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MAY 1972 AIAA JOURNAL VOL. 10, NO. 5

Measurement of Nitrogen Plasma Transport Properties

PAUL W. SCHREIBER* AND ALLEN M. HUNTER II†
Aerospace Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio

AND

KENNETH R. BENEDETTO‡
Systems Research Laboratory Inc., Dayton, Ohio

The electrical and thermal conductivities and radiant power per unit volume, P_R, of nitrogen are measured at atmospheric pressure between 10,500 and 12,250°K and are compared with the results of other investigators. A probe technique based on the Hall effect is used to determine the plasma electrical conductivity and P_R. In addition, P_R is determined by external optical techniques. A separate measurement technique which is used to determine the vacuum ultraviolet contribution to P_R is described. A correction for self-absorption is applied to the probe measurements of P_R. Thermal conductivity is obtained from an energy balance of the power input and measured loss terms.

Introduction

THE electrical and thermal conductivities and the radiant power per unit volume of nitrogen are measured at atmospheric pressure between 9000 and 12,250°K, and these data are compared with the results of other investigators. This investigation was initiated because a review of published data indicated that serious discrepancies exist in transport properties. These differences may be caused by: 1) errors in temperature measurements; 2) absorption of radiant energy by the plasma or external optical medium; 3) nonconstant spectral response of the detectors; 4) plasma impurities; 5) deviations from local thermodynamic equilibrium; and 6) assumptions used in obtaining and reducing the data.

In this investigation the radiant power per unit volume is measured by two independent methods, and the results are correlated with the measured temperature. Any discrepancy between these source strength measurements is therefore not attributable to an error in the temperature measurement, thus allowing other possible errors to be more easily evaluated. A probe technique based on the Hall-effect is used to determine the plasma electrical conductivity σ and also the radiant power per unit volume P_R. P_R is also determined by external optical methods which include a separate measurement technique to determine the vacuum ultraviolet contribution to the radiant power per unit volume. A correction for self-absorption at wavelengths greater than 2000 Å is applied to the probe measurements of P_R. Thermal conductivity is obtained from a balance of the measured power input and loss terms.

Presented as Paper 71-590 at the AIAA 4th Fluid and Plasma Dynamics Conference, Palo Alto, Calif., June 21–23, 1971; submitted July 9, 1971; revision received December 20, 1971.

Index categories: Atomic, Molecular, and Plasma Properties; Heat Conduction; Radiation and Radiative Heat Transfer.

* Research Scientist, Thermomechanics Research Lab. Member AIAA.

† Research Scientist, Thermomechanics Research Lab.

‡ Visiting Research Associate.

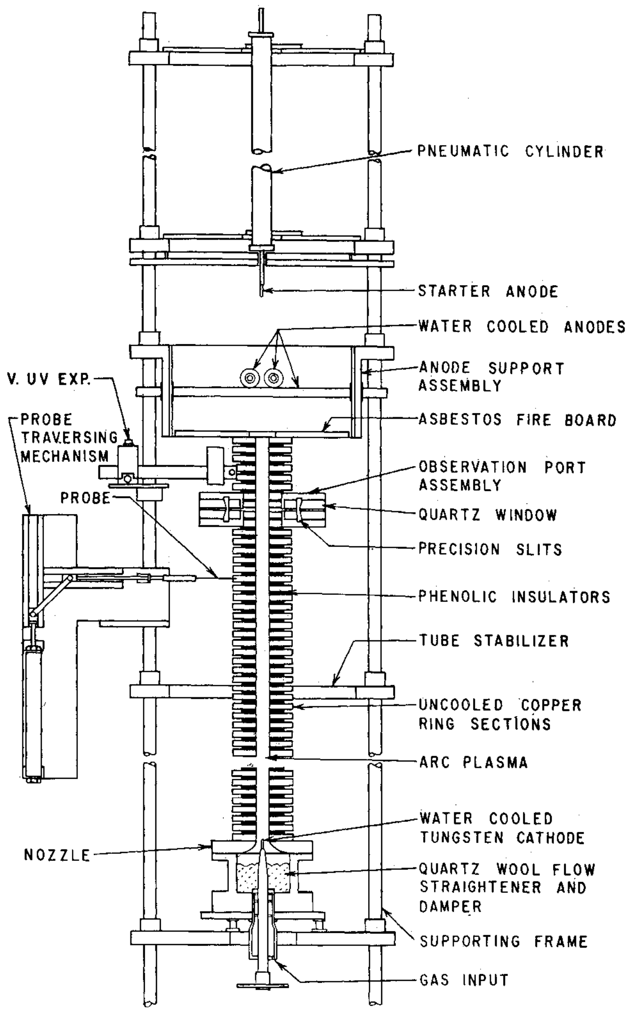

Fig. 1 Wall-stabilized plasma source.

