ELECTRONIC EFFECTS IN EXPANSIVE FLOW UNDER HYPERSONIC CONDITIONS

Martin H. Bloom

1. INTRODUCTION

Interest in electrical properties of flow around bodies relates to flight in the ionosphere, high speed flight in the neutral atmosphere, cosmic phenomena, and diagnostic probes, among other things. The extent of laboratory experiments in this regard has been relatively limited. Reasons for this include: the difficulty in providing test flows of known basic character in parametric ranges of interest, the difficulty in providing cross-checks on measurements, the state of the art of "non-classical" probe theory, and operational difficulties such as contamination of probes.

We have attempted to contribute in this area through hypersonic shock-tunnel studies, initially using air as the test medium. Our interest has centered on ionized flows of expansive and non-equilibrium character. In practice such flows arise when shock-processed gas at the nose of a blunt body passes laterally and rearward; in the near wake of a blunt-based body which inherits the shocked gas of a blunt forebody or the boundary layer heated (and perhaps contaminated) gas of a slender forebody; and in nozzles

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ABSTRACT

Experiments have been conducted on plasma effects in the nozzle of a hypersonic shock tunnel employing air as the test gas, at Mach 13, a density of $7.8\text{x}10^{-5}$ atm and static temperature of 140°K. Surveys of electron density have been made by S-band microwave resonance cavities of flow-through type, indicating a 20-in. diameter non-diffusive, uniform central core at a level of $6\text{x}10^{8}$ electrons/cc. These correlate with the extent of the neutral boundary layer as determined by heat transfer measurements. Electron temperatures of 3000°K were measured by current-probes and compared with the equilibrium supply temperature of 3900°K. On the basis of independent ion-current measurements with cylindrical probes in the range of probe diameters on the order of the Debye length, but otherwise free-molecular, the currents are seen to exceed the values of a collisionless (L-B-R) theory. The feasibility of making electron density profile surveys around bodies has been demonstrated. Finally, surface-probe ion-current distributions around a blunt body are seen to correlate with neutral density distributions.

and exhausts supplied by shock-drivers, combustion chambers and electrical sources.

Although there is an extensive body of literature on plasma diagnostics and non-equilibrium gas flow, only a few rather recent studies bear with reasonable directness on our current work. Therefore we do not provide here a comprehensive review of past work, but only cite some which relate most directly to our own efforts.

Prominent among these is the program at the University of Toronto Institute for Aerospace Studies (UTIAS) as described, for example, in works by Graf[1], Sonin[2] and Laframboise[3]. This concerns theoretical and experimental studies of the characteristics of Langmuir probes. The experiments were done with the use of subsonic and supersonic argon plasma jets. Only Graf provided independent measurements of current-collection by the probes and electron densities by microwave interferometry, in the range R_p/λ_D on the order of 10; here R_p is the radius of a cylindrical or spherical probe and λ_D is the Debye length of the stream. In his work, Sonin extended the range of current-collection data to the range R_p/λ_D on the order of unity but did not make additional interferometry measurements. Work of Glass[4] and his coworkers aims toward studies of a centered corner expansion in the flow behind an incident shock in a shock tube.

The extensive program at the Cornell Aeronautical Laboratories[5,6] (CAL) is also of significance here. Their computational studies of non-equilibrium nozzle flows of air, and their computer program for such flows, have been useful in our work. Also, they have employed shock-tunnels for experimental non-equilibrium gas studies, chiefly dealing with optical radiation diagnostics for measuring vibrational relaxations, but also including a limited number of X-band microwave attenuation measurements in air in the high electron-density region near the throat of a fiberglass nozzle.

A the General Electric Corporation, Missile and Space Division (GE-MSVD) experiments have been made recently in a combustion-driven shock tunnel using air as a test gas[7]. Current-collecting cylindrical probes were used as diagnostics in the free-stream of the test section and in the stagnation region of a blunt body. However, no independent check of the electron-density level was made by other means according to the report of this work.

Finally, at the Stanford Research Institute[8] (SRI) current-collection probes have been used to study the boundary layer and plasma sheath on a flat plate behind the incident shock in a shock tube. Again no independent measurements of electron density were made here to calibrate the probes.

2. PRESENT WORK

In the present work we have made spacial surveys of total pressure, stagnation point heat transfer, electron density, electron temperature and ion-current to probes across the test section of a hypersonic shock tunnel nozzle with air as a test medium. We have also made ion-current-to-probe surveys across the lateral portion of the shock layer adjacent to the cylindrical portion of a hemisphere-cylinder. Finally we have measured the distribution of current collected by flush-mounted probes over the model, the model itself being grounded.

The test flow was about 4 feet in diameter with about 3 feet of uniform central core. It was nominally at Mach 12.8 with an estimated density of 1×10^{-7} gm/cc or 7.8×10^{-5} atm and static temperature of 140°K. The test section Reynolds number was 10^4 per foot and neutral mean free path was 0.6 mm. The supply pressure and equilibrium temperature were 15 atm and 3900°K, respectively. The test flow estimates were based on a non-equilibrium air stream-tube calculation taking into account a boundary layer correction based on an assembled group of hypersonic nozzle experiments correlated at CAL. The resulting core pitot pressure was checked by our own measurements. The geometric area ratio was 10^4 and the boundary layer corrected area ratio was 3500.

The shock tunnel, shown schematically in Fig. 1, was helium driven and produced a Mach 6.9 shock. The nozzle throat diameter was 0.69 in. and the effective duration of run was about 800 μsec under the present conditions.

