 1040 ft per sec.

4. From 20,000 ft to 100,000 ft expected error less than ± .5°F.

5. Beyond 100,000 ft it is presumed that the humidity is sufficiently low so as to cause little difficulty. Additional information will be obtained regarding average relative humidities at these higher altitudes.

Available information indicates that the variation of γ (ratio of specific heat) and average molecular weight, except for moisture effects, is sufficiently small so as to be negligible.

Conclusion: Although the speed-of-sound technique has limitations and problems, it is still one of the more attractive methods and warrants further consideration. (See Section C-4.)

A-5. Measurement of Infrared Radiation Intensity.—Solar radiations which impinge upon the earth's atmosphere are absorbed and scattered by the atmospheric gases. The gases which absorb solar radiations, in particular, carbon dioxide, water vapor, and ozone, become excited and emit as well as absorb radiations; these radiatively active gases play an important role in atmospheric heat transfer by infrared radiation (Ref. A-5-7).

Consider a radiation-sensitive instrument which measures the intensity of radiant energy impinging upon it from a given field of view or beam (Fig. 3).

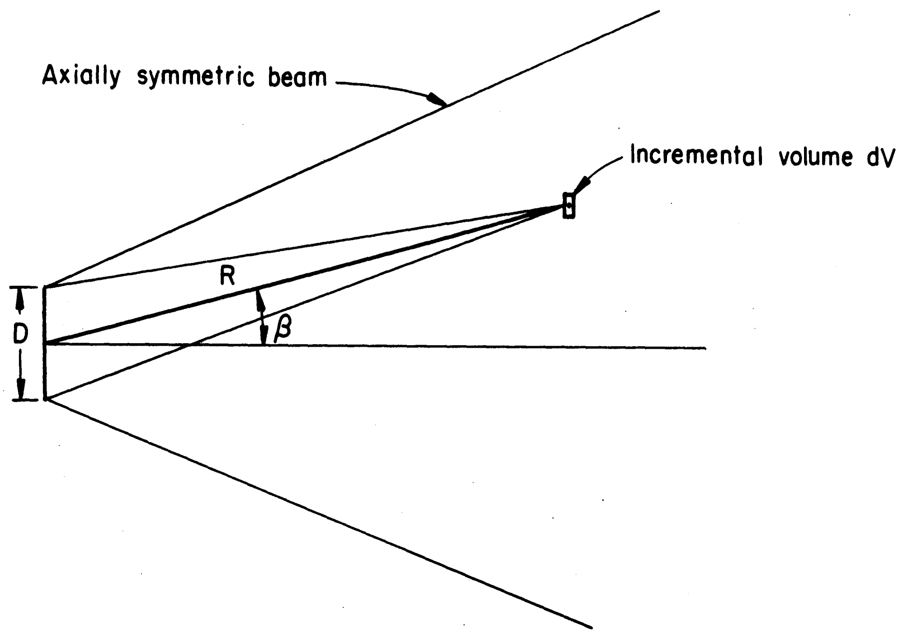

Fig. 3. Geometry of radiating beam.

Every incremental volume within the beam can contribute to the intensity of radiation measured at the collector. If the radiation field is isotropic (i.e., no preferred direction), then the fraction of radiant energy emitted by an incremental volume within the beam which will radiate in a direction so as to intercept the collector will be given by

$$\frac{3}{16}\left(\frac{D\cos\beta}{R}\right)^2 , \tag{1}$$

where D is the diameter of the collector, R is the distance of the incremental volume from the collector, and β is the impingement angle. A portion of that fraction of the radiant energy emitted by the incremental volume which is in the proper direction to intercept the collector will be absorbed by the gases which are in the line of transit. The fraction absorbed will depend on the length of the path, the composition and density along the path, and the frequency of the emitted radiation. If the radiation is essentially monochromatic, then the absorption coefficient is constant and the following expression will be obtained for the incident radiation, I, at the collector from an incremental volume at distance R and inclination β:

$$I(\nu) = \frac{3}{16}\left(\frac{D \cos \beta}{R}\right)^2 I_o(\nu) \sec \beta \exp\left(-k \int_o^R \rho dz\right) , \tag{2}$$

where $I_o(\nu)$ is the radiant energy at frequency ν emitted by the incremental volume and k is the absorption coefficient; ρ is the local gas density and it has been assumed that the atmospheric composition is constant over the path length.

If the atmosphere is assumed to be in local thermal equilibrium, then at each point the emission of radiant energy will be related to the local absolute temperature according to Kirchoff's law

$$I_o(\nu) = B_\nu(T) \rho dV , \tag{3}$$

where k is the absorption coefficient and $B_\nu(T)$ is the Planck function

$$B_\nu(T) = \left(\frac{2 h\nu^3}{c^2}\right)\left(\frac{1}{e^{h\nu/kT} - 1}\right) . \tag{4}$$

The symbol ν is the frequency of radiation and k and h are the Boltzmann and Planck constants, respectively (Ref. A-5-8).

Upon combining Equations 2, 3, and 4, the following expression is found for the radiant energy at frequency ν which impinges upon the collector and is contributed by an incremental volume at distance R and inclination β:

$$I(\nu,R,\beta) = \frac{3}{8}\left(\frac{D \cos \beta}{R}\right)^2 \sec \beta[(h\nu^3/c^2)(\rho dV/e^{h\nu/kT} - 1)] \exp\left(-k \int_o^R \rho dz\right) . \tag{5}$$

The total radiant energy which impinges at the collector will be obtained upon integrating Equation 5 over all volume within the field of view:

$$I(\nu) = \int_{volume} I(\nu,R,\beta) dv . \tag{6}$$

If the composition of the atmosphere, the density, and the absorption coefficient are known, then Equation 6 relates the dependence of the measured radiant energy on the static temperature of the gas within the field of view. If the temperature gradients within that portion of the field of view which contributes significantly to the measured energy are small, then the intensity of radiant energy can be used as an indirect measurement of the local static temperature in the forward field of view. A radiation-sensitive instrument such as a photometer, therefore, could be calibrated as a temperature-measuring device. In practice, however, the dependence of the radiation strength at the collector on the density field in the direction of view is a complicating factor.

