NASA Technical Memorandum 80156

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NOVEMBER 1979

NASA

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National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1979

SUMMARY

Total charge-transfer cross sections have been obtained for the N_2^+-N_2 system with relative translational ion energies between 9 and 441 electron volts. Data were obtained to examine the dependence of total cross section on ion energy. The effect of ion excitation on the cross sections was studied by varying the electron ionization energy in the mass-spectrometer ion source over an electron energy range between 14.5 and 32.1 electron volts. The dependence of total cross section on the neutralization chamber gas pressure was examined by obtaining data at pressure values from 9.9 to 19.9 $\times$ 10^{-5} torr. Cross-section values obtained were compared with experimental and theoretical results of other investigations.

INTRODUCTION

In recent years, a number of experimental and theoretical investigations have involved the study of reactions of charged and neutral atmospheric species. (See refs. 1 to 18.) Nevertheless, a detailed understanding of many atmospheric reactions is still lacking, due to a lack of precise experimental information concerning the discrete atomic and molecular processes involved.

Many satellite and reentry probe experiments have encountered serious measurement problems with atomic and molecular atmospheric gases. (See refs. 5 and 19 to 21.) One technique for studying and eventually solving such problems is to examine the reactions of energetic molecular beams which impinge on surfaces. In order to do this, techniques must be developed to generate neutral atomic and molecular beams with velocities equivalent to those of spaceborne satellites.

A primary concern in aerospace research is the development of methods for accurately calibrating mass spectrometers and ion gauges that are flown on spaceborne vehicles. In order to do this, high molecular speeds are required to simulate the high velocity of test instruments through a rarefied atmosphere.

The experimental investigations in the field of upper-atmosphere and interplanetary flight have reemphasized the need for a comprehensive analysis of the nature of surface reactions that occur with atmospheric gases. Because of the high chemical reactivity of many atmospheric species, the possibility of strong interaction with the instruments and chamber walls exists. Some molecular and atomic species become permanently adsorbed on surfaces or recombine to form other species. This type of interaction can result in spurious measurements of molecular concentrations.

Perhaps the most immediate interest in gas-gas and gas-surface collisions derives from the growing need for transport-property data. These data are required at temperatures at which viscosity, thermal conductivity, diffusivity, and mobilities cannot be directly measured. Spaceflight experiments at

Mach numbers above 8 correspond to interaction energies between the vehicle and atmospheric gases of more than 1 electron volt. Satellite and missile velocities correspond to interaction energies in the vicinity of 10 electron volts for nitrogen molecules. The activation energy for many common chemical reactions lies between 1 and 4 electron volts. Chemical bond strengths are of the order of 8 electron volts. Collision processes offer a means for investigating these bond strengths. The adsorption of gases on surfaces plays an important role in modern vacuum technology, where typically the first absorbed monolayer is bound by 1 to 4 electron volts. Additionally, considerable basic scientific interest is derived from the use of gas-gas collision experiments for the inference of intermolecular potentials, where accurate calculations for some intermolecular potentials are difficult or impossible to obtain. Collision experiments play an important role in providing information on systems not amenable to theoretical investigation and in checking the approximations involved in the calculations that are available.

The research described in this report was initiated to provide fundamental data on the charge-transfer method of generating high-velocity, low-intensity neutral molecular beams, and to report on important measurement parameters that characterize charge-transfer interactions in gases. Primarily, the purpose of this paper is to report on the cross-section data obtained.

The system chosen for study was the symmetric charge-transfer reactions between N_2^+ and N_2. Nitrogen was chosen partly due to its prevalence in the atmosphere and because it is readily available for use in many calibration systems. The following reactions were considered, which included the ground state and first two excited electronic states for the incident nitrogen ion and the ground state for the nitrogen molecule. The following reaction products include nitrogen ions and molecules in excited vibrational states also:

$$N_2^+(X^2\Sigma_g^+,\ \nu_o') + N_2(X^1\Sigma_g^+,\ \nu_o'') \rightarrow N_2(X^1\Sigma_g^+,\ \nu'') + N_2^+(X^2\Sigma_g^+,\ \nu')$$

$$N_2^+(A^2\pi_u,\ \nu_o') + N_2(X^1\Sigma_g^+,\ \nu_o'') \rightarrow N_2(X^1\Sigma_g^+,\ \nu'') + N_2^+(A^2\pi_u,\ \nu')$$

$$N_2^+(B^2\Sigma_u^+,\ \nu_o') + N_2(X^1\Sigma_g^+,\ \nu_o'') \rightarrow N_2(X^1\Sigma_g^+,\ \nu'') + N_2^+(B^2\Sigma_u^+,\ \nu')$$

(ν' includes ν_o', ν_1', and ν'' includes ν_o'', ν_1'', . . .)

The studies were carried out for relative translational energies in the range from 9 to 441 electron volts. Since the target gas possesses only thermal energies, the relative energy is effectively that of the ion beam. Exact control of the primary-ion states was not possible with the typical electron impact-ionization ion source used in this work. However, some control in specific-state population was possible by selecting the electron ionization energy approximately at the threshold of a specific electronic state. Three

particular electronic states of N_2^+ were of interest: $X^2\Sigma_g^+$, $A^2\pi_u$, and $B^2\Sigma_u^+$ have formation thresholds which occur at electron energies of 15.63, 17.0, and 18.94 electron volts, respectively. (See ref. 22.)

Most measurements in charge-exchange experiments at low energies have been made on beams of positive ions passing through a neutral, thermal target gas. Charge-transfer cross sections are obtained from measured currents of slow ions formed in the passage of a fast ion beam through a target gas of known density. In this research, charge-transfer cross sections were deduced from measurements of three separate currents: I_{CTC}, the current to the charge-transfer cell; I_{CTCS}, the current to the charge-transfer-cell-screen; and I_{BF2}, the current to beam-flag-two. (See fig. 1.) From these current measurements and the known reaction path length, cell pressure, and cell temperature, charge-transfer cross sections were readily obtained.

Efforts were directed to determine the effect of the internal excitation state of the primary ion beam on the charge-transfer process. Data were collected for four different pressures to check for any apparent dependence of the charge-transfer cross sections on the charge-transfer-cell pressure.

SYMBOLS

I	current, amperes
$I(x = 0)$	current at entrance to charge-transfer cell, amperes
k	Boltzmann's constant, 1.38×10^{-16} erg/kelvins
p	pressure, torr (1 torr = 133.3 pascals)
T	temperature, kelvins
Δx	length of charge-transfer cell, centimeters
σ	cross section, centimeters^2
ϕ	electrical potential, volts
$\phi(app)$	applied electrical potential, volts
$\Delta\phi$	potential difference between CTCS and CTC, volts

Subscripts:

BF1	beam flag 1
BF2	beam flag 2
CT	charge transfer

CTC charge-transfer cell

CTCS charge-transfer-cell screen

EE electron energy

IE ion energy

Abbreviations:

BF1 beam flag 1

BF2 beam flag 2

CTC charge-transfer cell

CTCE charge-transfer-cell enclosure

CTCS charge-transfer-cell screen

FD1 focus deflection for first electrode

FD2 focus deflection for second electrode

FD3 focus deflection for third electrode

FD4 focus deflection for fourth electrode

L1 lens 1

L2 lens 2

R/D ring-drawout electrode

T1 tube 1

T2 tube 2

T3 tube 3

THEORETICAL CONSIDERATIONS

A beam of ions traversing a gaseous target will be attenuated due to collisional scattering processes. Some collisions will cause a change in the internal energy of either one or both of the collision partners; such collisions are said to be "inelastic." A collision cross section is a microscopic property of the collision system and is related to the probability that a particular collision event will occur under specified conditions. Values of cross sections depend on the nature and state of the reacting particles, their relative velocity, and the impact parameter. Measurements are meaningful only under the experimental conditions for which the cross section is operationally

defined. Accuracy of a cross-section measurement is directly related to the accuracy or level of confidence with which the experimental parameters are defined.

Charge transfer between an ion and a neutral species involves a class of inelastic collisions whose probability can predominate over other reactions. If either of the collision partners are molecular, these other processes can include rotational and vibrational excitation and dissociation.