In this brief paper we shall not go into the details of tunnel operation and calibration or the total pressure and heat transfer measurements. The electron density measurements were made in the test stream with S-band (2.6 kmc) microwave resonance cavities of a flow-through type developed by our group and shown in Figs. 2 and 3. This device provides a total electron count within the cavity at a given instant. This total count is related to the free-stream value through a boundary layer correction. In this case the strong-interaction viscous-inviscid effects were taken into account, since the interaction parameter was on the order of 25 within the cavity. In this way it was estimated that the free-stream electron density was 1.5 times the mean electron density within the cavity.

For current-collection, cylindrical probes of 0.25mm diameter and length-to-diameter ratios of 50 were used. These were oriented parallel to the flow. By varying the bias on the probes the current-voltage characteristic was obtained. This gave an electron temperature estimate of 3000^{o}K in the core of the flow. The ion-current was obtained with a large negative bias, about 10 volts above plasma potential. Based on the cavity-measured core electron density of 6×10^{8} cm^{-3}, the Debye length of the stream was of the order of the probe radius. Also observe that the ratio of ion-to-electron temperature ratio is small if we assume that the ion and neutral temperatures are about the same.

A schematic of the blunt model in the tunnel is shown in Fig. 4.

3. RESULTS

Some calculated results of the non-equilibrium nozzle calculations are shown in Figs. 5-7. The flow becomes chemically frozen close to the throat.

The results of electrical measurements are shown in the remaining Figs. 8-12.

The electron density n_e profiles as determined by cavity survey at a station shown in Fig. 3 are shown in Fig. 8 normalized with respect to the peak values in the central core. The non-diffusive core is seen to be of about 20 in. diameter at this section. No difference could be detected in the electron temperatures (T_e) as measured by probes in this region. The value of $T_e = 3000^{o}K$ is to be compared to the equilibrium stagnation temperature of $3900^{o}K$.

Moreover, from the electron densities shown, and the corresponding ion currents measured at large negative potential, the dimensionless current I_η (see Refs. 2 or 3) was essentially constant across the section. For a given electron temperature and probe bias, I_η is essentially proportional to the ratio of current collected to electron density. Hence the relative current-collection profile is the same as that of the electron density profile shown in Fig. 8.

Also shown in Fig. 8 is the normalized stagnation point, thin-film, heat transfer profile measured at the same station. It indicates the extent of the neutral boundary layer on the nozzle surface. The neutral boundary layer would be expected to be somewhat thinner than the charged particle boundary layer due to the ambipolar diffusion effect. However, the present results do not show this conclusively. Moreover, pitot pressures did not have sufficient ability to resolve this point. Further studies of this matter are being conducted.

In the course of this study the value of nondimensional current I_η, as measured, exceeded the theoretical collisionless value calculated by Laframboise on the basis of a theoretical study by Bernstein and Rabinowitz (see Ref. 3). Here this collisionless theory will be denoted as L-B-R. Sonin's extension of Graf's measurements show the same high current effect in the range $R_p/\lambda_D \lesssim 3$, whereas our range was between 0.5 and 0.8. If we reinterpret the measurements cited in Ref. 7, assuming a match to the theory at the higher values of R_p/λ_D instead of in the lower range as apparently assumed in Ref. 7, we observe a similar excessive current in the small-probe limit. This state of affairs is summarized in Fig. 9, and indicates that further consideration of the theory in this range may be warranted. It has been suggested that the effect of collisions may be entering here.

Fig. 10 shows a fuller radial probe survey extending to the tunnel wall. Fig. 11 shows a probe-deduced electron density profile through the shock layer at the side of a grounded blunt metallic body. The boundary layer is 1 in. thick at this station, and the calculated shock position is 8 in. from the body. The electron densities outside the boundary layer vary qualitatively like the neutral density. The flow is believed to be chemically frozen in the expansion region.

Finally, Fig. 12 shows the ion current collected by negatively biased flush-mounted probes along the surface of the body. The probes were insulated from the otherwise grounded body. The distribution is presumably proportional to the electron density a distance of about a Debye length from the surface of the body. This distribution has been compared with the neutral inviscid density distribution over the body, and is seen to be roughly correlated with it.

4. CONCLUSIONS

Experiments have been conducted on plasma effects in the nozzle of a hypersonic shock tunnel employing air as the test gas, at Mach 13, a density of 7.8×10^{-5} atm and static temperature of 140^{o}K. Surveys of electron density have been made by S-band microwave resonance cavities of flow-through type, indicating a 20-in. diameter non-diffusive, uniform central core at a level of 6×10^{8} electrons/cc. These correlate with the extent of the neutral boundary layer as determined by heat transfer measurements. Electron temperatures of 3000^{o}K were measured by current-probes and compared with the equilibrium supply temperature of 3900^{o}K. On the basis of independent ion-current measurements with cylindrical probes in the range of probe diameters on the order of the Debye length, but otherwise free-molecular, the currents are seen to exceed the values of a collisionless (L-B-R) theory. The feasibility of making electron density profile surveys around bodies has been demonstrated. Finally, surface-probe ion-current distributions around a blunt body are seen to correlate with neutral density distributions.

