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VUV Shock Layer Radiation in an Arc-Jet Wind Tunnel Experiment

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ABSTRACT

Measurements were made of the radiating gas cap of a blunt body in an NASA-Ames 20MW arc-jet wind tunnel. The test gas was air. Spectra of the flux incident on a small aperture centered at the stagnation region were obtained. A helium-cooled, magnesium fluoride window transmitted the flux into an evacuated collimating system that focused the aperture onto the entrance slit of a spectrometer. Data were obtained with films and by photomultipliers. The spectral ranges covered were the vacuum ultraviolet, VUV, (120 nm to 200 nm) and the ultraviolet to near infrared (200 nm to 900 nm) with resolutions from 0.05 nm to 0.5 nm. This paper presents the preliminary VUV results from the experiment. Results from the 200 nm to 900 nm spectral range have been presented elsewhere. Representative spectral records from 120 nm to 200 nm are shown. The intense atomic oxygen and nitrogen lines which are concern to hypersonic flight are measured. Carbon lines are are also seen. These results will be used to help develop and validate aerothermodynamic computational models of arc-jet wind tunnel performance and help to assess the importance of VUV heating to entering spacecraft.

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INTRODUCTION

High speed flight, such as an earth entry from a space mission (low earth orbit, LEO, or further), involves flowfield gases which are not in thermochemical equilibrium *(references A and B)*. This can include important levels of transport of radiative energy *(reference C)*. *Figure A* shows flight regimes experienced for the entries of the Shuttle, Apollo and a proposed Aeroassisted Space Transfer Vehicle (ASTV). An ASTV is a conceptual vehicle which utilizes aerodynamic forces to decelerate and alter orbit parameters to rendezvous with the Shuttle or a space station *(reference A)*. The design of future, highly efficient heat-shields (i. e., not overdesigned) for these vehicles, and others, requires the capability of making accurate heating predictions. At present we cannot accurately predict the environmental conditions surrounding these spacecraft. Real gas computational models are being developed *(reference E)* but validating data are lacking.

The VUV radiative heating of an maneuvering ASTV is a subject of concern. Various models predict widely different radiative heating levels. For example, predictions of ASTV radiative heating from only the VUV atomic lines range from insignificant amounts to levels dominating the overall heating *(references F, G and H)*. There is no flight data to assist in choosing between, or refine, these conflicting theories. The Aeroassist Flight Experiment, now cancelled, was to be instrumented to measure the intensity of certain of these lines under large scale and realistic conditions, during the spacecraft entry, by an on-board experiment. These measurements would have provided a validating measurement for predictive codes. Although the present experiment was conducted in an arc-jet wind tunnel it is expected, as predictive codes are developed, that this VUV data set is important because of its uniqueness of providing a level of VUV validating data.

Arc-jet wind tunnels can produce the enthalpy and pressure conditions simulating these high speed entries. These facilities can be used to conduct experiments to validate computational codes even though the size scale cannot be simulated. A flow-field, rich in non-equilibrated, radiating gas can be generated. Computational models can be exercised on arc-jet test conditions for comparison with experimental results. There are some major difficulties in this approach, however. The free stream plasma flow conditions (enthalpy, species distribution, energy states distribution, etc.) in an arc-jet wind tunnel flow are not well understood. Upstream conditions for shock layer computational models can only be estimated. At present there are efforts at the Ames Research Center *(reference J)* to calculate the model test environments using computational models. Preliminary estimates of the shock layer radiating have been made with a hybrid code starting with the arc column, continuing through the conical or contoured expansion nozzle, and culminating in the flow field of a model located in the exit flow from the nozzle. The radiation falling on the surface of a blunt model placed in this flow is a result culminating the entire modelling process. Experimental results, such as the spectra developed in this work, are needed to support the development of this important theoretical work.

This paper reports on results of an arc-jet wind tunnel experiment. The experiment measured the spectral radiative flux emanating from the shock layer and incident on the stagnation region of a blunt model placed in the supersonic stream. The data shown in this paper are preliminary and do not benefit from final calibrations. The flux was spectrally resolved from 120 nm to 900 nm. This paper presents the VUV results, from 120 nm to 220 nm. The results from 200 nm to 900 nm have been presented in reference N.

Reasonable agreement between the theoretical predictions and this data would be a very convincing test of the veracity of the modelling capability of the arc-jet wind tunnel processes. Understanding this flow would be valuable for development and validation of advanced arc-jet wind tunnel design codes and help extend the capability of this class of facility to advanced aerothermodynamic testing. Validating the capability to predict the VUV measurements in the arc-jet experiment would enable improved predictions of VUV aerothermodynamic radiative heating which are needed to answer the question of the importance of this heating.