The transfer of charge between an ion and a neutral atom results in the formation of slow ions at thermal energies and neutrals having an energy practically equal to the initial energy of the projectile ion. Ions that have traveled a single-charge transfer-free path become neutrals but retain their initial velocity. The atoms that give up electrons and become ions continue to move at essentially thermal velocities.

Charge-transfer reactions are often classified as being either symmetric or asymmetric. Symmetric charge transfer is the process of charge transfer between an ion and its neutral parent. Resonant charge transfer is charge transfer in which the energy defect is zero; that is, there is no change in the internal energy of the target-projectile system. In discussions of charge transfer, the term "accidental resonance" is sometimes used; this term refers to cases in which the energy defect is small or zero, not because of a symmetry, but by chance. The structures of resonant and nonresonant charge-transfer cross-section curves (cross section versus ion impact energy) are usually different. Most of the structural difference has often been attributed to symmetry, but this idea is not universally accepted. (See ref. 23.) For endothermic systems (positive energy defect) structural curves show an energy threshold. Exothermic charge-transfer (negative energy defect) processes show no such threshold. However, the cross-section curves for both exothermic and endothermic processes frequently have similar appearances; they rise from an apparent onset to reach a maximum and then slowly decrease with increasing ion impact energy. The theoretical treatment of charge-transfer reaction is sometimes confused because of poor correlations between reported results. Some researchers make no mention of the sign in discussions of energy defect. As an example, in the theoretical treatments of references 12, 13, and 16, no attempt was made to note the sign of the energy defect. Experimental results have shown that cross sections for symmetric resonant transfer usually are larger than cross sections for nonresonant transfer. Because of this, ion-beam neutralization by charge transfer is usually done in the parent gas to obtain a neutral atomic and molecular beam of high translation energy. The variation of symmetric resonant charge-transfer cross section σ with ion impact energy ϕ_{IE} has been approximately represented by an expression of the following form (see refs. 24 to 26); $\sigma^{1/2} = a - b \ln (\phi_{IE})$, where a and b are constants. No such functional relation for nonresonant charge-transfer cross section has been universally accepted.

Experiments have been conducted to define the operational definition of a collision cross section in terms of such macroscopic observables as beam flux, beam current, and target density. This definition then means that the observed parameters are determined from the experimental apparatus used for the measurement. Two basic geometrical arrangements have been used. The most frequently

used method involves a projectile-beam incident on a static gas target. A second technique involves the intersection or crossing of a projectile beam with a target beam. The first technique is sometimes referred to as the condenser method; it was developed many years ago by Goldmann (ref. 27) and Rostagni (ref. 28), and has been employed successfully. (See refs. 1, 2, 4, and 29 to 32.) The first technique was used in this research.

Most of the detailed calculations showing how total charge-transfer cross sections are obtained from an ion-beam and target-gas collision experiment was discussed in reference 33.

BACKGROUND DISCUSSION

Many measurements of charge-transfer cross sections involving molecular ions have been described in the literature. (See refs. 7, 34, and 35.) In these measurements, it was expected that some of the ions would be in long-lived excited states. In general it can be stated that charge-transfer cross sections may be different for the excited-state ions. It has been stated that the effect of ion-beam excitation not only can influence the reaction channels but could account for the entire cross section in some cases. (See ref. 7.) Amme and Utterback (ref. 7) measured charge-transfer cross sections for the N_2^+-N_2 system, as a function of ion energy and ion-source electron energy. The resonant N_2^+-N_2 system cross-section data were shown to vary as a function of ion energy in the manner generally reported by other investigators. However, the cross-section data also showed a decrease of 15 percent in going from 17 to 23 volts electron ionization energy. This was attributed to metastable ions in the beams, which were believed to transfer in a less efficient way. The usual practice has been to ignore beam excitation effects. Until recently, little importance was attached to the mode of formation of ions (refs. 7, 34, and 35); it was considered sufficient in most studies to simply use a mass-analyzed beam of the correct chemical and molecular species. The inadequacy of ion-beam-preparation procedure has been demonstrated in a number of experiments (refs. 7, 34, and 35) where the collision properties of ions of a given chemical type have been observed to depend upon the nature and mode of operation of the ion source. In the case of electron-bombardment ion sources, the collision properties of the resulting ions have been shown in many cases to be extremely sensitive to the energy of the ionizing electron. (See refs. 7 and 35 to 37.) Therefore, a full description of an ion-beam experiment requires that not only the type of ion, but also its state be known for the reactants and products. Unfortunately, few experiments have been designed to identify the states of the parent ion and even fewer to identify the states of the products.

It has been reported (ref. 38) that the technique of photoelectron spectroscopy offers an approach to determining fractional populations of the various ionic states resulting from photoionization; there is a plan for an eventual extension of this work to study the composition of ion beams formed by electon bombardment. For the present, however, there is extreme difficulty in inferring the final distribution of ions in a beam from a knowledge of the initial distribution formed in an electron-impact-ionization process. The problem remains,

therefore, to study and evaluate directly the ion beam by such methods as controlling the electron ionization energy of the ion source. Such methods do not, in general, yield a complete description of the internal-energy-state distribution in the beam. In the case of molecular nitrogen ion beams, these methods could permit studies of N_2^+ in its ground electronic state $\left(X^2\Sigma_g^+\right)$ and its first two electronic states $\left(A^2\pi_u \text{ and } B^2\Sigma_u^+\right)$. These states are separated by approximately 1.4 and 3.3 electron volts, respectively (ref. 39). By carefully calibrating the electron ionization energy one could produce ion beams in the ground electronic state, in a mixture of ground state, and in the first two excited states (fig. 2).

Turner et al. (ref. 34) were the first to report on a technique of using attenuation curves to investigate the abundance of excited states in ion beams. This principle is based on the linear attenuation of an ion beam in collision when one particular state is present. When two or more states are present, curvature of the attenuation should be detected. In principle this technique shows promise but in practice the interpretation and evaluation of attenuation curves is much more complicated, because many experimental factors such as ion-source operation, ion-beam stability, pressure fluctuations, and time of flight of the ion-beam versus excited-state lifetimes influence the beam composition. One can also see that where more than two states are involved, the problem is compounded.

In the measurement of total charge-transfer cross sections, consideration should be given to the lifetimes for the existence of the various excited states of N_2^+. The electron energies used to produce the N_2^+ ions were selected to be between 14.5 and 32.1 electron volts in this experiment. Only the ground state $\left(N_2^+\left(X^2\Sigma_g^+\right)\right)$ and the first two excited states $\left(N_2^+(A^2\pi_u) \text{ and } N_2^+\left(B^2\Sigma_u^+\right)\right)$ need to be considered, because the lifetimes of any other states are too short. The lifetimes of the $B \rightarrow X$ radiative transitions (refs. 40 to 45) have been shown to be on the order of 40 to 70 nanoseconds, so that all the $N_2^+\left(B^2\Sigma_u^+\right)$ ions formed in the electron-impact ionization undergo transitions to the ground state $\left(N_2^+\left(X^2\Sigma_g^+\right)\right)$ long before they arrive at the CTC region. The lifetimes of the $A \rightarrow X$ transitions (refs. 46 to 51) are on the order of 5 to 15 μsec for the first few vibrational levels. For typical collision experiments, the ion transit times are on the order of 10 to 12 μsec. For these transit times, some undecayed $N_2^+(A^2\pi_u)$ excited states could be present in the primary ion beam. Flannery et al. (ref. 12) considered the presence of excited states in their experiments where the ions were contained for 9.6 to 14.2 μsec in their time-of-flight apparatus. This ion-transit time, the time required to travel from the ion source to the center-of-reaction region, is about the same (8 to 9 μsec) as expected in the apparatus used in the present study.

