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CONDUCTIVITY OF CESIUM-SEEDED ATMOSPHERIC PRESSURE PLASMAS NEAR THERMAL EQUILIBRIUM

by

L. P. Harris

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ABSTRACT

Measurements have been made of the electrical conductivities of gaseous mixtures formed by the addition of small fractions of cesium vapor to nitrogen, helium, neon, or argon. The mixtures studied were maintained near thermal equilibrium at temperatures in the 1500° to 2000°K range and a total pressure of 1 atm. The cesium vapor pressures ranged over two decades, from 0.1 to 10 torr.

The apparatus consists, in essence, of two heated zones connected by a slow flow. The first zone is a low-temperature (200° to 400°C) oven where the body-gas flow picks up the cesium vapor. The second zone is a small electrically heated furnace (1250° to 1850°C) containing a diode test section.

The principal measurements taken were the seeding temperature, furnace temperature, and voltages and currents in the test section.

The results exhibit variations with temperature, seeding pressure, and gas species that correlate reasonably well with simple theory and values for electron collision frequencies and cross sections taken from the literature.

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I. INTRODUCTION

Because mixtures of common gases seeded with small fractions of an easily ionized metal vapor are being used widely in experiments directed toward magnetohydrodynamic propulsion and power generation, there is considerable interest in the electrical conductivities of such mixtures, both at thermal equilibrium and also when subject to strong electric fields. Mullaney and co-workers[1, 2] have performed an extensive survey of equilibrium conductivities in hydrogen-oxygen and propane-oxygen combustion flows seeded with water solutions of various compounds of the alkali and alkaline-earth metals. Rosa[3] has reported on the conductivities obtained by seeding kerosene-oxygen combustion products with potassium compounds. Kerrebrock,[4] BenDaniel and Bishop,[5] and Lapp and Rich[6] have described experiments directed at measurements of extrathermal contributions to the conductivities in a potassium-seeded argon flow, a helium-cesium diode at breakdown, and potassium-seeded flames, respectively. An apparatus for studying the conductivity of cesium-seeded inert gases and some preliminary measurements have been described by Ralph.[7] The theoretical basis for calculating conductivities at thermal equilibrium has been treated by Frost;[8] the extrathermal effects have been discussed by Kerrebrock[4] and by Hurwitz, Sutton, and Tamor.[9]

Despite the large efforts expended in these and other works, there still remains an uncertainty of one to two octaves in the values of equilibrium conductivities, and measurements of the extrathermal effects still are in an early stage. There are questions concerning the effects of electron attachment to OH radicals and the loss of alkali-metal seed by the formation of alkali hydroxides; these have not been apparent in measurements on flame gases even under conditions where theoretical calculations indicated reductions in conductivities by factors of two or three. There also are major discrepancies between the values of electron collision cross sections, especially those of the alkali metals, used by recent experimenters in correlating their conductivity data and the cross sections that have resulted from measurements in beam and drift tubes over the past 30 years.

II. EXPERIMENTAL APPARATUS

The present experiments were undertaken to provide data on the conductivities of cesium-seeded inert gas plasmas and to provide equipment in which extrathermal augmentation of conductivity could be studied. The apparatus is sketched in Fig. 1. In essence, it consists of two connected hot zones, a seeding oven (200° to 400°C) and the main furnace (1250° to 1850°C) through which passes a small flow of gas (about 1 cc/sec). The body gas under study attains seeding temperature in a copper coil near the entrance to the seeding oven, is seeded with cesium, and then flows on to the main furnace. The test section in the main furnace is cylindrical in shape, bounded on the side by a Lucalox alumina tube and

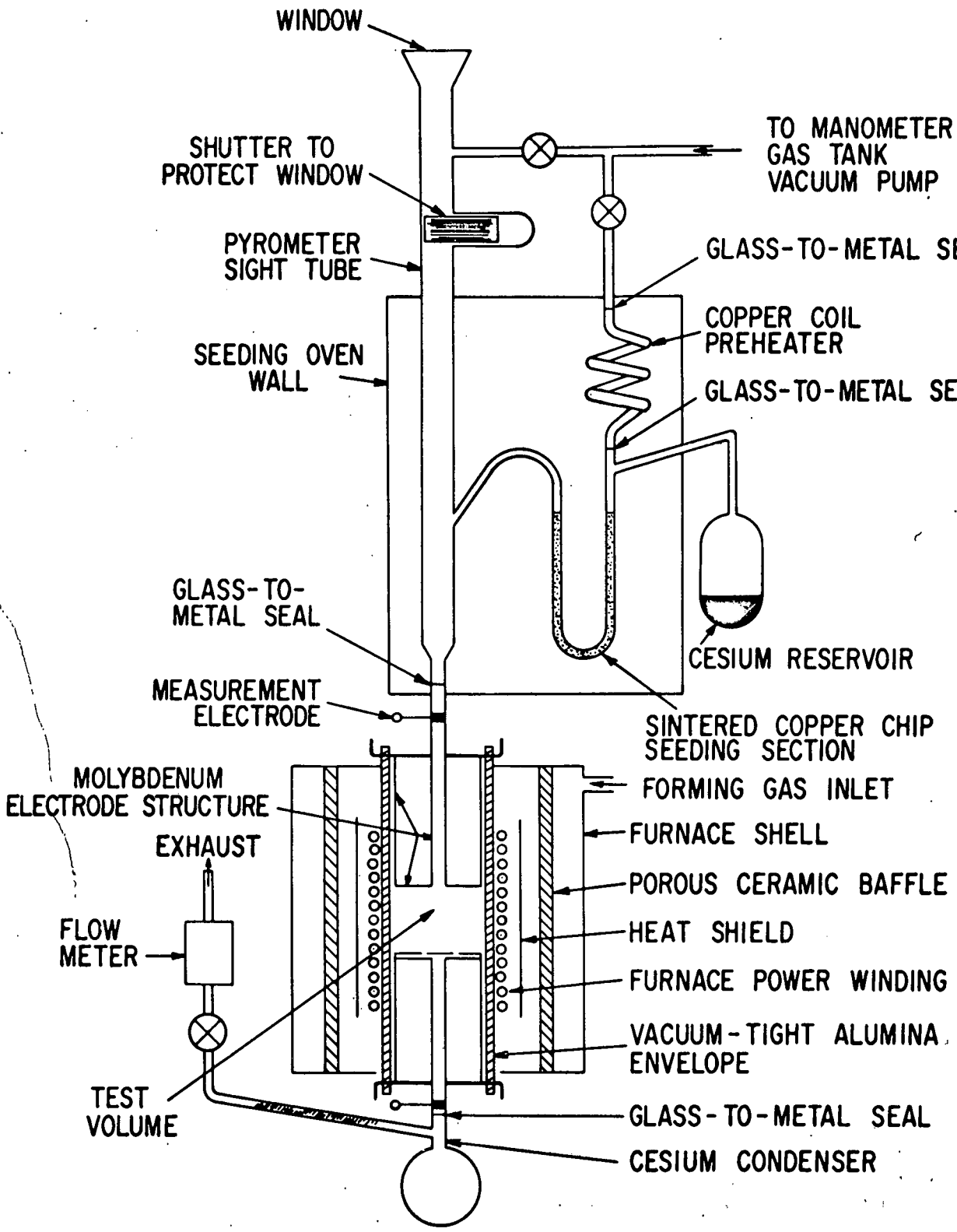

Fig. 1 Sketch of apparatus (not to scale).

on top and bottom by molybdenum electrodes. Two sizes of test section have been used; 1/2 inch in diameter by 1 inch long, and 3/4 inch in diameter by 1 1/2 inches long. The seeded gas flows in through a small hole in the center of the top electrode and out again, after a dwell time that typically is 5 to 20 seconds, through several baffled holes in the bottom electrode. The cesium vapor condenses in a cool zone at the furnace exit and the body gas discharges to the atmosphere.

The seeding oven consists of a volume approximately 4 by 9 by 14 inches heated by three formed resistive heaters, each of which is driven separately to establish the desired temperature distribution in the oven. Thermocouples indicate temperatures at six points in the oven along the gas flow path. Figure 2 is a photograph of a seeding oven with the cover carrying the heating units removed. Except for the preheating coil near the oven inlet, which is made of about 5 feet of nickel-plated 1/8-inch-diameter copper tubing, the major structural material in the flow path is glass tubing. The seeding section consists of a U-bend of this tubing about 12 inches long filled with cleaned and lightly sintered copper chips. When cesium is distilled into this unit, it tends to wet the copper chips and spread more or less uniformly throughout the copper matrix, thus providing a large surface of liquid cesium in contact with the gas flow. This type of seeding unit, which also has been used with cesium and potassium in static systems, has several advantages: because of the high thermal conductivity of the copper matrix, the seeding unit is nearly isothermal; because of the large surface-to-volume ratio it provides, the seeding is accomplished quickly and with a relatively small investment in alkali metal; because there is no bubbling or splashing in the seeding unit, the danger of the gas carrying off droplets of seed is minimized. In a series of tests covering the range of gas flow rates and seeding temperatures used in these experiments, we found that the amount of cesium carried away from the seeding section by inert-gas flows could be predicted to within 20 per cent from readings of gas flow rate and seeding temperature. This accuracy is about as good as that of our flow-rate measurement.

