Nasa CR-65301

RADIANT HEATING SIMULATION

[redacted]

First Phase Report

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Contract NAS 9-3507

12 November 1964

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TABLE OF CONTENTS

I. SUMMARY

The overall objective of this study program is to define the requirements for simulation of the radiant heating attendant to atmospheric entry by manned spacecraft and assessment of techniques for achieving this simulation. Phase I of the study was to define the radiant heating inputs for manned missions. During this Phase the objectives have been met insofar as possible with existing data. This however is significantly short of the desired environment and simulation definition requirement. In several areas, particular information voids are discussed and illustrated. Possible action to improve this condition will be recommended in the midterm report. The obtaining of the information required for Phase II has been initiated and is slightly ahead of schedule. (See last section of this report.) During the subsequent reporting period the material on radiation sources will be evaluated in terms of the requirements established in Phase I.

II. INTRODUCTION

This is the Phase I Report submitted under contract NAS 9-3507 and covers the period of 23 September through 10 November 1964.

A. Program Objective

Phase I - Definition of Radiant Heat Inputs for Manned Missions

1. This phase of the program shall include definition and characterization of the radiant heating environment associated with manned entry into planetary environments. Consideration shall be given to re-entry velocities from those characteristic of Apollo (35,000 to 45,000 ft/sec) to those characteristic of manned planned planetary missions (50,000 to 70,000 ft/sec and greater).

2. The Contractor shall investigate and report his findings of scaling and other simulation criteria necessary for predicting material behavior under radiant entry heating conditions. Particular emphasis shall be placed on investigating the necessary sample model size of the required spectral distribution of the energy from the radiant source, and of the necessity for programming the radiant heat input.

Phase II - Evaluation of Existing Radiant Heater Technology

1. A study shall be carried out on those radiant sources which might be utilized in entry simulation facilities. The following radiation sources shall be evaluated: a) Solid and gas discharge lamps; b) Electron beam heaters; c) Resistance or induction heaters; d) Solar furnace; e) Direct arc column heating.

2. The evaluation of the performance characteristics of the sources shall include: a) Maximum radiant flux attainable; b) Spatial and temporal uniformity of flux at test section; c) Spectral distribution of the radiant flux; d) Compatibility with convective heating sources; e) Operational characteristics; and f) Economics.

Phase III - Definition of Future Research and Development Requirements

1. On the basis of existing technology the state of the art of radiative and combined convective-radiative simulators shall be established.

2. Comparison shall be made between the state of the art of radiant heater technology and the future re-entry environment requirements. On the basis of this comparison specific recommendations for future development efforts shall be made if the existing technology is not adequate.

B. Program Organization

This program originates from the Structures and Mechanics Division of the NASA Manned Spacecraft Center. Mr. D. H. Greenshields, Thermo-Structures Branch is the Technical Representative for NASA MSC. The Project Director at AVCO/RAD is Dr. R. R. John. Mr. T. K. Pugmire is the Project Engineer. Other participants in this phase of the study are Drs. S. Bennett, T. Laszlo and R. Timmins and Messrs. P. Andrews, M. Hermann and R. Liebermann. Several changes were made in participating personnel for this phase of the study over those originally proposed. The necessity of the changes was dictated by the program rather than external motivations and resulted more appropriate study inputs. P. Andrews and R. Liebermann contributed in the area of environment definition and S. Bennett and M. Hermann provided data and analyses pertinent to the evaluation of the simulation requirement. R. Timmins assisted with information of chemical reactions resulting from radiation fluxes and T. Laszlo provided data on a variety of radiation sources.

III. DEFINITION OF RADIANT HEAT INPUTS FOR MANNED MISSIONS

A. Stagnation Conditions

A literature search to establish the limits of possible radiant heating for the manned entry corridor (limits established by C_{Lmax} 12 g undershoot, C_{Lmax} overshoot, L/D_{max} 12 g undershoot and L/D_{max} overshoot) provided somewhat disappointing results. In general, predictions at the higher velocities, in excess of 40,000 feet per second, differ by factors of more than two.[1-8]

For flight velocities less than 40,000 feet per second in the more recent reports the agreement among investigators is relatively good. The radiant heating fluxes pertinent to those flight velocities are demonstrated by the trajectories shown in Figure 1. Figure 2 provides a velocity versus time plot of these flight profiles. For the re-entry trajectories the following other conditions apply:

C_{Lmax}:	W/C_DA	=	42 psf
	a	=	60°
	L/D	=	0.6
L/D_{max}	W/C_DA	=	147. psf
	a	=	30°
	L/D	=	1.2

The specific equilibrium radiation data used to predict the radiation heat transfer for these conditions was that of Allen and Textoris[4] and where considered applicable and valid the results of Kivel and Bailey[3]. (The earlier work of Kivel and Bailey's results considerably overestimate the radiative intensity at temperature above $9000^{\circ}K$.) For these calculations stagnation point shock detachment distances were estimated assuming a two-dimensional flow. Heating distributions were made for the windward side assuming a plane, optically thin slab model with linear temperature and density gradients normal to the surface. The shock geometry was derived from NASA-Langely schieren photographs. Nonequilibrium radiation calculations were based entirely on the experimental data of Allen et al.[7] No density dependence was considered and an arbitrary attitude cutoff of 280,000 feet was assumed. The heating rates for these conditions are shown in Figures 3-6. Some of the results are contained in Reference 9.

As indicated previously there exists an uncertainty as to the radiant heating expected for flight velocities over 40,000 feet per second. Figure 7 indicates a generalization of this uncertainty for velocities up to 65,000 feet per second. (Data used for this generalization is from References 1-8.) With only order of magnitude results being required for the purpose of outlining general radiation heating simulation requirements the stagnation point heating history curve of Figure 8 is felt to be an adequate guide. This curve is representative of the heating that can be expected to be associated with the earth re-entry following a planetary or space probe type mission.

A further generalization of entry corridors and the associated radiationheating is shown in Figure 9.

A generalized band including the results of various investigators[10-14] of radiant heating for entry into planetary atmospheres of any combination mixture of carbon dioxide and nitrogen is shown in Figure 10. By selection of the appropriate flight conditions, this band will provide adequate order of magnitude results for entry into the atmospheres of Mars and Venus.

B. Spectral Distribution (Air)

A literature search for the spectral radiance distribution for high temperature air provided difficulties similar to those encountered when attempting to establish the magnitude of radiation heating rates. The relatively current (in open literature) variation for spectral radiance of equilibrium air at 8,000°K for = 0.1 - 1.3 microns is shown in Figure 11. A generalization of the distribution for several temperatures for 1000-100,000 Å is shown in Figure 12. For comparison purposes a plot of normal shock nonequilibrium radiation for 9% CO_2, 90% N_2 and 1% A from Reference 12 is Figure 13.

IV. RELATIONSHIP OF FLIGHT PARAMETERS TO SIMULATION REQUIREMENTS

The spectral radiance significantly varies with composition, pressure and temperature. Therefore, the spectral distribution of radiant energy from the gas cap as seen by the heat shield material represents a rather complicated phenomenon as there are not only pressure, temperature and species and composition variation and gradients but also gas-phase and surface combustion, radiation absorption, blocking and re-radiation.[8] Production of all of these parameters can only be accomplished in a flight test. However, experience has shown in other aspects of laboratory simulation that meaningful evaluations and engineering design data can be obtained from less than exact duplication of flight conditions. What now remains is the establishment of relative importance of the several factors mentioned, necessary model sizes, combined radiative and convective heating and the effects on all of the factors resulting from parameter changes associated with the entry trajectory. As there are only several facilities capable of obtaining useful data in this field there is very little actual data on which to base decisions. The more significant reports are those of Howe and Viegas[8], Diaconis et al[15], Lundell et al[16], Howe[17], Lundell et al[18], Louis et al[19], and various internal reports. While reports of the nature of the latter classification are not generally available they can provide additional useful data. In this regard References 20-22 have applicable data.

In spite of the availability of references, data in this field is sparse and inclusive. One is not able at this time to specify which parameters in radiant heating simulation of entry conditions must be duplicated.

From data on the more simple heat protection materials such as teflon, graphite and phenolic nylon it would appear that if the total net heat to the material surface (surface temperature constant) the material performance is nearly constant regardless of the ratio of convective to radiative heating. This is confirmed in the data of Lundell et al[18]. It should be noted that considerable significance can be attached to duplication of the total net heating input and maintaining a surface temperature equivalent to that which would be associated with flight conditions even for the simple materials. Constant gross heating with variations of the ratio of convective and radiative heating seem to produce significant changes in total net heating.

Importance of a matched spectral distribution in radiation simulator cannot be determined at the present time. Data in this area is extremely sketchy and in one instance even contradictory. At low net flux levels, less than a few watts/cm^2, it has been observed that certain organic materials may react differently chemically. A good example of this is the film coatings which produce different colors dependent on the spectral distribution of the incident radiation. It is also a well established fact that a material's emissivity is wave length dependent. Though slight this has some effect on re-radiation and hence the net heat flux. It has also been noted in several cases similar material performance has been observed in materials tests of pure radiative fluxes with an argon arc discharge source and one with a plasma heater convective source. The following data and analysis is cited to demonstrate this point.

A. Pure Radiative Materials Test

A diagram of the experimental apparatus is shown in Figure 14. A gas stabilized arc column was maintained between a thoriated tungsten cathode and a copper anode as shown. The viewing port, quartz window, allowed a complete view of the arc column. A radiometer was used to measure the emitted radiation per unit arc column length. Spectral radiance was also determined with a Littrow mount prism spectrograph. (One of the curves of spectral radiance of argon in this device is shown in the following section.) The distance R (see Figure 14) from the geometrical center of the generator to the face of the radiometer is large in comparison to the dimensions of the observed arc column so that the exposed column could be treated, for a first approximation, as a point source. Neglecting the effect of the window, less than 10%, the radiant intensity I_r, at the receiver is related to the total radiant energy $\mathcal{E}$, of the exposed column by

$$I_r = \mathcal{E}/4 \quad R^2$$

Division of the total radiant energy by the exposed length of arc column provided the emitted radiation per unit length of the observed column. This estimation was checked by varying both the distance R and the exposed length of arc column and the results agreed within experimental error. It was interesting to note that this first order approximation was only 20% higher than the results obtained from the spectral radiance measurements obtained spectrographically. For the materials testing the model was located directly opposite the viewing port normal to the arc column. To compensate for material recession during the test and hence the change in incident flux the following analysis was applied. Assuming ℓ is the distance of the front surface of the model to the center of the arc column and ℓ_o is this distance at time t_o then:

$$\frac{d\ell}{dt} = k_1 \dot{q}_r$$

and $$\dot{q}_r = \dot{q}_r (\ell_o) \frac{\ell_o}{\ell}$$

$$\frac{d\ell}{dt} = k_i \dot{q} (\ell_o) \frac{\ell_o}{\ell}$$

$$\frac{\ell^2}{2} + C = k_i \dot{q}_r (\ell_o) \ell_o t$$

$$\ell^2 - \ell_o^2 = 2 k_1 \dot{q}_r (\ell_o) \ell_o t$$

A plot of $\ell^2 - \ell_o^2$ versus $\dot{q}_r (\ell_o) t$ yields a straight line with a slope of $5.25 \times 10^{-3} \frac{in^2}{\frac{kw}{cm^2} - sec}$ (admittedly inconsistent units).

Therefore $2k_1 \ell_o = 6.59 \times 10^{-3} (\frac{in}{sec} / \frac{kw}{cm^2})$ in. For these tests $2\ell_o = 0.394$ in, therefore

$$k_1 = 1.67 \times 10^{-2} \frac{in}{sec} / \frac{kw}{cm^2}$$

The material being tested has a density of 1.65 gm/cm^3 or 4.2 gm/cm^2 - inch. Therefore, a recession rate of 1 inch/sec is a mass loss rate of 4.2 $gm/cm^2 sec$ hence, $\dot{m} = 7.02 \times 10^{-2}$ gm/kilojoule.

From this a material performance or Q_T^* can be calculated:

$$Q_T^* = 14.3 \text{ kilojoules/cm}$$

or

$$Q_T^* = 3{,}430 \text{ cal/gm}$$

To relate this performance to the performance of the material that might be observed in a straight convective heating test, reflection must be accounted for. A reasonable value of material emissivity with a surface temperature of 3000°K is 0.75. Reflection of incident flux would reduce Q^*_T by 25% and re-radiation would reduce it by 10%. (Note under the present test conditions blocking could not be considered as a significant factor.) With these reductions Q^*_T is reduced by 37% to 2500 cal/gm. Recognizing that this evaluation is rough and preliminary it is noted that this value is almost identical with the Q* for this material obtained in straight convective heating simulation facilities. The plot of the data points on the $\ell^2 - \ell_o^2$ versus $\dot{q}_r(\ell_o)t$ graph is shown as figure 15.