It has been shown (ref. 12) that certain low vibrational levels are most strongly populated by the electron-impact-ionization process. A fraction of

the ions entering the analyzer tube in the $A^2\pi_u$ state will transit the collision region in the same state. The presence of this fraction of undecayed ion in the $A^2\pi_u$ state may have an effect on observed charge-transfer cross sections. Flannery et al. (ref. 12) have shown that the population of the $X^2\Sigma_g^+$ and $A^2\pi_u$ ionic states are in the ratio of approximately 9 to 1 for an electron-impact energy of 20 electron volts. Ions formed at this electron energy have two possible reaction paths available in the charge-transfer process: A channel where secondary ions are formed in the $X^2\Sigma_g^+$ state and a channel where secondary ions are formed in the $A^2\pi_u$ state. From the analysis in reference 12, it was pointed out that the reaction channel where the secondaries are formed in the $A^2\pi_u$ state is an order of magnitude more favorable than the $X^2\Sigma_g^+$ channel. As a result, the contribution to the total charge-transfer cross section due to the $A^2\pi_u$ ions would be smaller than the population of this state in the reactant ion beam. It appears from the preceding discussions that certain excited-state ions can charge transfer less efficiently than ground-state ions and may have some influence on the magnitude of cross sections observed. An object of this research was to probe the relative contributions of excited states in the N_2^+-N_2 reaction.

EXPERIMENTAL DATA AND RESULTS

The experimental system can be divided for the purpose of discussion into three component parts: a mass spectrometer, an ion-optics section, and a charge-transfer section (fig. 3).

The purpose of the mass spectrometer was to provide a mass-selected primary ion beam with a known kinetic energy. The mass-spectrometer system contains an electon-bombardment ion source, a gas inlet system, a vacuum pumping station, a pressure monitoring system, and electronic controls.

The purpose of the ion-optics section was to direct and guide the transport of the primary ion beam from the mass-spectrometer analyzer exit at the ring-drawout (R/D) electrode to the charge-transfer cell (CTC). This was done by employing conventional ion-optic techniques with lens elements of three basic geometric configurations: cylindrical, disc, and flat-plate type. The electrical potentials on all optical elements were separately controlled by regulated power supplies to obtain a stable ion beam of maximum intensity at the CTC section.

The charge-transfer section consists of three parts: the charge-transfer cell (CTC), the charge-transfer-cell screen (CTCS), and beam flag two (BF2). This section is utilized to detect and measure the primary and product ions made in the charge-transfer process. Detection of the ion beam was accomplished by absolute current measurement, using three precision electrometers to measure total currents to CTC, CTCS, and BF2.

It was important that the apparatus be maintained in the 10^{-6}-torr pressure range. This was accomplished by three separate pumping stations. The volume enclosing the mass spectrometer, L1 optic section, and T1 was maintained at working pressures of 2×10^{-6} to 4×10^{-6} torr by a 5.08-cm (2-in.), 80-liter-per-second oil-diffusion pump and mechanical pump arrangement. The volume enclosing T2 and BF2 was maintained at working pressures of 5×10^{-7} to 5×10^{-6} torr using a 400-liter-per-second turbo-molecular pump. Another 5.08-cm (2-in.), 80-liter-per-second oil-diffusion and mechanical pumping station was used to help evacuate the volume at the exit of the charge-transfer cell. A detailed description of the experimental apparatus is given in reference 52.

In order to account for uncertainties in the applied electron-ionization energy, a vanishing-current measurement of the appearance potential for the N_2^+ ion was performed. This experiment was conducted at two locations in the ion beam; at the charge-transfer-cell position (fig. 4), and at the normal collector position of the mass spectrometer (fig. 5). In both cases it was observed that the applied electron energy at the threshold of ionization did not correspond to the exact known appearance potential (ref. 22) of 15.63 ± 0.02 electron volts. Since the purpose of this study in part was to examine cross sections as a function of electron energy, it was important to get a calibration between the applied electron energy and the true electron energy required to produce the ground state of N_2^+. From the vanishing-current measurements made at the CTC position there appeared to be a threshold ionization to the ground-state ion at about 14.5 electron volts. This implies that there was an error in the applied electron energy of approximately 1 electron volt. This error is typical for electron-bombardment-type ion sources. There appears to be a phenomenon occurring such that the vanishing-current data does not show a definite drop to zero ion current at a finite electron energy. There is an extended long tail in the data as the applied electron energy is reduced to the vicinity of 4 electron volts. Since the current was collected at the CTC position for the data shown in figure 4, other vanishing-current data were needed to see if the ion-optics focusing elements were causing this phenomenon. A vanishing-current experiment was then performed with the ion collector at its original position in the mass spectrometer. The results of these data are shown in figure 5. From these data it can be seen that the essential characteristics of this plot are very similar to those of figure 4; for example, there is an analogous long tail as the electron energy potential is decreased toward zero. These data imply then that the preappearance potential structure of figure 4 is an artifact of the mass-spectrometer ion source, and is not created by the ion-optics elements.

Data were collected for eight values of electron energy, seven values of ion energy, four values of charge-transfer gas pressure, and 12 values of $\Delta\phi$. The total ion-beam current to the CTC $I(x = 0)$ was calculated as a sum of three currents:

$$I(x = 0) = I_{CTCS} + I_{CTC} + I_{BF2} \tag{1}$$

In table I the function $\ln (1 - I_{CT}/I(x = 0))$ is tabulated for a typical range of corrected electron energy, ion energy, and neutral charge-transfer-gas (N_2) pressure. Data for all other ranges of electron energy, ion energy, and the CTC pressure were tabulated in a similar manner.

In table II, the final experimental results are tabulated. These results represent the values obtained for the charge-transfer cross sections as a function of ion energy and electron energy. The cross-section values were obtained by plotting the function $-\ln (1 - I_{CT}/I(x = 0))$ versus p_{CTC} for eight values of electron energy and seven values of ion energy. All the cross sections shown were obtained from the following relation:

$$\sigma = \frac{kT}{1330\Delta x} \text{ slope} \tag{2}$$

where k is Boltzmann's constant. The cross sections were calculated for an absolute temperature (ambient) of 295 K and for a charge-transfer-cell length Δx of 5.08 cm. The slopes were obtained from plots as shown in figure 6. The data were obtained by extrapolating to zero pressure to determine a best fit through the four pressure data points and the origin. The number 1330 is included in the denominator of equation (2) to convert from torr pressure units to dynes/cm^2 pressure units.

From the data in table II, there appears to be a considerable difference between the average magnitude of cross sections for the 9-eV ion energy and average cross sections obtained for the other ion energies. The behavior of the cross sections at low ion energy (9 electron volts) shows the typical resonant charge-transfer structure where the cross sections appear to increase with a decrease in ion energy. Typically, this structure has been reported in the literature, where specific control of ion-state excitation was not studied. In this work it can be stated with reasonable certainty that only ground-electronic-state ions $\left(X^2\Sigma_g^+\right)$ could have been involved in the charge-transfer process at the lowest ϕ_{EE} value of 14.5 electron volts. It is known that the threshold for the ground-electronic-state ion is about 15.63 electron volts. (See refs. 22 and 39.) It should be noted that the data show ϕ_{EE} values slightly below the apparent threshold for the N_2^+ ground-state ion. In figures 4 and 5 the offset error associated with the characteristic operation of the electron-impact-type ion source is shown. This offset error was taken to be approximately 1 electron volt where the steep slope of the graph is extrapolated to a $\phi(\text{app})_{EE}$ value of 14.5 electron volts. The characteristic long tail (ref. 53) shown in the vanishing-current measurements of figures 4 and 5 is attributed to nonmonoenergetic electrons being emitted from the hot filament and illustrates the fact that the electrons come off the filament with a distribution of energies.

It is apparent from the preceding discussion that there is a small uncertainty in the assumed values of ϕ_{EE}; however, the low ϕ_{EE} value is separated

from the next ϕ_{EE} value by an energy spread of approximately 2.6 electron volts. Thus, all data reported at the low ϕ_{EE} value involved only ground-electronic-state ions and the data at the other ϕ_{EE} values involved some excited state ions ($A^2\pi_u$) whose lifetime is on the order of 12 μsec, long enough to be involved in the charge-transfer process. In this work special efforts were made to look for differences in the structure of the charge-transfer curves that could be attributed to ion-beam-state excitation. A study of our data for both low and high ϕ_{EE} does not give any supporting evidence that contributions of excited-state ions make any significant difference. If there were differences, they were too low to have been detected in this work.