Fortunately, however, a temperature-measuring device can be constructed which effectively cancels out the density dependence through utilization of a null measuring technique involving the measurement of the difference between the energy direct from the atmosphere and the energy modified by transmission through a temperature-controlled gas cell (see Ref. A-5-5 for details). The authors of Ref. A-5-5 have considered the design and application of such a device for meteorological research in cloud physics and suggest that a workable though unrefined temperature-measuring photometer-type instrument could be packaged for low-speed flight in a 10-inch cube.

During the next report period the following items will be considered:

1. Determination of the effective path length over which the local static temperature will be averaged, related to the length of beam from which the contribution to the incident radiation at the collector is significant.

2. Consideration of the relative advantages of measuring incident radiation in a water-vapor or carbon-dioxide band; other things being equal, the latter would appear to be more feasible due to the smaller and more predictable variation in carbon-dioxide concentration.

3. Block diagram for a typical bread-board model.

4. Literature search will be expanded, using Ref. A-5-9 as one basic source.

5. If time permits, the influence of a bow shock wave in front of the collector and of scattering by rain drops and/or dust particles will be briefly considered.

Conclusion: At the present stage of study it can only be stated that free-stream static-temperature measurement by means of a calibrated photometer shows promise but that a considerable study and development program will be required.

A-6. Thermal Conductivity.—Here the temperature relationship is

$$\lambda/\lambda_1 = (T/T_1)^n \quad .$$

It is concluded by virtue of the above that the same type of reasoning can be used for thermal-conductivity measurement as was used for viscosity.

Conclusion: Any further consideration of thermal conductivity as a means of determining free-stream temperature should be discarded.

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GROUP B—FUNCTION OF PRESSURE AND TEMPERATURE

B-1. Density.—A direct measurement of density involves determination of the mass of a given volume of the matter under consideration. In an open-flow system involving a compressible fluid, such as the problem under consideration, this is not conceivable It is necessary then to measure properties of the fluid which are influenced by the density and calculated density from these measurements.

Determination of the mean free path would essentially establish density directly, but here again the method is not apparent. The items discussed below are concenred with properties of air which are a function of density.

Conclusion: Direct measurement of free-stream density does not offer any promise for the problem of obtaining free-stream air temperature.

B-2. Electrical Discharge.—The circuit characteristics of electrical discharges in a gas depend in a complicated manner on the following variables: atomic properties of the gas and its impurities; gas pressure, gas temperature, atomic and thermal properties of electrode material, configuration, shape, spacing, and surface condition of the electrodes, electrical circuit through which the discharge current flows, frequency and magnitude of driving sources and relative velocity between electrodes and gas (Ref. B-2-8). The preceding statement applies in particular to a point-to-point electrical discharge. Because of the relation between electrical discharge and relative gas velocity a point-to-point discharge system appears useless for this study. In fact, much work has been done in developing point-to-point electrical-discharge anemometry because of this gas-velocity—electrical-discharge relationship.

The phenomenon of point-to-space discharge, which differs somewhat from point-to-point discharge, has attracted relatively little attention. There are some indications that this type of discharge might be adaptable to air-density measurements (Ref. B-2-3), but very few data of this nature have come to the attention of the authors.

The moisture content of the air apparently has no effect upon the performance of a point-to-space discharge (Ref. 5). From this same reference

$$E_{mc} = A\rho + B\sqrt{\rho/r} \quad ,$$

where

E_{mc} = maximum electric field at surface of conductor when corona first appears (onset voltage),

ρ = density,

r = radius of wire conductor, and

A and B are constants.

An investigation of the properties of a point-to-space discharge has been made (Ref. B-2-2) with regard to its usefulness in discharging the static charge from a subsonic aircraft. Most references pertinent to electrical discharge discuss the variation of discharge current as a function of some variable other than density. In Ref. B-2-2, the steady-state current is shown to be very sensitive to flight velocities up to 200 mph. At this air speed the positive ion drift velocity is stated to be of the same order of magnitude as the air velocity. The hypothesis is offered that as speed is appreciably increased above 200 mph, the saturation point is reached and current will no longer be a function of air velocity. Also, it may be that the onset voltage (i.e., the voltage required to initiate a current) is independent of velocity.

In view of the above it appears that a point-to-space corona discharge may hold some promise as a method for determining air density under the specified flight conditions. Additional information regarding velocity effects in the upper-subsonic and lower-supersonic ranges should be obtained before deciding definitely on this method. Such information may possibly exist in literature which has not yet been located in this study.

Conclusion: The literature search regarding this subject should be continued. It is not evident at this time that the point-to-space discharge system will be suitable for the problem under study.

B-3. Ionizing Radiation.—It is possible to measure air density through the use of ionizing radiation. The following general methods are to be considered:

1. Collection of Ions Produced
2. Absorption of Radiation
3. Back-Scatter of Beta Radiation

Each of these methods is discussed below:

1. Collection of Ions.

The passage of a charged particle or of a photon of gamma or X-radiation through a gas produces ionization of the gas. If the ionized gas is between the plates of a condenser, the ions so produced may be collected by applying a voltage across the condenser. The number of ions formed can then be calculated from the measured change in the charge on the condenser. This principle is used in many devices which measure the absorption of radiation.

For a given type and energy of radiation the ionization produced in a volume of gas is proportional to the density of the gas, provided the average path length of the radiation in the gas is large compared to the dimensions of the volume from which the ions are collected. If the ions produced in the volume are collected, a measure of the gas density should be obtained.

If the gas under consideration is air, an important consideration in the collection of the charge produced by the radiation is the formation of negative ions. The tendency of a neutral atom to attach itself to a free electron produced, for example, by ionization may be described as the attachment coefficient (Ref. B-3-4). A gas with a high attachment coefficient is considered a negative-ion former. Both oxygen and nitrogen are negative-ion formers. The large negative ions move much more slowly than electrons in a collecting electric field. This tends to increase the collection time for the negative charge and may also increase the possibility of recombination. For application to the problem under consideration the condenser plates must be placed in the free stream. The collection of the slow-moving negative ions would then be influenced by the free-stream velocity so that the system would be velocity dependent. These considerations make this method undesirable.