The construction of the main furnace is shown in Figs. 1 and 3. Its major structural element is a 1-inch OD by 1/8-inch wall by 10-inch-long alumina tube. On this tube is wound 12 feet of 0.025-inch-diameter molybdenum wire in a furnace winding 4 inches long that is coated with alumina cement. The pitch between turns is varied to give a winding density near the ends of the winding about twice that in the center and a resulting temperature distribution that is nearly uniform within the middle half of the winding. At the ends of the Lucalox tube are butt seals to Fernico metal assemblies that are brazed and spot-welded to the molybdenum electrode assemblies within the furnace and fastened outside through oxide-free seals to the glass tubes coming from the seeding oven and going to the cesium condenser. The electrode assemblies consist of circular molybdenum-sheet electrodes mounted at the ends of 3/16-inch-diameter molybdenum tubes, which serve both as electrical connections and as a flow channel, with added stiffness and heat shielding provided by cylindrical skirts formed from 0.005-inch molybdenum sheet.

Minor modifications of the structure just described have been and are being used. One of these is shown in Fig. 3, which pictures a tube partially

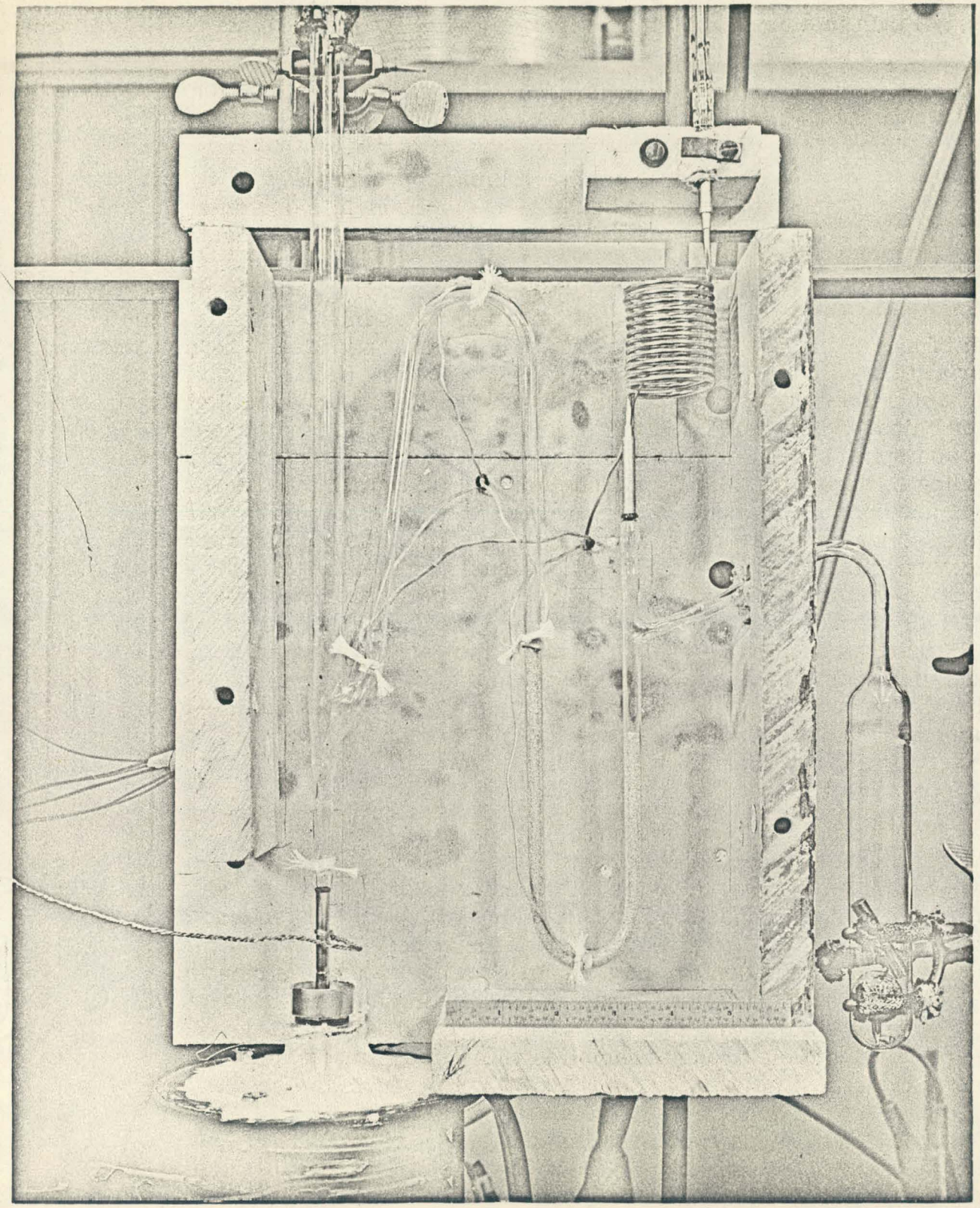

Fig. 2 Seeding oven with cover and heaters removed.

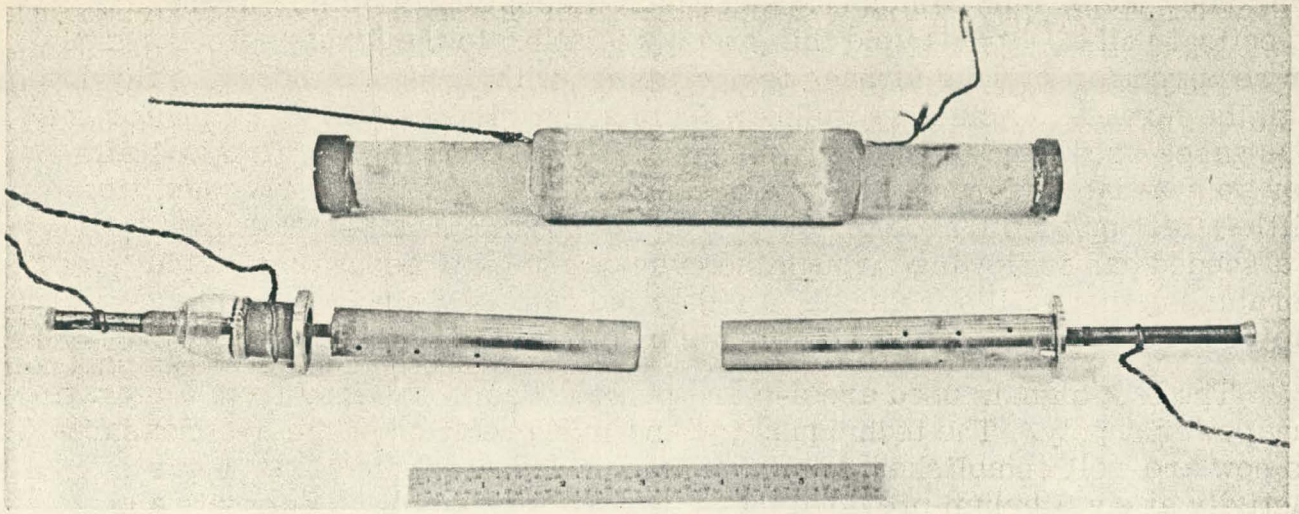

Fig. 3 A partially disassembled furnace tube.

disassembled after 15 weeks of continuous operation. The electrode assembly shown on the left has an extra glass insulator inserted between the Lucalox tube and the measuring lead to permit measurement of any leakage currents along the walls of the alumina tube. These measurements showed that those leakage currents always were negligible in our experiments. Another modification currently in use consists in the provision of two electric probes, for measuring voltage gradient, within the test volume.

The furnace assembly is mounted within a system of two ceramic heat shields and a water-cooled brass casing through which flows a protective atmosphere of forming gas. With this arrangement the life of the main furnace is about 3 to 4 months, limited by the life of the copper brazes or the molybdenum furnace winding. The life of the seeding oven is not known, for we have not yet had any failures in this section. Ordinarily the seeding unit is replaced each time a new charge of cesium is introduced into the system, about every 4 weeks.

III. EXPERIMENTAL MEASUREMENTS

The measurements taken are the voltage and current to the test section, the voltage and current to the furnace winding, the seeding temperature, the test-cell temperature, and the gas flow rate. Additional temperatures are monitored to assure that the temperature of the flow increases steadily after leaving the seeding unit. Flow rates in the range 0.3 to 3.0 cm^3/sec give similar results for the impedance of the test cell. Higher impedances are associated with flow rates outside this range, presumably because excessive amounts of cesium seed are lost by chemical reaction with the walls at lower flow rates, and because the flow does not attain full furnace temperature at the higher flow rates. The temperature of the test cell is measured by sighting an optical pyrometer down the flow bypass and pyrometer sight tube shown in Fig. 1 through the hole in the top electrode onto the surface of the lower electrode. Although this arrangement provides approximately black-body conditions at the port to the

test cell, substantial errors in this measurement (over 100°C) due to optical absorption by the cesium dimer Cs_2 can occur if cool cesium vapor is present in the optical path.[10] To avoid this error we calibrate the furnace for the input power required for various furnace temperatures with unseeded body gas flowing through the furnace. Actually, we know from comparisons of calibrations for the various gases used, and from comparisons of calibrations for gas flow at 1 atm and for an evacuated furnace, that the presence of the flow in normal quantities has little effect on the furnace temperature. Although pyrometer readings taken when a seeded gas is flowing through the oven do not give accurate furnace temperatures, they still are useful, for they indicate well changes in the thermal characteristics of the main furnace or in the operation of the seeding oven.