An exact comparison of this work with others could not be made because in most cases, ϕ_{EE} was not reported. Where ϕ_{EE} was reported only one value was given. Tabulated results of other investigations are given in table III along with the cross section determined in this work. A composite plot of all data for this work is shown in figure 7 for comparison with the experimental results of other investigations given in table III, along with some additional experimental cross sections. Ghosh and Sheridan (ref. 54) stated that their data included N_2^+ ions in the ground state when leaving their Heil-type ion source. The pressure in their collision chamber was measured with a Knudsen gauge to be 17×10^{-5} torr. The electron energy in the ion source of Stebbings, Turner, and Smith (ref. 3) was 200 electron volts. Nichols and Witteborn (ref. 10) measured cross sections at low ion energies of less than 17.3 electron volts. The electron energy in their ion source was 95 electron volts, and their reaction-chamber pressure was varied between 0.1×10^{-5} and 80×10^{-5} torr. Lehrle et al. (ref. 2) studied charge-transfer cross sections for a ϕ_{EE} value of 25 electron volts and collision pressure of 2×10^{-5} torr, measured with an ionization gauge. Homer et al. (ref. 6) obtained their data using 70 electron volts of electron energy and collision pressures not quoted. The data of Gustafsson and Lindholm (ref. 55) was taken at a collision pressure of 17×10^{-5} torr, but ϕ_{EE} was not given. Utterback and Miller (ref. 1) used 22-eV electrons in their ion source, and the pressure in their collision region was 20×10^{-5} torr. Potter (ref. 11) claims to have only ground-state ions in his incident beam, although this might be doubtful since his ion source was operated at 75 electron volts. In the experimental results of Leventhal et al. (ref. 13), no information was given about ϕ_{EE} or collision chamber pressure.

In figure 8, a comparison of the present results is made with theoretical calculations of Flannery et al. (ref. 12) and Leventhal et al. (ref. 13). The full multistate treatment and low-velocity approximation were calculated in reference 12 using the distribution of vibration levels in the incident-ion beam corresponding to an electron excitation energy of 22 electron volts. Additional calculated cross-section data from reference 13, using the impact parameter method, is also shown in figure 8. The results of Moran et al. (ref. 14) are shown in figure 8. They obtained much lower values of cross sections using the multistate impact parameter method (ref. 12) to obtain data for individual channels and integral cross sections summed over all product channels. Theoretical cross sections were obtained as a function of the square root of incident-ion kinetic energy for nitrogen when both incident-ion and target

neutrals were in the ground-electronic and vibrational states and the resultant product neutrals and ions in vibrational states (ν'', ν') equal (0, 1), (1, 0), and (0, 2) for the total excitation products. Moran et al. also obtained theoretical cross sections for total vibration excitation with the incident ion in the ground-electronic state $\left(N_2^+\left(X^2\Sigma_g^+\right)\right)$ and vibrational state (0, 1, 2, 3), with the target neutral in the ground-electronic and vibrational states $\left(N_2\left(X^1\Sigma_g^+,\ \nu = 0\right)\right)$ as a function of incident-ion kinetic energy. The cross sections obtained were less than 10×10^{-16} cm^2 for incident-ion energies larger than about 75 electron volts.

The cross-section data obtained from this work agree reasonably well with the results of other investigations for the N_2^+-N_2 system. There is reason to believe that a higher level of confidence can be placed in the present results since special emphasis was placed on details such as the pressure measuring technique in CTC and calibration of relative error in the ϕ_{EE} energy scale to determine when ground-state and excited-state ions were involved in the charge-transfer process.

CONCLUSIONS

(1) $\sigma\left(N_2^+ + N_2 \rightarrow N_2 + N_2^+\right)$ values were determined to be in the range of 25 to 33 $Å^2$.

(2) At the energies used in the present study, internal excitation of the N_2^+ beam, if present, did not affect the $\sigma\left(N_2^+ + N_2 \rightarrow N_2 + N_2^+\right)$ values.

(3) The cross-section values obtained in the present study agree with the reported values, even though a determined effort was made to detect the effects of N_2^+ internal excitation on $\sigma\left(N_2^+ + N_2 \rightarrow N_2 + N_2^+\right)$.

(4) The fractional error in $\sigma\left(N_2^+ + N_2 \rightarrow N_2 + N_2^+\right)$ values was found to be in the range of 6 percent $< \frac{\Delta\sigma}{\sigma} <$ 17 percent. Calculated errors were based solely on measurement errors in individual parameters.

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September 26, 1979

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TABLE I.- EXPERIMENTAL DATA FOR THE FUNCTION $\ln (1 - I_{CT}/I(x = 0))$ AND SELECTED VALUES OF ELECTRON ENERGY, ION ENERGY, AND PRESSURE IN THE CTC

Electron energy, eV	Ion energy, eV	p_{CTC}, 10^{-5} torr	$\ln\left(1 - \frac{I_{CT}}{I(x = 0)}\right)$
14.5	9	16.6	-0.0651
	36		-.0758
	81		-.0704
	144		-.0736
	225		-.0704
	324		-.0758
	441		-.0790
17.1	9	16.6	-0.0704
	36		-.0736
	81		-.0747
	144		-.0758
	225		-.0736
	324		-.0704
	441		-.0758
20.1	9	16.6	-0.0650
	36		-.0704
	81		-.0683
	144		-.0578
	225		-.0736
	324		-.0758
	441		-.0790

TABLE II.- CHARGE-TRANSFER CROSS SECTIONS

FOR THE N_2^+-N_2 SYSTEM

Ion energy, eV	Electron energy, eV	σ, cm^2
9	14.5	24.0×10^{-16}
	17.1	24.9
	20.1	22.6
	24.1	33.9
	26.1	38.6
	28.1	40.3
	30.1	36.3
	32.1	39.5
36	14.5	26.5×10^{-16}
	17.1	24.5
	20.1	24.3
	24.1	26.4
	26.1	26.0
	28.1	24.1
	30.1	24.5
	32.1	26.0
81	14.5	23.7×10^{-16}
	17.1	24.5
	20.1	25.2
	24.1	26.0
	26.1	26.0
	28.1	25.6
	30.1	24.9
	32.1	25.4
144	14.5	27.4×10^{-16}
	17.1	25.6
	20.1	26.0
	24.1	25.4
	26.1	26.4
	28.1	25.6
	30.1	25.0
	32.1	25.4

TABLE II.- Concluded

Ion energy, eV	Electron energy, eV	σ, cm^2
225	14.5	25.6×10^{-16}
	17.1	27.7
	20.1	27.9
	24.1	23.3
	26.1	25.8
	28.1	25.8
	30.1	25.0
	32.1	26.0
324	14.5	27.5×10^{-16}
	17.1	27.1
	20.1	27.3
	24.1	25.4
	26.1	27.0
	28.1	26.2
	30.1	25.0
	32.1	25.0
441	14.5	27.5×10^{-16}
	17.1	28.1
	20.1	28.1
	24.1	27.0
	26.1	27.7
	28.1	25.8
	30.1	26.0
	32.1	26.7

TABLE III.- COMPARISON OF CHARGE-TRANSFER CROSS SECTIONS

FOR THE N_2^+-N_2 SYSTEM FROM SEVERAL SOURCES

Ion energy, eV	σ, cm^2		Electron energy, eV	Reference
	Calculated	Experimental		
0.5	----------	96.7×10^{-16}	95	10
1	39.0×10^{-16}	39.1	----------	13
6	----------	36.9	95	10
9	----------	36	75	11
9	----------	34.7	95	10
9	----------	[a]32.5	14.5 to 32.1	This work
10	----------	23.1	----------	13
17	----------	34.8	95	10
20	31.0	22.7	----------	13
32	45.4	----------	----------	12
36	----------	[a]25.3	14.5 to 32.1	This work
50	26.4	21.7	----------	13
81	----------	[a]25.2	14.5 to 32.1	This work
100	----------	26.8	22	1
144	----------	[a]25.8	14.5 to 32.1	This work
150	----------	27	----------	11
150	----------	30	----------	14
150	----------	28	200	3
150	----------	24	----------	4
150	----------	28	25	2
150	----------	33	70	6
156	36.73	----------	----------	12
225	----------	[a]25.9	14.5 to 32.1	This work

[a]Average values.

