24 August 1965

National Aeronautics and Space Administration
Office of Advanced Research and Technology
Washington, D. C. 20546

Attention: Chief, Physics of Fluids Branch/Code RRP

Gentlemen:

Subject: Quarterly Progress Report
Contract NASW-1188

Transmitted herewith in accordance with the provisions of Article III to the Contract are two (2) copies of Avco's First Quarterly Progress Report under Contract NASW-1188 covering the period 29 April 1965 through 28 July 1965.

Very truly yours,

AVCO CORPORATION
Research and Advanced Development Division

Robert Lemay
Contract Administrator

RL:ms

Attachments (2)

cc: NASA/Washington, D. C. (1)
Office of Technology Utilization
Att'n: New Technology Representative/Code ATU

NASA/Post Office Box 5700, Bethesda, Maryland (2)
Att'n: Representative/Contract NASW-1188
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EVALUATION OF HIGH-TEMPERATURE GAS TRANSPORT PROPERTIES

First Quarterly Progress Report
29 April 1965 through 28 July 1965

Prepared by
RESEARCH AND ADVANCED DEVELOPMENT DIVISION
AVCO CORPORATION
Wilmington, Massachusetts

RAD-SR-65-190
Contract NASw-1188

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
RESEARCH DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
Washington, D.C.
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16 August 1965

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

Arc column temperature distributions and voltage gradients have been determined in nitrogen for various arc currents at pressures of 0.5, 1, and 2 atmospheres. These data have been analyzed to determine thermal conductivity as a function of temperature by integrating the Elenbaas-Heller equation. The thermal conductivities were found to have an anomalous dependence upon the ambient pressure of the arc column and upon the arc current. It is postulated that these effects may be attributed to radiative losses, particularly in the far ultraviolet. Significantly better agreement is obtained between the experimental and theoretical thermal conductivities when these radiative losses are included in the energy balance.
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I. INTRODUCTION

A. PROGRAM OBJECTIVES

The objectives of this program -- Evaluation of High Temperature Gas Transport Properties -- are:

1. To investigate the discrepancy between theoretical and experimental values of the thermal conductivity of nitrogen at high temperature and when, or if, the discrepancy is resolved.

2. To determine the electrical and thermal conductivity coefficients as functions of temperature for air and oxygen at several pressures in the temperature range of 8000° to 15,000°K. (Efforts will be made to extend the range of transport property determination to 20,000°K.)

B. PROGRAM ORGANIZATION

This program is being carried out under the sponsorship of the Research Division, Office of Advanced Research and Technology, National Aeronautics and Space Administration, under the technical supervision of Mr. Alfred Gessow, Chief of the Physics of Fluids Program. The Avco RAD Project Director is Dr. Stewart Bennett, and Dr. C. F. Knopp is Project Engineer.

Theoretical calculations for the thermal and electrical conductivity of nitrogen at various pressures were performed by Dr. J. M. Yos. Mr. R. W. Liebermann carried out the theoretical predictions for the radiation, based upon experimental data supplied by Mr. J. M. Morris.

C. TECHNICAL SUMMARY

During the previous (first) year of this program, major effort was devoted to establishing the wall-stabilized arc as a standard tool for experimental determination of transport properties of high-temperature gases, and to the development of analytical techniques for the calculation of the transport properties, particularly thermal conductivity of gases at high temperature. Both argon and nitrogen were examined during this initial year. It was found that the experimentally determined thermal conductivity for argon agreed to within approximately 40 percent with analytical predictions. In view of the fact that ultraviolet radiation losses were not included in the energy balance for the argon column, the agreement is considered to be satisfactory. As a consequence, it is felt that a wall-stabilized arc is a suitable experimental tool for the determination of the thermal conductivity of high-temperature gases.
The experimental results reported for nitrogen in the previous year's effort agree substantially with results reported by other investigators. These results, which do not include the effect of ultraviolet radiative losses, lead to a value for thermal conductivity an order of magnitude larger than theoretical predictions in the neighborhood of 14,000°K. It was determined that the disagreement between theory and experiment should be resolved prior to proceeding with experimental measurements in nitrogen at higher temperatures. In an effort to explain this discrepancy, the best available analytical estimates for ultraviolet radiation were included in the energy balance for the nitrogen arc column. It was demonstrated that inclusion of this estimated ultraviolet radiation as a mechanism for energy transport produced satisfactory agreement between experiment and theory, indicating the strong possibility that radiative heat transfer is a major factor.