2. Absorption of Radiation.

Absorption of nuclear radiation is dependent only on absorbing matter if composition and thickness of the matter are held constant. This phenomenon could be utilized to measure air density.

For a collimated beam of beta or gamma radiation and a thin absorber, the fraction of radiation transmitted can be approximately described by the following equation

$$I/I_o = e^{-\mu x} , \qquad (1)$$

where

I = intensity transmitted,
I_o = initial intensity,
μ = linear absorption coefficient (1/distance), and
x = absorber thickness (distance).

If Equation 1 is to be used for measurement of air density with the thickness, x, of absorber held constant, it may be written

$$I/I_o = e^{-\mu_1 t} , \qquad (2)$$

where $\mu_1 = (\mu/\rho)$ and is constant for a given composition of air, independent of density, and $t = \rho x$; ρ is the air density. The product ρx thus expresses the mass of absorber interposed into each unit area of the beam of radiation. For a constant x it depends only on the air density.

The change in fraction of intensity transmitted with change in ρ is seen from Equation 2 to depend on ρ. Taking the derivative of Equation 2,

$$d(I/I_O) = \mu_1 e^{-\mu_1 t} dt . \qquad (3)$$

But the quantity $e^{-\mu_1 t}$ decreases with t. Hence, the smaller ρ is, the larger will be the change in intensity per unit change in ρ.

The altitude range under consideration produces a great density change, almost 1 to 1/1000. The change of the fraction transmitted is then a strong function of altitude. Any use of this method would require some type of feed-back circuit which could compensate for altitude. This would have to operate on the most sensitive term in Equation 3 and accurate measurement of temperature seems impractical.

3. Back-Scatter of β Radiation.

A beta particle traveling through matter may have the direction of its path changed due to interaction either with atomic electrons or nuclei. The deflection of the particle is sometimes referred to as scatter. The number of beta particles scattered from air to a given point would be a function of the density of the air. No literature was found on the use of beta back-scatter for air-density measurements nor has it been possible to predict the sensitivity of back-scatter to density change. For this reason a small-scale qualitative experiment was performed. A brief description and a discussion of the results of this experiment are given below.

An initially collimated 10-millicurie strontium-90 source, a halogen-quenched Geiger tube, and a Nuclear Chicago 1615 B count-rate meter were placed on the roof. A schematic diagram of the arrangement of the source and Geiger tube is shown in Fig. 4.

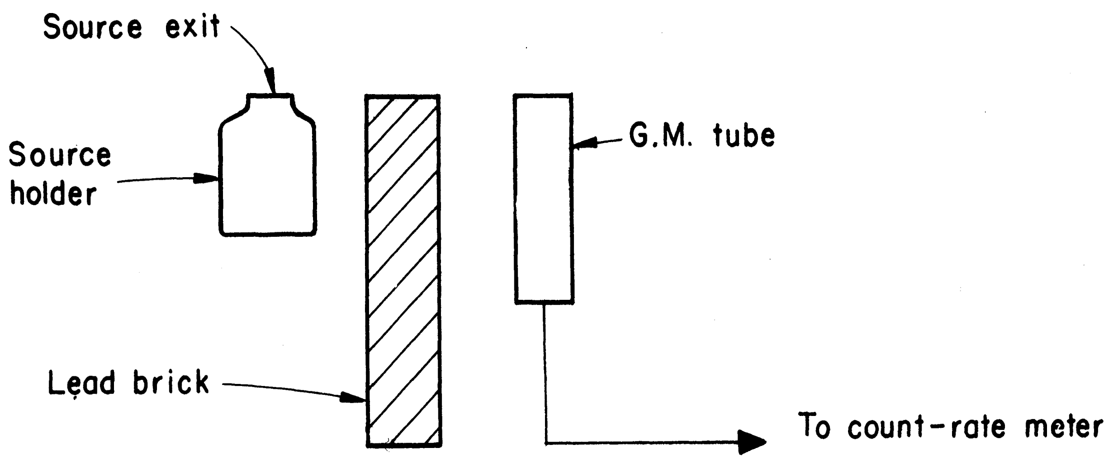


Fig. 4. Beta back-scatter experimental setup.

Care was taken to insure no back-scatter from solid objects and that the GM tube received no direct radiation from the source. The barometric pressure, relative humidity, and temperature were recorded as well as the count rate of beta back-scatter. The background count rate (normal radiation always present in the atmosphere) was established by placing a lead shield over the exit of the source holder and was found to be 30 cpm. It was found that the count rate could be greatly changed by changing the relative angle between the collimated beam of beta rays and the Geiger tube. Since it was not known how much the count rate would vary, and it was undesirable that the meter go off scale, a geometry that gave the lowest count rate was used. To reduce the count rate further, to less than half scale, two pieces of paper were placed over the GM tube window. The experiment was started at 1 p.m. on October 18 and ended at 7 a.m. on October 19.

Results for every hour during the run are tabulated in Table I and the air density is plotted vs counts per minute on Fig. 5.

TABLE I

BACK-SCATTER DATA

Date	Time	T °F	P in. Hg	R.H. %	A.H. lb Water/lb Dry Air	ρ lb/ft^3	CPM
Oct. 18	1 p.m.	66	29.3	54	.0074	.074	530
	2	67	29.3	51	.0074	.0739	530
	3	67	29.3	49	.0068	.0739	530
	4	65	29.3	48	.0063	.0741	555
	5	62	29.3	51	.0057	.0745	590
	6	57	29.3	56	.0051	.0754	620
	7	55	29.4	56	.0051	.0758	630
	8	51	29.4	53	.0043	.0764	670
	9	49	29.4	69	.005	.0767	690
	10	48	29.4	73	.0051	.0769	670
	11	48	29.4	75	.0053	.0769	680
	12	46	29.4	84	.0054	.0772	685
Oct. 19	1 a.m.	45	29.4	84	.0053	.0773	685
	2	44	29.4	82	.005	.0774	685
	3	43	29.4	81	.0047	.0776	700
	4	43	29.4	79	.0044	.0776	700
	5	42	29.4	79	.0043	.0778	690
	6	42	29.5	83	.0047	.0779	690
	7	41	29.5	87	.0047	.0781	690