TABLE III.- Concluded

Ion energy, eV	σ, cm^2		Electron energy, eV	Reference
	Calculated	Experimental		
250	-----	21	75	11
324	-----	[a]26.3	14.5 to 32.1	This work
400	38.7	-----	----------	12
400	-----	26	----------	11
400	-----	29	50	2
400	-----	19	----------	4
400	-----	24	25	2
400	-----	27	----------	14
400	-----	26	200	3
441	-----	[a]27.1	14.5 to 32.1	This work
625	-----	26	22	1
733	31.38	-----	----------	12
900	-----	26	----------	11
900	-----	23	----------	14
900	-----	23	200	3
900	-----	29	75	6
900	-----	22	25	2
1000	-----	26	22	1
1175	24.21	-----	----------	12
1225	-----	28	70	6

[a]Average values.

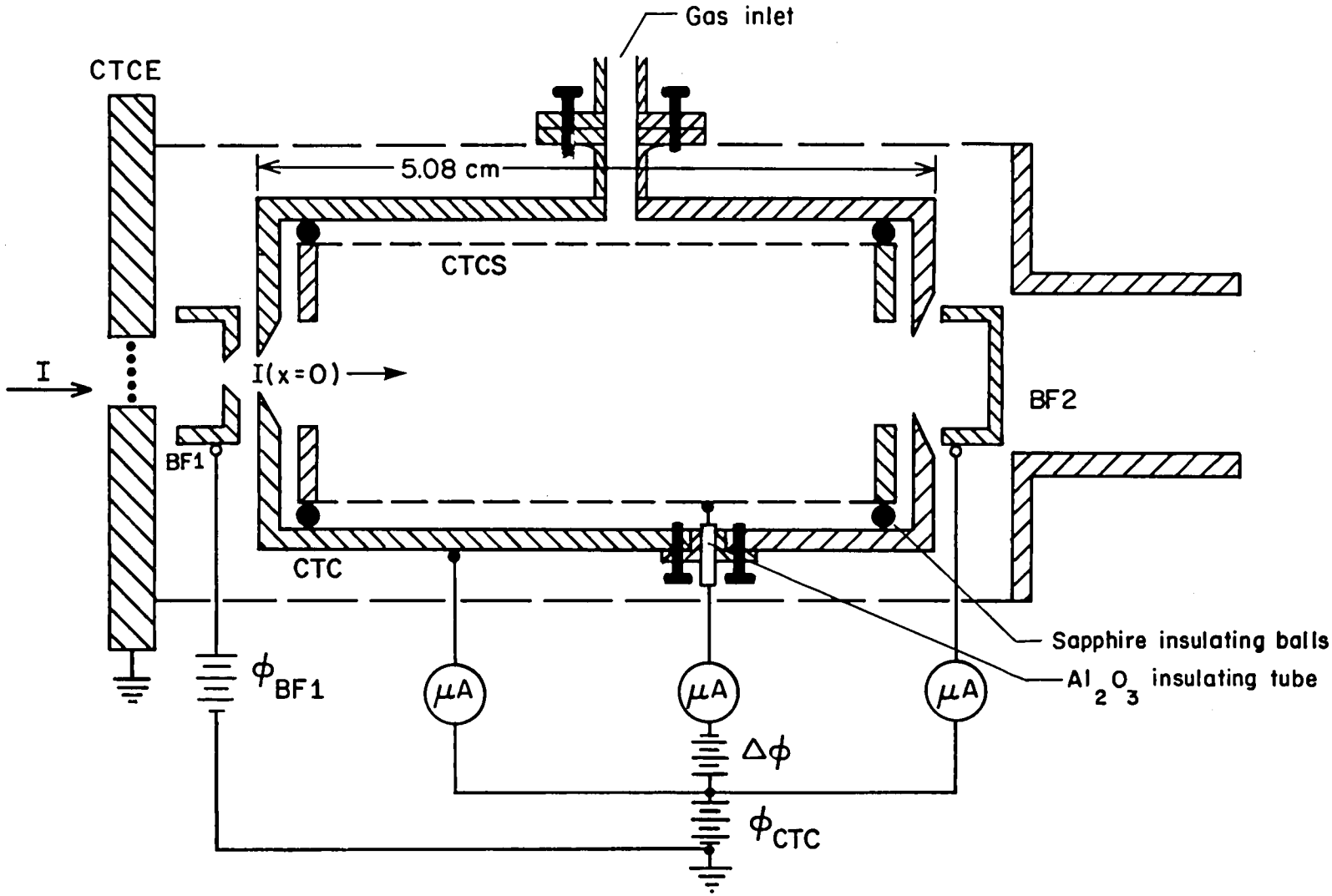

Figure 1.- The ion detection and collection system.

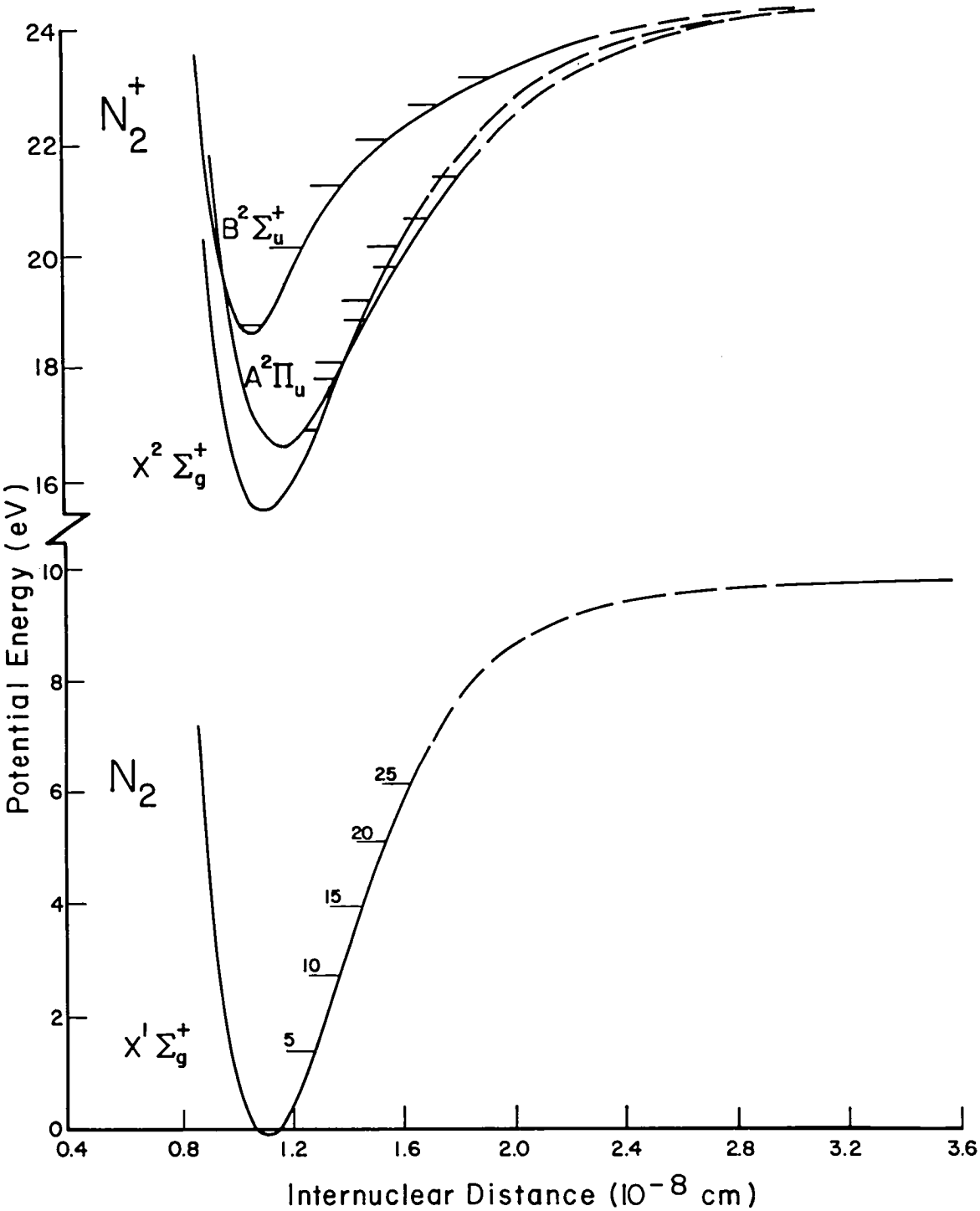

Figure 2.- Potential-energy curves for N_2^+ and N_2.