ACKNOWLEDGEMENT

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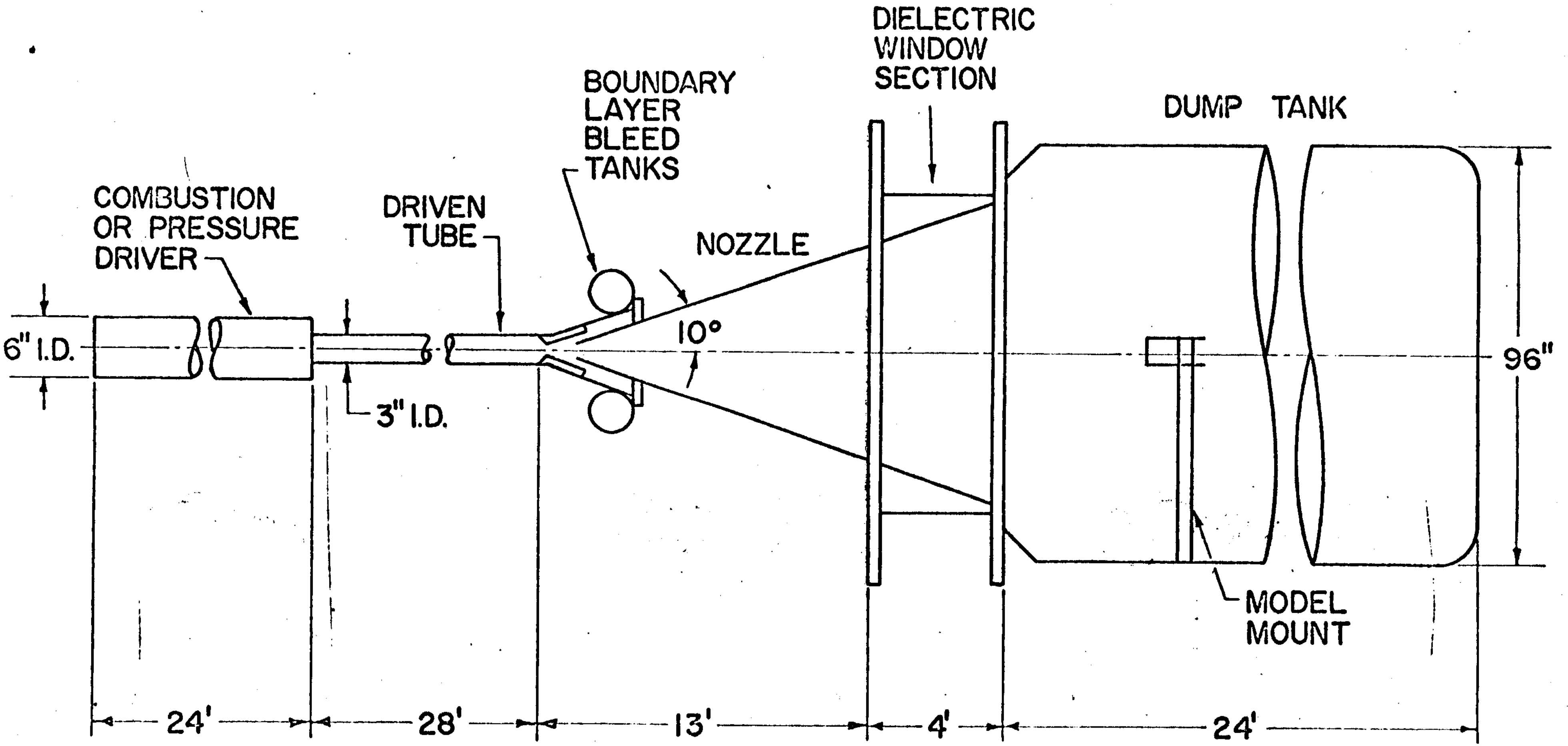


FIGURE I SCHEMATIC DIAGRAM OF SHOCK TUNNEL.