B. Spectral Radiance of Sources

For initial comparison purposes the spectral radiance of several gas has been obtained. For the most part this data was obtained in various arc sources in the AVCO/RAD laboratories except where otherwise noted. Particular attention should be given to figures 16 and 17 which show the dependence of spectral radiance of nitrogen and oxygen on temperature. Nitrogen at 7.7 atmospheres is shown in Figure 18, Xenon, Reference 23, Figure 19, Argon, Figure 20, and a carbon arc, Reference 24, in Figure 21.

REFERENCES

1. Nerem, R. M. and Strickford, G. M., "Shock Layer Radiation During Hypervelocity Re-entry", AIAA Entry Technology Conference, Williamsburg and Hampton, Va., October, 1964.

2. Nardone, M. C., Breene, R. G., Zeldin, S. S. and Riethof, T. R., "Radiance of Species in High Temperature Air," GE R63SD3, General Electric Space Sciences Lab., June, 1963.

3. Kivel, B., Bailey, K., "Tables of Radiation from High Temperature Air", AVCO-Everett Research Report 21, December, 1957.

4. Allen, R. A., Textoris, A., "New Measurements and a New Interpretation for High Temperature Air Radiation," Presented at the AIAA Aerospace Sciences Meeting, New York, January, 1964, Preprint No. 64-72.

5. Page, W. A., "Shock-Layer Radiation of Blunt Bodies Traveling at Lunar Return Entry Velocities," Presented at the IAS 31st Annual Meeting, New York, N. Y. January 21-23, 1963.

6. Hoshizaki, H., "Equilibrium Total Radiation Measurements in Air at Super-orbital Entry Velocities," Lockheed Missiles and Space Co., Report No. 6-90-63-97, October, 1963.

7. Allen, R. A., Rose, P. H., and Camm, J. C., "Nonequilibrium and Equilibrium Radiation at Super-Satellite Re-entry Velocities", IAS Preprint No. 63-77, Presented at IAS 31st Annual Meeting, New York, N. Y., January, 1963.

8. Howe, J. T., and Viegas, J. R., "Solutions of the Ionized Radiating Shock Layer, Including Reabsorption and Foreign Species Effects, and Stagnation Region Heat Transfer," NASA TR R 159, November, 1962.

9. Midterm Progress Report, "Integrated Wall Construction For Re-entry Vehicles," RAD-SR-64-115, AVCO Research and Advanced Development Division, April, 1964.

10. James, Carlton S., "Experimental Study of Radiative Transport from Hot Gases Simulating in Composition the Atmospheres of Mars and Venus," AIAA Paper No. 63-455, August, 1963.

11. Gruszczynski, J. S., and Warren, W. R., Jr., "Experimental Heat Transfer Studies of Hypervelocity Flight in Planetary Atmospheres," AIAA Entry Technology Conference, Cambridge, Mass., August, 1963, Paper No. 63-450.

12. Thomas, G. M., and Menard, W. A., "Experimental Measurements of Nonequilibrium Radiation from Planetary Atmospheres," AIAA Entry Technology Conference, Williamsburg and Hampton, Va., October, 1964.

13. Breene, R. G., Jr., and Nardone, M. C., "Radiant Emission in the Atmospheres of the Terrestrial Planets," Symp. on Dynamics of Manned Lifting Planetary Entry," John Wiley and Sons, 1963.

14. Fairbairn, A., "The Spectrum of Shock Heated Gases Simulating the Venus Atmosphere," AIAA Entry Technology Conference, Cambridge, Mass., August, 1963, Paper No. 63-454.

15. Diaconis, N. S., Weber, H. E., and Warren, W. R., Jr., "Techniques for Severe Radiative and Convective Heating Environments for Materials Evaluation," Third Hypervelocity Techniques Symposium, Denver, Colorado, March, 1964.

16. Lundell, J. H., Winovich, W., and Wakefield, R. M., "Simulation of Convective and Radiative Entry Heating," Second Hypervelocity Techniques Symposium, Denver, Colorado, March, 1962.

17. Howe, J T., "Shielding of Partially Reflecting Stagnation Surfaces Against Radiation by Transpiration of an Absorbing Gas," NASA TR R-95, 1961.

18. Lundell, J. H., Wakefield, R. M., and Jones, J. W., "Experimental Investigation of a Charring Ablative Material Exposed to Combined Convective and Radiative Heating in Oxidizing and Nonoxidizing Environments," AIAA Entry Technology Conference, Williamsburg and Hampton, Va., October, 1964.

19. Louis, J. F., Decher, R., Allen, R. A., and Brogan, T. R., "Simulation of Re-entry Radiation Heat Transfer," AVCO-Everett Research Laboratory, August, 1963.

20. Hermann, M., and Liebermann, R., "An Investigation of Radiation Emitted from a High Temperature Arc Column and Its Potential as a Source for High Radiant Heat Flux Simulators," R530-63-82, AVCO Research and Advanced Development Division, Technical Release, November, 1963.

21. "Apollo Monthly Progress Report", RAD SR-64-287, AVCO Research and Advanced Development Division, November, 1964, Confidential.

REFERENCES

22. Stein, E., Shaw, R., and Hermann, M., "Ablation Tests on Apollo Materials Subjected to Radiation Heating from the Arc Imaging Furnace," R720-63-903, AVCO Research and Advanced Development Division, Technical Release, December, 1963.

23. Fromm, D., "Absolute Spectral Distribution Measurements of Xenon High Pressure Discharges". U. S. Army Engineer Research and Development Laboratories, May, 1963.