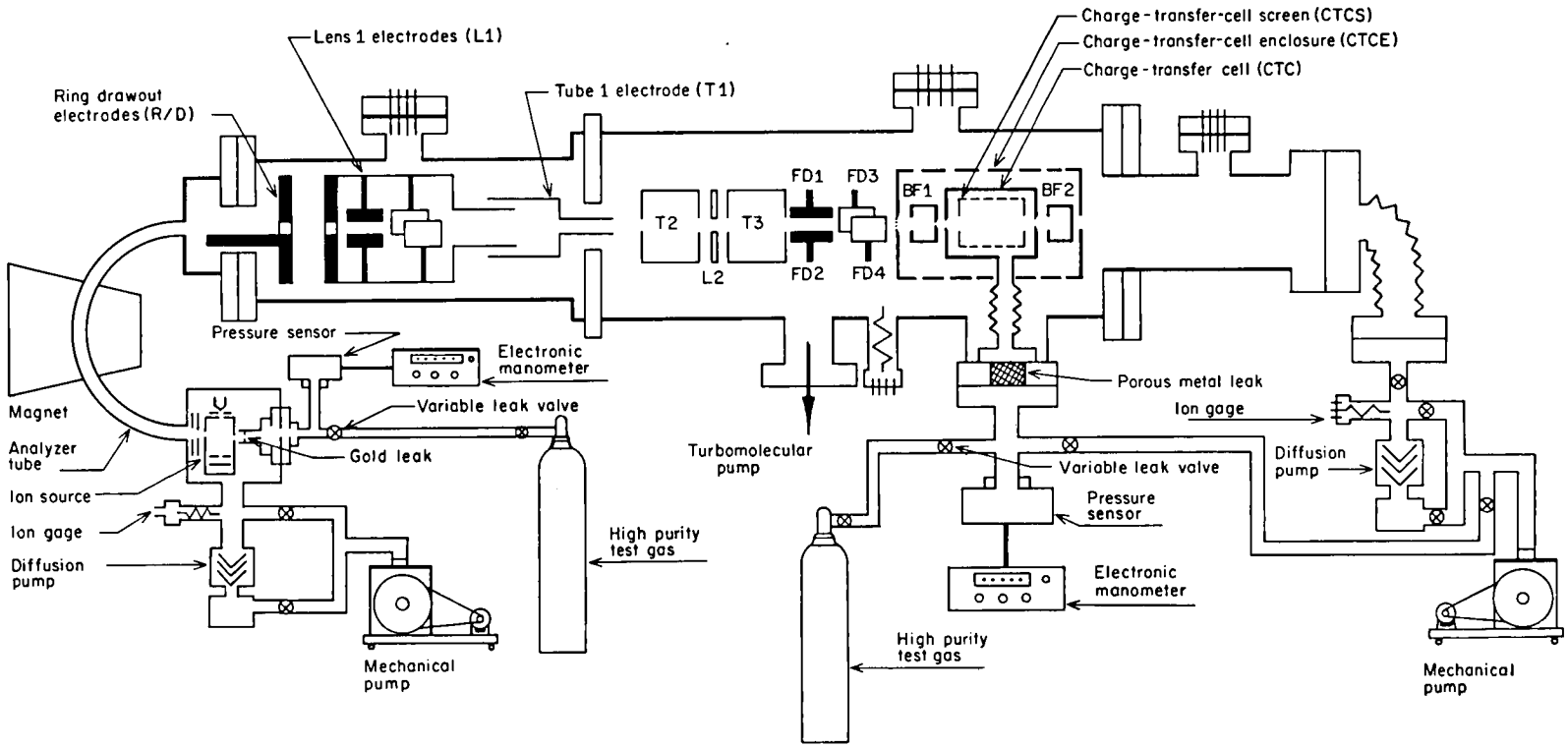

Figure 3.- Schematic diagram of total system.

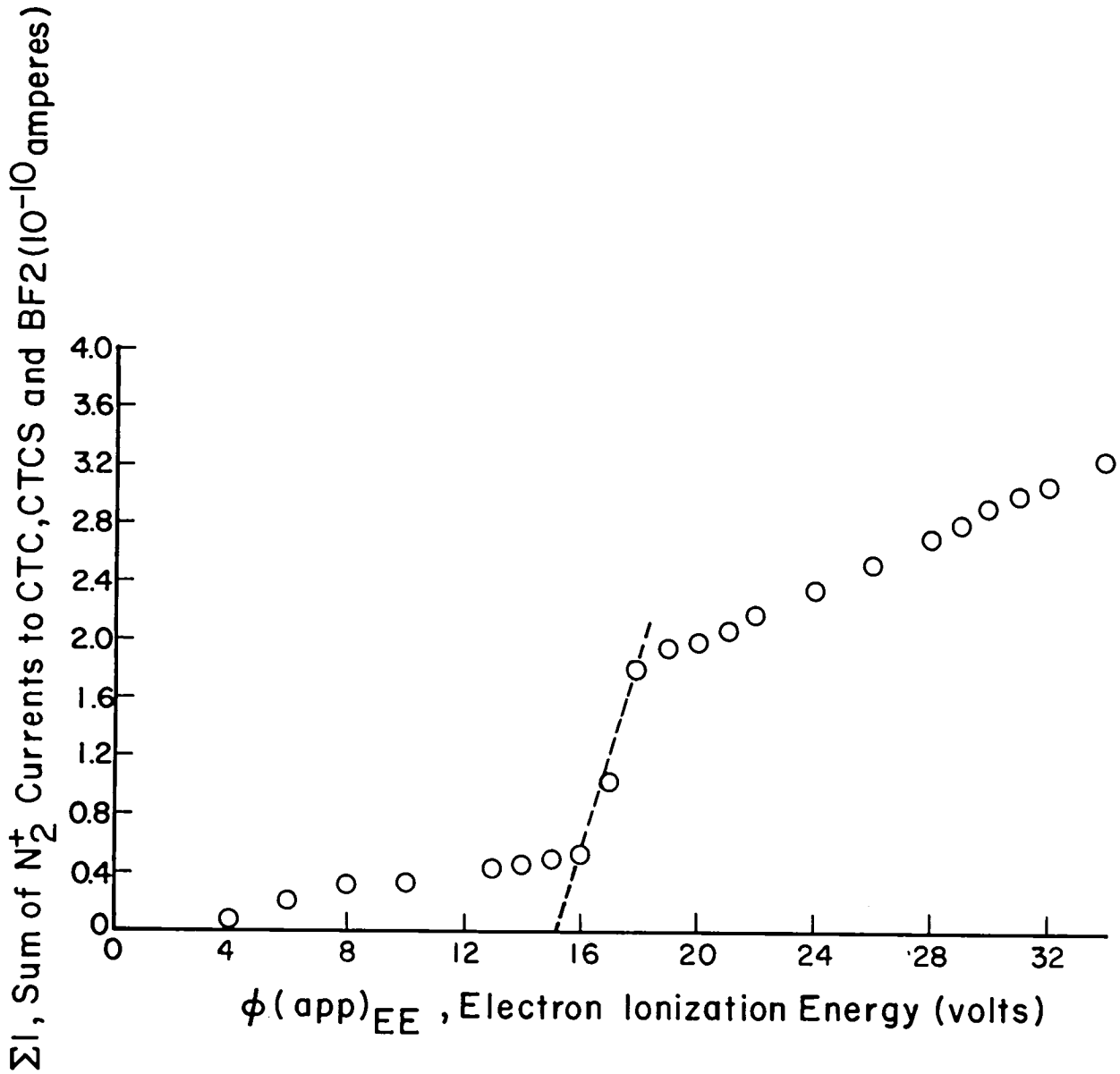

Figure 4.- Vanishing-current measurement for N_2^+ ion current at the CTC position versus $\phi(app)_{EE}$.