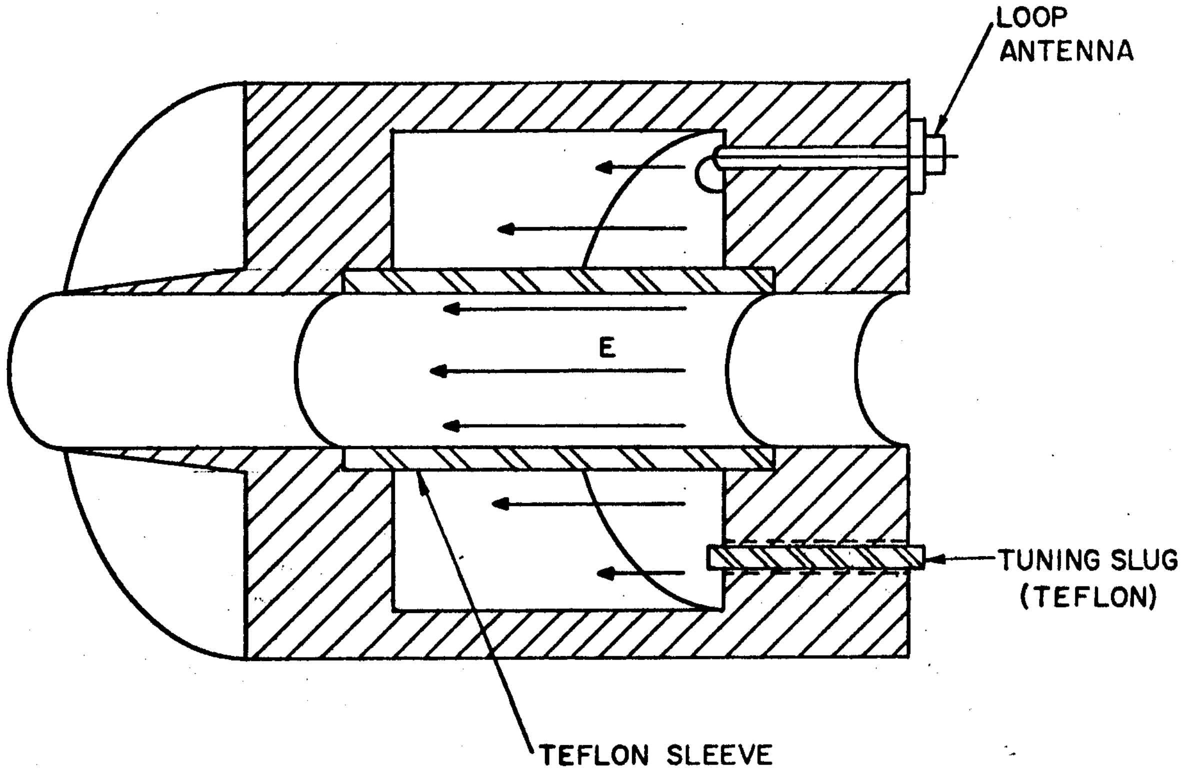
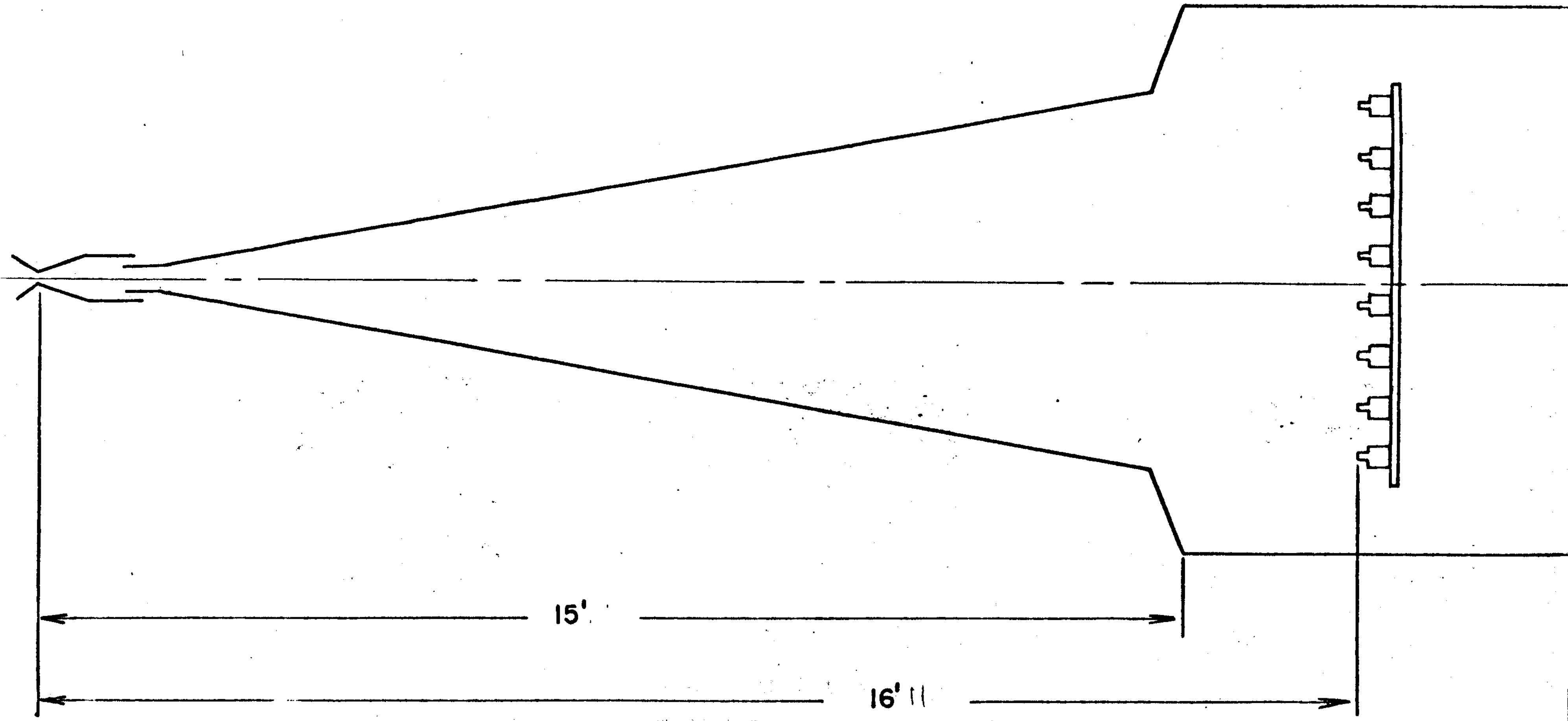