A fully developed laminar flow electric arc discharge is used as the plasma source for these investigations. Important features of this source include purity, column stability, and, because of a large region of constant temperature, the existence of thermodynamic equilibrium is more likely.

Arc Facility

The arc discharge facility consists of 1) a 54-cm-long, 1-in.-diam, wall-stabilized electric arc, 2) a 1 Mw d.c. power supply, 3) an automatic control system, 4) a gas supply system and instrumentation to measure mass flow rate, and 5) diagnostic equipment including probes, spectrometers, radiometers and recorders.[1] The arc column is a cascade of 54 insulated copper ring sections. These sections operate as heat sinks during the discharge period and are water cooled only between arc runs in order to bring them back to room temperature. The arc is

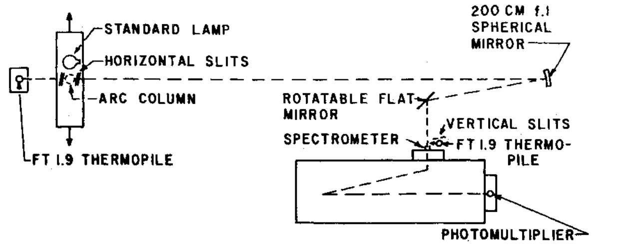

Fig. 2 Optical system used for temperature measurements.

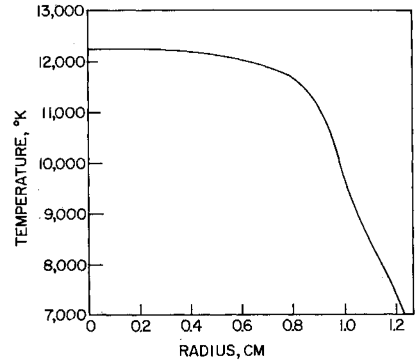

Fig. 3 Nitrogen arc temperature distribution.

operated in a pulsed mode, and the maximum pulse duration is in the order of one second. The events during a run are sequenced by a motorized cam switch controller. Nitrogen mass flow rate is controlled by a calibrated sonic orifice, and for these experiments the flow rate was 0.0044 lb/sec. A drawing of the discharge facility is shown in Fig. 1.

Temperature Measurements

The plasma column temperature distributions are determined by measuring lateral profiles of the absolute continuum intensity at a specific line-free region of the nitrogen spectrum (4955 Å).[2] The measurements are calibrated using a tungsten ribbon standard of spectral radiance which was previously calibrated at NBS. The lateral intensity profiles are converted to radial distributions of emission coefficient by employing a computer technique developed by H. N. Olsen et al.[3] The emission data are correlated with temperature by referring to published measurements of the continuum emission coefficient vs temperature for nitrogen at atmospheric pressure.[4]

The optical system used for these measurements is shown in Fig. 2. The arc column is scanned by stepping the plasma source across the optical axis in increments of 0.01 in. or less while the optical system remains fixed. At each location, the arc was operated for approximately 0.5 sec several times. The reproducibility from run to run was approximately $\pm 2\%$ at a given arc position and for each run the intensity was constant for the last 0.4 sec. A temperature distribution for an arc current of 1450 amp is shown in Fig. 3.

Electrical Conductivity

The electrical conductivity of the plasma is determined by using the measured electric field strength and the local current density in conjunction with Ohm's law

$$\sigma = j_z/E \quad (1)$$

The electric field strength is determined by traversing dual probes through the arc column and measuring the potential between them. A plot of electric field strength vs arc current is shown in Fig. 4. The axial current density is obtained by using Maxwell's

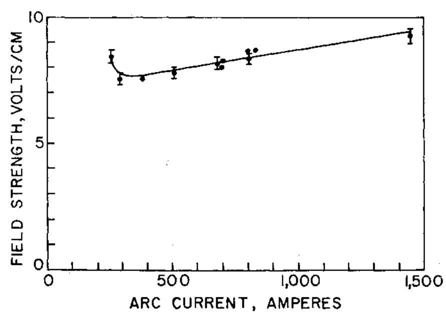

Fig. 4 Electric field strength as a function of arc current.

steady-state field equation, $\nabla \times \vec{B} = \mu_0 \vec{j}$, in cylindrical coordinates. This yields

$$j_z = (1/\mu_0)[\partial B_\theta/\partial r + B_\theta/r] \tag{2}$$

where μ_0 is the permeability of free space.