The test signals used are d-c and pulse voltages obtained from a storage-battery power supply. The techniques for and interpretation of the d-c measurements now are well established; they give fairly accurate indications of gas conductivity at equilibrium provided that we restrict attention to currents and voltages well below those causing electrode current saturation or extra heating of the gas. The pulse measurements are not as well established but eventually should provide more information. From oscilloscope photos of pulse responses we can get values for "conductivities" as a function of bulk gas temperature and electric field strength or current density. In addition, we hope to get good values for electron temperature and average ionization frequency in both equilibrium and nonequilibrium conditions. Because these pulse measurements still are in an early stage, however, the remainder of this report is confined to the techniques and results of the d-c measurements.

IV. PROCEDURE

Once the system is assembled, the discharge valve at the outlet of the cesium condenser is closed, the valves permitting flow through and around the seeding oven are opened and the entire system is pumped down by a conventional vacuum system to pressures of about 10^{-5} torr for leak testing. Once vacuum tightness is assured, the seeding oven and main furnace are turned on and their temperatures gradually raised while the system pressure is held at a few microns. When the furnace temperature reaches 1400°C, the vacuum is replaced by a flow of the gas to be studied at 1 atm pressure, and the furnace then heated to and held at a temperature somewhat above the highest to be used in the current measurements, usually about 1750°C. The main furnace temperature is then reduced below 1400°C, the system evacuated again, and the seeding oven given a final bakeout at 425°C while exposed lines are torch heated. Next,cesium is distilled into the seeding unit, the gas flow is started again, and the system is readied for measurements. When this procedure is followed, the purity of the gas flow should be limited principally by the purity of the compressed-gas source.

V. EXPERIMENTAL ERRORS

The basic data from these experiments consist of tables of voltage V applied to the test section and the resulting current I over a range of voltage magnitudes from perhaps 30 millivolts to perhaps 10 volts. Both positive and negative voltages of each magnitude are applied and the resulting currents averaged to yield V-I plots that are not affected by the small (about 50 mv)

d-c voltages generated within the cell because of residual thermal asymmetry. These curves invariably have a linear range at low voltages and currents and a nonlinear region at higher voltages and currents. In the nonlinear region, the incremental conductance $\partial I/\partial V$ may either increase, presumably because either the test gas or the free electrons are being heated by the discharge, or it may decrease, presumably because of thermionic current saturation at the cathode. Because of the high emission capability of molybdenum in the presence of cesium vapor, the former usually occurs first. Eventually, if the voltage applied is made too large, the discharge develops into an arc.

From the linear portion of the V-I characteristic, we compute a gas conductivity from the simple formula

$$\sigma = \frac{I}{V} \quad \frac{\ell}{A}$$

where ℓ and A are the length and cross-sectional area of the test section. Because the current and voltage measurements are accurate to perhaps 2 per cent and the tube dimensions are well known, this process gives accurately a gas conductivity, provided that the gas within the discharge space is uniform in temperature and composition. Our seeding technique assures uniform composition; temperature measurements along the axis of the test cell have indicated that the gas temperature is uniform to within 5°C. The most significant errors arise, therefore, when we try to relate these values of conductivity to specific furnace temperatures and seeding pressures.

Reading errors in the pyrometric measurements of T_F, the temperature of the main furnace, are estimated at 10° to 15°C over the 1500° to 2000°K interval where we took most of our measurements. The main effect of furnace temperature on electrical conductivity is described by an exponential function $\exp(-eV_i/2kT_F)$, where V_i, e and k are the seed ionization potential (3.89 volts for cesium), the electron charge, and the Boltzmann constant. Thus errors $\Delta\sigma$ in conductivity for the stated temperatures occasioned by errors ΔT_F in furnace temperature measurements are given by

$$\frac{\Delta\sigma}{\sigma} \simeq \left(\frac{eV_i}{2kT_F}\right) \frac{\Delta T_F}{T_F},$$

which yields conductivity errors of 8 to 10 per cent for our conditions.

Errors in seeding pressure may arise from errors in the temperature of the seeding oven or from absorption or release of cesium by reactions with containing walls at any point between the seeding unit and the test cell. The thermocouple measurements of seed-oven temperature can be made with accuracies better than a degree, but because our seeding unit extends over a large area in an oven with deliberately introduced thermal gradients, our measurements of seeding temperatures might contain errors up to about 3°C. Since the seeding

pressure p_s varies with seeding temperature T_s mainly as exp $(- eV_\nu/kT_s)$, where V_ν is the potential (0.813 volt for cesium) corresponding to the heat of vaporization, the effective errors in seeding pressures are related to the temperature errors by

$$\frac{\Delta p_s}{p_s} \simeq \left(\frac{eV_\nu}{kT_s}\right) \frac{\Delta T_s}{T_s} ,$$

which gives maximum errors in seeding pressure of 6 to 12 per cent for our conditions. From visual observation of the glass tubing, from electrical measurements made during thermal transients, and from titration measurements performed upon dismantling the system, we conclude that substantial reductions in seed pressures--perhaps 20 to 30 per cent--can be caused by chemical reaction of the cesium seed with the walls of the system. Because the compounds thus formed are likely to be rather loosely bound, it is possible, during a period when the temperatures in the system are rising, to get some decomposition and recovery of lost seed. This effect can be bothersome when making measurements with increasing temperatures at the lowest seeding pressures, but can be overcome simply by waiting sufficiently long at each temperature for the excess cesium to be flushed away and a steady state established.

To relate the errors in seeding pressure to apparent errors in conductivity, we need some simple theory. The gas conductivity ordinarily is expressed as

$$\sigma = \frac{e^2}{m} \frac{n_e}{\nu_{eb} + \nu_{es} + \nu_{ei}} \qquad (1)$$

where m is the electron mass, n_e the electron density, and ν_{eb}, ν_{es}, and ν_{ei} the frequencies for momentum transfer in collisions with body-gas atoms, seed atoms, and ions, respectively. For the range of conditions with which we deal here, less than 1 per cent of the seed atoms are ionized and the electron density is proportional to $(p_s)^{1/2}$ when the furnace temperature T_F is fixed. Then since

$$\nu_{eb} \sim p_b$$

$$\nu_{es} \sim p_s$$

$$\nu_{ei} \sim n_e \sim p_s{}^{1/2}$$

when T_F is held constant, we can write the conductivity as

$$\sigma = K \frac{(p_s/p_{s\,max})^{1/2}}{1 + \left(\frac{p_s}{p_{s\,max}}\right) + A\left(\frac{p_s}{p_{s\,max}}\right)^{1/2}} \qquad (2)$$

where, for a given body gas and seed material, and fixed body-gas pressure p_b and furnace temperature T_F, K and A are strong functions and $p_{s\,max}$ a weak function of T_F only. When $p_s = p_{s\,max}$, electrons face equal probabilities for collisions with body-gas atoms and seed atoms, and the conductivity is a maximum. When the electron-ion interactions are relatively unimportant, as in all our experiments, the conductivity goes as $p_s^{1/2}$ at low seeding pressures, as $p_s^{-1/2}$ at high seeding pressures, and is independent of p_s at intermediate seeding pressures where $p_s \simeq p_{s\,max}$.

By combining the preceding estimates we come to expected errors in conductivities for stated furnace temperatures and seeding pressures of 8 to 10 per cent due to errors in furnace temperature measurements and perhaps as much as 20 per cent due to errors in seeding pressures.

VI. RESULTS

The major results of these measurements consist of values for the equilibrium conductivities of cesium-seeded nitrogen, helium, neon, and argon for a range of seeding pressures from 0.1 to 10 torr and for gas temperatures in the range 1500° to 2000°K. The body gases used were of commercially available grades having nominal maximum impurity levels specified in Table I. No special efforts were made to purify these gases further although efforts were made, as outlined before, to assure that our system did not add impurities (other than cesium vapor). Actually, the cesium oven probably removes most active-gas impurities such as O_2, H_2, H_2O, and possibly CO as seeding occurs.