FIG. 1 SCHEMATIC DIAGRAM OF THE TM_{010} CAVITY



IG. [illegible] RELATIVE POSITION OF THE MICROWAVE CAVITY RAKE IN THE TUNNEL

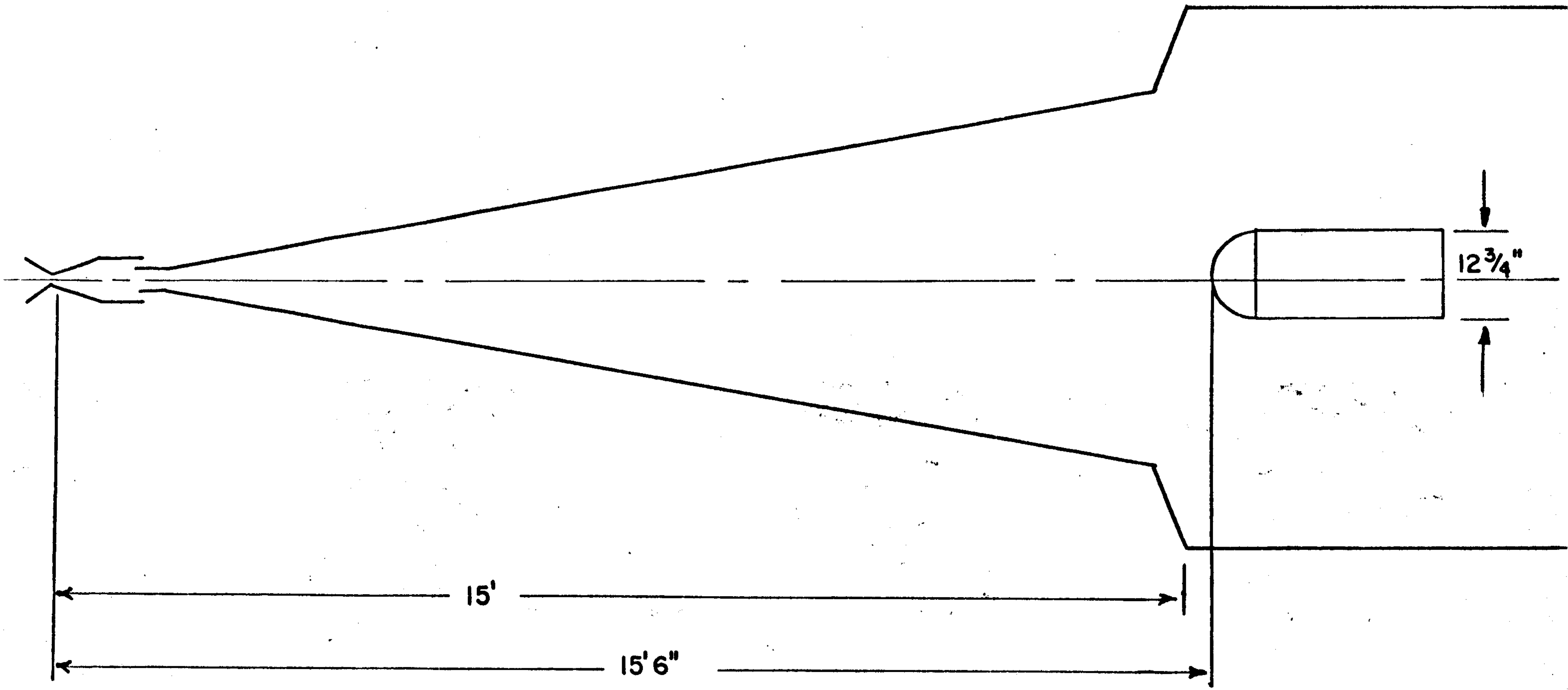
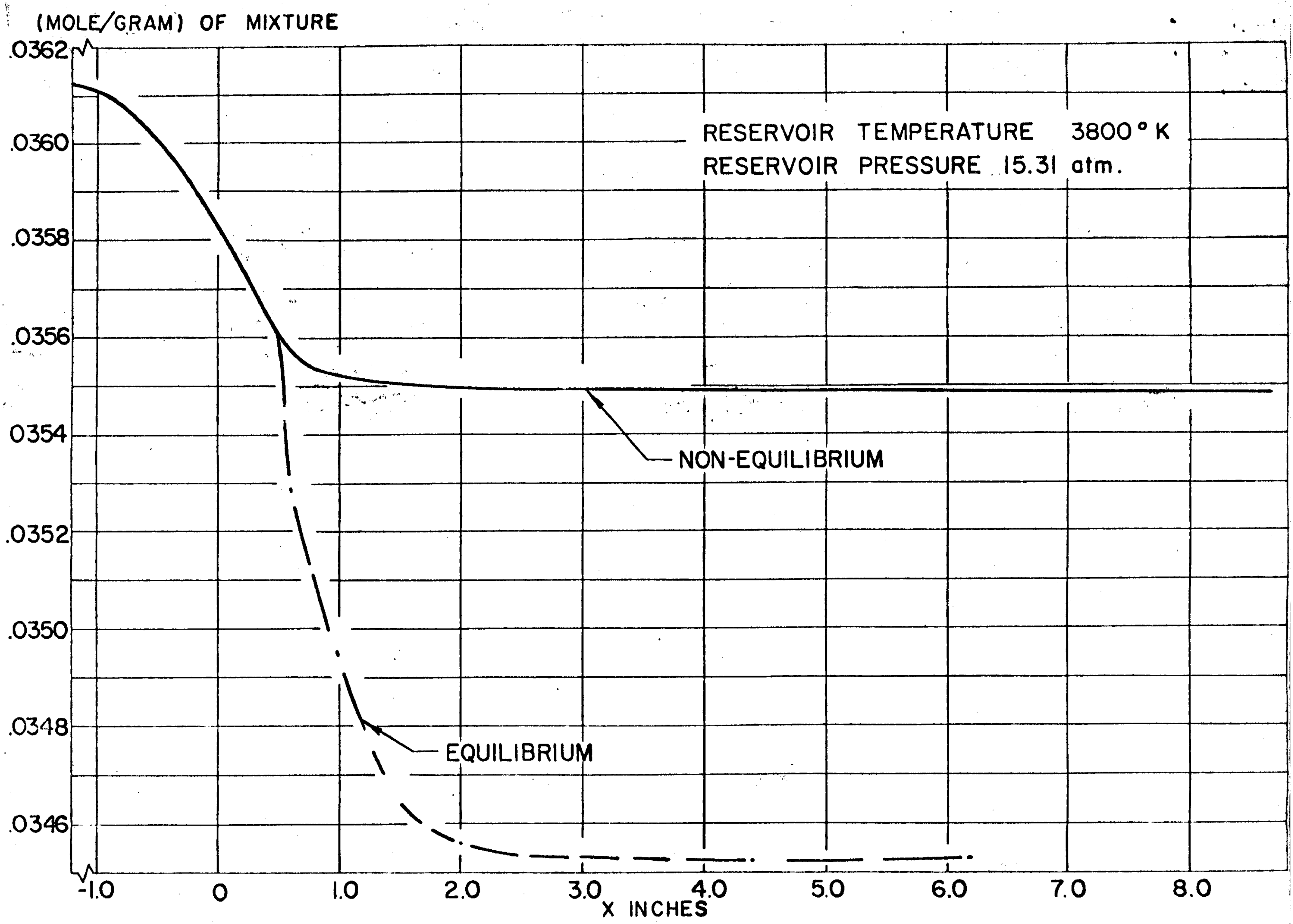
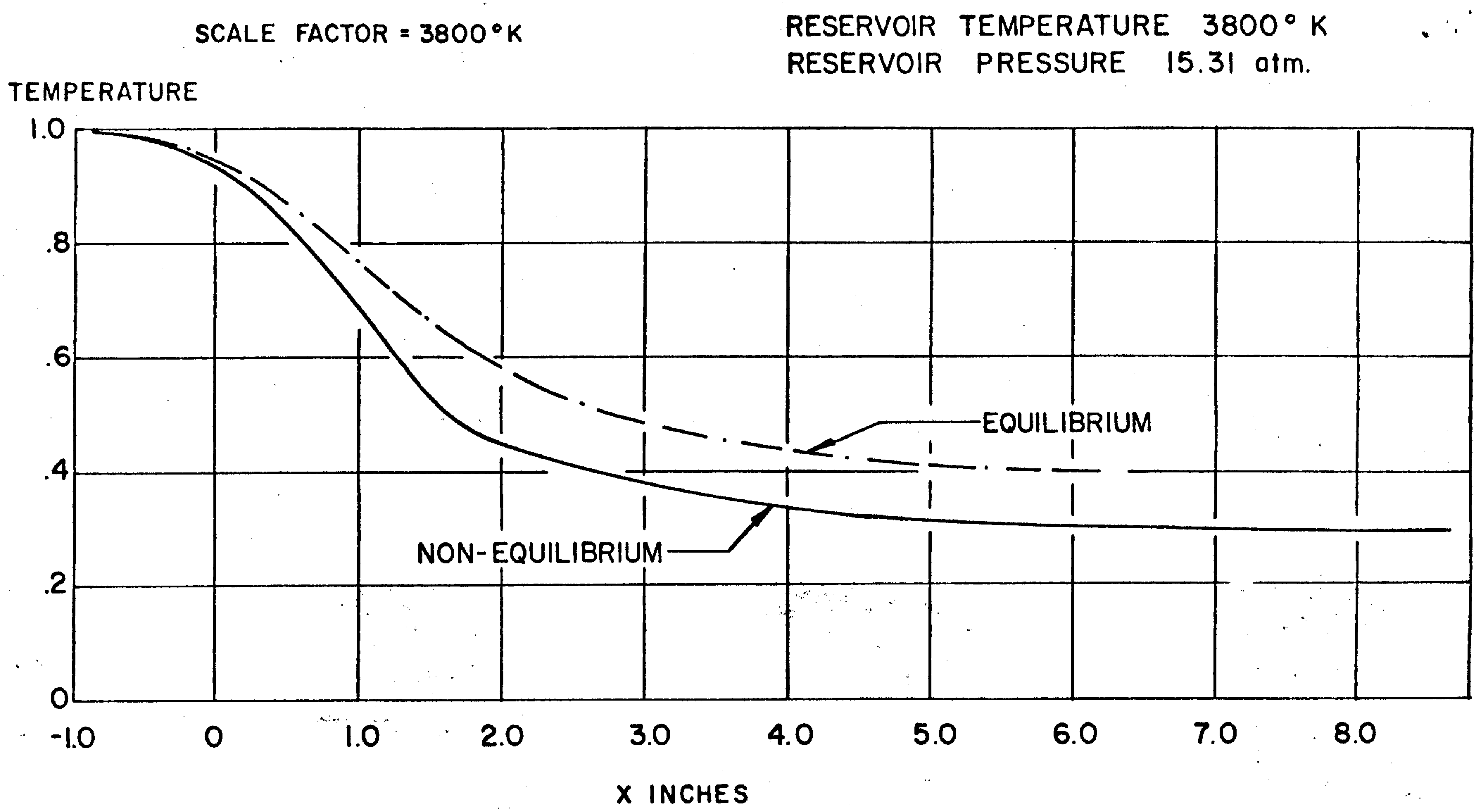