While the ultraviolet radiation from high-temperature nitrogen was calculated using the best available analytical prediction, the results are not felt to be quantitatively correct. There is at present a parallel experimental investigation being conducted at this laboratory to make quantitative measurements of this radiation. Pending the results of this investigation, an alternate method of evaluating the effect of ultraviolet radiation upon the measurement of thermal conductivity has been followed. This approach relies upon the fact that both the thermal and electrical conductivities of high-temperature nitrogen are insensitive to pressure, while radiation is a strong function of pressure. Thermal conductivity measurements have been made in nitrogen at 0.5 and 2 atmospheres, in addition to the data at 1 atmosphere reported previously. For the 0.5 and 1 atmosphere cases, data were obtained in the temperature range of 8500 to approximately 14,000°K, while the upper temperature for the 2-atmosphere data was limited to about 13,000°K. Thermal conductivity values were deduced from the Elenbaas-Heller equation assuming no radiative losses. Under this assumption, it was found that the experimentally measured thermal conductivity decreased approximately as the particle density over the factor of 4 change in the ambient pressure. Conversely, theory predicts that, for the temperature range where disagreement exists between experiment and theory, the thermal conductivity should increase slightly as the particle density decreases.

Solutions of the Elenbaas-Heller equation were also obtained using the radiation data of Morris, et al. These data, which include estimates of the ultraviolet radiation, are felt to be the most reliable now available. The Elenbaas-Heller equation was solved under the assumption that all of the arc column is transparent to radiation of all wavelengths. Although it is recognized that this assumption is not valid, particularly for the ultraviolet, it is felt that such an approach has the advantage of providing trends in a straightforward manner.

*This work is being performed under contract AF33 (615) - 2967 for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force.*
For the pressures investigated, the inclusion of radiative energy transfer has the effect of bringing the experimental data into much better agreement with theory. Further, it demonstrates that it is necessary to postulate a phenomenon, such as radiation, which is temperature-dependent as well as pressure-dependent, to remove the discrepancy between theory and experiment, as well as the apparent dependence of the thermal conductivity upon arc current.
II. EXPERIMENTAL INVESTIGATION OF THE THERMAL CONDUCTIVITY OF NITROGEN

A. EXPERIMENTAL APPARATUS

The constricted arc facility used in obtaining a nitrogen arc column at 0.5 and 2 atmospheres is the same as that used in the previous investigation of atmospheric pressure nitrogen. This facility was described in detail in reference 1. Initially, some difficulty was experienced in obtaining a stable arc at 2 atmospheres. This instability was traced to several small leaks in the system, the arc operating in a very stable mode when the leaks were eliminated. Little difficulty was encountered in operating subsequently at 0.5 atmosphere. At each pressure, the cathode and anode of the arc are blanketed in argon to prevent the electrode erosion characteristic of high-current nitrogen arcs. Prior to each set of measurements, the flow rates of argon and nitrogen are adjusted such that there is no argon observed spectroscopically in the portion of the arc column used for the measurements.

The correct pressure in the arc column is maintained with a needle valve located upstream of a mechanical vacuum pump in the case of the 0.5-atmosphere runs, and by a needle valve exhausting to atmosphere for the 2-atmosphere tests. The pressure is monitored on a differential manometer which can be read to 1 mm Hg. This gives an accuracy of approximately ± 3 percent for the 0.5-atmosphere case and ± 1.5 percent for the 2-atmosphere case. In all cases, ambient atmospheric pressure was very close to the nominal value. No fluctuations in pressure were discernible during any of the runs at either pressure.