The internal distribution of the magnetic field is measured with a miniature, water-cooled probe which contains a Hall-effect element. This "Hall probe" is traversed across the arc column in thirty milliseconds or less to measure $\langle B_{\theta_m}(r)\rangle$ where the measured field is spatially averaged over the finite length of the Hall element.

A correction for plasma disturbance caused by the probe is applied to the measured data such that

$$\langle B_\theta(r)\rangle = \langle B_{\theta m}(r)\rangle + \langle B_{\theta c}(r)\rangle \tag{3}$$

where $\langle B_\theta(r)\rangle$ is the self-magnetic field averaged over the length of the Hall element, and $\langle B_{\theta c}(r)\rangle$ is the required disturbance correction.

The disturbance correction may be estimated by the equation

$$\langle B_{\theta c}(r)\rangle = H\int_{-a}^{R_w - r} j_z(x_1)\left\{\frac{1}{[(l/2-x_1)^2+b^2]^{3/2}} - \frac{1}{[(l/2+x_1)^2+b^2]^{3/2}}\right\}dx_1 \tag{4}$$

where R_w = boundary radius of the current-carrying region, r = radial position of the center of the Hall chip, a = distance from the probe tip to the magnetic element, x_1 = distance from the center of the probe element along the path of integration from the probe tip to the magnetic element, x = distance from the center of the probe element along the path of integration from the probe tip to the current boundary, l = length of probe element, and b and H are constants which are obtained from the measured data.[3] $j_z(x_1)$ is assumed in the first approximation to be linear with temperature and represents the relative current density distribution.

A relation is derived in Ref. 3 which allows $B_\theta(r)$, the local self-magnetic field, to be calculated from $\langle B_\theta(r)\rangle$. The resulting equation is

$$B_{\theta c}''(r) = (24/l^2)[\langle B_\theta(r)\rangle - B_\theta(r)] \tag{5}$$

A computer program is used to solve Eqs. (1–5) to obtain the electrical conductivity as a function of temperature using the known corrections at the discharge center and boundary to eliminate the unknown constants H and b.

Radiative Power per Unit Volume

Radiant power per unit volume is measured as a function of temperature using two independent diagnostic techniques. The optical measurements of P_R for wavelengths greater than 2000 Å utilize calibrated total radiation thermopiles as shown in Fig. 2. One thermopile is used to determine the total power radiated per unit arc length. There are no mirrors in its optical path so that reflection corrections are only required for losses at the quartz window. An identical thermopile is placed in the optical path, and the arc is optically imaged on a precision slit placed in front of the thermopile element. The arc is stepped across the optical path, and a lateral distribution of the integrated total arc radiation is measured. An Abel integral inversion is applied to the lateral radiation profile to yield the radial radiation distribution.

The errors associated with mirror reflectance and optical losses are minimized by normalizing the radial distribution to the measured total radiation per unit length. The normalization is accomplished by letting $P_R = AP_{Ru}$ and evaluating the integral

$$P_{RL} = 2\pi A\int_0^{R_w} P_{Ru}\, r\, dr$$

where A = calibration constant, unitless; P_{Ru} = measured uncalibrated values, w/cm³; P_{RL} = total radiation per unit length, w/cm.

The resulting radial distribution of $P_R(r)$ is correlated with the temperature measurements to obtain the total radiation

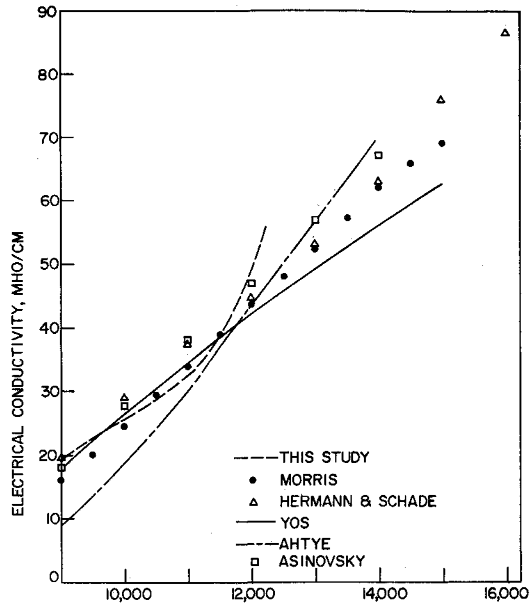

Fig. 5 Nitrogen electrical conductivity.

source strength as a function of temperature. The spectral bandpass of these measurements is limited by quartz optics and consequently limits the data to wavelengths between 0.2 and 4μ.