TABLE I

Nominal Maximum Impurity Levels in Body Gases

Nitrogen	3000 ppm
Helium	100 ppm
Neon	50 ppm
Argon	20 ppm

Figure 4 shows the conductivities obtained during two series of measurements performed with seeded nitrogen several months apart in time and in tubes of differing geometries, and thus gives a good indication of the repeatability of the measurements. There is a systematic shift of unknown cause between the two

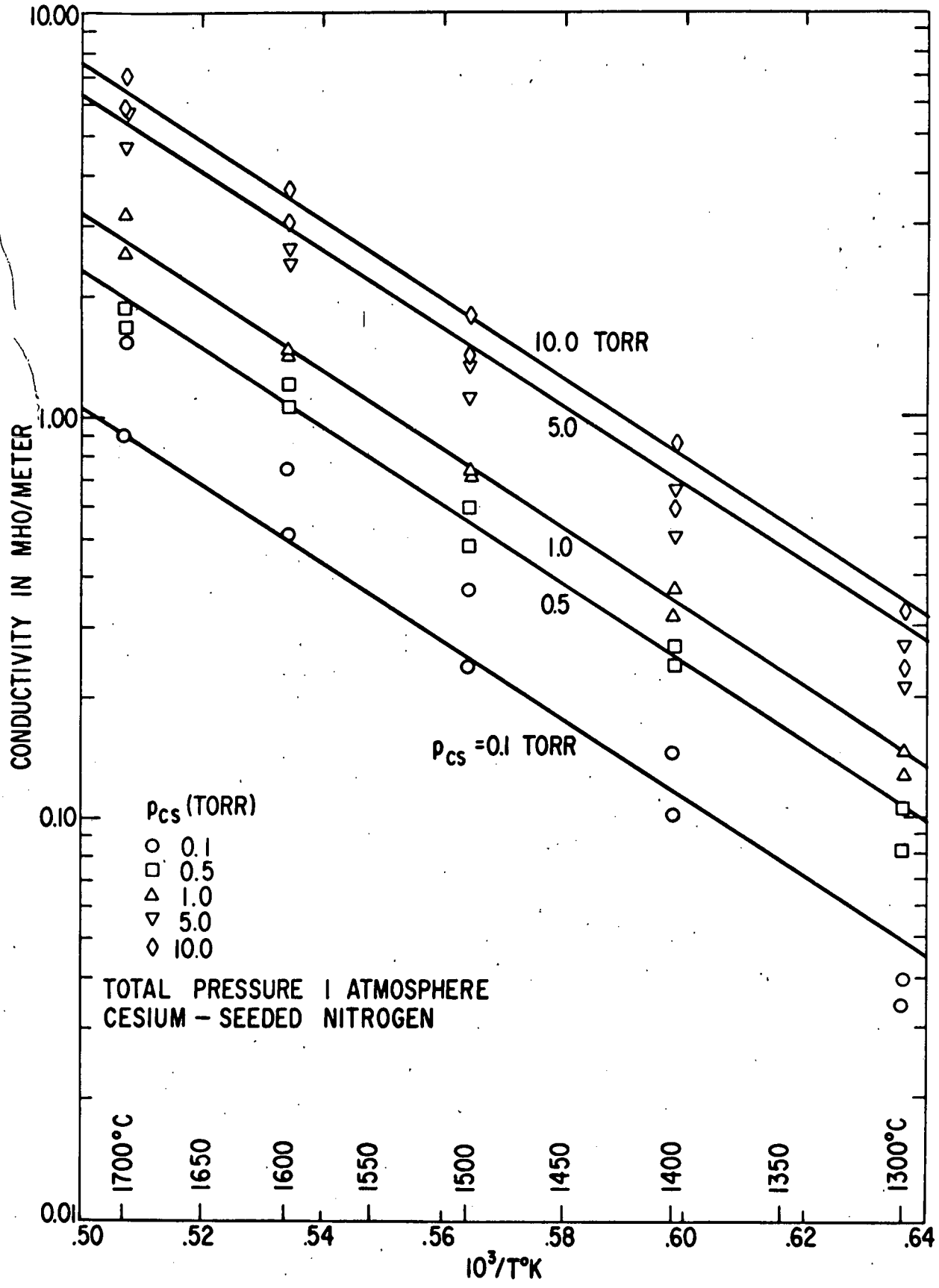

Fig. 4 Conductivity of cesium-seeded nitrogen.

sets of results of about 25 per cent and superimposed random variations of about the same size; in nearly every case the larger of the two values of conductivity shown for a single seed pressure and gas temperature came from the first series of measurements. Also from the first series is the set of points for $p_{Cs} = 0.1$ torr that indicates an abnormally high increase in conductivity with increasing temperature. This phenomenon has appeared in experiments on other body gases and apparently is caused by cesium coming off the walls of the flow path as the furnace temperature is increased and the seed-oven temperature is held constant. When sufficient care is taken to wait until the system is stabilized for each experimental reading, the results plot along a line whose slope is determined by the cesium ionization potential as shown by the lower set of circles in Fig. 4.

When electron-ion interactions are negligible, as in these measurements, Eq. (2) shows that the conductivities for each temperature should vary with seeding pressure as

$$\frac{(p_s/p_{s\,max})^{1/2}}{1 + (p_s/p_{s\,max})} .$$

Figure 5 contains a plot of this type of curve for $p_{s\,max} = 25$ torr with the data from Fig. 4 superimposed. For this comparison the measured conductivities for each temperature were normalized by a factor just sufficient to bring the normalized conductivity for $p_{Cs} = 10$ torr into agreement with the curve; thus there is a different normalizing factor for each temperature. Theory and experiment were constrained to be equal at $p_{Cs} = 10$ torr because the measurements presumably are least sensitive to errors in cesium pressure at this point. The value of 25 torr for $p_{s\,max}$ was obtained by trial and error and gives about the best obtainable representation of all the data. We should expect $p_{s\,max}$ to vary somewhat with temperature, perhaps as much as 50 per cent over our temperature range, but the scatter in the data is too great to permit reliable detection of such small changes in $p_{s\,max}$.

The pressure dependence shown in Fig. 5 was used to determine the spacings between the lines drawn for each seeding pressure in Fig. 4. These lines satisfy the equation

$$\sigma = C \frac{(p_s/p_{s\,max})^{1/2}}{1 + (p_s/p_{s\,max})} \exp - \left(\frac{eV_i}{2kT}\right)$$

where $p_{s\,max} = 25$ torr and C is a constant adjusted to get the best general agreement between the lines and the corresponding experimental points. Inspection of Fig. 4 indicates that this technique is quite successful; except for the line for $p_{Cs} = 5$ torr, which runs somewhat above the average of the corresponding experimental points, the lines thus obtained do not differ much from a "best fit" to the corresponding valid points.

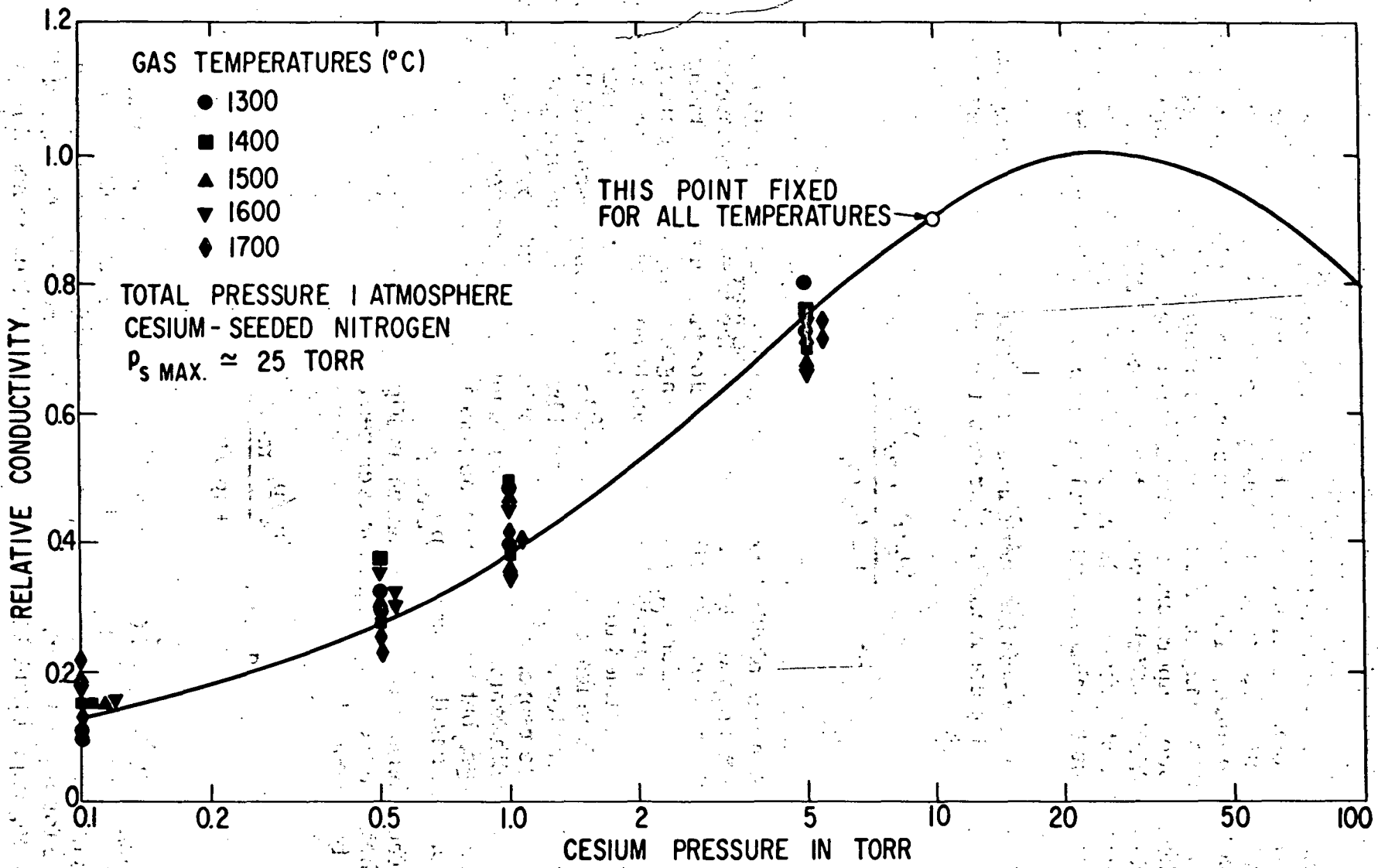

Fig. 5 Variation with seeding pressure of conductivity in cesium-seeded nitrogen.