A 0.75-meter, f/10 grating monochromator, employing a Czerny-Turner mounting, is used to obtain the spectroscopic measurements necessary for the determination of the radial temperature distribution within the arc column. The radiation detector is an EMI type 6255B photomultiplier. The image of the arc column is focussed upon the entrance slit of the monochromator by an imaging lens which is apertured to alleviate distortion and to provide a large depth of field. The f-number of the optical system is approximately f/70, providing a depth of field sufficient to ensure that both the front and back of the arc column are in focus. This is a necessary criterion, since the monochromator must measure accurately the radiation enclosed within an optical path through the column to obtain meaningful radial intensity distributions from the measured intensity distributions. Spatial resolution is approximately 0.2 mm along the axis of the column and approximately 0.05 mm perpendicular to the axis. This resolution is sufficiently fine to measure the large gradients in intensity across the diameter of the arc column.

Calibration of the detection, recording, and optical system is provided by an NBS tungsten standard lamp located at the same position relative to the optical system as that normally occupied by the arc facility.
B. SPECTROSCOPIC TECHNIQUES

The basic variable determined experimentally in this study is the temperature of the plasma column.

The basis of all spectroscopic determination of temperature is that the measured quantity (radiation intensity) is determined by two variables of state of the gas (temperature and number density of the radiating species):

\[ I_i = I_i(n_i, T) \]

where \( I_i \) is the radiative intensity emanating from the number density \( n_i \) of particles of type \( i \) at a temperature \( T \). For a gas in equilibrium at a given pressure, the species number densities are related to temperature by the laws of statistical thermodynamics. When this relationship is taken into consideration, equation (1) reduces to:

\[ I_i = I_i(T) \]

and a measurement of \( I_i \) then determines the value of the temperature \( T \) for a known pressure.

The absolute radiant intensity of a spectral line which is emitted spontaneously per unit solid angle by a unit volume of the plasma is given by:

\[ I_{mn} = \frac{1}{4\pi} \frac{A^n_{m} h \nu_{mn} n_a \xi_m}{Q_a} \exp\left(-\frac{E_m}{kT}\right) \]

where \( A^n_{m} \) is the spontaneous transition probability for a transition from the upper energy state \( m \) to the lower energy state \( n \); to the total number of atoms \( n_a \); to the energy of the light quanta \( h \nu_{mn} \) (\( \nu_{mn} \) = frequency of emitted light); to the statistical weight of the upper state \( \xi_m \) having an energy \( E_m \); and to the partition function of the atom, \( Q_a \). Equation (3) may be applied when the radiating volume is optically thin and the number of exciting collisions is large compared with the number of emissions. These conditions are well satisfied in the visible region of the nitrogen spectrum for the operating conditions employed in the experiments reported here.

Transition probabilities for nitrogen have been determined experimentally by several investigators. Unfortunately, there is a great deal of scatter in the reported data. Following a suggestion of Solarski and Wiese, the nitrogen transition probabilities calculated by Bates and Damgaard have been employed. These calculated transition probabilities are quite close to the mean of the available experimental data.

Energy levels for numerous gases, including nitrogen, have been tabulated by Moore.
Partition functions and number densities of the various components of high-temperature nitrogen were taken from the tables of Drellishak, et al. \(^8\)

Figures 1, 2, and 3 show the dependence of the intensity of the 4935-A NI line on temperature at pressures of 0.5, 1, and 2 atmospheres, respectively. Because of the strong dependence of the intensity upon temperature, the temperature determined by absolute intensity measurements of a spectral line is very insensitive to errors in intensity measurement. The error analysis for an argon spectral line given in reference 1 is representative of the errors to be expected when using the intensity versus temperature relationships given in figures 1 through 3.

C. EXPERIMENTAL OBSERVATIONS

The objective of the experimental measurements has been to determine the thermodynamic state of the gas as a function of the radial coordinate of the arc column, and to use this measured state to determine the thermal conductivity as a function of temperature. The general approach has been to determine the temperature from absolute line intensity measurements for a known pressure in the arc column.

The governing equation for the energy transport in a cylindrically symmetric arc column is given by the Elenbaas-Heller equation:

\[
\sigma E^2 \frac{1}{r} \frac{d}{dr} \left( r K \frac{dT}{dr} \right) - P_{\text{rad}} = 0.
\]

The remaining information necessary for the determination of the thermal conductivity \( K \) is obtained from measurements of the applied electric field strength in the column \( E \), the volumetric radiation losses \( P_{\text{rad}} \), and the electrical conductivity \( \sigma \).