24. Genarco Inc., Jamaica, New York.

LIST OF FIGURES

LIST OF FIGURES

-2-

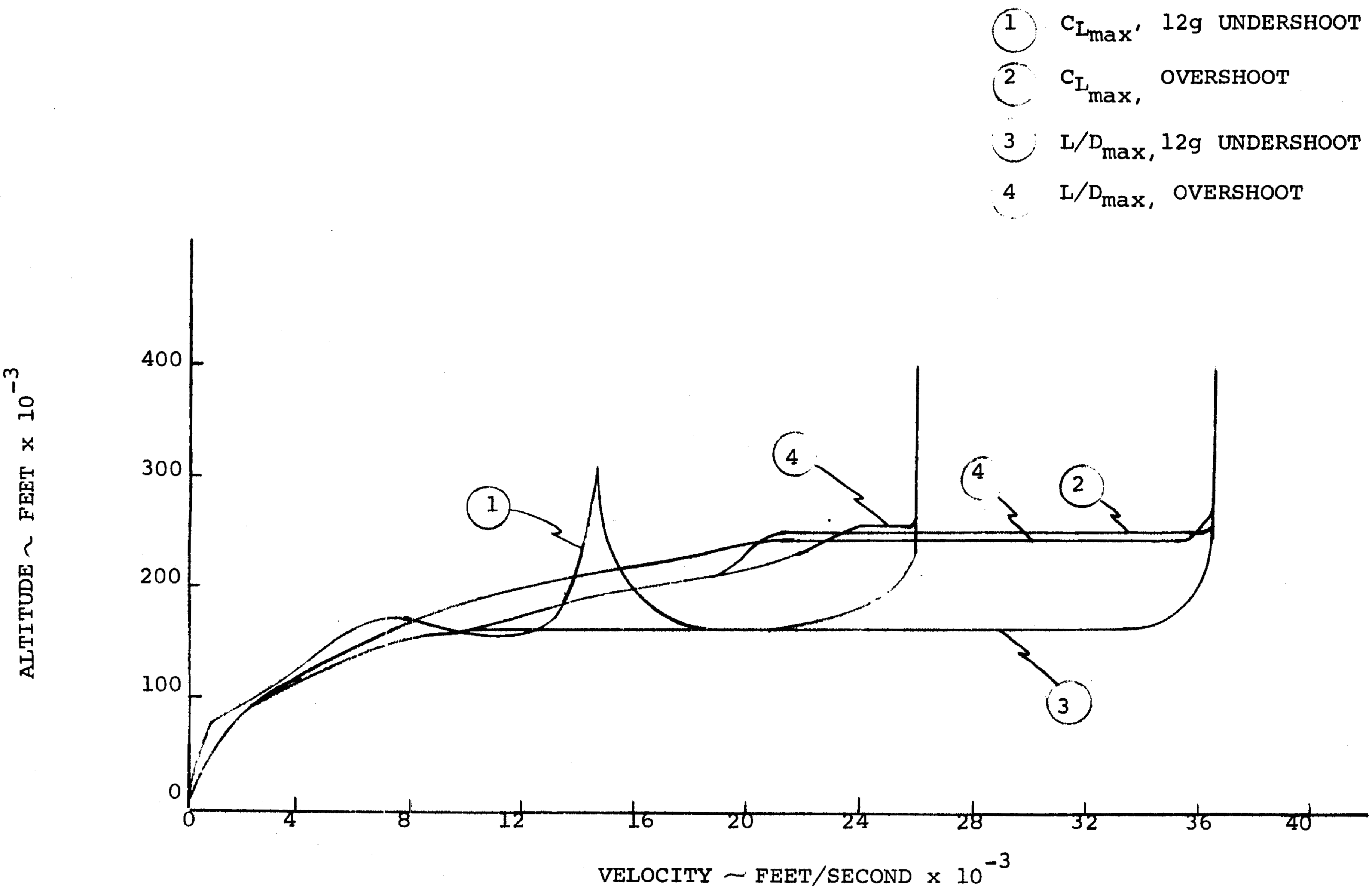


FIGURE 1 VELOCITY ALTITUDE PROFILE

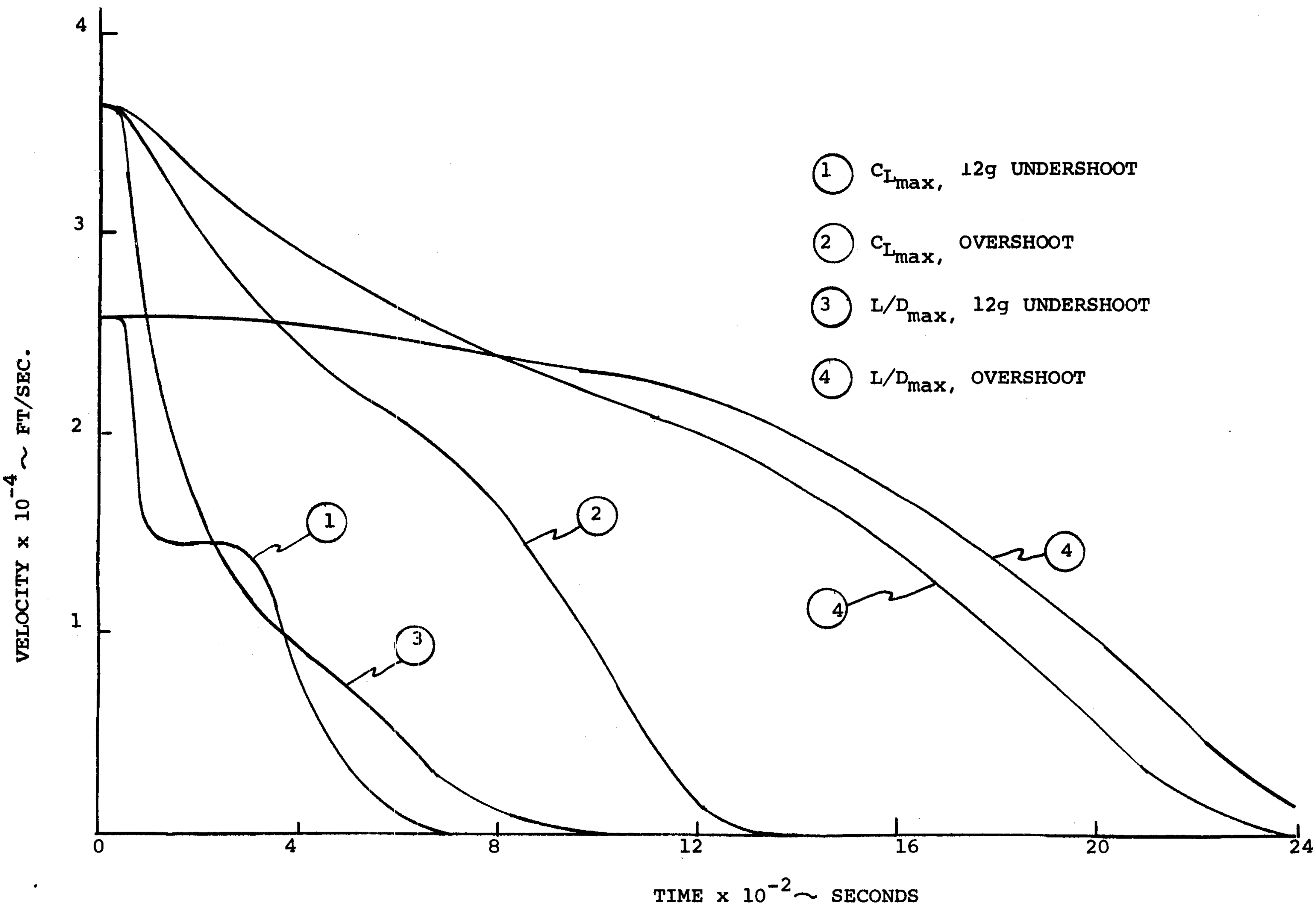


FIGURE 2

VELOCITY-TIME ENTRY HISTORIES

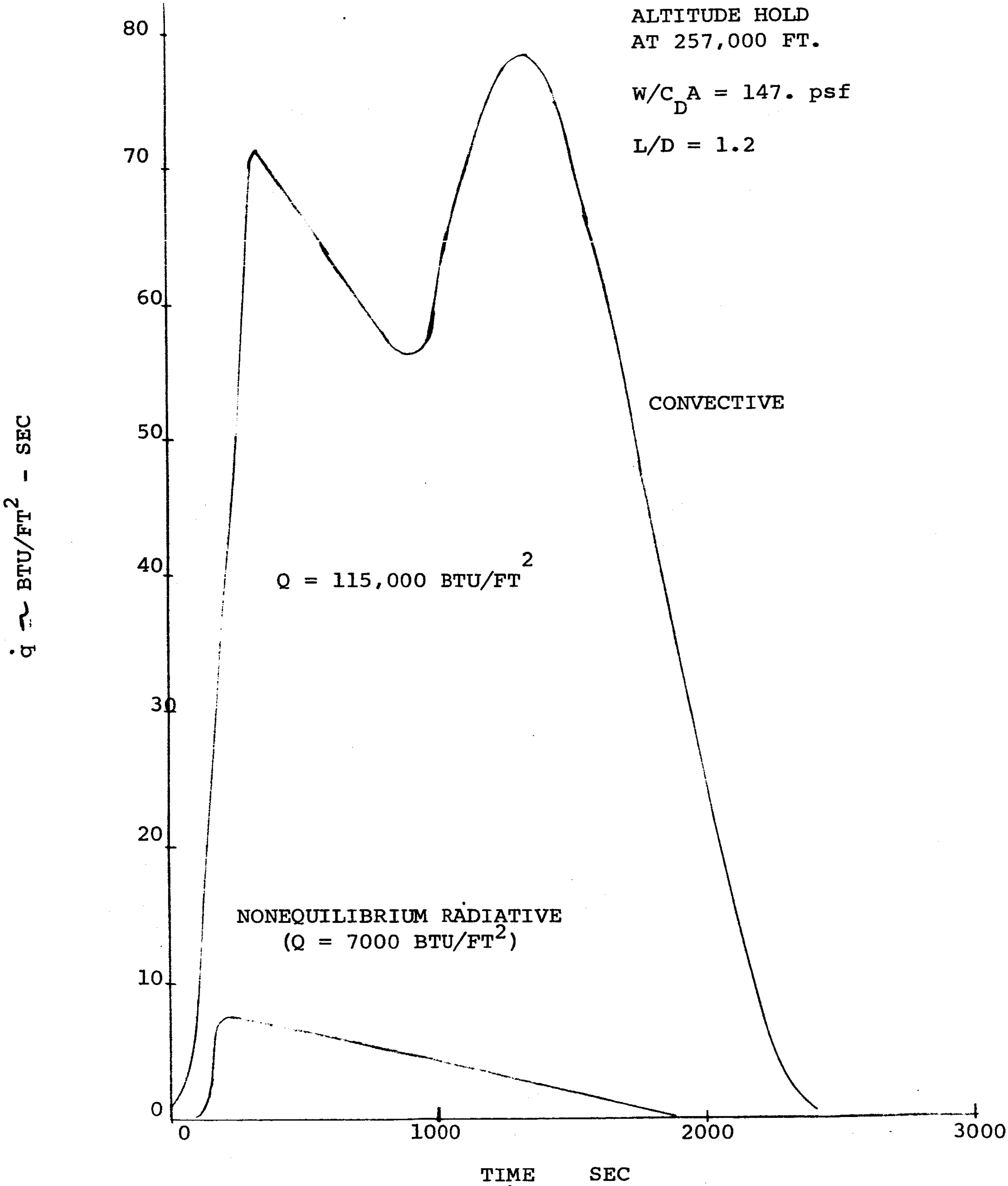


FIGURE 3 - STAGNATION POINT HEAT TRANSFER TIME HISTORY, RE-ENTRY
V_e = 26,000 FT/SEC, L/D = 1.2

Reference 9