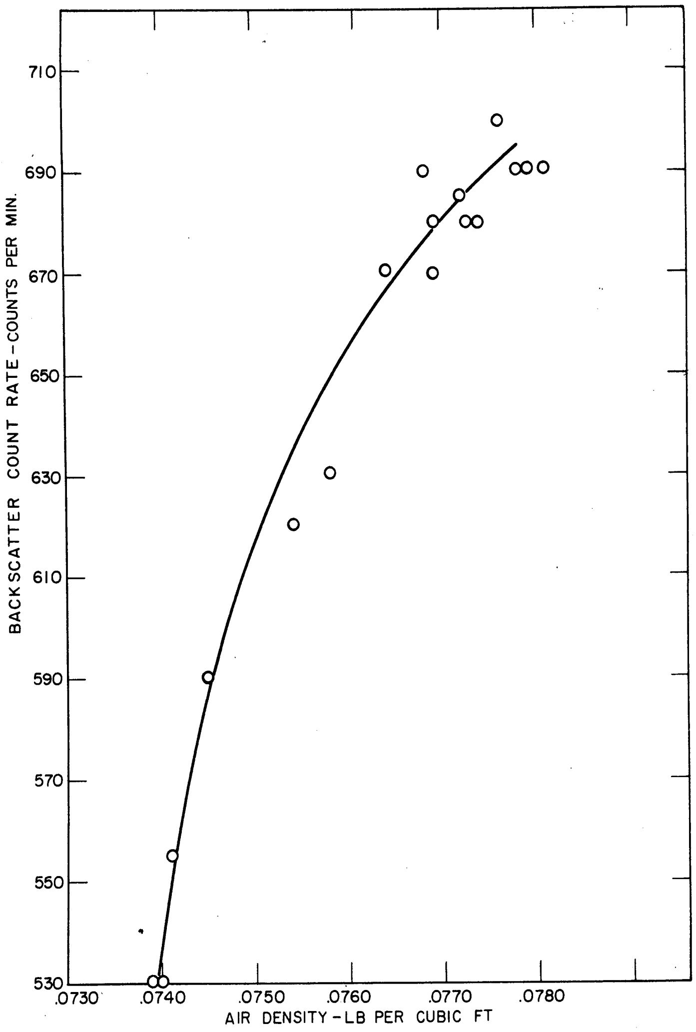


Fig. 5. Back-scatter count rate vs air density.

Although there is scatter in the data, the results are not discouraging. The 25° temperature change shows a count-rate change of 180 counts per minute or about 7 counts per degree Fahrenheit. This represents a 1% change in count rate per degree Fahrenheit. This is a measurable change in count rate. Reduction in the scatter of the data could be brought about by

1. increasing the count rate appreciably and
2. integrating and averaging the count rate over some time period such as one second.

Another possible improvement would be to measure the energy back scattered instead of the number of particles. Also, this might result in less instrumentation. Some scatter of the data also probably results from the meteorological data taken. In attempting to keep the experiment simple and quick, some accuracy was sacrificed.

The effect of humidity on beta back-scatter would be expected to be negligible. The back-scatter is determined by the electron density of the air.

Since N_2 has an atomic number of 14, O_2 16, and H_2O 18, the electron density is not greatly affected by addition of water vapor. Humidity changes have a negligible effect upon density. Dust in the air, solid objects, and water droplets in the vicinity of the source and detector are likely to produce the greatest error.

It should be pointed out that it would not be necessary to employ hazardous quantities of radiation for this determination.

Conclusion: The Collection of Ions Produced and the Absorption of Radiation are impractical techniques. The Beta Back-Scatter technique warrants further study.

B-4. Index of Refraction.—The index of refraction of electromagnetic radiation in air is related to the air density and to some extent to the wavelength of the light. The index of refraction of air at 0°C and 760-mm pressure is 1.0002926. This number is only slightly greater than k, the index of refraction in a vacuum (by definition). The index of refraction in air will change only slightly as a result of the small changes in density resulting from temperature changes of a few degrees. The interferometer is the only tool that we know of that is capable of measuring these small changes in index of refraction. No detailed discussion of the interferometer will be attempted here, but some of the problems in the use of it will be discussed. The interferometer requires the use of two light paths, one in the free stream and one through a standard cell. This would require a standard path that must be maintained in its initial state to a high degree of accuracy. Windows would be necessary for the free-stream path, so compensating windows would be needed in the standard path. These windows must produce exactly the same ambient of retardation, which would mean they would have to be at the same temperature. Boundary-layer formation on the windows in the free-stream path would produce a greater change in the light path than some temperature changes. These problems alone seem to rule out the use of an interferometer. There are actually other problems, such as keeping it lined up and in adjustment and the scale problem of following a fringe shift. The great change in density due to altitude would mean a large-scale deflection which would have to be followed, so the change in density due to a small change in temperature may not be detected.

Conclusion: Measurement of index of refraction appears to be impractical for the objectives of this contract.

B-5. Absorption of Electromagnetic Waves.—The absorption of electromagnetic radiation by a gas may be given by the following equation:

$$I/I_0 = e^{-\mu x} , \qquad (1)$$

where

I_O = intensity emitted,
I = intensity received,
x = distance between transmitter and receiver, and
μ = absorption coefficient.

The absorption coefficient, μ, is a function of the nature of the gas, gas density, and wavelength of radiation being absorbed. If we consider absorption of a particular wavelength or band of wavelengths by a particular component of the air, then the absorption coefficient will be mainly a function of the number of absorbing particles in the air, which is proportional to the air density.

Let us consider an instrument consisting of a transmitter which radiates a known wavelength of radiation located at a known distance from a radiation receiver. Then

$$c = z\rho \quad ,$$

where

c = concentration of absorbing component,
ρ = air density, and
z = fraction of absorbing component in air.