EXPERIMENTAL SETUP

The experimental setup is as described in *reference N. Figures B and C* are from this reference and are included here. *Figure B* is a schematic plan view of the experiment. Supersonic flow from the arc is produced in the nozzle and the model is placed in the free stream. The standing shock layer over the model is indicated. *Figure C* is a schematic view of the model. The model face is a 6" diameter flat disk and has a small aperture centered on the forward face to admits the surface radiative flux. A MgF_2 window is immersed in a cavity below the aperture and transmits the surface flux into the optical system to be imaged onto the entrance slit of the spectrograph. The spectrograph was a 0.5 meter vacuum instrument and operated as a scanning monochromator and a film spectrograph. *Figure D* shows the model arrangement in the test box. The nozzle exit can be seen at the left, and the aperture can be seen centered on the model face. The optical axis in front of the model was canted 15° from the centerline to avoid radiation from the arc column. The entire optical system, from the MgF_2 window to the transducer in the spectrograph, was evacuated to the order of 0.01 microns of Hg.

TEST CONDITIONS

The test was conducted in the Ames 20 Megawatt Aerodynamic Heating Facility. The facility was operated with a supersonic nozzle with a 1.5 inch diameter throat and an 18" exit diameter. The facility operating parameters were as follows:

Test gas mixture: 80% air* and 20% Argon by mass,
arc current: 1000 amperes,
arc column pressure: 15 psia,
nozzle pressure: 7.5 psia,
test box pressure: 0.2 to 0.3 mm Hg, and
stagnation pressure: 9 mm Hg.

The resulting free stream conditions for the present experiment is approximate as indicated in by the circle in *figure A*.

Figure E is a photograph taken during a test. The shock is seen well formed over the flat model face. The intense radiation from the high temperature shock layer gases is clearly evident.

Data were obtained using VUV film and a solar blind VUV (MgF_2 windowed) photomultiplier tube.

RESULTS AND DISCUSSION

Computed Spectral Details.

The radiating shock region is very non-homogeneous and involves many kinetically controlled processes. Substantial radiation emanates from the nonequilibrated regions immediately behind the shock. Here the kinetic temperature is extremely high, approaching 50,000 K. The VUV spectral line radiation is strongly Doppler broadened by this high temperature. These lines are from transitions to the ground state so there will be absorbers in the cooler parts of the shock and boundary layer. Absorption of strong features

* Dried and filtered ambient air

directed toward the surface will occur but only around the line centers because the absorption features are narrow due to the low kinetic temperature. The VUV surface radiative heating flux is thus seen to be the aggregate radiation and absorption from regions of very different conditions. Estimates from computational codes involve consideration of complex interactive and kinetic processes. *Figure H* is a calculated spectrum from 120 nm to 500 nm. The intense VUV lines are well represented. The Birge-Hopfield system (BH-1) of molecular nitrogen is the underlying background.

Test Results

Neutral atomic oxygen radiates at wavelengths as short as 81 nm, and neutral atomic nitrogen at 109 nm. To cover the entire spectral range would have necessitated windowless spectroscopy. Considering the energetics of the shock layer it was decided to conduct this experiment with a windowed design. MgF_2 was chosen for the window to permit measurements from the VUV to 1000 nm in the near infrared. The vender supplied, VUV spectral transmission curve for MgF_2 is shown in *figure I.* Also shown in the figure are estimates for the grating (150 nm blaze) efficiency, the spectral performance of the VUV photomultiplier tube and the losses due to the MgF_2 overcoated optical elements *(reference M)*. The optical system utilizes seven reflecting surfaces (including the spectrograph) and one MgF_2 window, and has an optical path of 3.5 meters. All reflecting surfaces have a MgF_2 overcoat.

The values shown in *figure I* were used to estimate the VUV spectral response of the system with the VUV tube as the transducer. This estimate, shown in *figure J*, shows useful VUV performance to 120 nm.

As indicated above the data were taken with film and with photomultiplier tubes. The film data presented herein are not corrected for instrument or film spectral response. This correction will be done with future work. The photomultiplier data has not been calibrated, but an estimated adjustment for spectral sensitivity was made based on generic data of *figure J.*

The VUV performance of the overall instrument was verified with VUV film by illuminating the model aperture with an air discharge lamp. Detailed spectra were obtained from 120 nm to 200 nm. Of special interest were the well resolved presence of the atomic oxygen and nitrogen lines at 130 nm, 149 nm and 174 nm.

The radiant flux incident on the aperture is shown in *figure K3.* This figure is a densitometer trace of a relatively low resolution, survey film record and show the spectrum from 120 nm to 500 nm. The sensitivity range in this record is from the VUV instrument limit to the VUV film limit. This figure should be compared with the calculated spectrum in *figure H* to put into context the features of the various radiating species. The spectral sensitivity of the overall system, including the film, varies over a large extent, therefore the film density should not be used to compare relative intensities of different spectral regions. To spite this shortcoming, the degree of similarity is encouraging- the predicted ,intense atomic lines are observed as well as the molecular systems of NO, N_2, and N_2^+. *Reference N* contains a more detailed identification of the features above 200 nm.