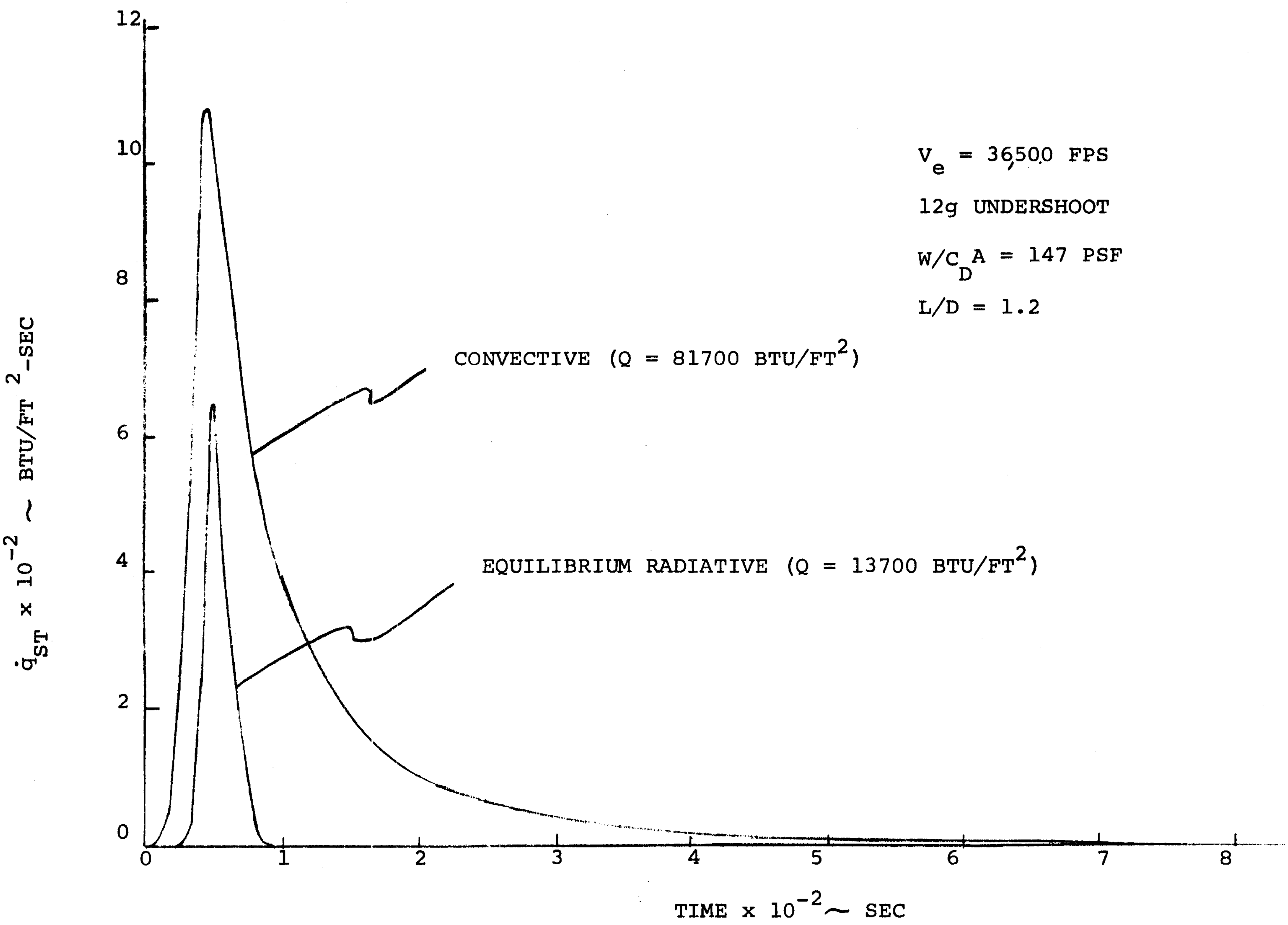


FIGURE 4 STAGNATION POINT HEAT TRANSFER ENTRY HISTORIES

Reference 9

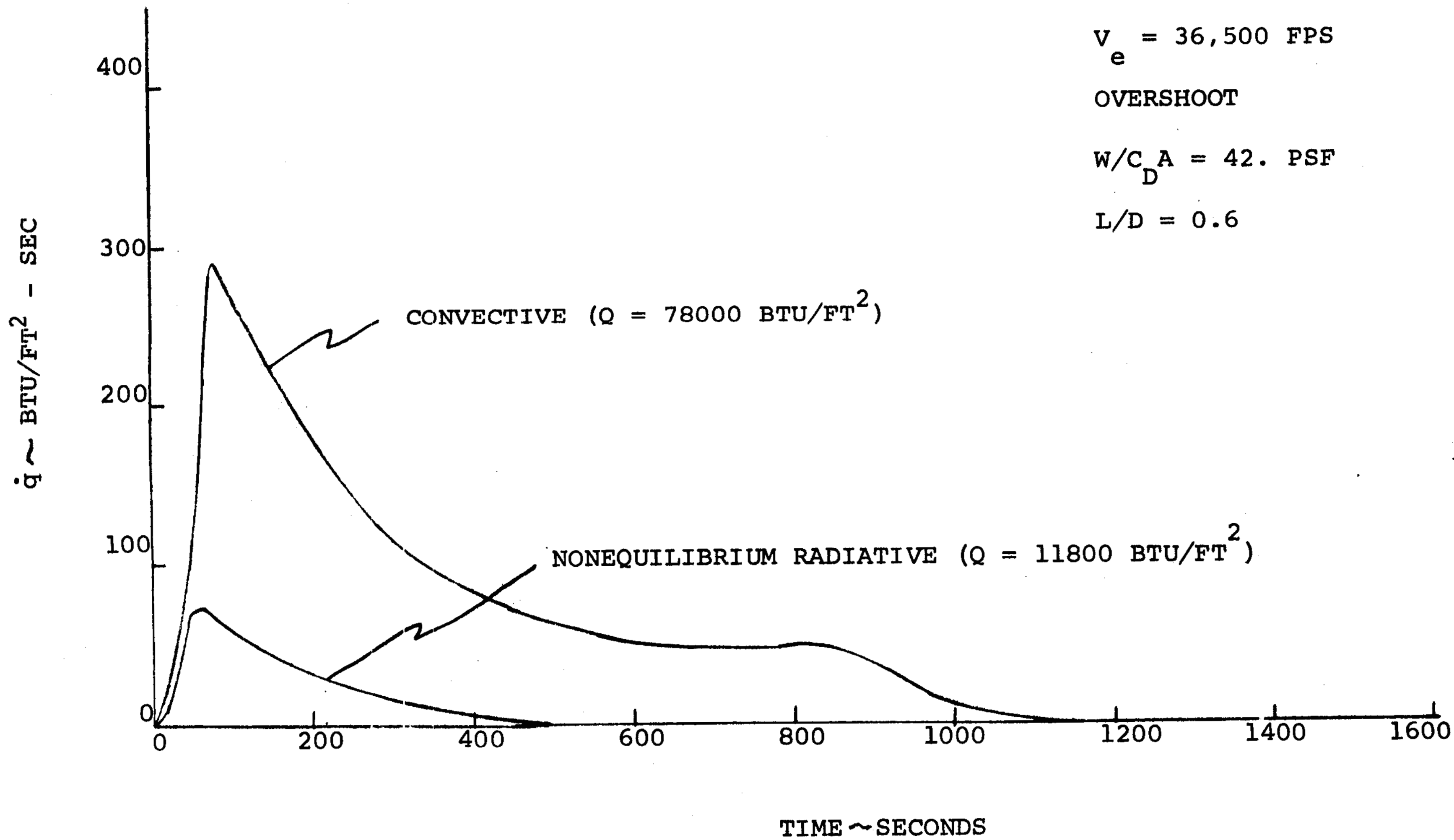


FIGURE 5 STAGNATION POINT HEAT TRANSFER ENTRY HISTORIES

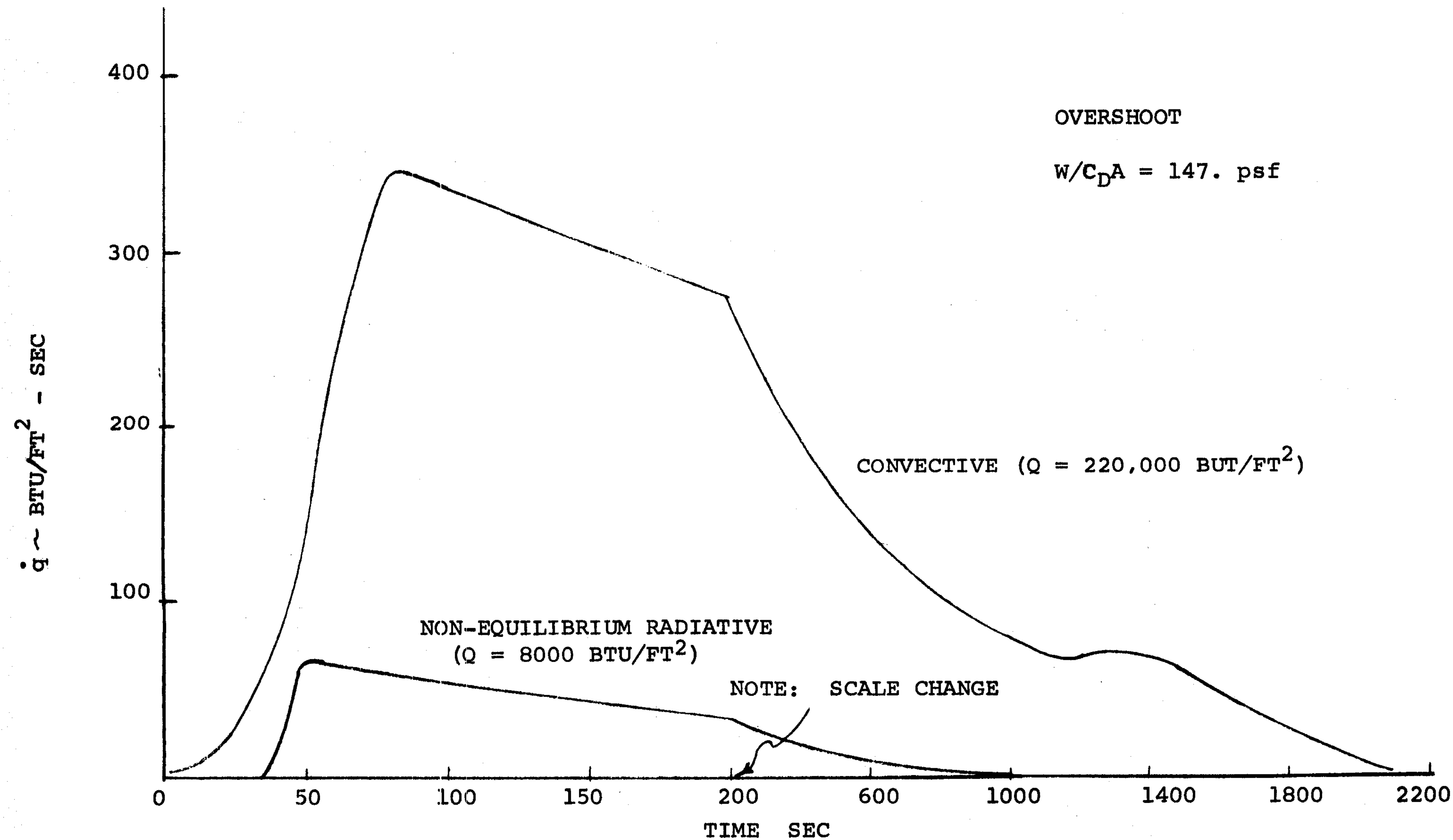


FIGURE 6 - STAGNATION POINT HEAT TRANSFER **TIME HISTORIES**, RE-ENTRY
$V_e = 36,500$ FT/SEC, L/D = **1.2**

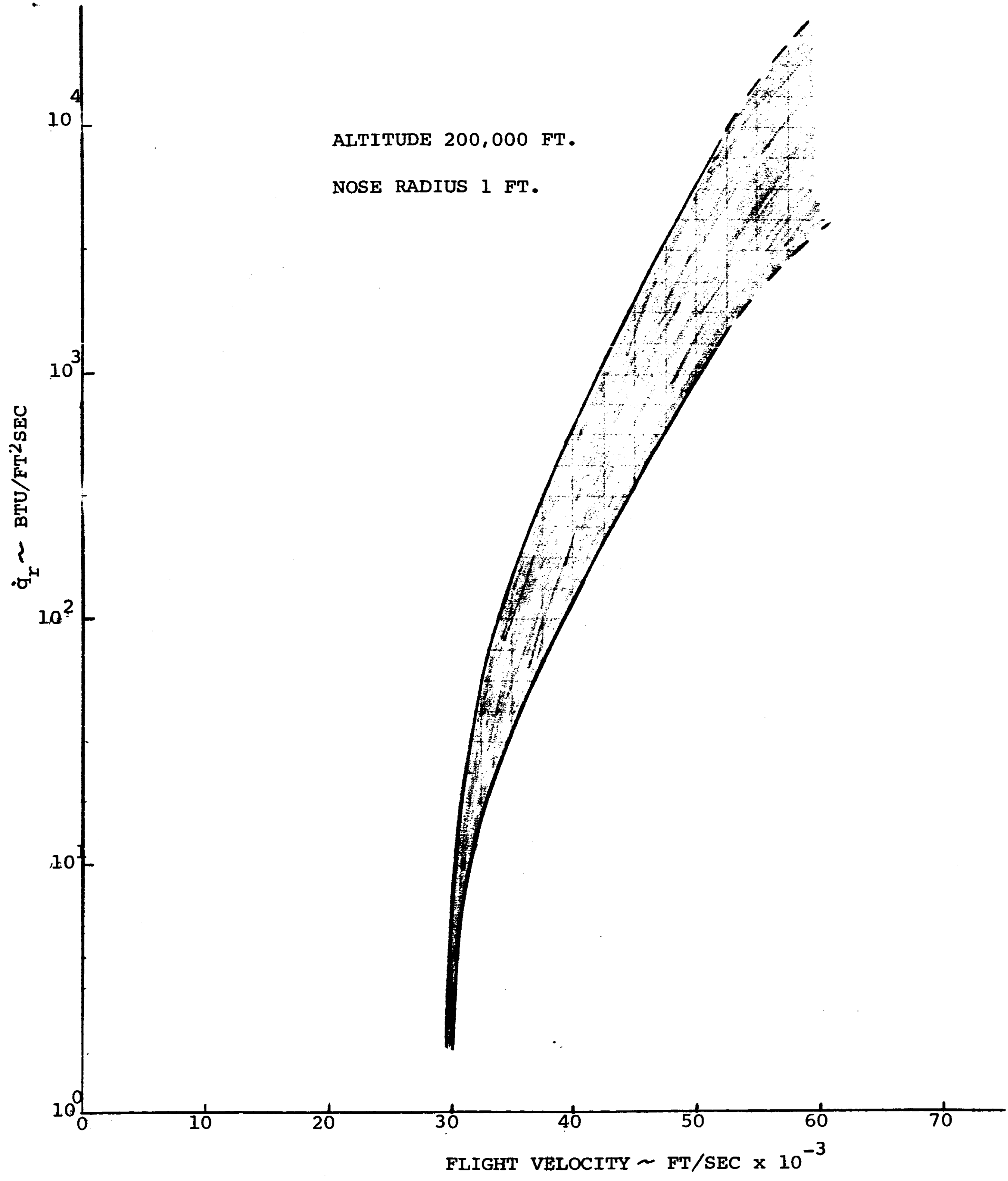