Assuming

$$\mu = cf(\lambda) = z\rho f(\lambda)$$

$$I/I_O = e^{-\rho xzf(\lambda)}$$

$$\ell n\, I - \ell n\, I_O = -\rho xzf(\lambda)$$

$$\rho = \frac{(\ell n\, I_O - \ell n\, I)}{xzf(\lambda)} \quad .$$

That is, at constant x, z, λ, and I_O, ρ is a function only of the intensity received at the receiver.

At least two systems are visualized to obtain temperature from the above analysis.

1. Direct Measurement of Electromagnetic Absorption.

A possible system is shown in Fig. 6. This system has the following disadvantages:

a. If I is very close to I_O, it must be possible to regulate very closely the intensity put out by the transmitter. Also, it must be possible to detect

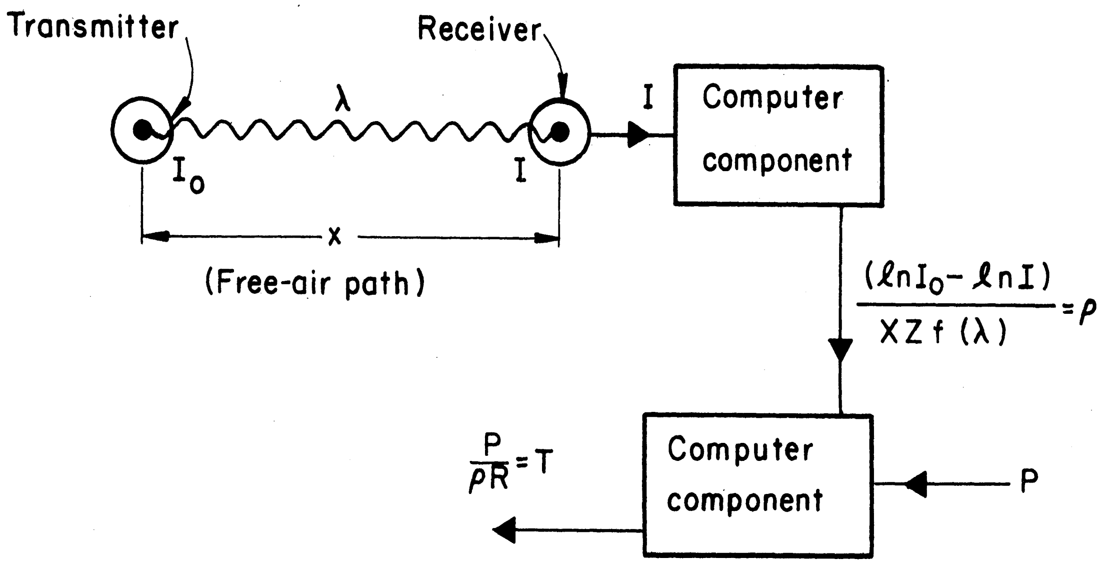


Fig. 6. Direct measurement of unabsorbed radiation.

the received intensity to a very high degree of accruacy.

b. Computers are necessary to convert the receiver output to ρ, which must then be divided into P to obtain T.

c. Change in absorptivity is a function of the absolute value of density as well as the change in density. This is discussed more fully in the section on ionizing radiation, absorption of radiation (Group B-3, above).

2. Alternate Path - Intensity Difference Measurement.

A possible system is shown in Fig. 7. In this system, light from a common source would fall on two receivers, each the same distance from the transmitter. One receiver is in the air stream, the other is in a chamber. A window of the same thickness as the one in the chamber is placed between the transmitter and the outside receiver to compensate for intensity loss. A null system is used with inputs received from the two detectors. If the density in the chamber equals the density outside, the null galvanometer will register zero and no action takes place. The temperature inside the chamber and the pressure inside and outside the chamber are measured. Then,

$$T_o = T_i \, P_o / P_i \, .$$

If the density in the chamber does not equal the density outside, a servo motor in the null system may operate a value on the chamber, regulating its pressure until the null system registers a zero density difference.

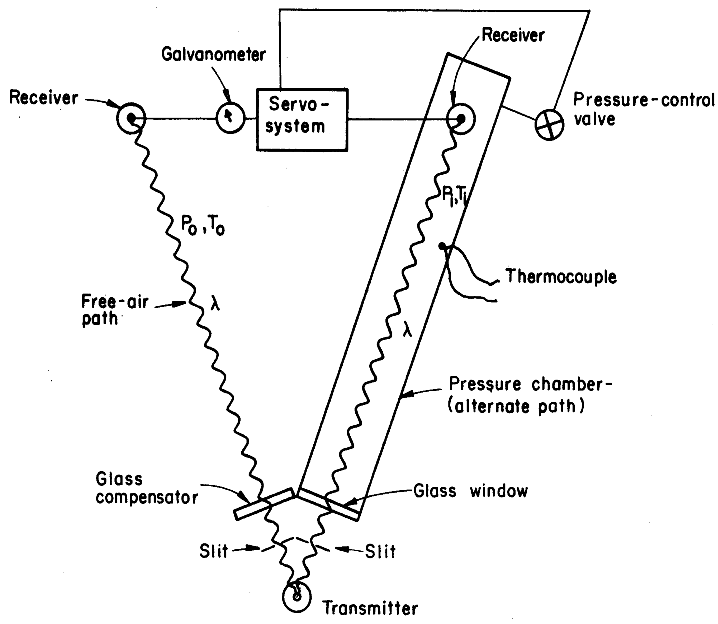


Fig. 7. Alternate path - nullification of intensity difference.

This system has the following disadvantages:

a. The servo system required may be bulky.
b. The response of the mechanical system may be too slow.
c. It will be very difficult to obtain a glass-window compensator identical in absorbing qualities to the chamber window.
d. Computers are still necessary to do the $T_i \; P_o/P_i$ operation .

Other variations of these ideas may be developed. The main disadvantage of any of these systems is the possibility that the fraction of light absorbed may be so small that slight instrumental imperfections may completely overshadow the quantity being measured. Some data on the absorptive properties of the various components of air as a function of radiation wavelength will be necessary before the feasibility of this method may be completely evaluated.