A radiometric technique is employed to determine the contribution to P_R from the vacuum ultraviolet region of the spectrum. A windowless thermopile, which is assumed to have a constant spectral sensitivity over the wavelength range of these measurements, is placed in a sealed tube which is mounted to the side of one of the cascade ring sections. A micrometer-adjustment slide is used to traverse the tube horizontally in order to scan the integrated lateral radiative intensity distribution. The solid angle subtended by the arc at the thermopile is limited by a small aperture and antireflection baffles inside the tube. The tube is purged with helium gas and is maintained at a small positive pressure relative to the plasma static pressure in order to prevent the hot gas from entering the tube. The helium "window" is transparent to radiation at wavelengths greater than 500 Å although the tube construction allows a quartz window to be inserted into the optical path.

By making measurements with and without the quartz window in the optical path, a percentage of the total radiation reflected

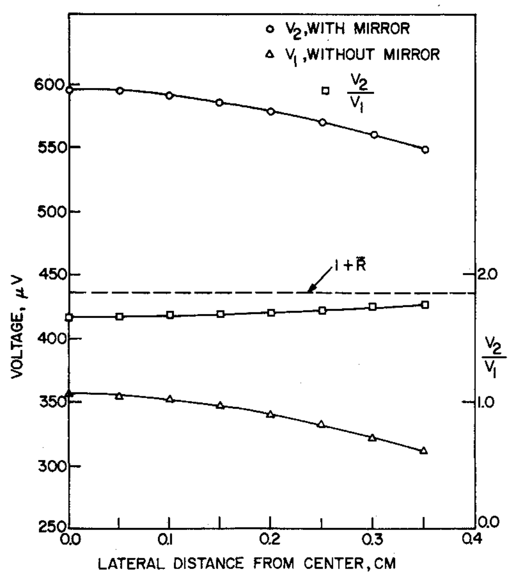

Fig. 6 External intensity measurements for estimating absorbed radiation.

and absorbed is obtained. Any difference between the two measurements is essentially due to the spectral bandpass of quartz. Most of the increased radiation measured without the window can be attributed to plasma emission at wavelengths less than the lower transmission limit of quartz.[4] An average window reflectance of 7% is accounted for in the "window-in" measurement. Lateral scans of the percentage difference in radiation with and without the window are transformed to radial distributions using the Abel inversion computer program. The contribution of the vacuum ultraviolet radiation is included in the reported data for P_R.

In addition to the external radiation measurements, the Hall probe measurements are used to obtain the total radiative source strength. The technique, as applied to the cylindrical arc column, relies on properties of the energy balance which is described in the following equation

$$\nabla^2\phi + j_z E_z + P_A - P_R = 0$$

where

$$\phi = \int_{T_w}^{T} \lambda(T)\,dT; \quad P_R = 4\pi \int_0^\infty \varepsilon_\lambda\, d\lambda; \quad P_A = \int_{4\pi}\int_0^\infty a_\lambda I_\lambda\, d\lambda\, d\omega$$

$\lambda(T)$ = thermal conductivity, ε_λ = spectral emission coefficient, α_λ = absorption coefficient, and I_λ = specific intensity.

In the constant temperature region of the plasma source, $\nabla^2\phi = 0$ and the energy balance reduces to

$$P_R = j_z E_z + P_A \tag{6}$$

It has been shown that P_A is small if the plasma has only a small temperature gradient over a large portion of the discharge diameter.[5] If the absorption in the plasma is small over the wavelength range transmitted by quartz, as indicated by the radiometric measurements, it is possible to estimate the power absorbed per unit volume in the wavelength interval from 0.2 to 4 μ. The procedure requires making use of the previously described radiometer measurements. Data obtained through the arc center along with the measured total radiation per unit arc length are needed for this estimate. These data are used in the equation

$$P_A \approx (P_{RL}/4R_c^{\,2}\bar{R})[(1+\bar{R}) - V_2/V_1]$$

to approximate the power absorbed per unit volume at the arc centerline.[6] This equation was derived for an arc of infinite length and overestimates the absorbed power by several percent. V_2 and V_1 are the thermopile output voltages corresponding to measurements through the arc center with and without a mirror placed behind the arc to focus its image on itself. R_c is the radius of the constant temperature region as determined from the measured temperature profile and $\bar{R}$ is the average mirror reflectivity. Thus, P_R can now be calculated using Eq. (6).