FIGURE 7 EQUILIBRIUM RADIATION DATA AND UNCERTAINTY BAND

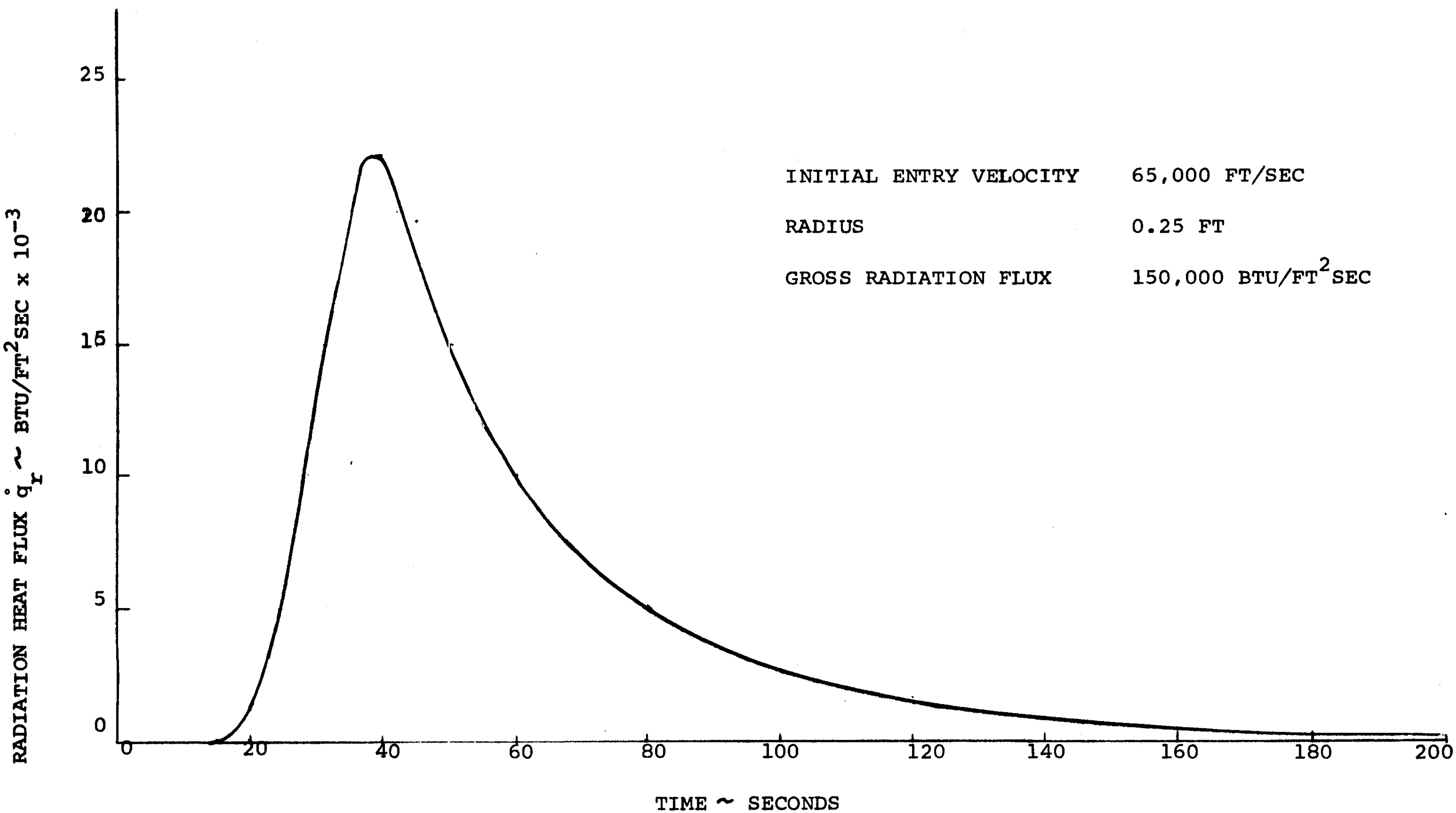


FIGURE 8 TYPICAL STAGNATION POINT RADIATION HEATING

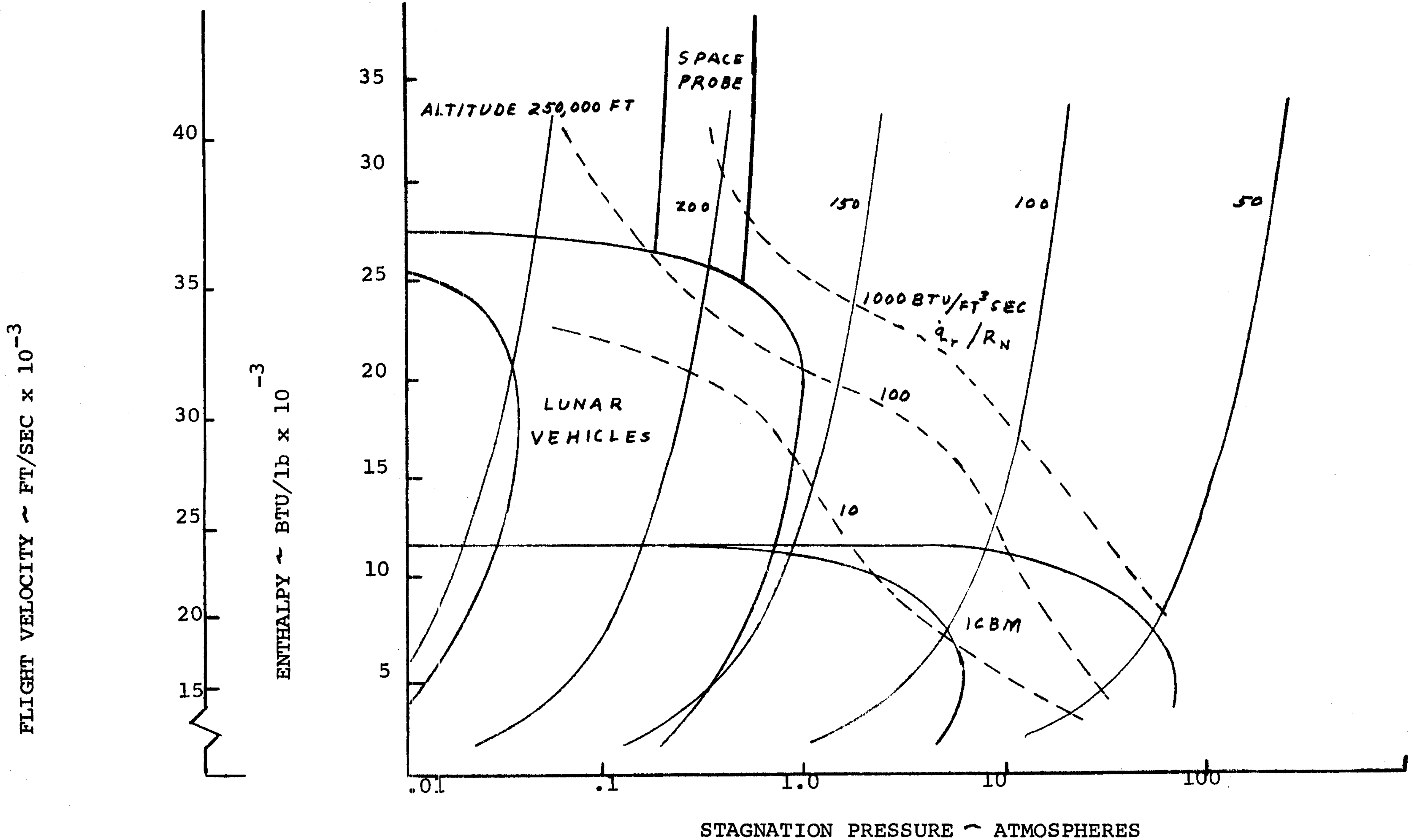
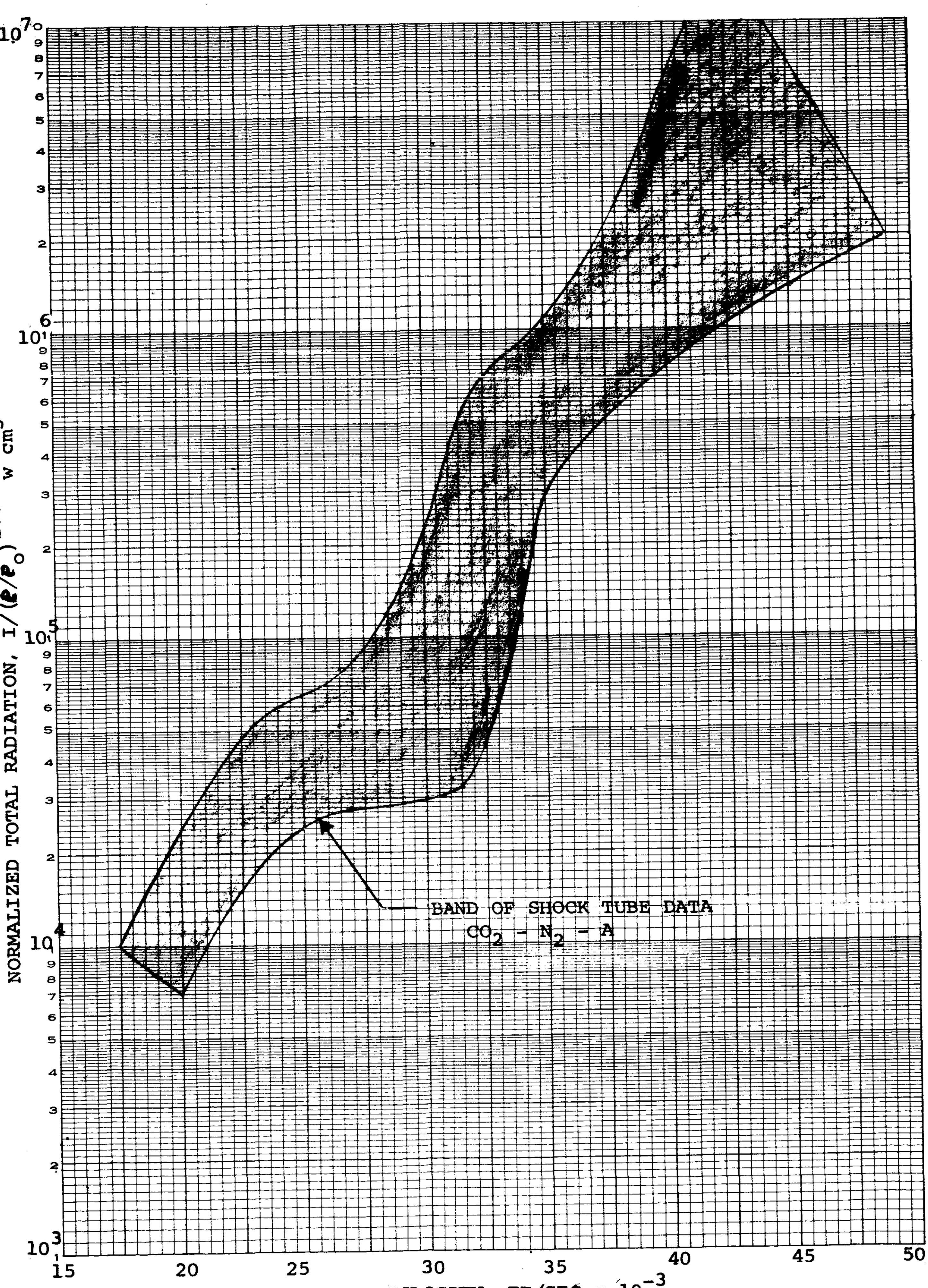


FIGURE 9 STAGNATION PROPERTIES FOR MANNED RE-ENTRY CORRIDORS



NORMALIZED TOTAL RADIATION, $I/(\rho/\rho_o)^{1.64}$ w cm^{-3}
BAND OF SHOCK TUBE DATA
$CO_2 - N_2 - A$
FLIGHT VELOCITY, FT/SEC x 10^{-3}