Another disadvantage of any system employing absorption of electromagnetic radiation is its humidity dependence. In fact, in recent years it has been utilized to measure rapid changes of air humidity (Ref. B-5-1).

Conclusion: It appears that the accuracy required by the terms of the contract would not be obtainable by these methods.

General Discussion of Temperature Determination Through Density Measurements.—At this point it seems proper to point out some of the problems in obtaining temperature from density measurements which would be applicable to all density-measurement methods. The first thing that becomes apparent is that the density varies by a factor of 1/760 in the altitude range under consideration. Pressure varies similarly. This immediately poses scale problems for both pressure and density measurements at various altitudes. It becomes necessary then for any instrument with a continuous linear response to be accurate to about 1/1000% at sea level in order to maintain a 1% accuracy at the maximum altitude. The recording or indicating scale used would thus need to be a logarithmic scale, or a device which shifts scales automatically at various altitudes would be required.

Another source of difficulty arises in applying the ideal-gas law. The assumption that the molecular weight of the gas remains constant is not absolutely valid. While humidity changes do not affect the density of the air significantly, changes in molecular weight do occur, particularly at low altitudes. Assuming that the molecular weight of dry air at 100°F and sea level is 29, then the molecular weight for 100°F and 99% relative humidity at sea level would be 27. This represents a 6% error in molecular weight and then a 6% error in temperature calculated from the ideal-gas law, assuming constant molecular weight. This represents a rather extreme condition at sea level. At higher altitudes the absolute humidity decreases appreciably, reducing the error considerably. It is doubtful that the error would ever exceed 1% at altitudes much above 10,000 ft (unless high humidities exist above 100,000 ft).

A computer would be required to perform the division of pressure by density. This requires the use of a servomechanism. This entire discussion is based on the assumption that static pressure can be measured with sufficient accuracy by existing equipment.

GROUP C—MISCELLANEOUS

<u>C-1.</u> <u>Combinations of Enthalpy, Entropy, and Thermodynamic Processes</u>.— The enthalpy or entropy of any given gaseous system cannot be determined without either employing some type of thermodynamic process, such as heat addition, or determining the state of the gas. In this latter case, if the state is known, the temperature is known; thus, it would not be necessary to measure enthalpy or entropy in order to determine temperature.

The total or stagnation probe involves one type of thermodynamic process, i.e., the nonisentropic but adiabatic compression of the air by virtue of its deceleration. In this case the extent of departure from a reversible process does not need to be either constant or known since the total temperature is independent of the adiabatic efficiency.

Some such thermodynamic process as the following would be useful:

1. Decelerate the free-stream air by a reversible adiabatic compression.

2. Expand the air isentropically to the free-stream static pressure by the removal of work.

3. Measure the air temperature after expansion. This would be the same temperature as the true free-stream air temperature.

Obviously, the difficulty here is the fact that such compressions and expansions cannot be expected to be perfectly reversible. In spite of the fact that the adiabatic efficiency will not be 100%, such a scheme might still be feasible if the efficiency of all parts of the process were known at all operating conditions. This, however, seems very unlikely in view of all the complications related to supersonic diffusers and expansion turbines when operating over a wide range of Mach numbers and densities. It is apparent that this type of system includes all the problems related to a Pitot-static-probe—total-temperature-probe combination without the simplicity of that system.

The vortex tube is another method which involves a thermodynamic process. In this case the process is not precisely defined and relative performance improvements are obtained largely by empirical approaches (Ref. C-2-1).

The use of some such thermodynamic process as discussed above does not appear impossible, but it is evident that such techniques as have been considered thus far have many inherent inaccuracies. The thermodynamic process as employed by the total-temperature probe appears more suitable than any other type considered.

Conclusion: Other than the exceptions discussed elsewhere in this report, techniques making use of combinations of enthalpy, entropy, and thermodynamic processes (involving measurable state changes of the surrounding air) do not appear to offer workable solutions to the problem of measuring free-stream air temperature.

C-2. Vortex Tube.—The vortex tube has been shown to be a useful tool in determining true free-stream air temperature, although it may be limited to low supersonic speeds.

The contract statement covering this work, however, specifically excludes the vortex tube from consideration.

Conclusion: The vortex tube is not within the scope of this study.

C-3. Stagnation Temperature Combined with Mach Number.—This system of obtaining air temperature has many desirable features. One objectionable feature is the reduced recovery factor of the stagnation probe at altitudes above 100,000 ft (Ref. C-3-5).

Conclusion: This system is also, by the contract work statement, beyond the scope of this study.

C-4. True Air Speed Combined with Mach Number and/or Speed of Sound.—In certain rocket test flights the flight velocity is determined at all times by continual radar observation. If the local wind can be assumed to have a negligible velocity, the rocket velocity together with Mach number yields the speed of sound and thus the ambient-air temperature. The Mach number can be determined by Pitot-static measurements, by measuring shock angles at supersonic speeds, etc.

It has been assumed throughout this study that information regarding true air speed would not be available from some source outside the vehicle.

Some of the techniques which have been considered for measuring true air speed from the vehicle itself are:

1. Acceleration integrators
2. Electrical discharge
3. Ions as tracers

1. Acceleration Integrators.

An acceleration integrator acting along the longitudinal axis of the vehicle would provide instantaneous velocity readings by integrating the acceleration from initial conditions of zero velocity to the current instant. More than one acceleration integrator might be required, but the longitudinal one alone should be adequate except for large angles of yaw or attack. It should also be noted that the single longitudinal acceleration integrator could be rigidly attached to the plane and would not require a gyro-stabilized platform or additional components, such as would be required by automatic navigation systems. The components could thus be relatively light and simple.

Assuming that Mach number information would be available at all times from the Pitot-static system, the speed of sound and thus temperature would be easily computable if true air speed were known.

Two immediate questions arise in regard to the use of such a system.

a. Moisture content of air. This problem is discussed in A-4 above.

b. Local winds. The acceleration integrator would provide the longitudinal velocity relative to the point of departure, and any local air velocity relative to that point would not affect the velocity indicated by the inertial system. Obviously, a low-speed aircraft flying with or against the "Jet Stream" would result in a very great error if the acceleration integrator were used. At higher speeds and under most atmospheric conditions this error may be tolerable. The acceptability of this system depends, therefore, to a great extent on the particular operating conditions to be encountered. Since the operating conditions specified for this study include flight Mach numbers as low as 0.3, the acceleration integrator does not appear acceptable.