Thermal Conductivity

The energy equation may be integrated two times to obtain the heat flux potential as a function of the radius. This yields

$$\phi(r) - \phi(0) = \int_0^r \frac{1}{r_b}\left\{\int_0^{r_b} [\sigma(r_a)E_z^{\,2} - P_R + P_A] r_a\, dr_a\right\} dr_b$$

Since the temperature distribution is known, the Hall probe data, $\sigma(T)$ and $P_R(T) - P_A(T)$, may be used in this equation to obtain $\phi(r) - \phi(0)$. $\phi(r) - \phi(0)$ is plotted as a function of temperature, and the derivative of this curve is the thermal conductivity.

$$\lambda = d\phi(r)/dT$$

This technique has three advantages over other methods which are used to determine the thermal conductivity: 1) the error due to absorbed radiation is minimized since the Hall probe can approximately measure $P_R - P_A$, 2) no assumptions are made on the analytic form of $\lambda(T)$, and 3) experimental errors are minimized by taking only one derivative of the measured data. This method allows λ to be determined in the region where reasonable temperature gradients exist.

Results and Conclusions

The measured values of electrical conductivity are compared with the experimental results of Morris, Hermann and Schade, and Asinovsky and the calculated values of Yos and Ahtye in Fig. 5 (Refs. 7, 8, 10, and 11). One must consider the errors in σ and T before drawing conclusions about comparisons among the data. The reported errors are tabulated in Table 1, and the uncertainty in σ alone is generally large enough for the various limits of error to overlap. Since some of the other electrical conductivities are obtained from measurements of total arc current, it is consistent to investigate the extent to which deviations among the conductivities are reflected in calculations of the total current. The current densities are formed by multiplying the various electrical conductivities by the voltage gradient measured in the pulsed discharge. Each current density is integrated over the cross section of the discharge, using our temperature distribution, to yield the total current. The calculations using the data of this study, Asinovsky, and Hermann and Schade give currents which agree very well with the measured 1450 amp.

The total radiative source strength is determined from Hall probe measurements in the constant temperature region of the arc using Eq. (6). A correction of 170 w/cm^3 for radiation absorbed at wavelengths greater than 2000 Å was determined using the mirror technique described previously and is included in the plot of centerline $j \cdot E$. External measurements of the total radiation with and without a mirror placed behind the plasma are shown in Fig. 6. The value of $\bar{R}$ was estimated from the measured reflectivity as a function of wavelength.

The external measurements at wavelengths greater than 2000 Å are made using the optical system which is illustrated in Fig. 2, and the measurements for wavelengths greater than 500 Å are obtained through the helium window. These measurements of P_R are compared with the experimental results of Morris in Fig. 7 (Ref. 9).

The total radiation measured externally through quartz optics agrees reasonably well with Avco's data and the difference could be largely due to errors in temperature measurements. The radiated power per unit volume obtained with the Hall probe is higher by as much as 400%. It is known that nitrogen has significant ultraviolet radiation so the measurement through helium was anticipated to be larger than the quartz-

Table 1 Comparison of electrical conductivity data

Source	Estimated errors σ	Estimated errors T	Maximum difference from σ of this paper	Difference between measured and calculated currents
This paper	±5%	±1–2%[a]	...	+1.6%
Hermann and Schade	Unknown	±1–2%[a]	17%	−0.6%
Asinovsky	±15%	±1–3%	14%	+0.06%
Morris	±10%	±200–300°K	18%	−8.8%
Yos	...	...	23%	−8.8%
Ahtye	...	...	78%	−16%

[a] These numbers represent the maximum scatter in the measured temperatures. The transition probabilities and the radiation standard which are used introduce additional systematic errors which contribute to the total uncertainty in temperature.