Figures 6 and 7 show the variations with temperature and seeding pressure of the conductivity in cesium-seeded helium. From Fig. 7 we deduce that the conductivity is greatest when the seeding pressure is $p_{S\ max} = 15$ torr. The corresponding lines for the various seeding pressures drawn in Fig. 6 give a good representation of the experimental data except for the experimental points for $p_{Cs} = 0.1$ torr which apparently are infected by the experimental error described before in connection with the cesium-seeded nitrogen data at low seeding pressures. Excepting these points, the average deviation between lines and points is quite small and the maximum deviations are about 35 per cent, much as for the nitrogen data.

A comparison of Figs. 4 and 6 shows that the conductivities obtained for a given seeding pressure and gas temperature are higher in helium than in nitrogen by a factor varying near 1.50, and that the spread in conductivities obtained at a fixed temperature by varying the seeding pressure from 0.1 to 10 torr is somewhat less in helium than in nitrogen.

Figures 8 and 9 contain the results of two sets of measurements in cesium-seeded neon performed in tubes of differing geometries. The seeding-pressure dependence plot in Fig. 9 indicates a maximum conductivity at about $p_{S\ max} = 4$ torr, and this value was used in selecting the vertical spacing of the lines drawn in Fig. 8. The result is rather good agreement in Fig. 8 between corresponding points and lines except that the line for $p_{Cs} = 10$ torr indicates somewhat lower conductivities than that for $p_{Cs} = 5$ torr while experimentally the conductivities in the two cases were about equal. Even for $p_{Cs} = 10$ torr, however, the agreement is within limits of expected errors.

Comparison of Figs. 4, 6, and 8 shows that the conductivities in neon run well above those in nitrogen and helium (the ordinate of Fig. 8 differs by a decade from those of Figs. 4 and 6) and that the spread of conductivities obtained with the same seeding pressures is correspondingly reduced. Variations within a seeding-pressure range of two decades, 0.1 to 10 torr cesium pressure, give at most a factor of about 3.2 change in the conductivity of the seeded neon.

The trends established before are continued in Figs. 10 and 11, which also contain data from two sets of measurements. The pressure-dependence curve in Fig. 11 indicates that $p_{S\ max} = 1$ torr for the cesium-seeded argon. Here there may be indications that $p_{S\ max}$ increases with gas temperature at the higher temperatures, but the scatter in the data is such that we really cannot be sure. The vertical distribution of the experimental points in Fig. 10 presents a picture that is confusing at first, but rather well sorted out by the lines drawn in conformance with the dependence on seed pressure shown in Fig. 11.

Comparison of Fig. 10 with Figs. 4, 6, and 8 shows, as expected, that the argon conductivities run above any others, and that they are relatively insensitive to the cesium pressure over the pressure range studied here. Variation of the seeding pressure over two decades caused no more than 60 or 70 per cent change in the measured conductivity.

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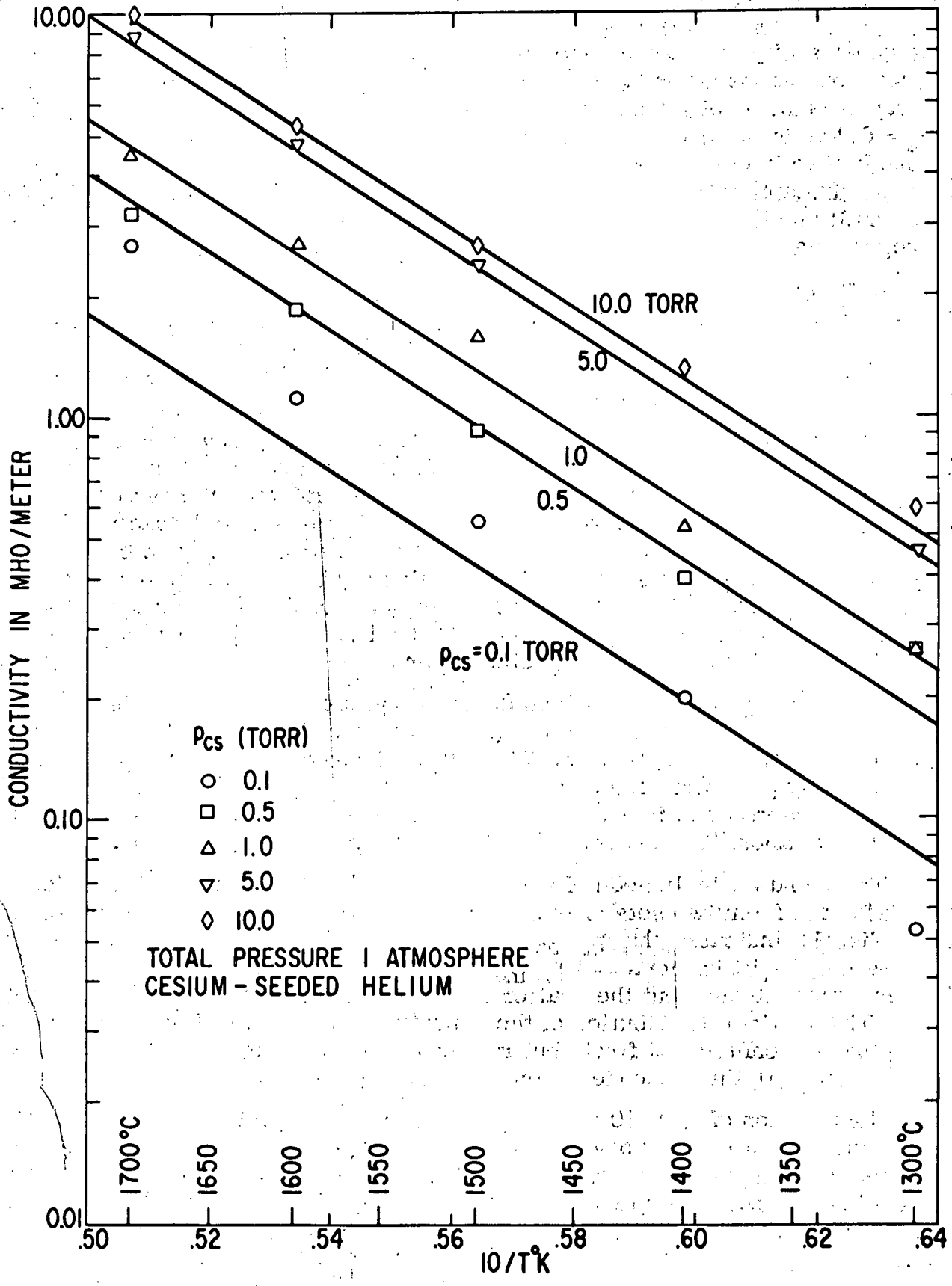

Fig. 6 Conductivity of cesium-seeded helium.