Figure K is a measurement of the surface flux spectrum from 120 nm to 210 nm. The spectral resolution is 0.13 nm. This record is from the photomultiplier output, with the estimated correction for spectral sensitivity described above. The important atomic line groups are well resolved from the background in this survey and are given below.

O and N	130 nm to 133 nm
N	141 nm
N	149 nm
N	174 nm

Other features can be seen. The feature at 166 nm is likely from atomic carbon lines grouped around 165.75 nm.

It is not possible to show on this figure the richness of details which are present in this data record. *Figure K2* is an expanded portion of this data set showing the spectral region around the 130 nm to 133 nm lines.

Because of the interest of the shapes of the lines, high resolution, low noise spectra were obtained over selected atomic lines during dedicated runs. *Figure L* shows the photomultiplier record from 173 nm to 175.5 nm. This spectral region was scanned to examine in detail the group of atomic nitrogen lines at 174 nm. These lines are predicted to be possibly important to the surface heating of a spacecraft (*reference F).* The two lines shown are each doublets separated by 0.001 nm. However, they are not separated at the resolution (0.05 nm) of this test. *References F and L* discuss the importance in evaluating the line wing shapes in assessing the heating importance of the VUV atomic line radiation. The shape of the line wings is distinguished from the background in this scan.

These details will be subsequently used to help verify the line shapes calculated by the predictive codes.

CONCLUSIONS

Spectra have been obtained from the flux incident on the stagnation surface of a flat model placed in the supersonic stream in an arc-jet wind tunnel. The resulting data set is detailed at high resolution from 120 nm to 220 nm. Important radiators are evident. The wing shape of the atomic N lines at 174 nm is shown. The data set will be further developed and used to help refine and calibrate computational models of the aerothermodynamics of entry and of arc-jet wind tunnels.

ACKNOWLEDGMENTS

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FIGURES

Figure A.

Flight regimes of mission returns for ASTV, Shuttle, and Apollo. The point indicated by the circle is an estimate of the altitude and velocity simulated by the arc-jet conditions used during the present tests.

Figure B.

Schematic diagram of experimental setup. The arc column is to the left of the nozzle.

Figure C.

Schematic diagram of model showing the aperture and window and orientation of the bow shock. Radiation incident onto the surface is reflected by the turning mirror to the concave mirror and thence to the spectrograph. Vacuum was maintained <0.01μ for the VUV tests.

Figure D.

Photograph of model in test box. The optical system is protected by the water cooled coils shown as well as internal water cooling. The aperture can be seen in the face of the model. The nozzle exit can be seen at the left.

Figure E.

Photograph of model during test. The stagnation shock is seen well formed over the model face and the intense radiation from the shock heated air is evident.

Figure H.

Preliminary calculation of the spectral surface flux from the stagnation region of a model placed in an arc-jet wind tunnel.

Figure I.

This figure shows vender supplied characteristics of the VUV transmission of the MgF_2 window, the spectral response of the VUV photomultiplier tube, and estimates for the grating efficiency (150 nm blaze) and reflection losses due to the MgF_2 overcoating on the optical surfaces.

Figure J.

Estimation of overall instrument spectral characteristics in the VUV with the photomultiplier tube. The estimate is based on the values given in figure G.

Figure K

VUV surface flux data from the arc-jet wind tunnel test. Atomic lines from nitrogen and oxygen are well resolved. The strong atomic nitrogen feature at 174 nm is seen to be off-scale. Carbon lines are tentatively identified.

Figure K2.

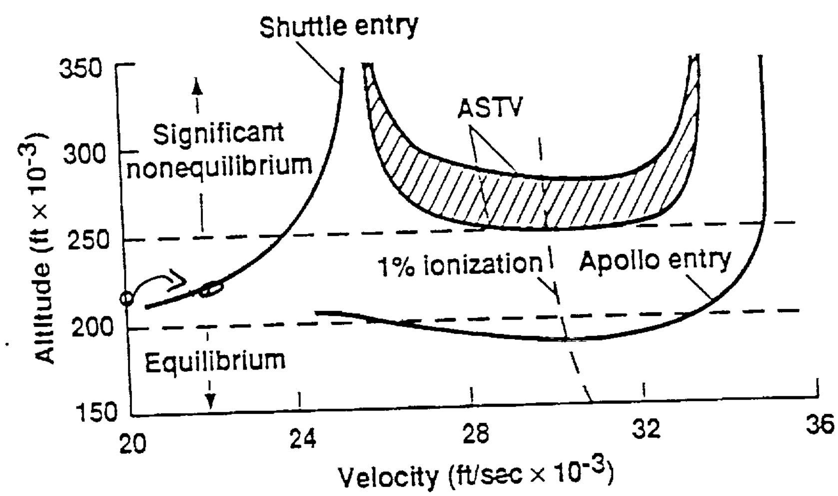
Portion of VUV survey record in the vicinity of the 130 nm atomic lines to indicate the spectral details available for analysis. The strong atomic oxygen at 130.22 nm is off scale. Not all features have been identified at the present writing.Figure M.