The integrated intensity distribution of the arc column is obtained by translating the image of the column across the entrance slit of the monochromator. The centerline of the column is determined by taking intensity measurements across the entire arc diameter and then "folding" the signals obtained so that the curves to the right and left of the center are mirror images.

The integrated distribution is converted to a radial intensity distribution by an inversion of the Abel integral equation in a manner similar to the numerical technique employed by Barr. \(^9\) The accuracy of the inversion technique has been checked by inverting numerically a function which could be inverted analytically. It was found that the numerical technique gives excellent results with the exception of the first three inverted points. These points, which lie at the periphery of the arc column, are not included in the analysis of the temperature profile for thermal conductivity.
Figure 1 ABSOLUTE INTENSITY OF THE NITROGEN ATOM LINE NI 4935 AS A FUNCTION OF TEMPERATURE AT A PRESSURE OF 0.5 ATMOSPHERE
Figure 2: ABSOLUTE INTENSITY OF THE NITROGEN ATOM LINE N1 4935 AS A FUNCTION OF TEMPERATURE AT A PRESSURE OF 1 ATMOSPHERE
Figure 3  ABSOLUTE INTENSITY OF THE NITROGEN ATOM LINE NI 4935 AS A FUNCTION OF TEMPERATURE AT A PRESSURE OF 2 ATMOSPHERES
Temperatures in the arc column were determined on the basis of absolute intensity measurements of continuum radiation for the 1-atmosphere runs, the continuum having been previously calibrated against absolute line radiation, and on the basis of absolute line intensity of the 4935-A Ni line for the 0.5- and 2-atmosphere runs. Radial temperature profiles are shown in figures 4 and 5 for arc currents of 50, 60, 80, and 100 amperes at an ambient pressure of 0.5 atmosphere. Figures 6 and 7 depict the radial temperature distribution for the atmospheric pressure arc at 40, 50, 60, 80, 100, and 150 amperes. The atmospheric pressure data have been previously reported and are included here for the purpose of comparison. Figure 8 gives the radial temperature distribution at 2 atmospheres for 42, 55, and 72 amperes.

The temperature profiles in the region from 1000 to 5000°K were calculated from the conductive energy flux to the wall and the thermal conductivity given by Yos.10 The dotted portion of the temperature profiles represents interpolation between the calculated and measured portion of the profile. Neither the calculated nor the interpolated portions were used to obtain thermal conductivity. For the data at atmospheric pressure, it is expected that the uncertainties in the standard lamp, detection and recording system, and in the transition probability could result in an error of approximately ± 15 percent in the absolute line intensity. This corresponds to a ± 1.5 percent uncertainty in the temperature at 12,000°K. To date, the investigation of nitrogen at 0.5 and 2 atmospheres has not been so exhaustive as that at 1 atmosphere. In view of this, the temperature profiles for the 0.5- and 2- atmosphere runs are estimated to be accurate to ± 3 percent.

Voltage gradients in the nitrogen arc column were measured using the circuit shown in figure 9. In this circuit, the constrictors at each end of the nitrogen portion of the column serve as probes. A small amount of current is supplied to these constrictors to negate the effect of contact resistance between the constrictor and the arc column. The effect of random errors on the measurement is minimized by measuring the voltage between several pairs of constrictors separated by a known distance.

The electric field associated with each of the arc currents is given in the temperature-profile plots (figures 4, 5, 6, 7, and 8).