It appears very likely that, because of other operational advantages accruing from the use of acceleration integrators, they may soon become standard equipment on many aircraft. If the velocity of the vehicle is given, the use of $M = V/\sqrt{\gamma gRT}$ appears to be a very practical and economic method of determining air temperature.

2. Electrical Discharge.

Some use has been made of the electrical-discharge current as a velocity indicator (Ref. 3). The information available deals mainly with tests conducted at relatively low subsonic speeds and there is little to indicate that electric-discharge anemometry would be useful at transsonic or higher speeds. Its use is particularly questionable in view of the effect of density and water vapor on electric discharges.

3. Ions as Tracers.

One way in which ion tracers can be used to indicate flight velocity is the ionization of a small isolated region of air as it passes a particular point in space. The time required for the ion cloud to reach some other point in space—the second point being at a known distance downstream of the first point—determines the air velocity (Ref. 3). Little information is available regarding the development of this technique, but it appears to be very promising.

A system is conceivable which involves the use of both ion tracers and speed-of-sound measurement. A schematic of this system is shown in Fig. 8.

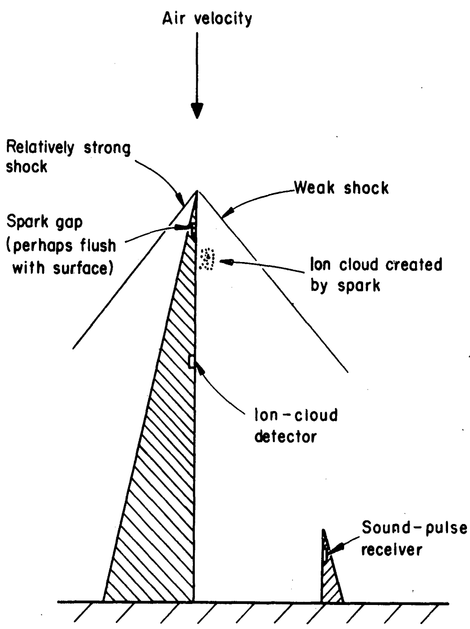
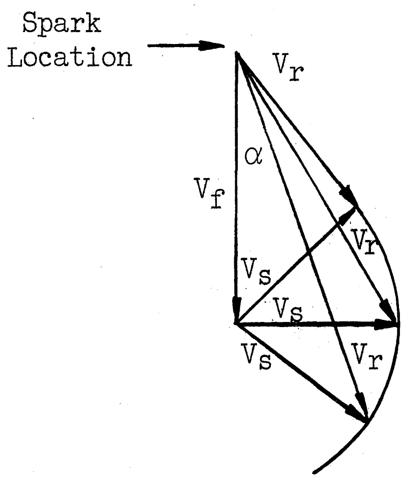


Fig. 8. Flight velocity and speed-of-sound probe measurement.

Any one of the vector diagrams below could describe this situation as regards relative air velocity and velocity of sound.



V_f = flight velocity

V_s = speed of sound

V_r = a resultant velocity

Note: when $V_f = 0$; $V_s = V_r$

Now, if the microphone and the spark are fixed relative to each other and separated by a distance = C ft,

$$C = V_r t_s ,$$

where t_s = time required for sound wave to reach the microphone, sec.

By the cosine law,

$$V_s^2 = V_f^2 + V_r^2 - 2 V_f V_r \cos \alpha .$$

But α is fixed for a fixed geometry. Multiplying through by t_s^2,

$$V_s^2 t_s^2 = V_f^2 t_s^2 + V_r^2 t_s^2 - 2 t_s V_f V_r t_s \cos \alpha$$

or

$$V_s^2 t_s^2 = V_f^2 t_s^2 + C^2 - 2 t_s V_f C \cos \alpha .$$

Let

$$K_1 = C^2 \text{ and } K_2 = 2 C \cos \alpha ,$$

then

$$V_s^2 t_s^2 = V_f^2 t_s^2 + K_1 - K_2 V_f t_s .$$

Now, using the information available from the ion-tracer technique, where t_i = time between the formation of the ion cloud at the spark gap and its arrival at the ion sensor, and d = the fixed distance between the spark and ion sensor,

$$V_f = d/t_i .$$

The overall equation now becomes

$$V_s^2 \, t_s^2 = \frac{d^2}{t_i^2} t_s^2 + K_1 - K_2 \, d \, \frac{t_s}{t_i}$$

or

$$V_s^2 = \frac{d^2}{t_i^2} + \frac{K_1}{t_s^2} - \frac{K_2 d}{t_i \, t_s} .$$

V_s can be computed from the above, provided t_i and t_s are measured. By proper design, t_i and t_s would always be of the same order over a reasonable flight-velocity range. Thus all terms in the above equation will also be of the same order.

With this technique the speed of sound, V_s, and hence the air temperature; the true air speed, and hence the flight Mach number; can be computed.

Now,

$$V_s^2 = \gamma gRT , \quad \text{thus} \quad T = V_s^2/K_4 .$$

It should be noted that the above discussion deals with the general case of the ion-tracer—speed-of-sound technique. One modification of this general system would be to locate the sound-pulse receiver directly downstream of the ion source. The computing process would thus be considerably simplified since speed of sound would be proportional to the difference of the reciprocals of sound-pulse travel time and ion-cloud travel time. One probable difficulty of this particular system would be the boundary-layer effect on the speed of sound.