FIG. RELATIVE POSITION OF THE MODEL IN THE TUNNEL

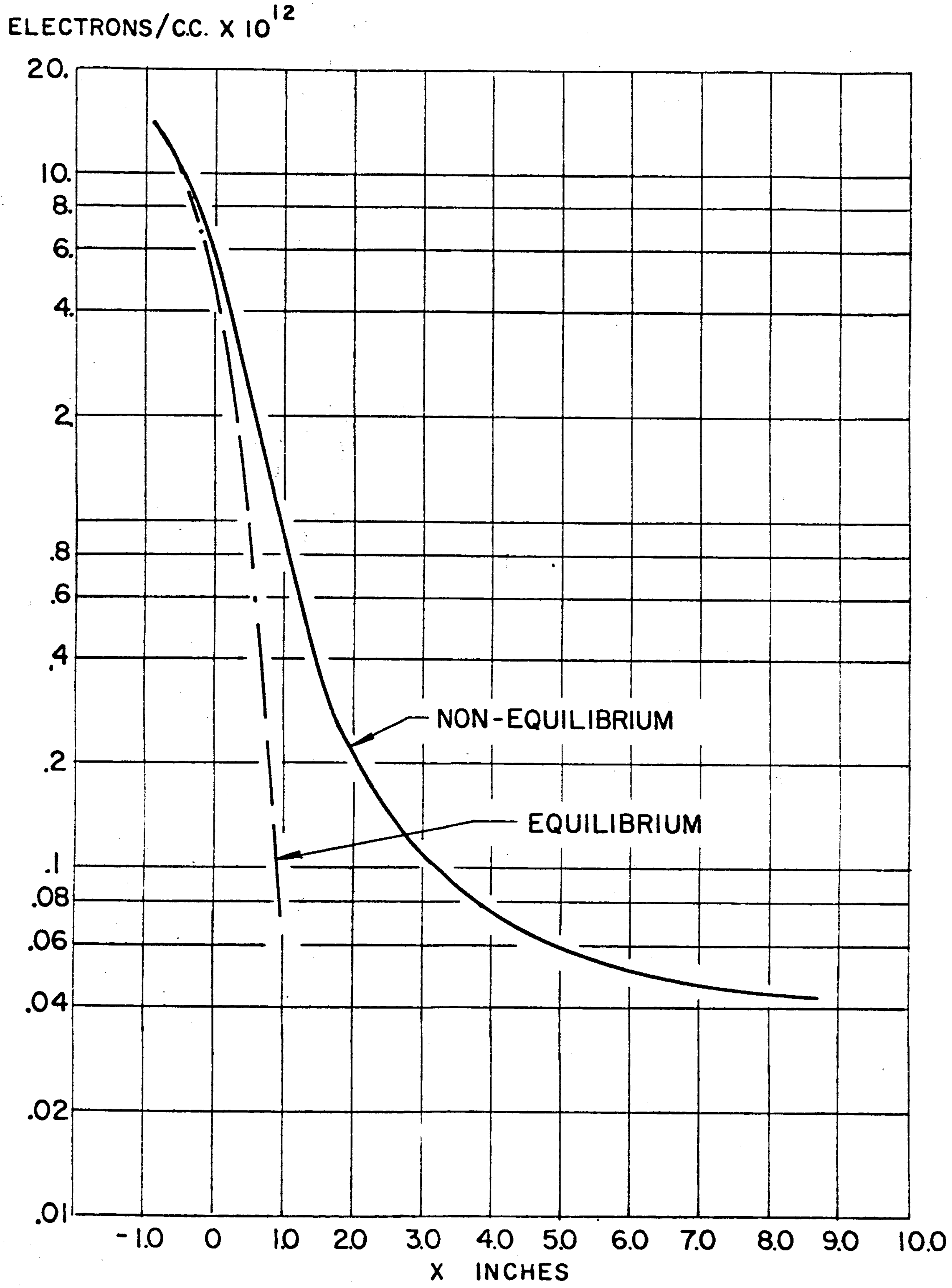


MIXTURE MOLE/GRAM VS X



STATIC TEMPERATURE VS X

RESERVOIR TEMPERATURE 3800° K
RESERVOIR PRESSURE 15.31 atm.