Figure K3

120 nm to 500 nm photographic survey of the surface flux data from the arc-jet wind tunnel test.

Figure L.

Details of the atomic nitrogen lines at 174 nm. The feature at 174.27 nm is from two lines 0.001 nm apart, and the feature at 174.52 nm is from two lines 0.002 nm apart. The wings from these lines can be seen as a rise in the background continuum.



Shuttle entry
350
300
250
200
150
Significant
nonequilibrium
Equilibrium
ASTV
1% ionization
Apollo entry
Altitude (ft × 10-3)
20
24
28
32
36
Velocity (ft/sec × 10-3)

Figure A

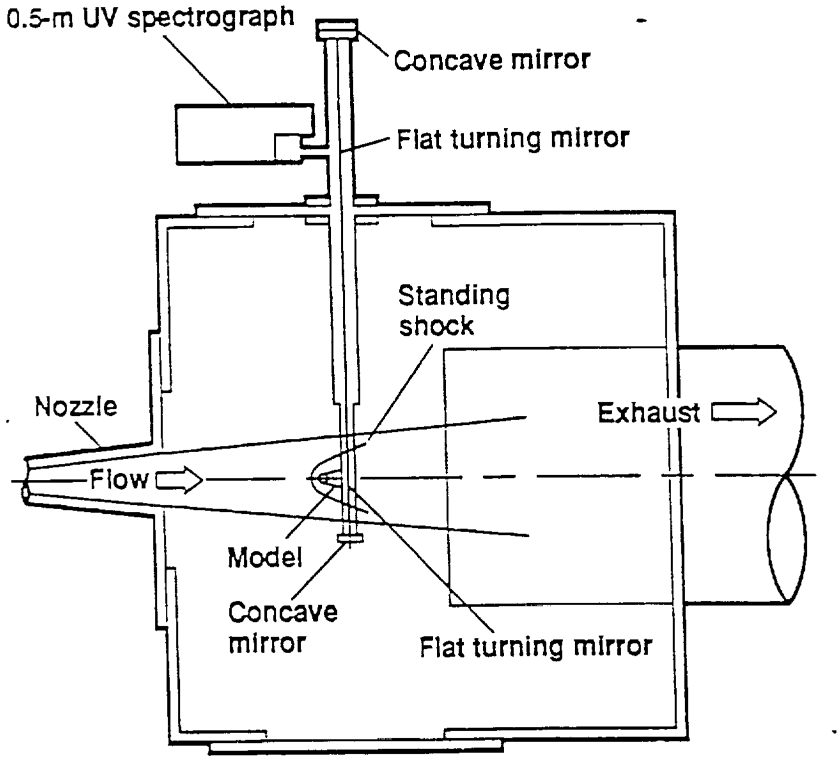

0.5-m UV spectrograph
Concave mirror
Flat turning mirror
Standing
shock
Nozzle
Exhaust
Flow
Model
Concave
mirror
Flat turning mirror