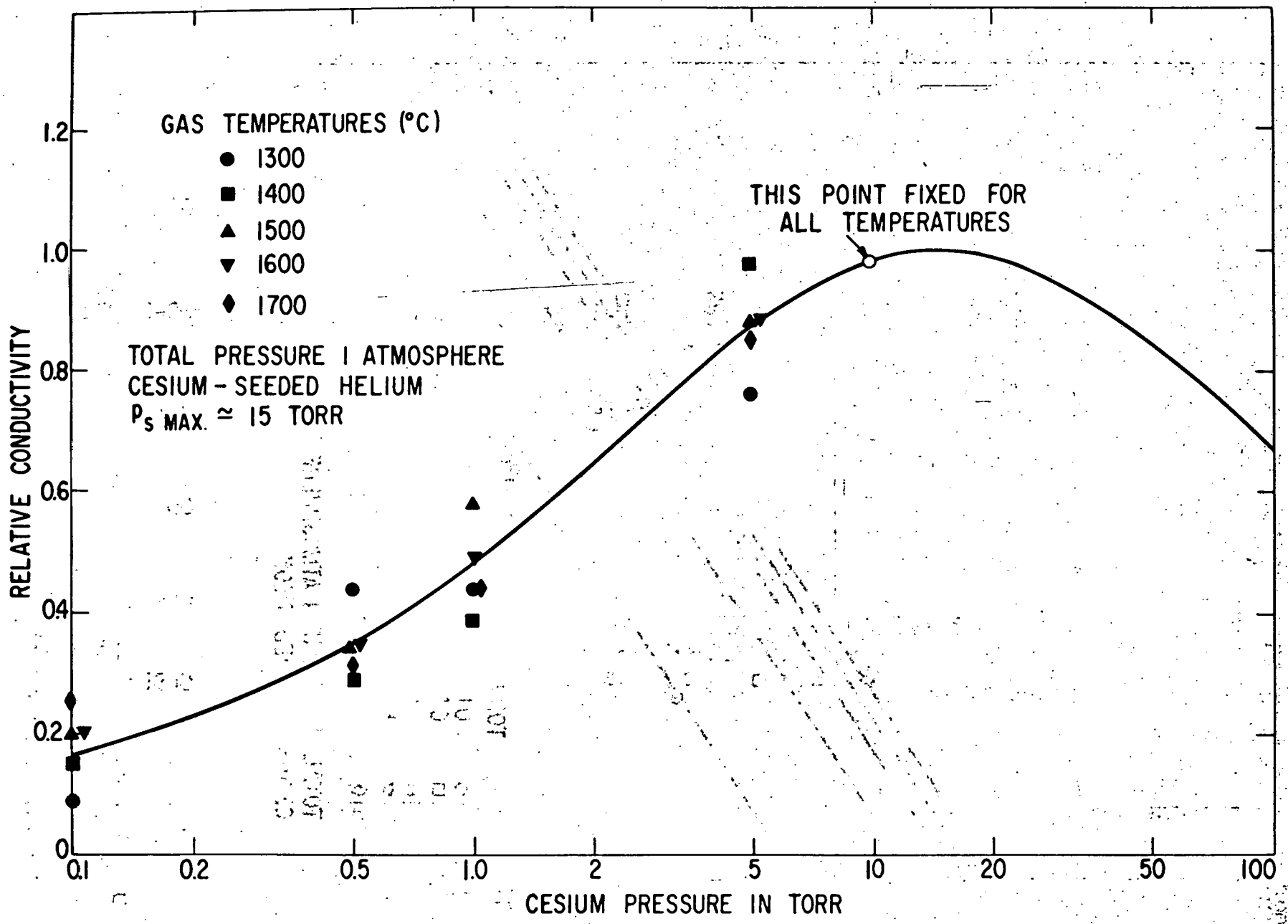

Fig. 7 Variation with seeding pressure of conductivity in cesium-seeded helium.

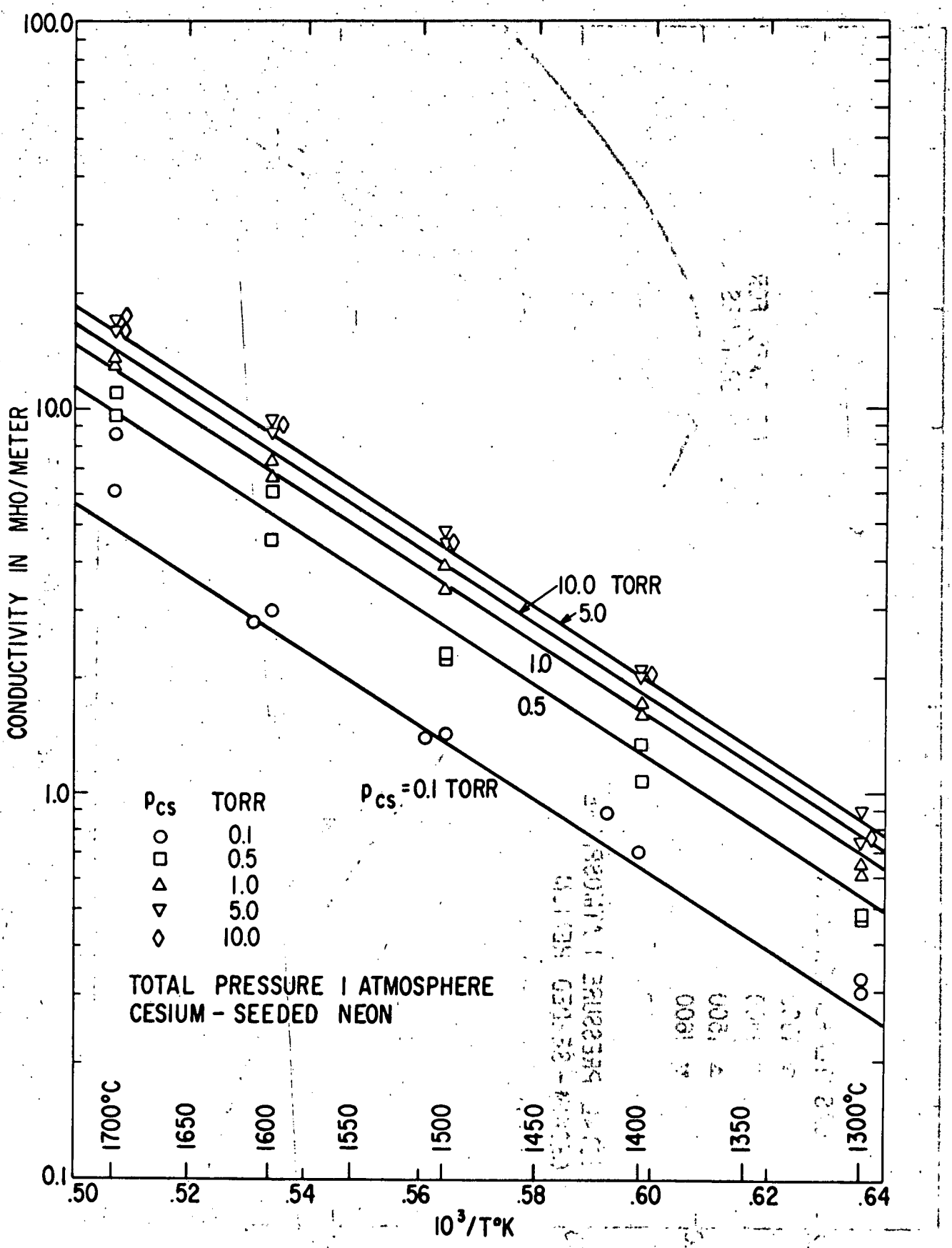

Fig. 8 Conductivity of cesium-seeded neon.