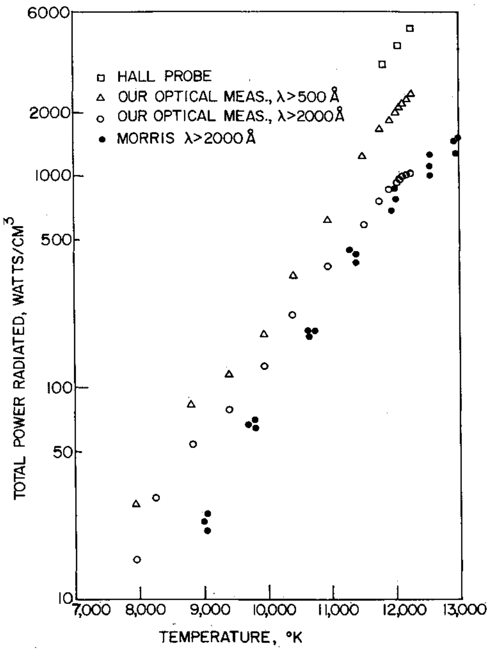

Fig. 7 Total power radiated per unit volume.

limited data. The difference between the internal $j \cdot E$ measurement and the external data obtained through helium could occur for several reasons, the most probable of which are 1) the improper use of an Abel inversion since the ultraviolet radiation may not be optically thin, 2) an overestimation of the electrical conductivity at the arc centerline, 3) radiation outside of the spectral bandpass of helium which would be measured by the Hall probe, and 4) nonuniform spectral sensitivity of the windowless thermopile.

If the total ultraviolet radiation were optically thick, then the ultraviolet contribution to $P_R - P_A$ would add to zero, and $j \cdot E$ would be equal to the quartz-limited measurements of P_R. The data at 12,000°K indicates that this is not correct, and in fact it shows that P_R should be much greater than P_A at ultraviolet wavelengths. Also, if the total ultraviolet radiation were optically thick, the radiation should appear to be radiated from the surface of a circular cylinder. The measured ultraviolet radiation profile is unlike the profile which would be obtained from a radiating cylinder. If the electrical conductivity were in error, it is unlikely that the integrated total current would compare with the measured current to within 1%. The difference between the two radiation measurements could be due to emitted radiation which is absorbed by the helium window, but we were unable to investigate that possibility. The most likely error is due to the absorption of line radiation in the ultraviolet spectral region.

The nitrogen thermal conductivity is compared with the measurements of Morris and Hermann and Schade and the theory of Yos in Fig. 8 (Refs. 7 and 8). Energy transport by vacuum ultraviolet radiation must be accounted for in the determination of thermal conductivity, and it is the most probable reason that the data disagree. Morris accounts for the energy transport by using measurements of continuum radiation and calculations of line radiation in the vacuum ultraviolet. The Hall probe measurements include radiation over the entire spectrum. Data scatter is still a problem due to the difficulty in accurately measuring temperature gradients.

In conclusion, the experimental values of the electrical conductivity of nitrogen are in agreement within the limits of error. Yos' theoretical values compare well with measured data below 11,800°K. At higher temperatures, his calculated values appear to be significantly lower than measured data. Ahtye's calculations are in error below 11,800°K, but they are in reasonable agreement with measured data above this temperature. Measured radiant powers per unit volume for $\lambda > 2000$ Å are in reasonable agreement with Morris' data. However, the large amount of additional optically thin radiation below 2000 Å, as indicated by the Hall probe measurements, requires additional study. The discrepancies in the measured thermal conductivities are probably due to the different methods of treating the vacuum ultraviolet radiation and the differences in the measured electrical conductivities. When limits of error are considered, the results of this study are in agreement with Morris' values. This comparison may be improved if corrections to Morris' electrical conductivity are used to determine the thermal conductivity.[10] Since estimated limits of error were not given by Hermann and Schade, it is not possible to make a complete comparison with their data.

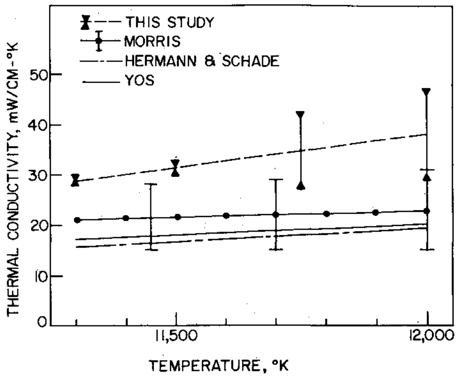

Fig. 8 Nitrogen thermal conductivity.

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