Fig B

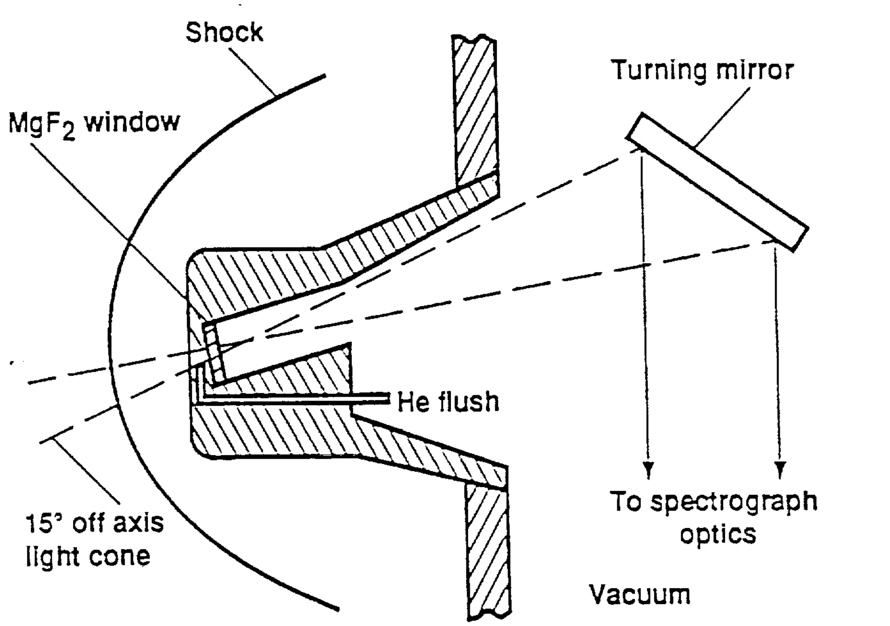
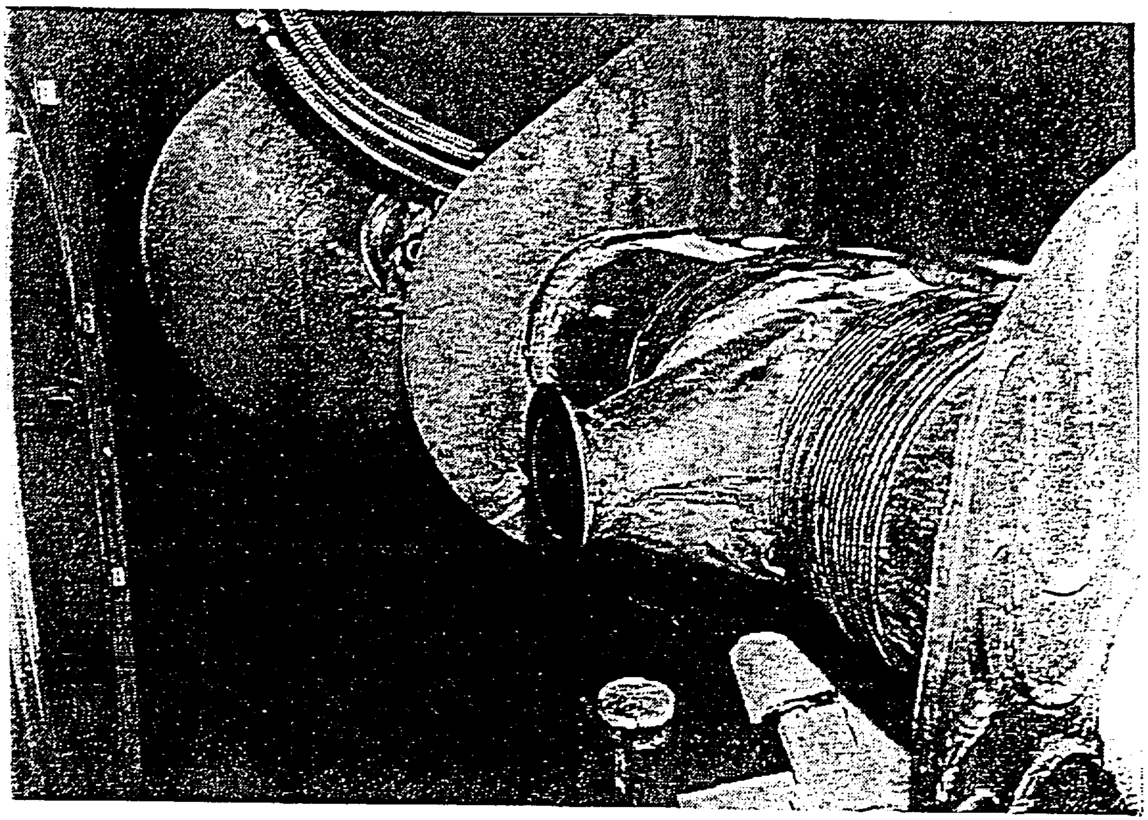
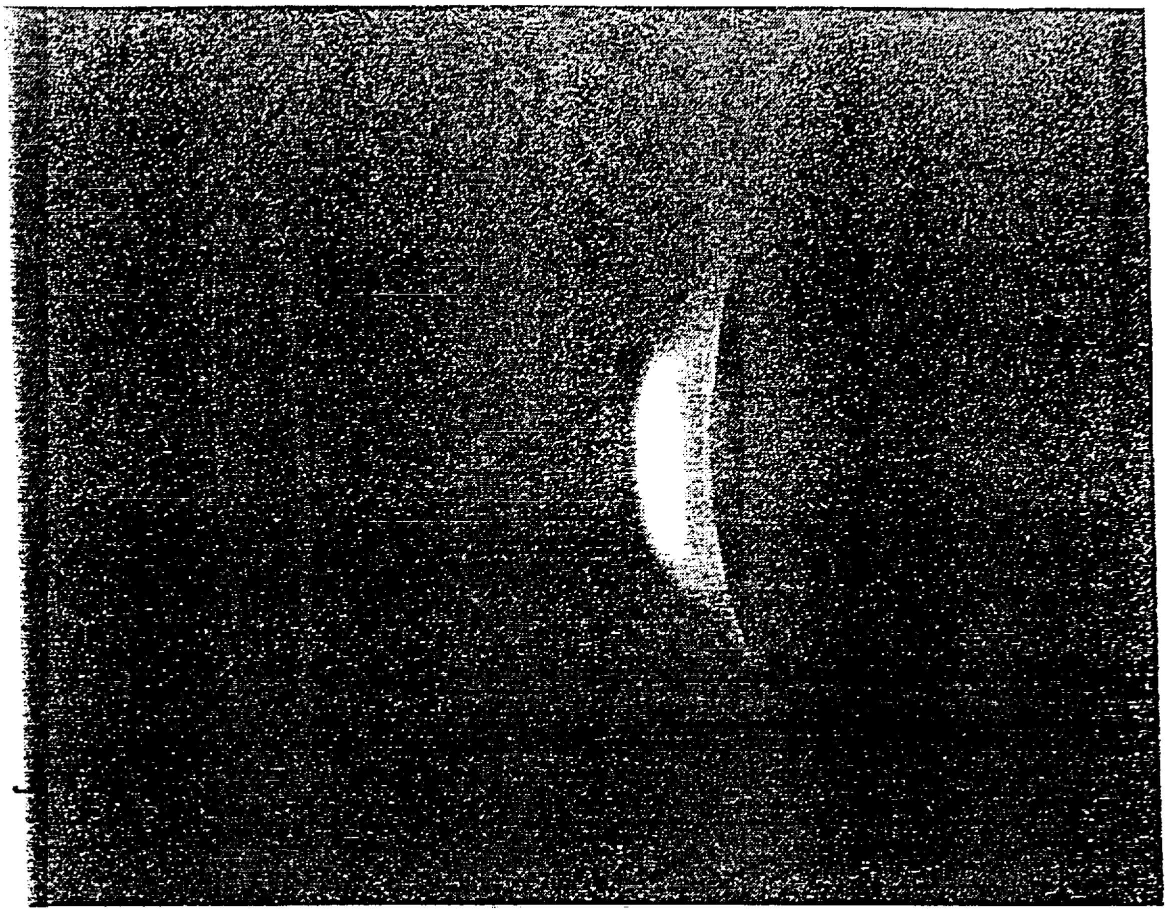