D. ANALYSIS OF EXPERIMENTAL OBSERVATION

Solution of the Elenbaas-Heller equation for both electrical and thermal conductivity has been described previously.1 This technique has not been used in this phase of the investigation. Rather, emphasis has been placed upon using existing analytical values for the electrical conductivity in an attempt to explain the gross discrepancy between theoretical and experimental values of the thermal conductivity. Figure 10 shows the electrical conductivity as a function of temperature for nitrogen at pressures of 0.5, 1, and 2 atmospheres.10
Figure 4 RADIAL TEMPERATURE DISTRIBUTIONS FOR 50- AND 80- AMPERE NITROGEN ARCS AT A PRESSURE OF 0.5 ATMOSPHERE
Figure 5 RADIAL TEMPERATURE DISTRIBUTIONS FOR 60- and 100- AMPERE NITROGEN ARCS AT A PRESSURE OF 0.5 ATMOSPHERE
Figure 6 RADIAL TEMPERATURE DISTRIBUTIONS FOR 40-, 60-, AND 100-AMPERE NITROGEN ARCS AT A PRESSURE OF 1 ATMOSPHERE
Figure 7 RADIAL TEMPERATURE DISTRIBUTIONS FOR 50-, 80-, AND 150-AMPERE NITROGEN ARCS AT A PRESSURE OF 1 ATMOSPHERE
Figure 8 RADIAL TEMPERATURE DISTRIBUTIONS FOR 42-, 55-, AND 72-AMPERE NITROGEN ARCS AT A PRESSURE OF 2 ATMOSPHERES
Figure 9. CIRCUIT FOR MEASURING VOLTAGE GRADIENTS IN THE NITROGEN ARC COLUMN
Figure 10 THEORETICAL ELECTRICAL CONDUCTIVITY OF NITROGEN AT 0.5, 1, AND 2 ATMOSPHERES
The radial temperature gradient appearing in equation (4) is determined by graphical differentiation of the radial temperature profiles. An estimate of the accuracy of this technique has been obtained by comparing the analytically and graphically evaluated slopes of a parabola. It was found that the errors of the graphical technique were approximately 2 percent for slopes in the neighborhood of one, rising to 7 percent for larger and smaller slopes. To reduce the effect of random errors, a smooth curve passing through the origin at zero radius is fitted by eye to graphically determined slopes of the temperature distribution.

The approach used to determine the thermal conductivity from the Elenbaas-Heller equation (4) consists of integrating the equation once and solving for the thermal conductivity of the gas at the radial distance \( r' \) from the column axis:

\[
(K)_{r'} = -\frac{\int_0^{r'} (\sigma E^2 - P_{rad}) \, dr}{r'(dT/dr)_{r'}}.
\]  

(5)

This is referred to as the calculated-current method in reference 1.

This equation is equivalent to the statement that the heat conducted out across a cylindrical surface of radius \( r' \) is equal to the heat generated inside the surface by Joule heating, less the heat lost from inside the surface by radiation.

Since the radial temperature distribution is known, equation (5) determines the thermal conductivity at the temperature associated with \( r' \), if the electrical conductivity \( \sigma \) and radiative power loss \( P_{rad} \) are known as functions of temperature.

Figure 11, 12, and 13 show the thermal conductivity obtained from the measured temperature profiles and voltage gradients given in figures 4 through 8, using the calculated-current method. The electrical conductivities given in figure 10 were used. In determining the thermal conductivities shown in figures 11 through 13, the radiative losses were assumed to be zero. This was done in order that the possible effect of radiation upon the thermal conductivity would not be confused by the inclusion of only a portion of the radiation, i.e., the radiation measured in the spectral region between 2000A and 6 microns.