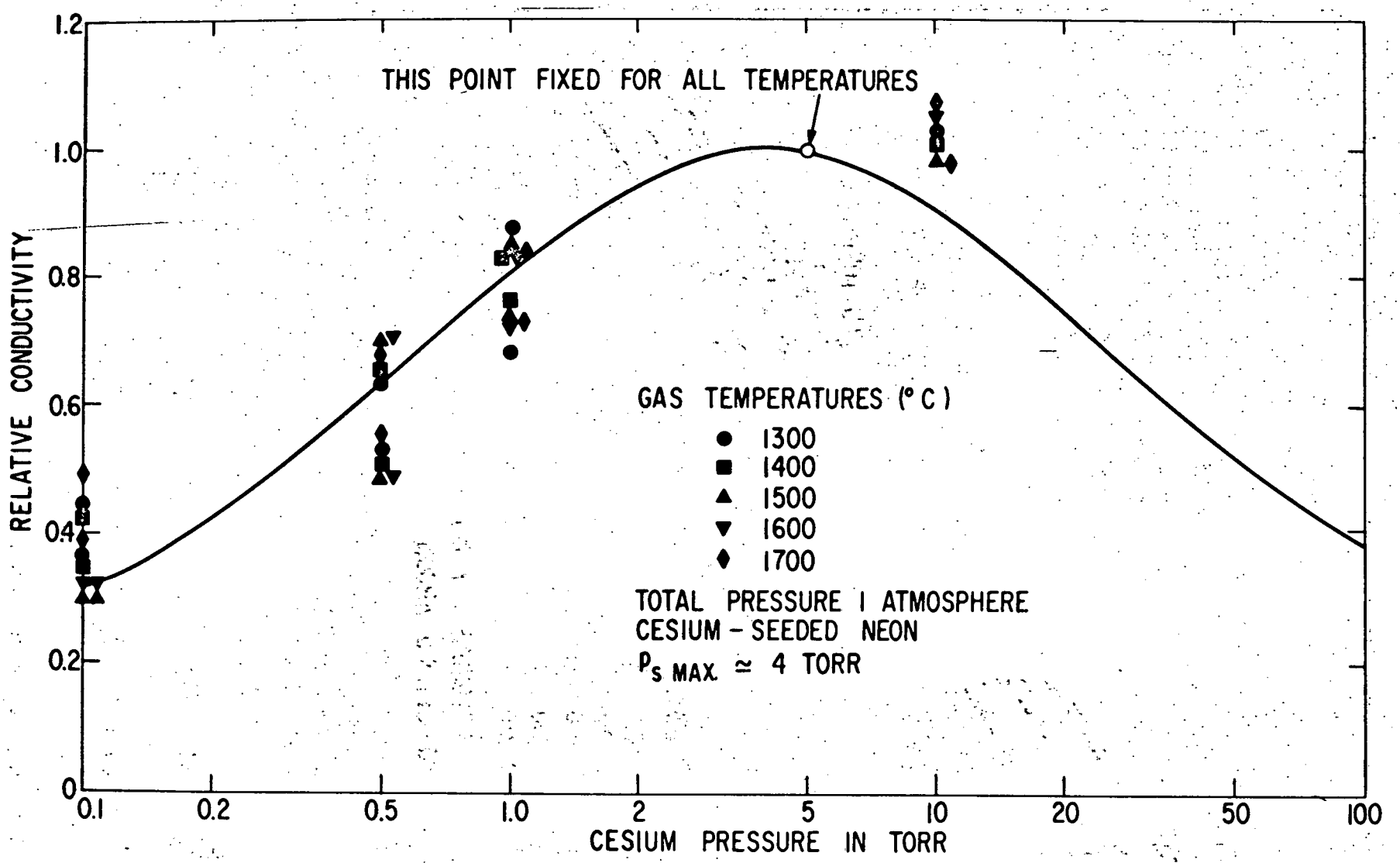

Fig. 9 Variation with seeding pressure of conductivity in cesium-seeded neon.

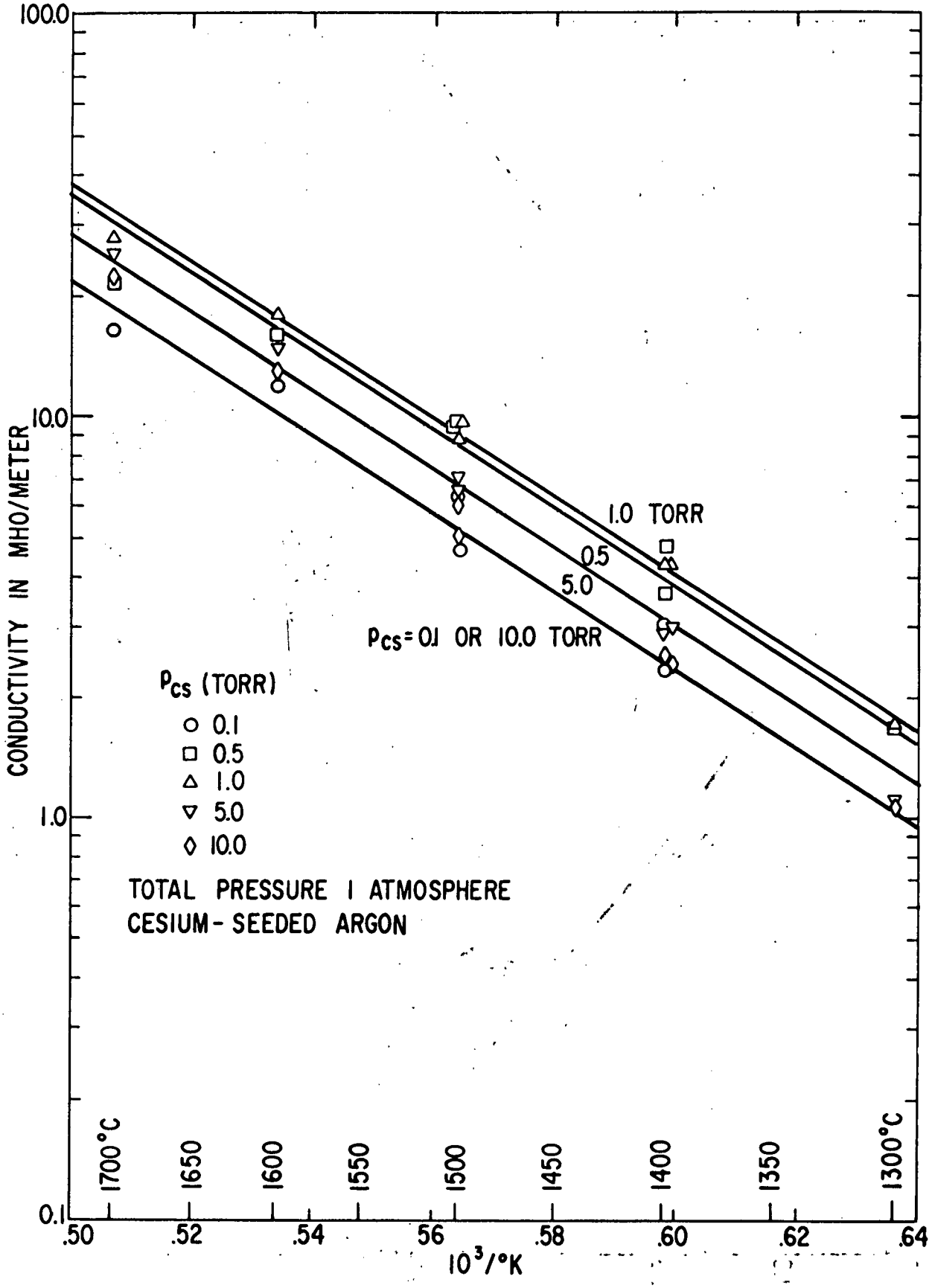

Fig. 10 Conductivity of cesium-seeded argon.

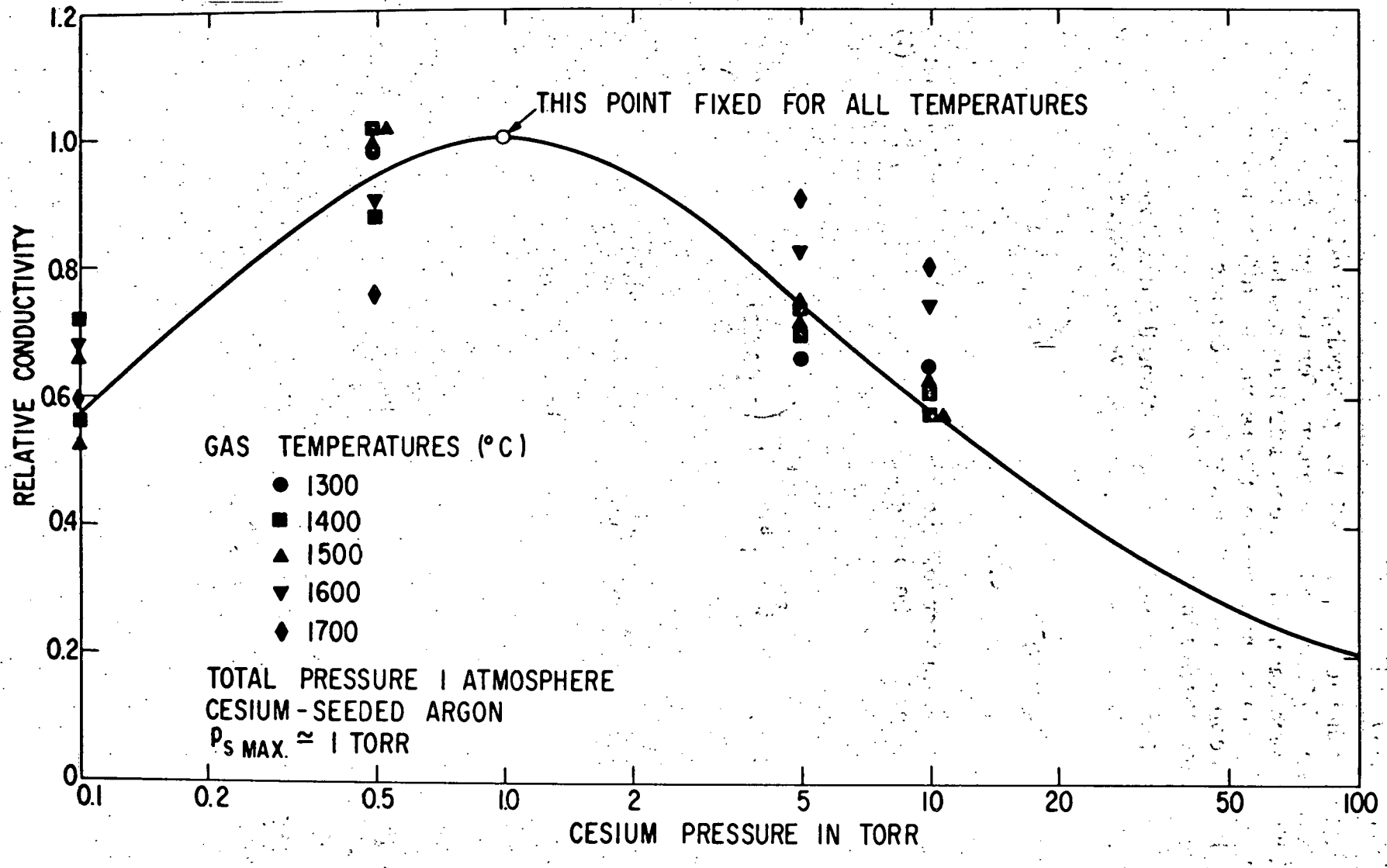

Fig. 11 Variation with seeding pressure of conductivity in cesium-seeded argon.