Shock
Turning mirror
MgF2 window
He flush
To spectrograph
optics
15° off axis
light cone
Vacuum

Fig C



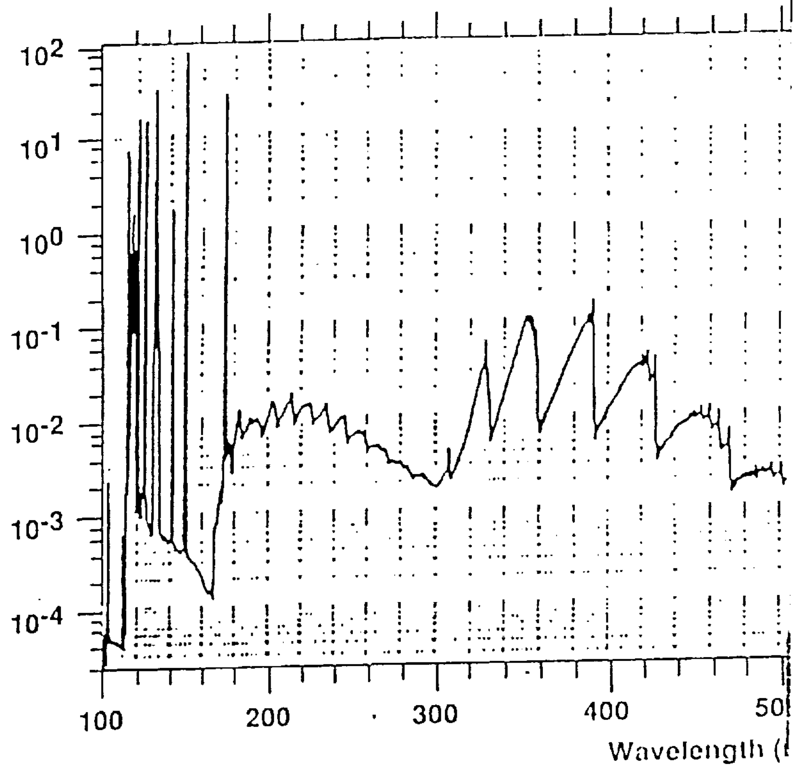
4

FIG D



5

Fig E



Fis H

F G

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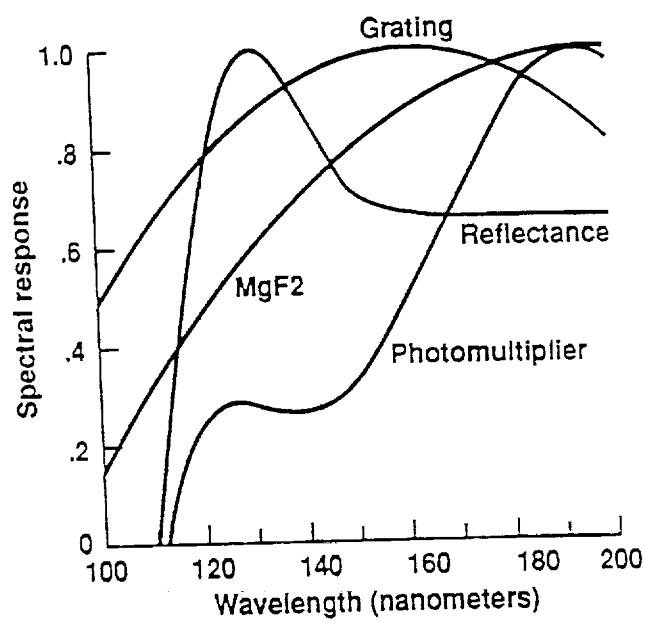
Grating
1.0
.8
.6
.4
.2
0
Spectral response
Reflectance
MgF2
Photomultiplier
100
120
140
160
180
200
Wavelength (nanometers)