The experimentally determined thermal conductivities at 0.5 atmosphere (figure 11) show significantly better agreement with theory than do the experimental values at 1 atmosphere (figure 12) for the same temperature range. Equally significant is the reduction in the current dependence of the experimental data obtained at 0.5 atmosphere as compared to the 1-atmosphere data. The thermal conductivity measured at a pressure of 2 atmospheres (figure 13) follows the same general trend of appearing to increase with increasing arc pressure, although the dependence of the data upon arc current is not so pronounced as that at 1 atmosphere.
Figure 11 THERMAL CONDUCTIVITY OF NITROGEN AT 0.5 ATMOSPHERE FROM THE CALCULATED-CURRENT METHOD WITHOUT THE INCLUSION OF RADIATIVE LOSSES
Figure 12 THERMAL CONDUCTIVITY OF NITROGEN AT 1 ATMOSPHERE FROM THE CALCULATED-CURRENT METHOD WITHOUT THE INCLUSION OF RADIATIVE LOSSES
Figure 13 THERMAL CONDUCTIVITY OF NITROGEN AT 2 ATMOSPHERES
FROM THE CALCULATED-CURRENT METHOD WITHOUT THE
INCLUSION OF RADIATIVE LOSSES
Comparing the data presented in figures 11 through 13, it appears that the discrepancy between theory and experiment may be attributed to a phenomenon which is characterized by two effects. First, the increase in the magnitude of the measured thermal conductivity for a constant temperature, but increasing pressure, indicates a pressure-dependent phenomenon. In particular, examination of the data indicates that the thermal conductivity determined from the Elenbaas-Heller equation under the assumption of no radiative losses increases in an approximately linear manner with pressure. Secondly, the dependence of the experimental data upon arc current, for a given temperature and pressure, suggests that the phenomenon is dependent upon geometrical considerations. Referring to the Elenbaas-Heller equation in its integrated form, equation (5), it is seen that the deduced value of the thermal conductivity depends upon the volume over which the integration is extended. Assuming the electrical conductivity to be correct, it is apparent that an error in the value of the volume integral of the radiation will produce an error in the thermal conductivity which is a function of the volume of integration. For different arc currents, a given temperature will be achieved at different radii in the arc, identical temperatures occurring at larger radii for higher arc currents. The volume enclosed within the surface at which the thermal conductivity is determined increases faster than does the surface area. Consequently, the effect of an error in the volume integral of radiation, for example, will affect the thermal conductivity at a given temperature in a manner that is a function of the radius at which the temperature occurs. Referring to figure 12, for example, it will be seen that as arc current increases, the thermal conductivity also increases for constant temperature. Further, this temperature is found at increasing radii as arc current increases weighting the effect of an error in the volume integral more heavily. On the basis of these arguments, it is concluded that the current dependence of the data shown in figures 11 through 13 is a direct result of failure to include radiative losses in the solution of the Elenbaas-Heller equation.

Turning now to the monatonic increase in thermal conductivity with pressure, it is instructive to examine the relationship between pressure and specific radiation. Figure 14 presents the total radiation from nitrogen between 2000A and 6 microns as a function of temperature for the three pressures of interest. The 1-atmosphere data were obtained experimentally. The radiation at 0.5 and 2 atmospheres was calculated from the known temperature dependence of continuum radiation, using the radiative cross section determined from the experimental data obtained at 1 atmosphere. The contribution of line radiation was obtained by the method of Bates and Damgaard.

Figure 15 depicts the total radiation from nitrogen over all wavelengths as a function of temperature for 0.5, 1, and 2 atmospheres. These data were obtained by choosing the theory which most accurately described the continuum radiation measured at 1 atmosphere (2000A < \lambda < 6 microns) and using this theory to predict the ultraviolet continuum radiation. The extension of the data to 0.5 and 2 atmospheres, and the inclusion of contribution of line radiation, was performed in the same manner as outlined above. Comparing figures 14 and 15, it
Figure 14  ESTIMATED ATOMIC LINE PLUS CONTINUUM RADIATION FOR NITROGEN AS A FUNCTION OF TEMPERATURE AT 0.5, 1, AND 2 ATMOSPHERES (λ>2000Å)
Figure 15  ESTIMATED ATOMIC LINE PLUS CONTINUUM RADIATION FOR NITROGEN AS A FUNCTION OF TEMPERATURE AT 0.5, 1, AND 2 ATMOSPHERES (λ > 0.0A)
is evident that the inclusion of ultraviolet radiation results in a specific radiation approximately five times larger than the radiation which is measured between 2000A and 6 microns.

Figures 16, 17, and 18 show the thermal conductivity determined from the temperature profiles of figures 4 through 8 by the calculated-current method using the radiation given in figure 15. The agreement between theory and experiment is substantially better than when the radiative losses are assumed to be zero. The agreement, however, is not entirely satisfactory, particularly for the 1-atmosphere data which are considered to be the most reliable. It appears also that the dependence of the thermal conductivity upon arc current has not been removed entirely, being most pronounced in the 1-atmosphere data. One of the striking features of the data in figures 16 through 18 is the apparent shift in the minimum of experimentally determined thermal conductivity toward lower temperatures with increasing pressure. The theoretical curves indicate that the minimum should shift toward higher temperature for increasing pressure. This anomaly is not understood at present, although it is believed to be a result of inaccuracies in the radiative term used in obtaining the data, and possibly to self-absorption of the arc column, which can become appreciable in the neighborhood of 9000°K.