ELECTRONS CONCENTRATION VS X

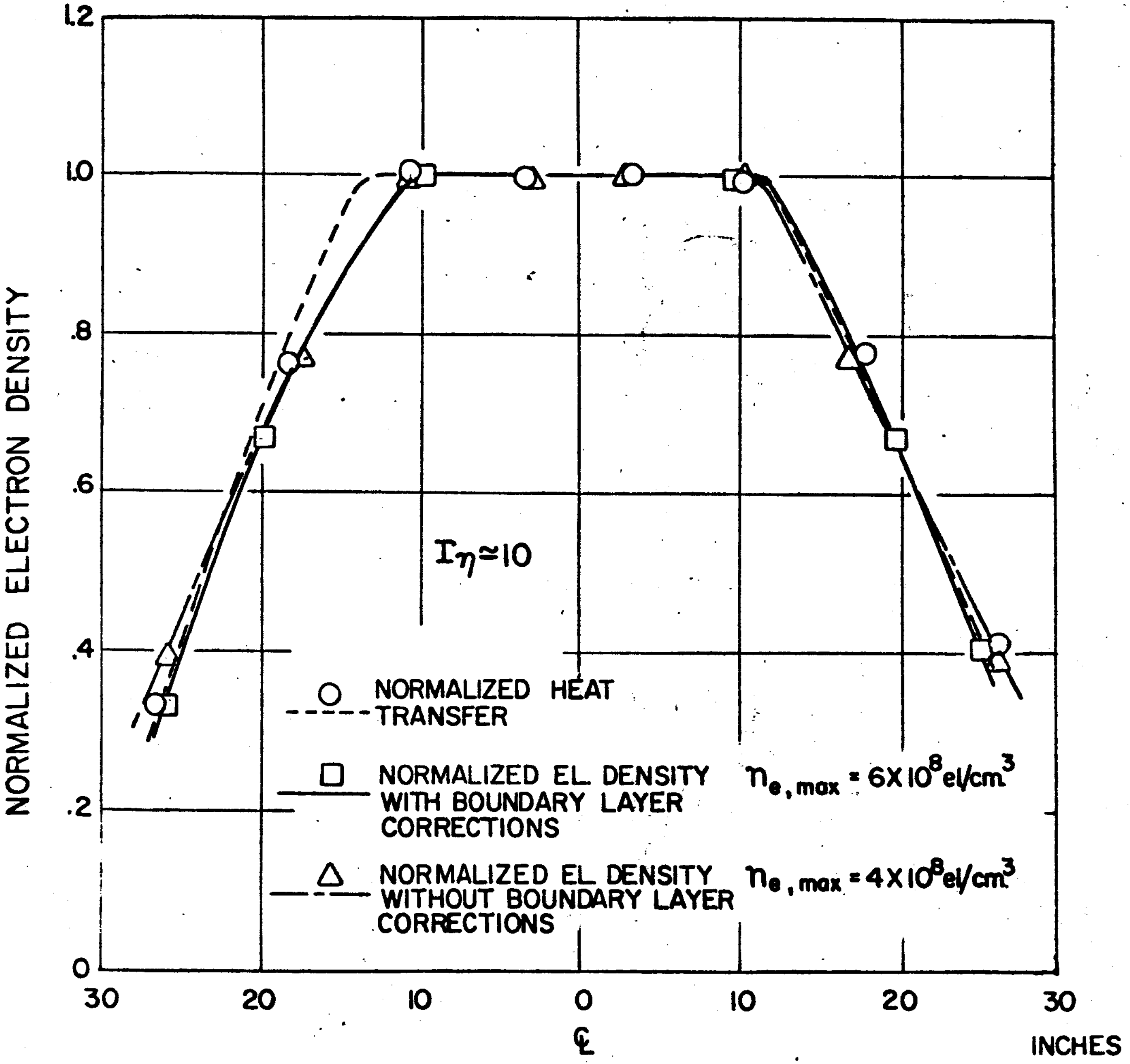
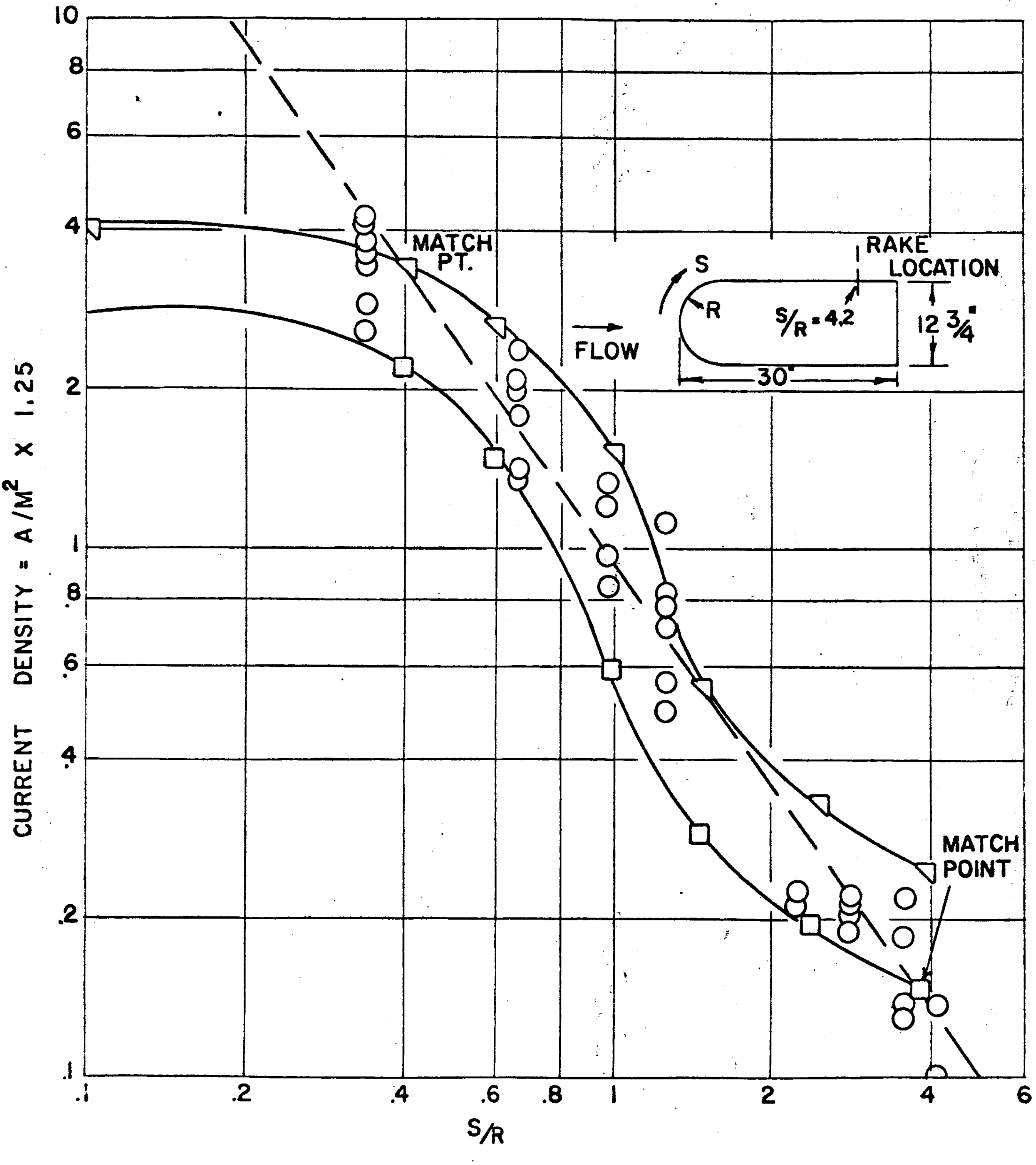


FIG. ( ) NORMALIZED ELECTRON DENSITY DISTRIBUTION CORRECTED AND UNCORRECTED FOR BOUNDARY LAYER IN THE CAVITY, ACROSS THE TEST SECTION AS MEASURED BY THE RESONANT CAVITIES, AND NORMALIZED HEAT TRANSFER



CURRENT AND DENSITY DISTRIBUTION ALONG THE HEMISPHERE CYLINDER SURFACE