Fig I

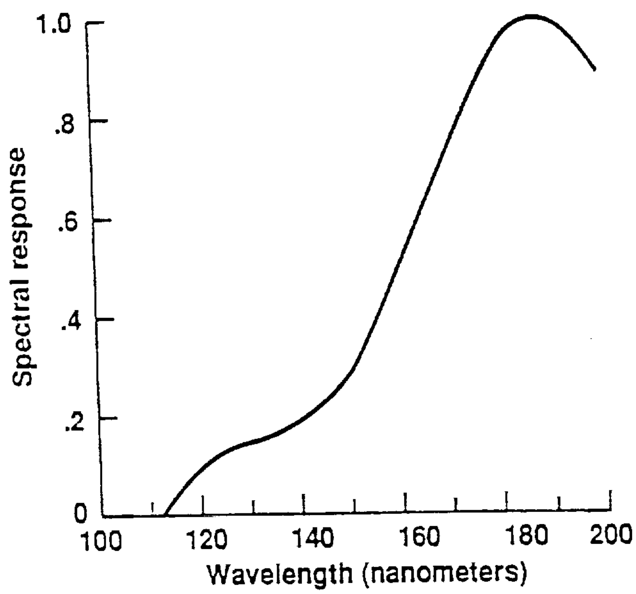

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FIG J

VUV surface flux data from the arc-jet wind tunnel test. Atomic lines from nitrogen and oxygen are well resolved. The strong atomic nitrogen feature at 174 nm is seen to be off-scale. Carbon lines are tentatively identified.

Figure K2.

Portion of VUV survey record in the vicinity of the 130 nm atomic lines to indicate the spectral details available for analysis. The strong atomic oxygen at 130.22 nm is off scale. Not all features have been identified at the present writing.Figure M.

Figure K3

120 nm to 500 nm photographic survey of the surface flux data from the arc-jet wind tunnel test.

Figure L.

Details of the atomic nitrogen lines at 174 nm. The feature at 174.27 nm is from two lines 0.001 nm apart, and the feature at 174.52 nm is from two lines 0.002 nm apart. The wings from these lines can be seen as a rise in the background continuum.