FIGURE 10

COMPARISON OF PREDICTIONS: RADIANCE OF EQUILIBRIUM AIR, $T = 8000^{\circ}K$, $\rho/\rho_0 = 1$

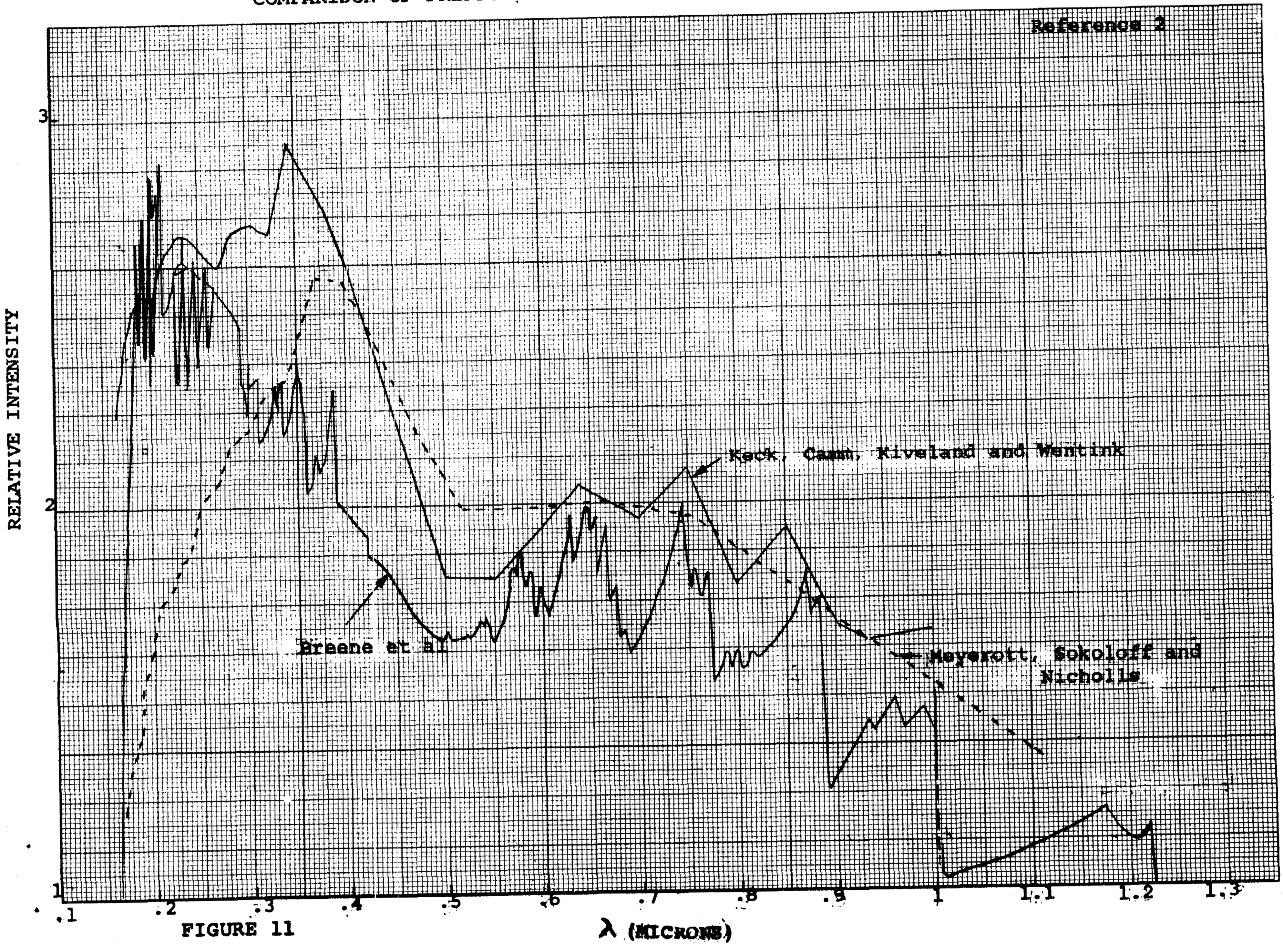


FIGURE 11

Reference 2

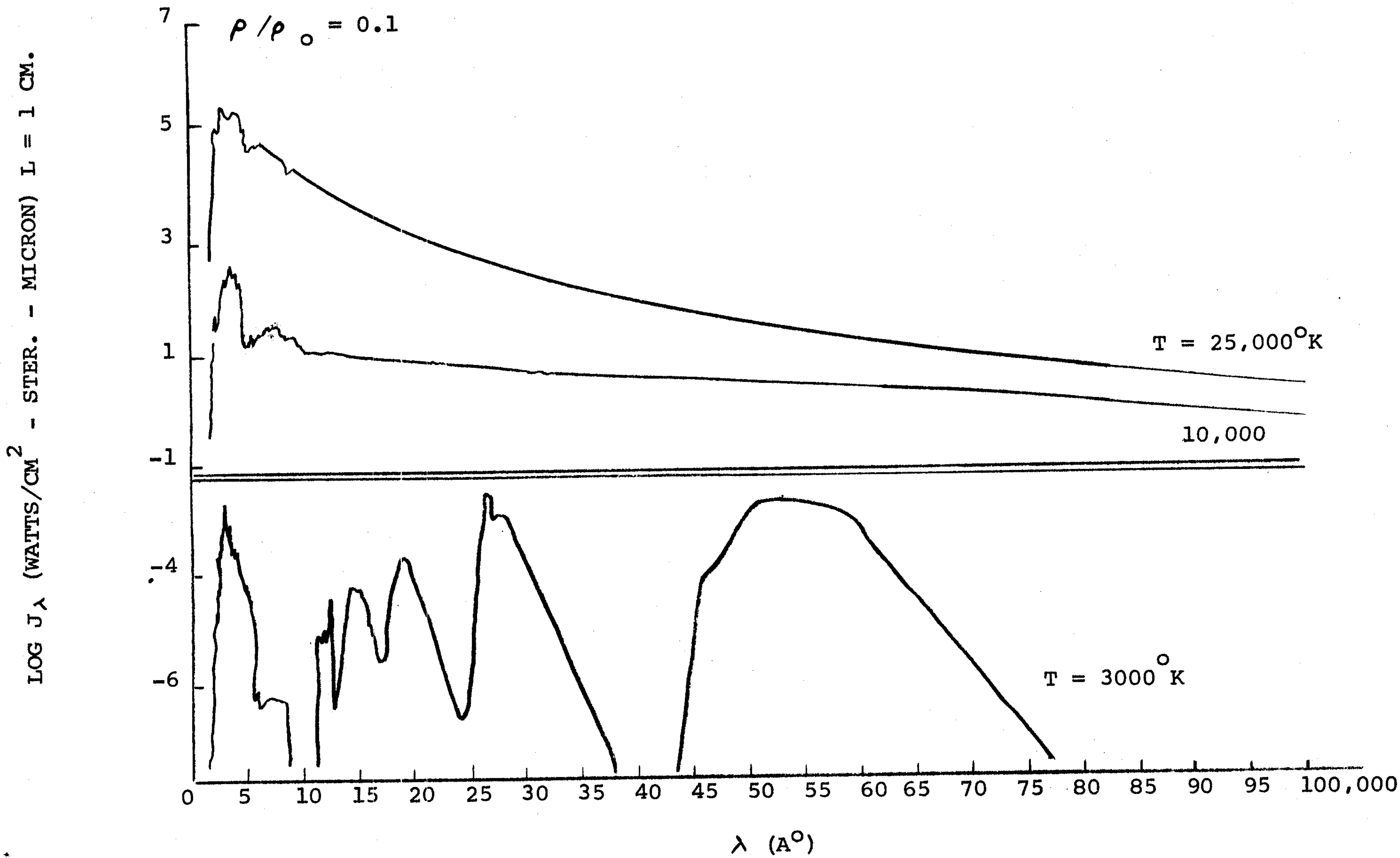


FIGURE 12 - SPECTRAL RADIANCE OF EQUILIBRIUM AIR (1000 - 100,000 A)

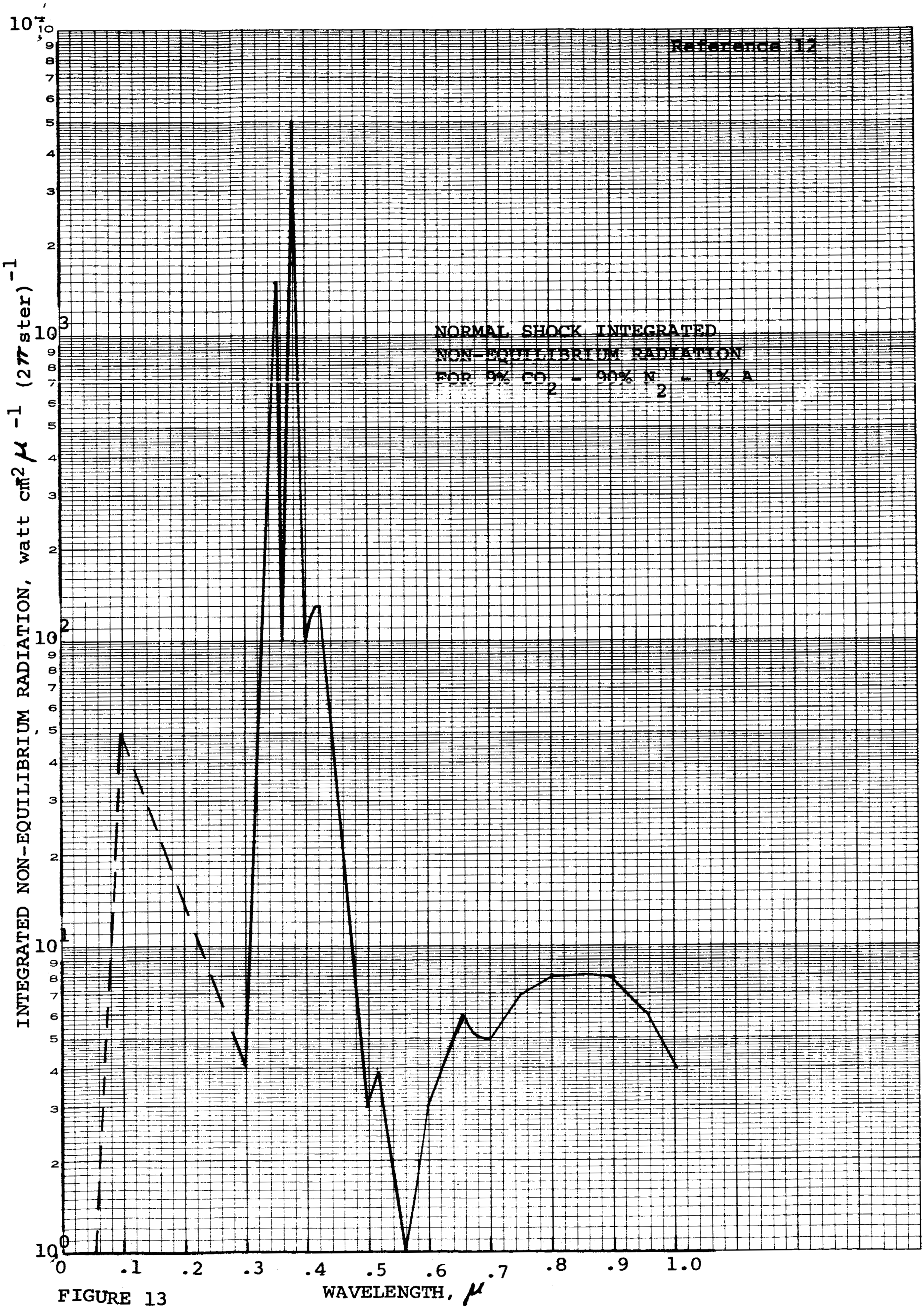

Reference 12
NORMAL SHOCK INTEGRATED
NON-EQUILIBRIUM RADIATION
FOR 9% CO_2 - 90% N_2 - 1% A
INTEGRATED NON-EQUILIBRIUM RADIATION, watt cm^{-2} μ^{-1} $(2\pi \text{ ster})^{-1}$
10^4
10^3
10^2
10^1
10^0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
WAVELENGTH, μ

FIGURE 13

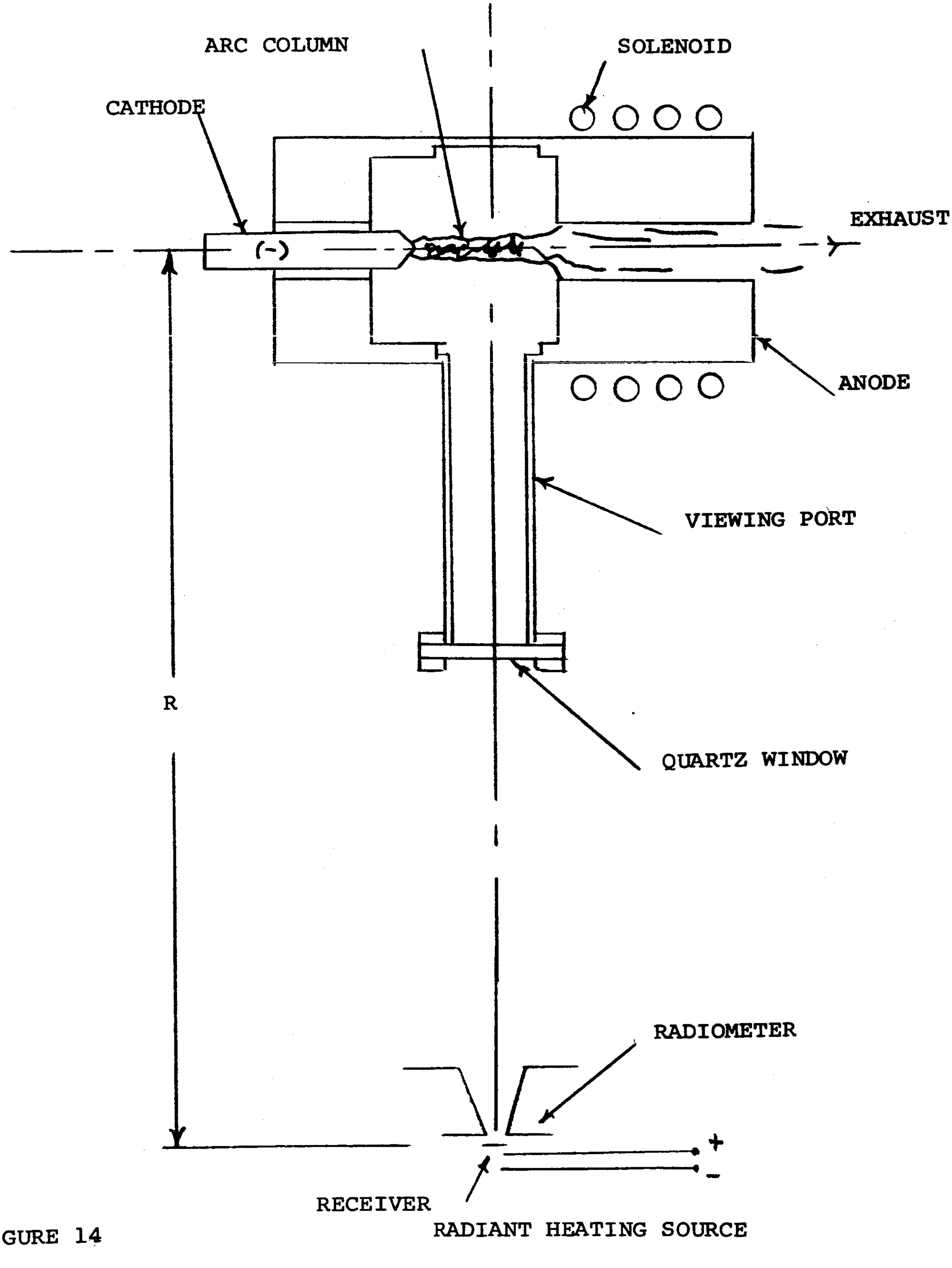
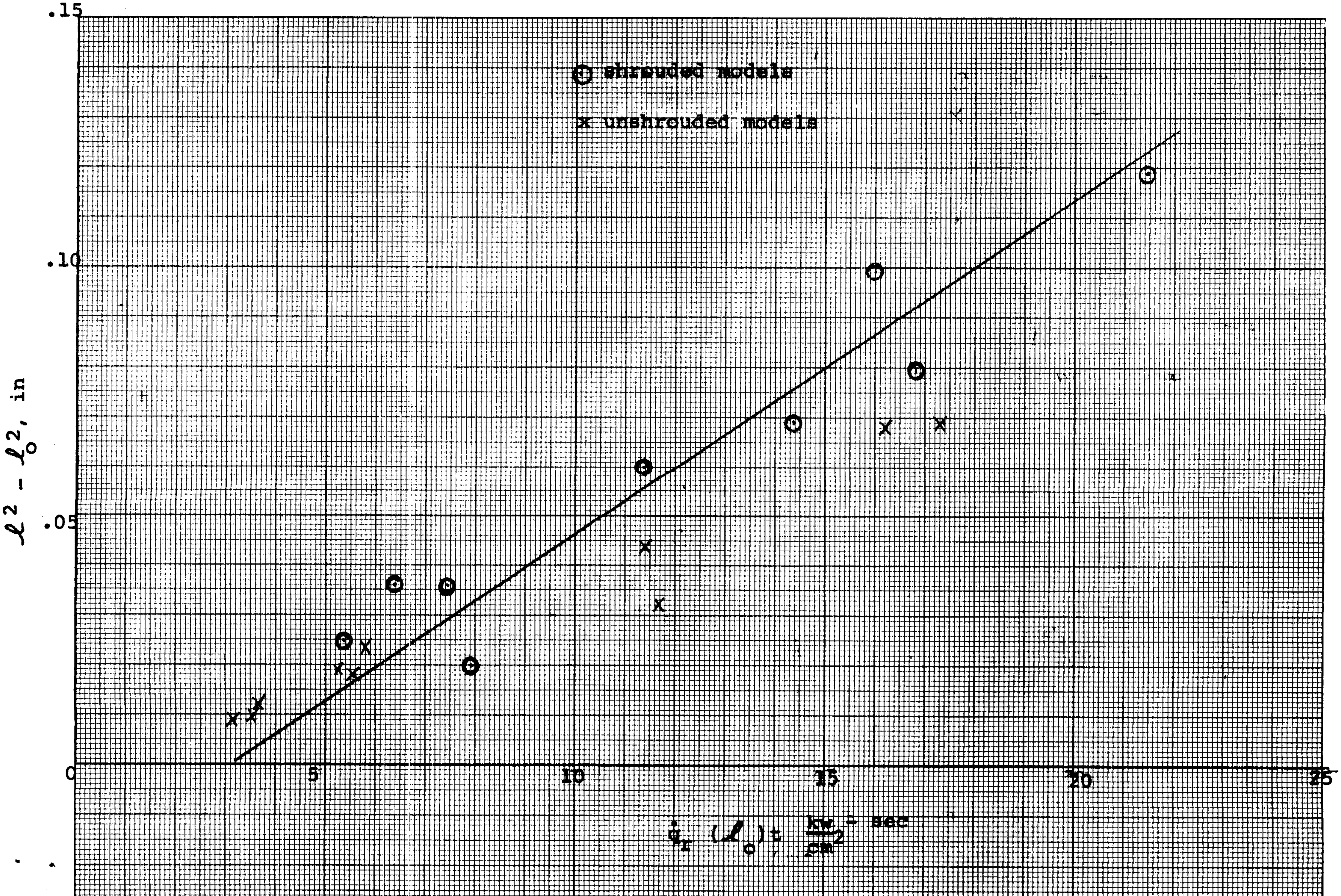