Such a scheme as the above has several inherent problems:

a. A spark discharge creates a pressure pulse which is appreciably stronger than a sound wave and will travel at a speed greater than the speed of sound. This situation is eliminated under some conditions in about 2 centimeters (Ref. 3), after which the transmission velocity of the pressure wave is essentially equal to the speed of sound. The correction necessary because of this initial condition can be made smaller by the use of relatively long paths.

b. The intensity of a sound wave at altitudes approaching 150,000 ft is very weak because of the low density. It is anticipated that considerable difficulty will be encountered in obtaining or developing a microphone of sufficient sensitivity for this application.

c. The cloud of ions created must, at least in the main, travel at the free-stream velocity. Hence, at least part of the ion cloud must exist outside the boundary layer. It should be noted that the ions can be sensed by the ion detector without actual contact between the ions and the detector. Some configuration could probably be conceived which would tend to counteract boundary-layer effect.

d. The spark discharge may be objectionable because of radio interferences. Some alternate type of ion-pressure pulse generator could perhaps be devised.

Conclusions: Regarding the use of techniques involving true air speed and Mach number:

1. This type of technique in general appears attractive.
2. The use of electrical-discharge anemometry does not appear feasible.
3. The use of an acceleration integrator would make a relatively simple system which should be very good, but such a system would have great errors inherent at low flight speeds and high winds. If the acceleration integrators are already in use on the vehicle for other purposes, their applicability to this problem at the higher flight speeds should be further considered.
4. In spite of the problems, the combined ion-tracer and acoustic system is very attractive and would supply valuable information in addition to air temperature.

C-5. Two-Temperature Method.—A method of determining static temperature has been devised by the Rockefeller Institute for Medical Research, which employs two conical bodies with different orientation relative to the flow. This technique utilizes the temperatures at the bases of the two cones, one temperature being total temperature, the other an undefined temperature. The main problem of this technique is to find a relationship between the two temperatures which eliminates the velocity effect and provides the static temperature.

Apparently such a relationship can be empirically found at subsonic speeds, but no references have been found regarding this technique for supersonic speeds. A strictly theoretical relationship between the two temperatures is apparently difficult to derive.

Conclusion: In the absence of additional data, this technique does not appear sufficiently promising to warrant further attention. However, the literature search will be continued in order to determine if any other information is available which might make this or some other type of dual-temperature system feasible.

GENERAL SUMMARY OF CONCLUSIONS

I. The following techniques or parameters suggested for use in obtaining true free-stream air temperature under conditions specified are considered either impractical for the present state of the art or specifically excluded by the terms of Contract AF 33(616)-3630, which covers this work.

A-1	$(V_m^2)_{avg}$ - i.e., essentially random molecular kinetic energy
A-3	Viscosity
A-6	Air conductivity
B-1	Density - direct measurement
B-4	Index of refraction
C-1	Thermodynamic processes, involving a combination of enthalpy and entropy
C-2	Vortex thermometers
C-3	Stagnation thermometer
C-4-2	Electrical-discharge anemometer combined with Mach number indicator
C-5	Dual-temperature method.

II. The following techniques might be useful in obtaining true free-stream temperatures, but in the absence of additional information they are considered to be relatively unfeasible.

B-2	Electrical discharge, used to determine density
B-5	Absorption of electromagnetic waves
C-4-1	Acceleration integration combined with Mach numbers.

III. The following techniques for measuring true free-stream temperature are considered promising, or at least worthy of further study.

A-2	Very small probe
A-4	Speed of sound
A-5	Intensity of an emission spectral line (infrared)
B-3	Ionizing radiation
C-4-3	Ion tracer and speed of sound

CONCLUDING REMARKS

Each of the techniques considered for measuring true free-stream air temperature has been evaluated in terms of its ability to produce the information desired under the conditions and restrictions outlined in Exhibit "A" to Contract AF 33(616)-3630. In the discussion of these techniques specific reference was usually not made to each of the requirements listed in Exhibit "A," but the anticipated ability of each technique to meet these requirements entered into the conclusions.

Although several methods for determining true free-stream air temperature appear feasible, none stands out as being exceedingly superior by virtue of its greater simplicity and accuracy. This conclusion would be expected since the problem of measuring free-stream temperature under conditions such as those considered herein has already received a great deal of study without producing as satisfactory a system as desired.

The following statements are made in an attempt to summarize briefly the relative merits of those techniques considered most feasible.

1. The very small probe (A-2) is one of the simpler techniques considered, but it is not yet evident that it will provide sufficient accuracy.

2. The intensity of an emission spectral line (A-5, infrared) is promising, but it will probably require a rather large amount of equipment in order to give satisfactory results. The variable and, in some cases, perhaps long path length may present a problem under certain flight conditions.

3. The beta—back-scatter technique (B-3) in itself is fairly simple. The wide ranges of density and pressure are inherent disadvantages. Additional information is required regarding this technique.

4. The speed-of-sound technique (A-4) involves considerable complications but may be one of the more desirable systems considered. The combinations of ion tracer and speed of sound (C-4-3) should be especially useful in that both true air speed and air temperature would be indicated. Flight Mach number could also be computed from this system rather than from a Pitot-static system if desired.

PROPOSED FUTURE PLANS

1. Continue to review in general any pertinent literature which has not yet come to our attention. (It is anticipated that additional ASTIA reports will be received.) It may well be that some of the conclusions drawn in this report will require altering as additional information becomes available.

2. In particular, a search will be made for additional information regarding the dependence of a point-to-space electrical discharge on density and relative air velocity (above $M = 0.3$).

3. The mathematical analysis of the use of a technique for measuring the intensity of an emission spectral line (infrared) will be continued.

4. Conduct a few preliminary experiments with a very fine probe in order to evaluate the possibilities of obtaining a recovery factor approaching zero.

5. Continue a general study of the more attractive methods listed above until one or more particular methods are settled upon by the contracting officer for this contract.

APPENDIX

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The following have been reviewed in the course of this study and have various degrees of relevance to the problem of static temperature measurements from a high-speed aircraft. Only a small number of the reports listed are specifically referred to in the text. The arrangement by sections (A-1, A-2, etc.) coincides with the arrangement of material in the foregoing text.

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Contract No. AF 33(616)-3630
Interim Report, November, 1956
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Page		Correct from	to
5	(Fig. 1)	$M > 71$	$M > 1$ (in 2 places)
8	(Fig. 2)	$M > 71$	$M > 1$
	top line	fans	planes
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16 1st line under item 2 - insert ahead of absorbing - "the density of the"