For the purpose of comparison, the specific radiation used to analyze the data in reference 1 is given in figure 19. Thermal conductivities of nitrogen at 1 atmosphere, assuming the higher radiative losses of figure 19, are shown in figure 20, which was first presented in reference 1. These data exhibit a markedly better agreement with theory over the temperature range of 8500 to 14000°K than do the data using the radiation given in figure 15. (It should be noted that one of the reasons for the apparently superior agreement is the difference in the analytical value of the thermal conductivity given in figure 20, and that given in figures 12 and 17. The analytical result shown in figures 12 and 17 is somewhat lower. This is the most recent calculation.) It is felt that the principal reason that the data of figure 17 do not show as good agreement between theory and experiment as that of figure 20 lies in the different functional dependence upon temperature exhibited by the specific radiation at 1 atmosphere, as shown in figures 15 and 19. Apart from the difference in functional dependence, the radiation given in figure 19, which was used to obtain the data of figure 20, is approximately a factor of 2 greater than the radiation used in the analysis of the results presented in figure 12. In spite of the better agreement between theory and experiment that is obtained using the radiation of figure 19, it is felt that the specific radiation presented in figure 15 is the more reliable.

In all of the analyses leading to the data shown in figures 16, 17, 18, and 20, the arc column was treated as if it were transparent to radiation at all wavelengths and temperatures. This is almost certainly not the case. Ultraviolet radiation is strongly absorbed by nitrogen at temperatures of approximately 10,000°K and below. It remains to be determined what effect self-absorption has upon the method of radiative energy transport.
Figure 16 THERMAL CONDUCTIVITY OF NITROGEN AT 0.5 ATMOSPHERE FROM THE CALCULATED-CURRENT METHOD USING THE RADIATION DATA OF MORRIS, ET AL, FOR λ>2000 Å TO ESTIMATE THE ULTRAVIOLET RADIATION
Figure 17 THERMAL CONDUCTIVITY OF NITROGEN AT 1 ATMOSPHERE FROM THE CALCULATED-CURRENT METHOD USING THE RADIATION DATA OF MORRIS, ET AL, FOR λ>2000 A TO ESTIMATE THE ULTRAVIOLET RADIATION.
Figure 18  THERMAL CONDUCTIVITY OF NITROGEN AT 2 ATMOSPHERES FROM THE CALCULATED-CURRENT METHOD USING THE RADIATION DATA OF MORRIS, ET AL, FOR λ>2000 Å TO ESTIMATE THE ULTRAVIOLET RADIATION
Figure 19 MEASURED AND MEASURED-PLUS-CALCULATED VALUES OF THE TOTAL RADIATION OF NITROGEN AT ATMOSPHERIC PRESSURE

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Figure 20. THERMAL CONDUCTIVITY OF NITROGEN AT 1 ATMOSPHERE FROM THE CALCULATED-CURRENT METHOD WITH THE INCLUSION OF CALCULATED AND MEASURED RADIATIVE LOSSES
Additional experimental temperature profiles will be obtained at 0.5-, 1-, and 2-atmosphere pressures during the next quarter. Since the purpose of these profiles is to enhance the reliability of the data at hand, the range of temperature will be approximately the same as reported in this work. Scrutiny of present and future data will continue in an effort to determine, in as quantitative a manner as possible, the continuing discrepancy between theory and experiment. As experimental data for ultraviolet radiation become available, they will be incorporated into the present system of data analysis. Self-absorption of radiation by the arc column will be included in the data analysis. At this time it appears that radiation is the principal source of the discrepancy between the measured and calculated thermal conductivity values, and it is necessary to treat the radiation accurately to obtain reliable values of thermal conductivity, although self-absorption is mathematically cumbersome. The amount of self-absorption is expected to be pressure-dependent.

Concurrent with further investigation of nitrogen in the temperature interval reported here, initial data will be obtained for nitrogen using a new arc facility which should be capable of temperatures well in excess of 15,000°K.
IV. REFERENCES


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