ARC COLUMN
SOLENOID
CATHODE
(-)
EXHAUST
ANODE
VIEWING PORT
R
QUARTZ WINDOW
RADIOMETER
+
-
RECEIVER
RADIANT HEATING SOURCE

FIGURE 14



shrouded models
x unshrouded models
.15
.10
.05
0
5
10
15
20
25
$\ell^2 - \ell_o^2$, in
$\dot{q}_r\ (\ell_o)t\ \frac{kw}{cm^2} - sec$

FIGURE 15

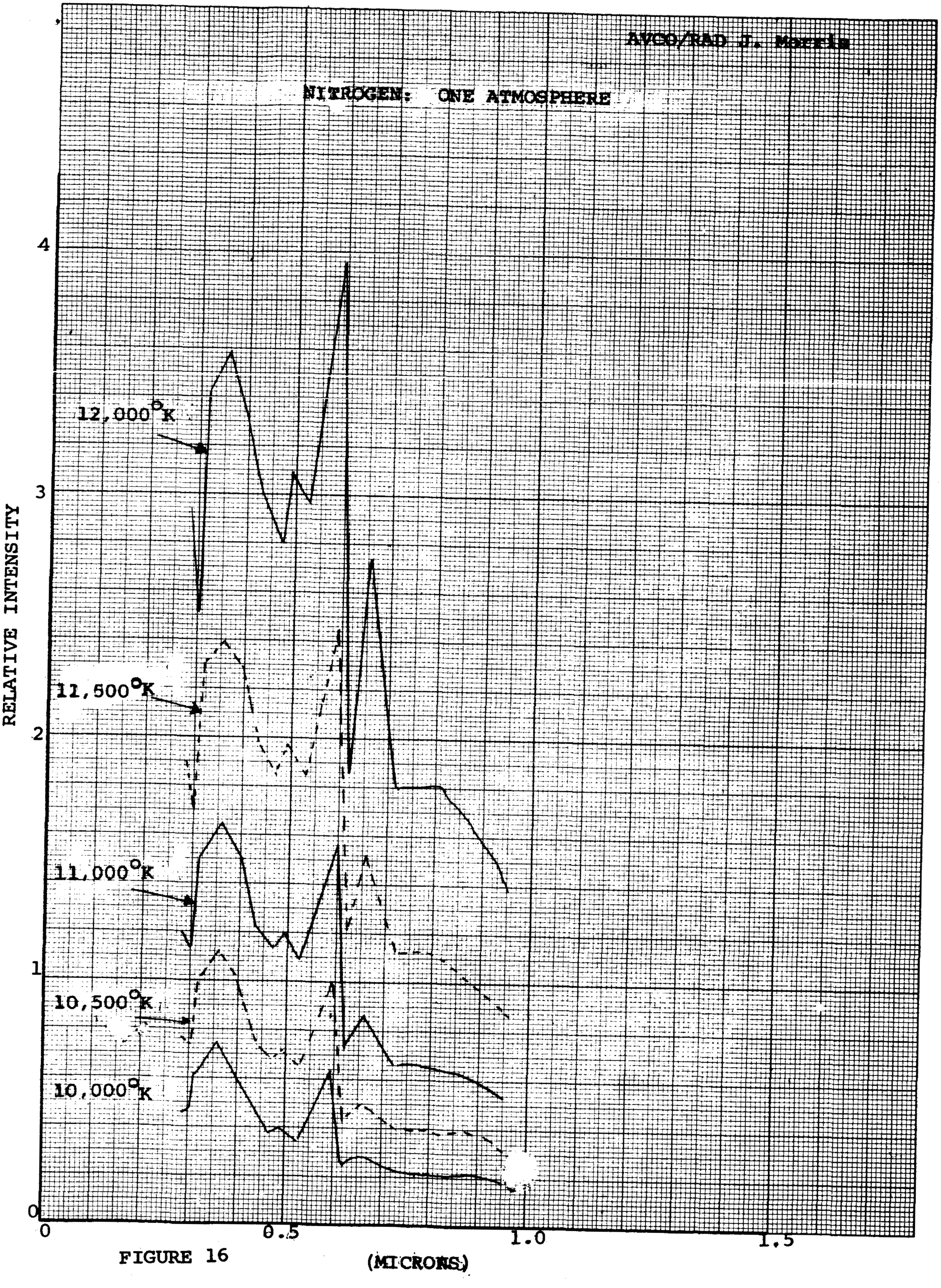

AVCO/RAD J. Morris
NITROGEN: ONE ATMOSPHERE
RELATIVE INTENSITY
12,000°K
11,500°K
11,000°K
10,500°K
10,000°K
0
1
2
3
4
0
0.5
1.0
1.5
(MICRONS)

FIGURE 16

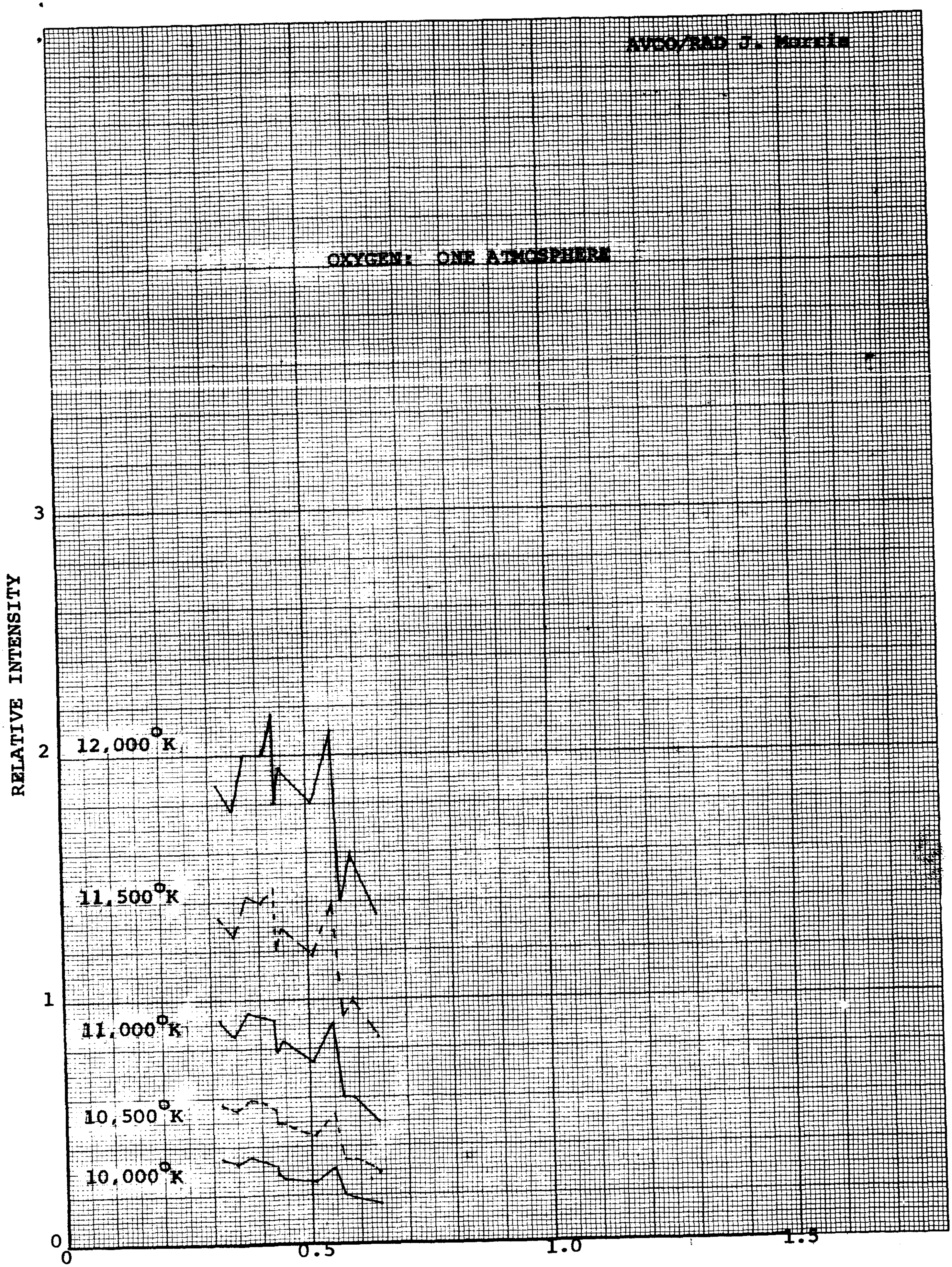


FIGURE 17 (MICRONS)