VII. DISCUSSION OF RESULTS

The presentation of results in the preceding section has shown a certain internal consistency within the measurements for each body gas. We can use the results derived there for maximum conductivities and the seed pressures at which they occur to check the consistency of the results for different body gases and to compute electron collision frequencies and/or cross sections that can be compared with corresponding results in the literature.

Because for our experimental conditions the fraction of seed atoms that become ionized always is less than 1 per cent, we can write the Saha equation as

$$n_e = 1.54 \times 10^{-2} \frac{N_s}{\sqrt{p_s}} T_F^{5/4} \exp\left(-\frac{eV_i}{2kT_F}\right) , \qquad (3)$$

where p_s is expressed in torr and the remaining quantities are in MKS units. The quantity N_s is the density of seed atoms. Substitution of Eq. (3) in Eq. (1) gives, with $\nu_{ei} = 0$.

$$\sigma = 1.54 \times 10^{-2} \frac{e^2}{m} T_F^{5/4} \exp\left(-\frac{eV_i}{2kT_F}\right) \frac{N_s}{\nu_{es}} \frac{(p_s)^{-1/2}}{\left(\frac{\nu_{eb}}{\nu_{eS}} + 1\right)} . \qquad (4)$$

At maximum conductivity $\nu_{eb} = \nu_{es}$, $p_s = p_{s\,max}$ and

$$\sigma_{max} = 0.77 \times 10^{-2} \frac{e^2 T_F^{5/4}}{m} \exp\left(-\frac{eV_i}{2kT_F}\right) \frac{(p_{s\,max})^{-1/2}}{\nu_{es}/N_s} . \qquad (5)$$

Thus, if we plot σ_{max} vs $(p_{s\,max})^{-1/2}$ for the different body gases studied here, all at one furnace temperature T_F, the result should be a straight line passing through the origin. Because we measure T_F and know the seed ionization potential V_i, the slope of this line gives us the ratio ν_{es}/N_s for that temperature.

Figure 12 shows the result obtained from the curves plotted in Figs. 4 through 11 for a furnace temperature of 1750°K, one near the middle of our experimental range. The points for the four body gases studied here lay close to the line

$$\sigma_{max} = 7.7 (p_{s\,max})^{-1/2}$$

which determines at 1750°K

$$\frac{\nu_{es}}{N_s} \approx 80 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1} .$$

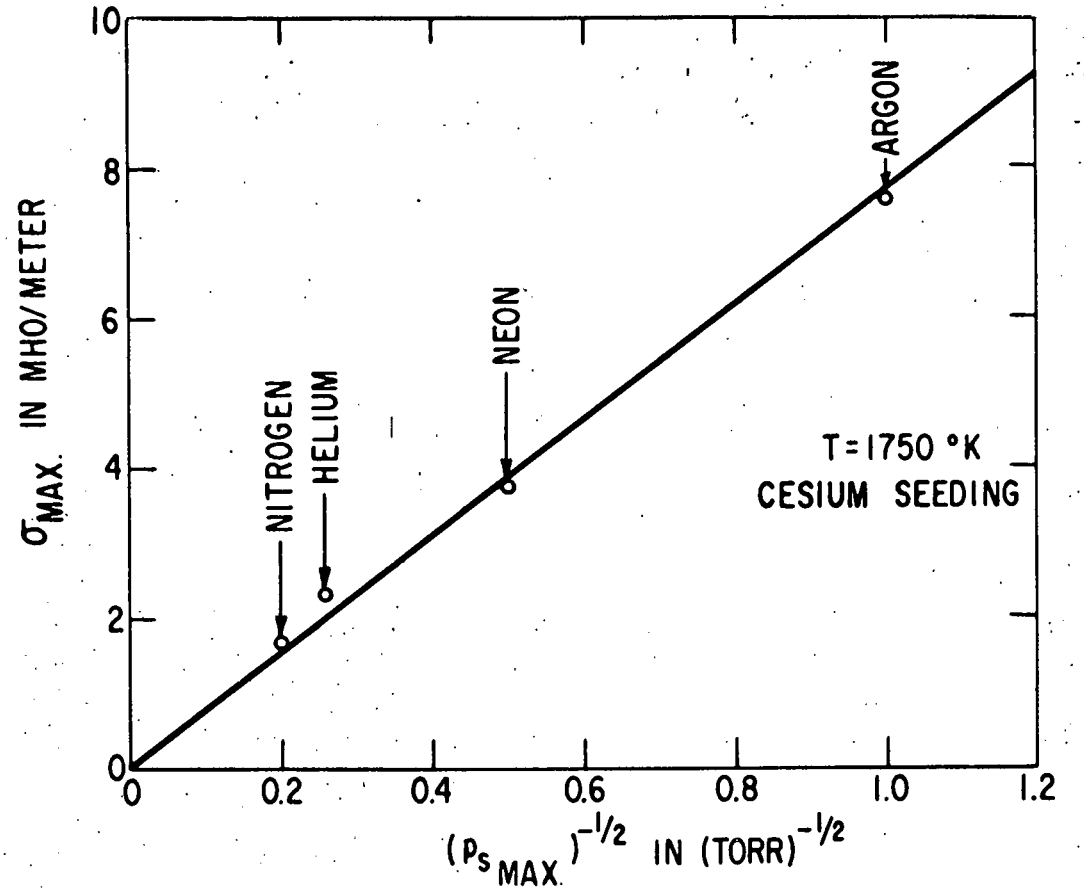

Fig. 12 Plot for determination of cesium cross section.

This value, which corresponds to a momentum transfer cross section near 300 x 10^{-16} cm^2, is lower by about a factor of 2 than the values deduced by Phelps[8] from cesium positive-column data and extrapolated by Chen[11] from recent microwave measurements. This agreement is not entirely satisfactory, but probably is within the expected accuracies of the experiments involved.

From this value for ν_{es}/N_s and the values of $p_{s\,max}$ determined before, the parameters ν_{eb}/N_b for each of the body gases are given by the relation

$$\frac{\nu_{eb}}{N_b} = \frac{\nu_{es}}{N_s} \frac{p_{s\,max}}{p_b} \qquad (6)$$

which holds because $\nu_{eb} = \nu_{es}$ when $p_s = p_{s\,max}$.

The results of these calculations are summarized in Table II. In comparison with the values obtained by averaging the ν/N functions given by Frost[8] over a Maxwellian distribution, the value given in Table II for N_2 is about 4 per cent low, that for He about 12 per cent high, and that for Ne about 60 per cent high. Frost gives no value of ν/N for argon, but his plots of electron mobility indicate close agreement with the value shown in Table II.

TABLE II

Average Electron Collision Frequencies and Cross Sections Deduced from Conductivities for 1750°K

Gas	10^8 ν/N cm^3 sec^{-1}	10^{16} (cross section) cm^2
Cs	80	300
N_2	2.7	10
He	1.6	6
Ne	0.4	1.6
A	.1	0.4

VIII. CONCLUSIONS

The preceding comparison of the experimental results obtained here with the earlier calculations of Frost suggests that, under the conditions studied here where the gases were near thermal equilibrium and where electron attachment and the formation of gaseous compounds involving the seed atoms are absent, a careful measurement yields approximately the same electrical conductivity as a careful calculation based on the established theory[8] for seeded gases and the momentum transfer cross sections[12, 13] obtained from beam, drift tube, and microwave experiments over the last three or four decades. Thus, this situation may be considered to be well understood.

The close correspondence obtained here between theory and experiment indicates that the operation of the apparatus also is well understood and gives hope of obtaining useful results on nonequilibrium conduction in the near future.

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Title Page

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Harris, L. P.	plasma physics	63-RL-3278G
		DATE: April 1963

TITLE: Conductivity of Cesium-seeded Atmospheric Pressure Plasmas Near Thermal Equilibrium

ABSTRACT: Measurements have been made of the electrical conductivities of gaseous mixtures formed by the addition of small fractions of cesium vapor to nitrogen, helium, neon, or argon. The mixtures studied were maintained near thermal equilibrium at temperatures in the 1500° to 2000°K range and a total pressure of 1 atm. The cesium vapor pressures ranged over two decades, from 0.1 to 10 torr.

The apparatus consists, in essence, of two heated zones connected by a slow flow. The first zone is a low-temperature (200° to 400°C) oven where the body-gas flow picks up the cesium vapor. The second zone is a small electrically heated furnace (1250° to 1850°C) containing a diode test section.

The principal measurements taken were the seeding temperature, furnace temperature, and voltages and currents in the test section.

The results exhibit variations with temperature, seeding pressure, and gas species that correlate reasonably well with simple theory and values for electron collision frequencies and cross sections taken from the literature.

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