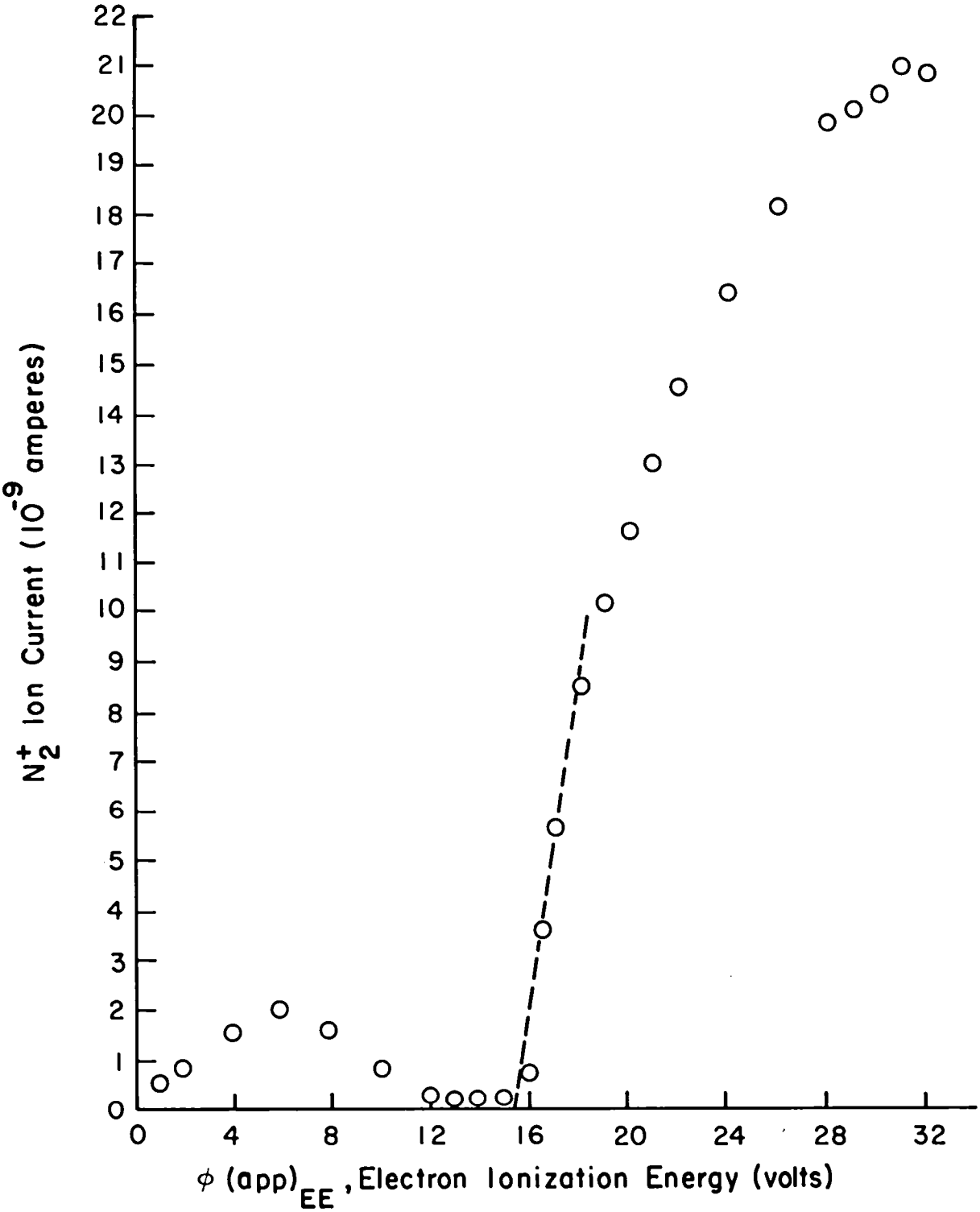

Figure 5.- Vanishing-current measurement for N_2^+ ion current at the mass-spectrometer position versus $\phi(app)_{EE}$.

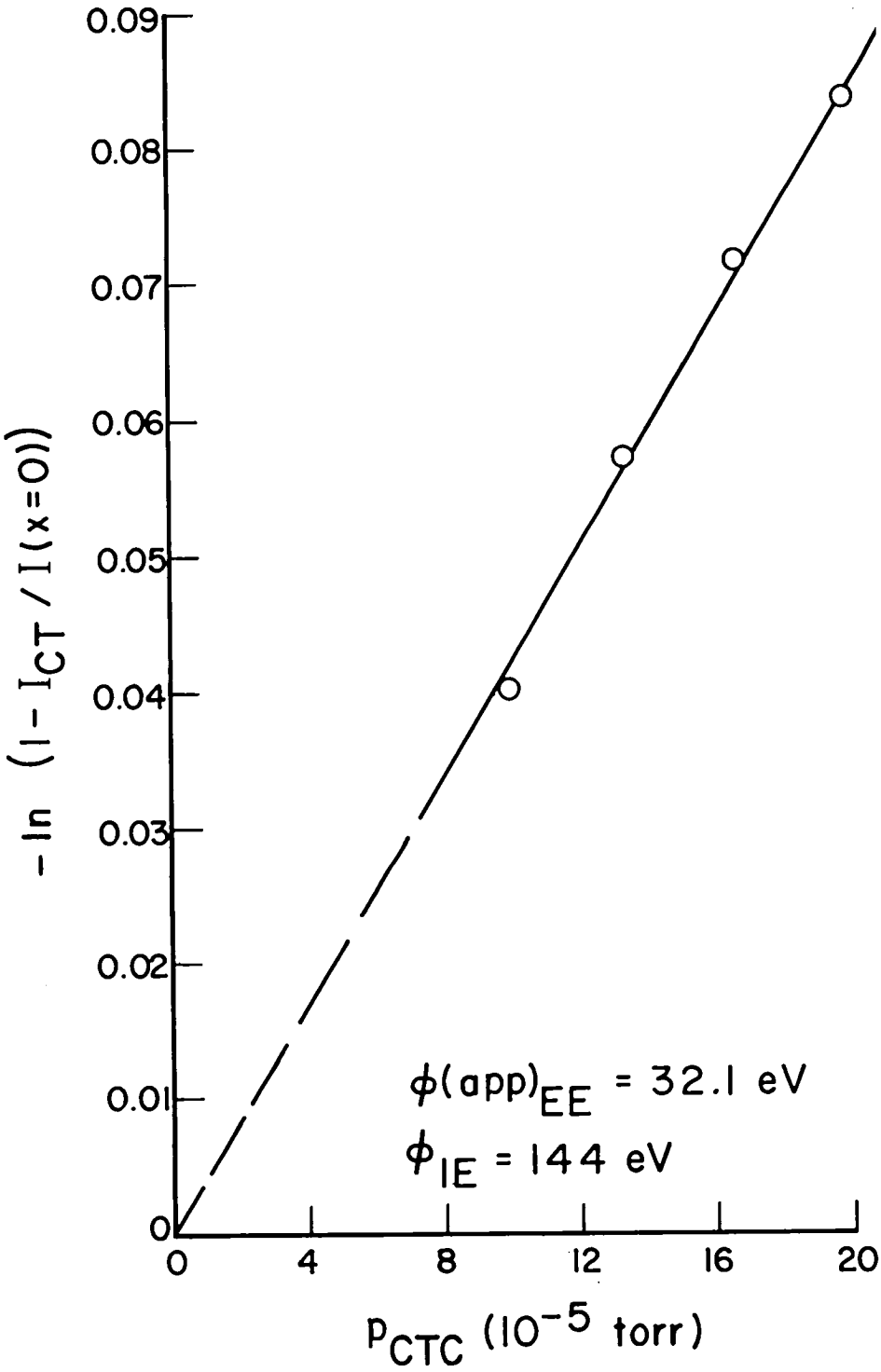

Figure 6.- Typical plot of the function -ln (1 - $I_{CT}/I(x = 0)$) versus pressure in the CTC.