AVCO NITROGEN ARC: 7.7 ATMOSPHERES

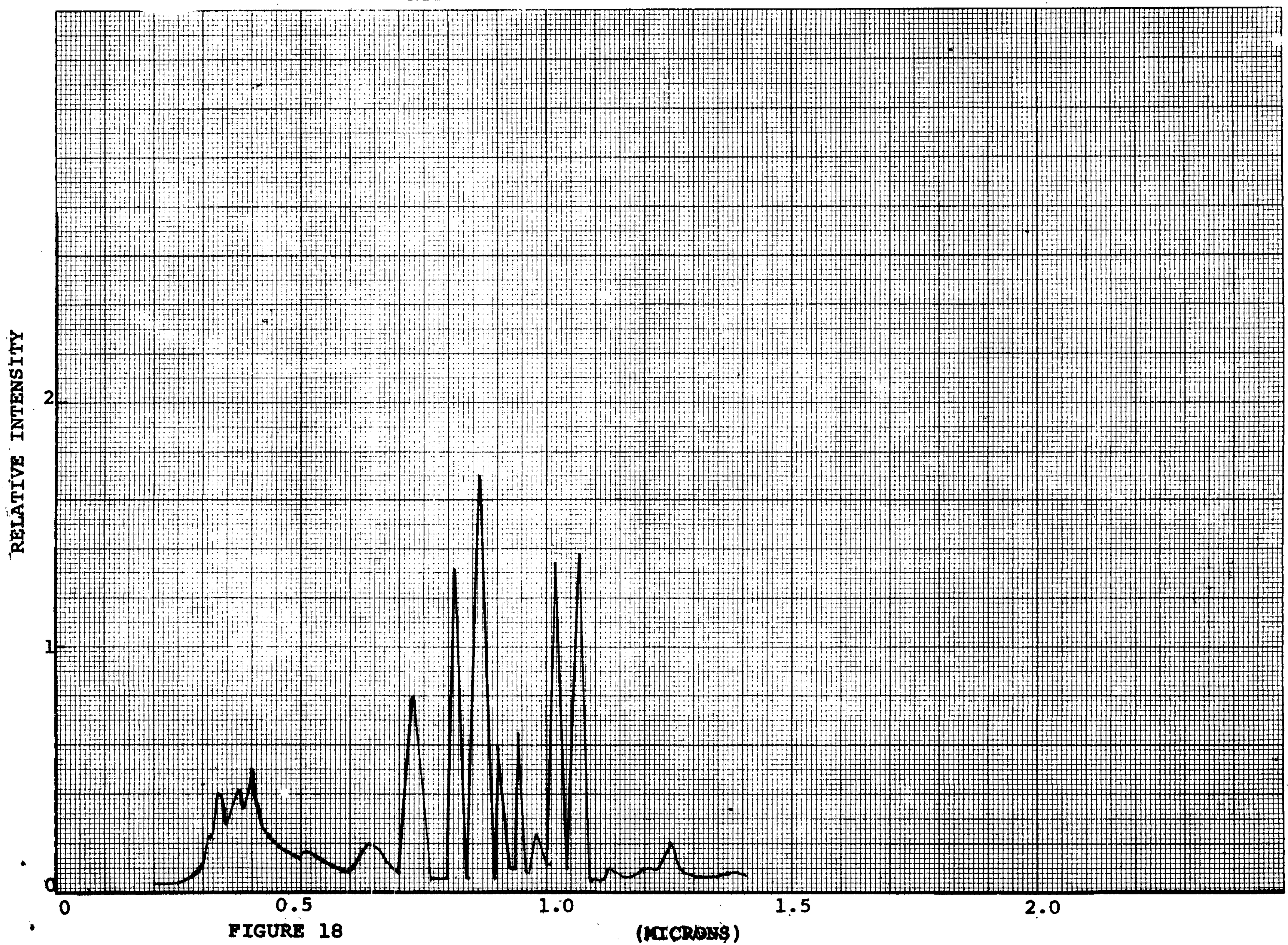


FIGURE 18

XENON DISCHARGE: 10 KW

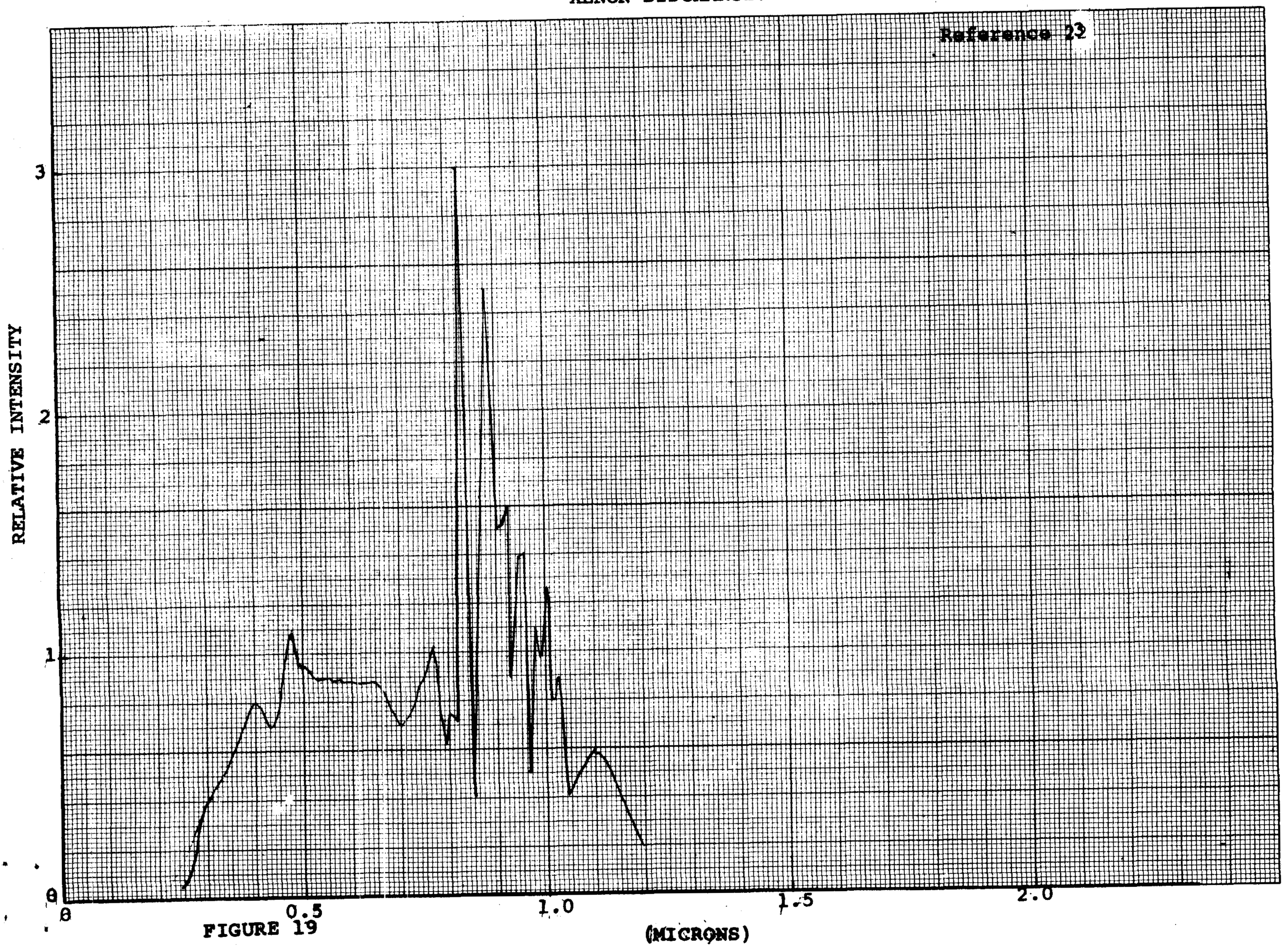


FIGURE 19

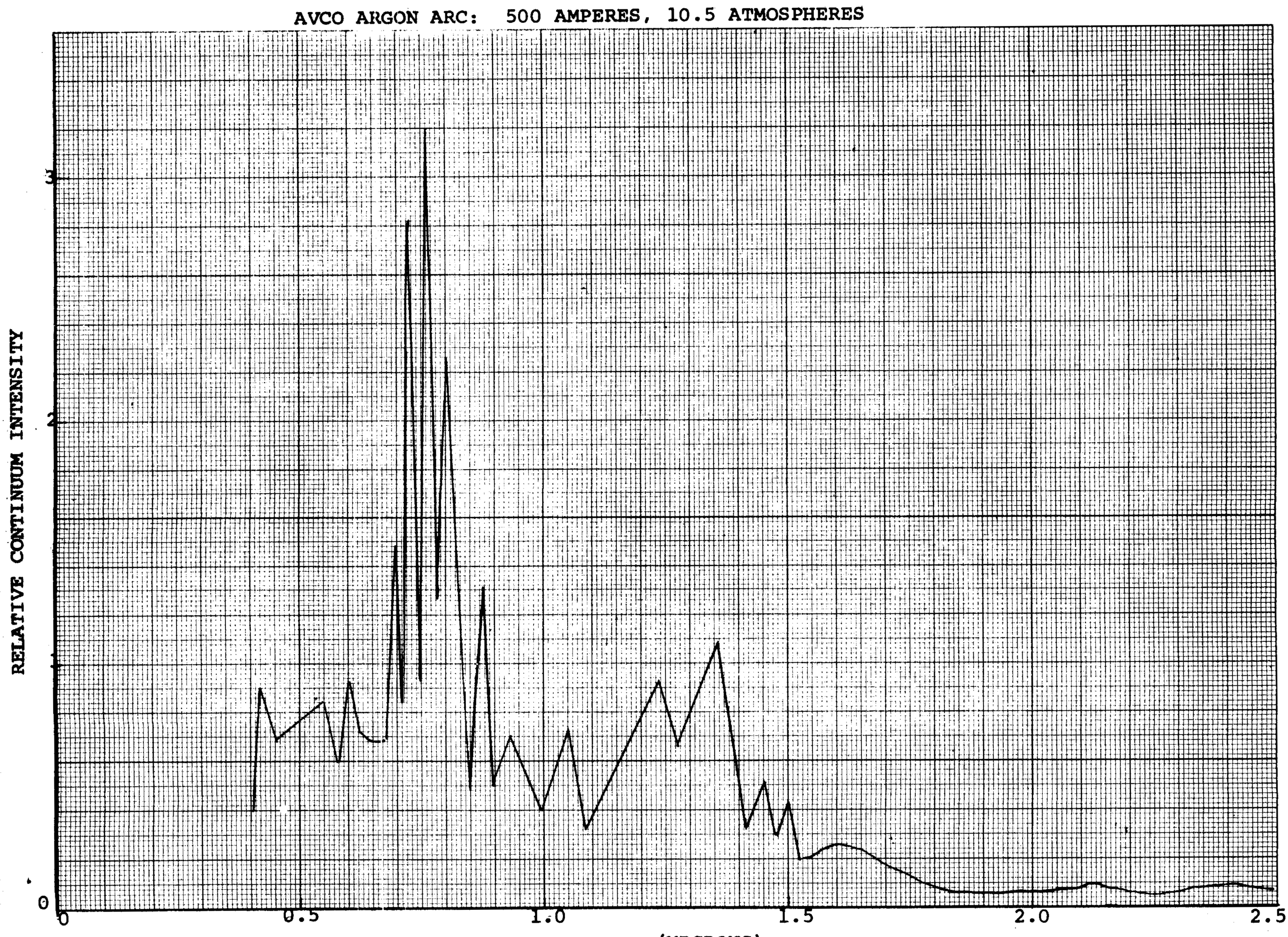

AVCO ARGON ARC: 500 AMPERES, 10.5 ATMOSPHERES
RELATIVE CONTINUUM INTENSITY
0
1
2
3
0.5
1.0
1.5
2.0
2.5
(MICRONS)

FIGURE 20

CARBON ARC: 13.6 mm CARBON @ 185 AMPERES

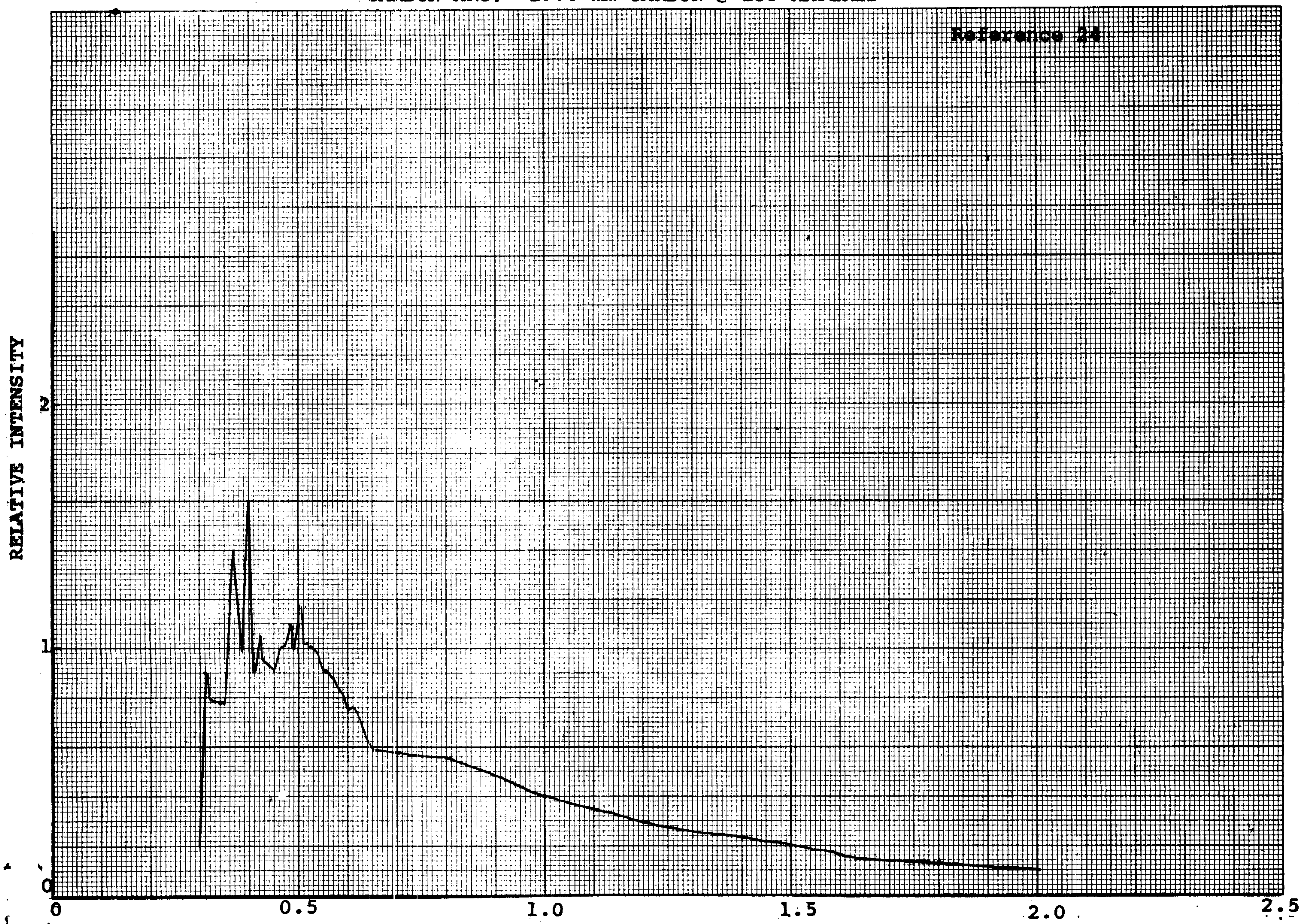


FIGURE 21