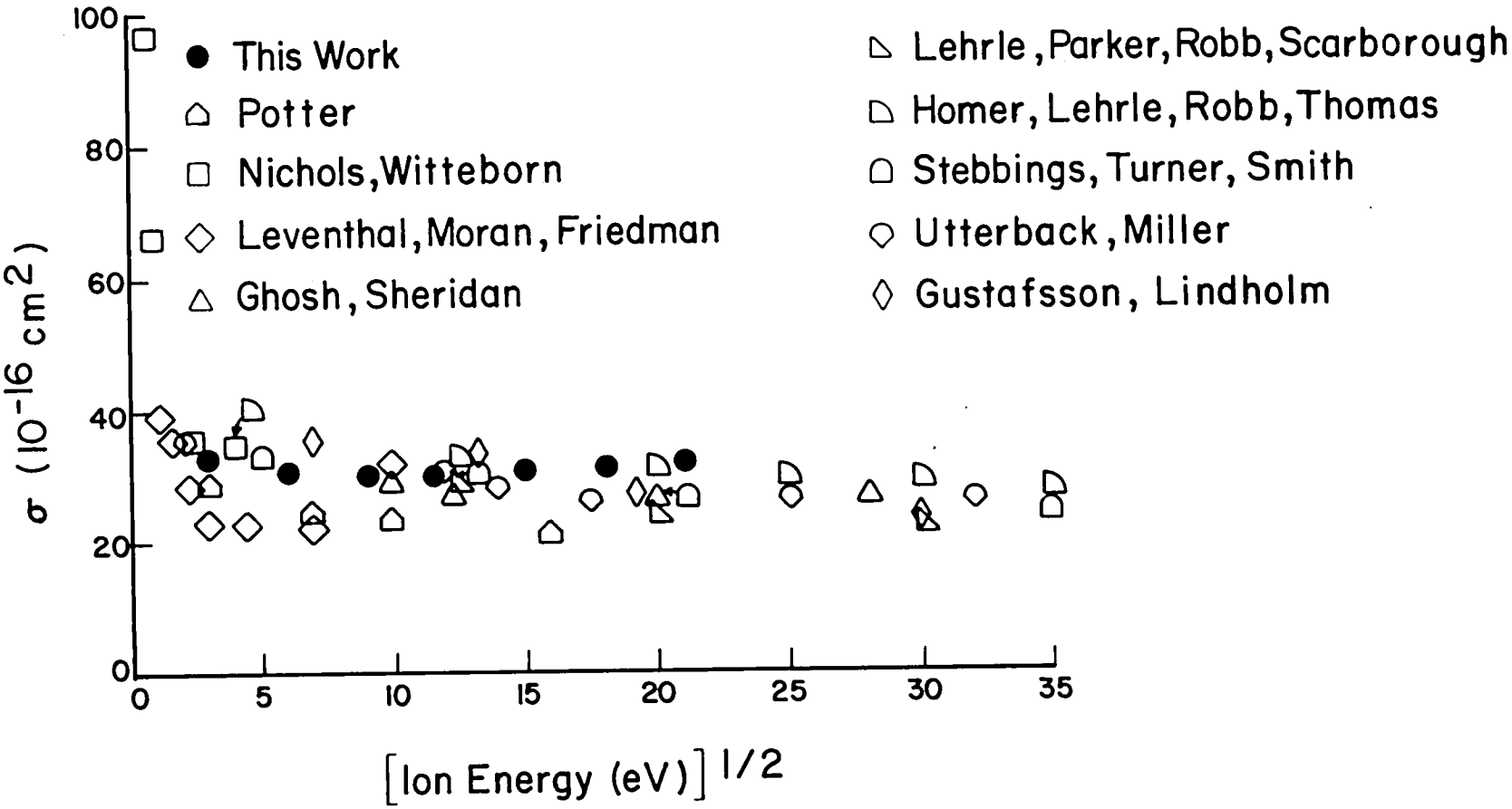

Figure 7.- Comparison of σ in this work with experimental results of other investigations.

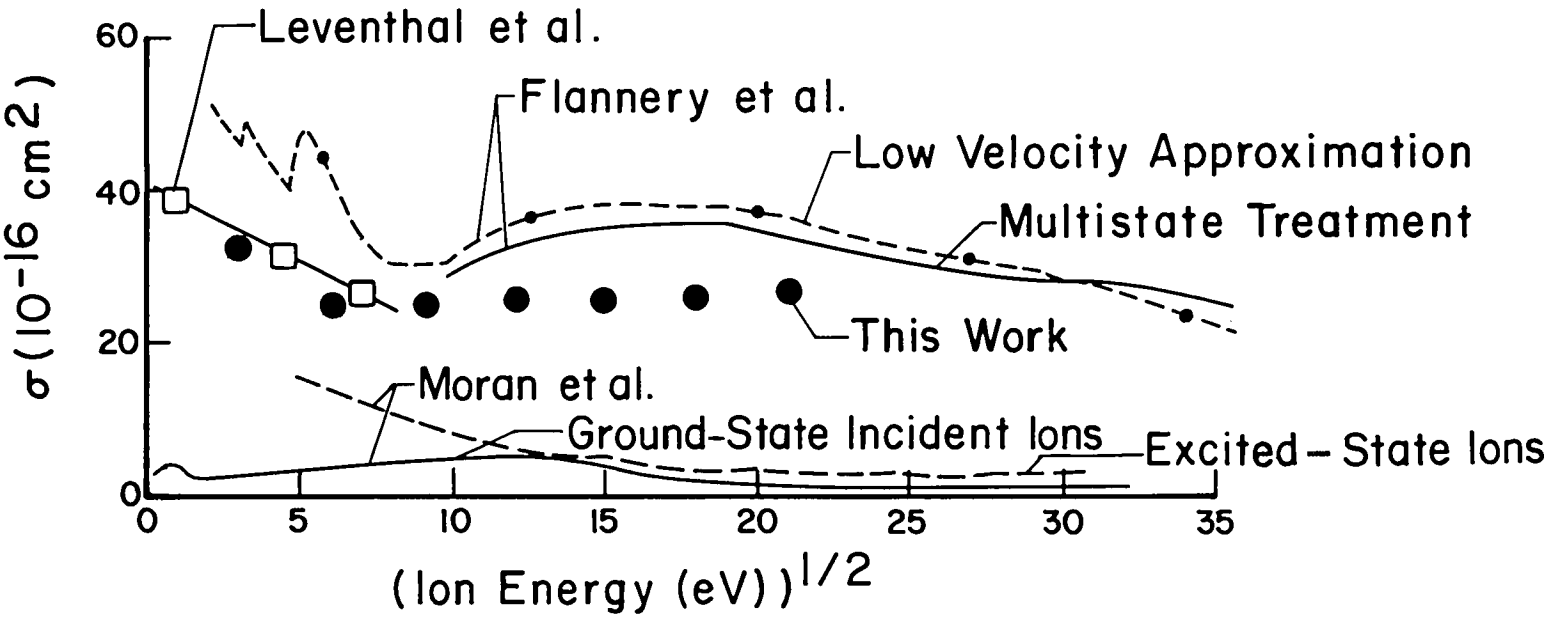

Figure 8.- Comparison of σ in this work with theoretical calculated results of other investigations.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-80156		

4. Title and Subtitle	5. Report Date
EXPERIMENTAL STUDY OF LOW-ENERGY CHARGE TRANSFER IN NITROGEN	November 1979
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Alphonsa Smith	L-13246
	10. Work Unit No.
9. Performing Organization Name and Address	146-20-10-04
NASA Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Total charge-transfer cross sections have been obtained for the N_2^+-N_2 system with relative translational ion energies between 9 and 441 eV. Data were obtained to examine the dependence of total cross section on ion energy. The effect of ion excitation on the cross sections was studied by varying the electron ionization energy in the mass-spectrometer ion source over an electron energy range between 14.5 and 32.1 eV. The dependence of total cross section on the neutralization chamber gas pressure was examined by obtaining data at pressure values from 9.9 to 19.9×10^{-5} torr. Cross-section values obtained were compared with experimental and theoretical results of other investigations.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Charge transfer Mass spectrometer Current measurement Molecular beams Ion beams	Unclassified - Unlimited Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	30	$4.50

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NASA-Langley, 1979