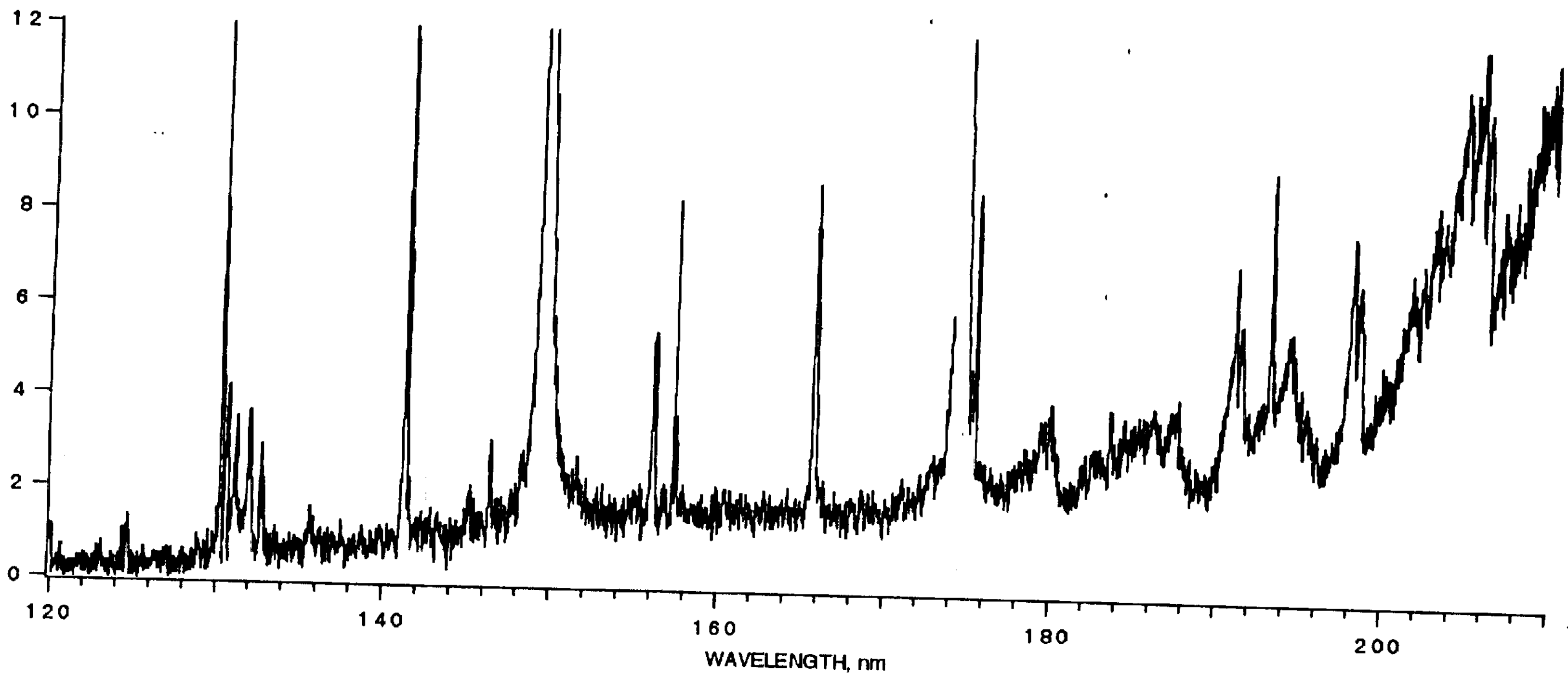
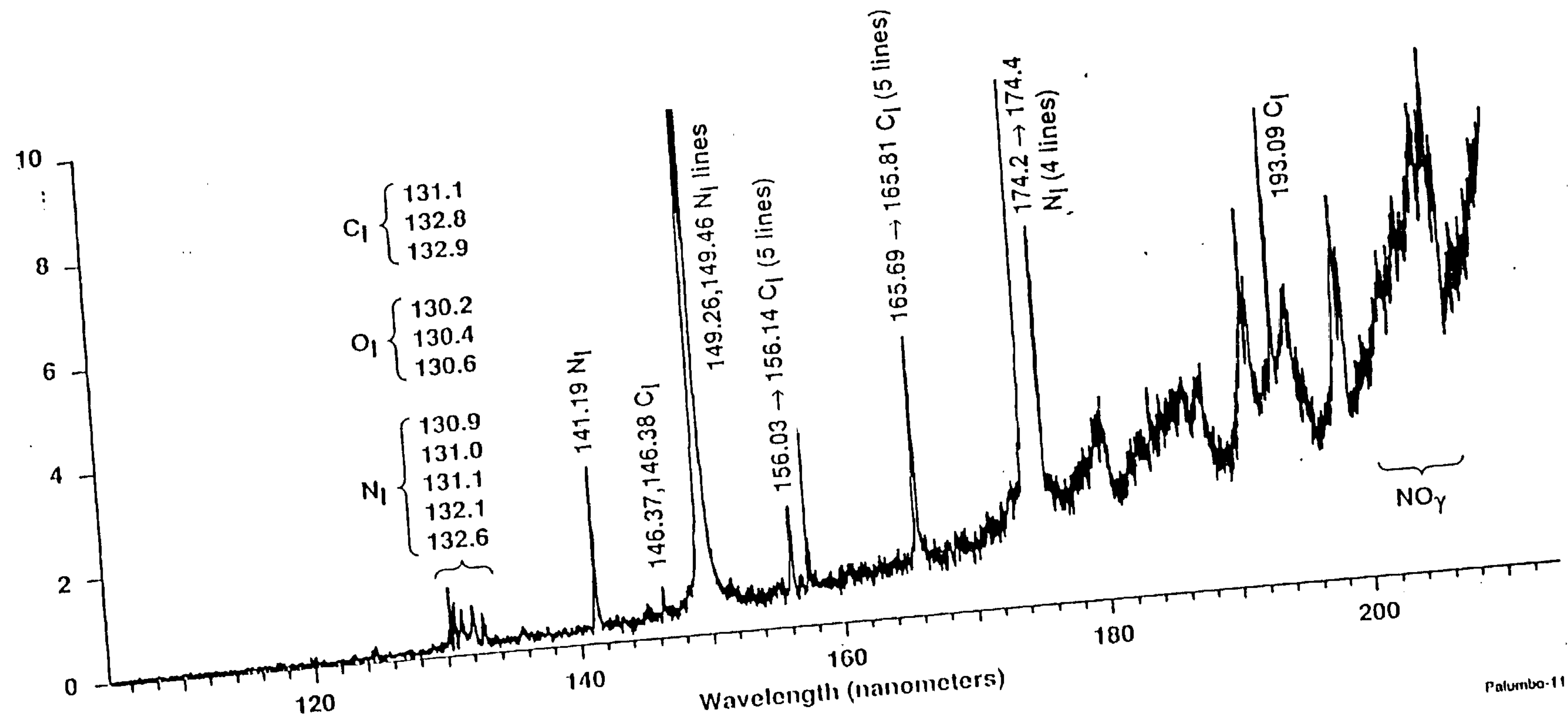


Fig K



~~reference Fig K~~

Reference for Fig K

This is an uncorrected spectrum
These labels will be on ~~B~~ Fig K

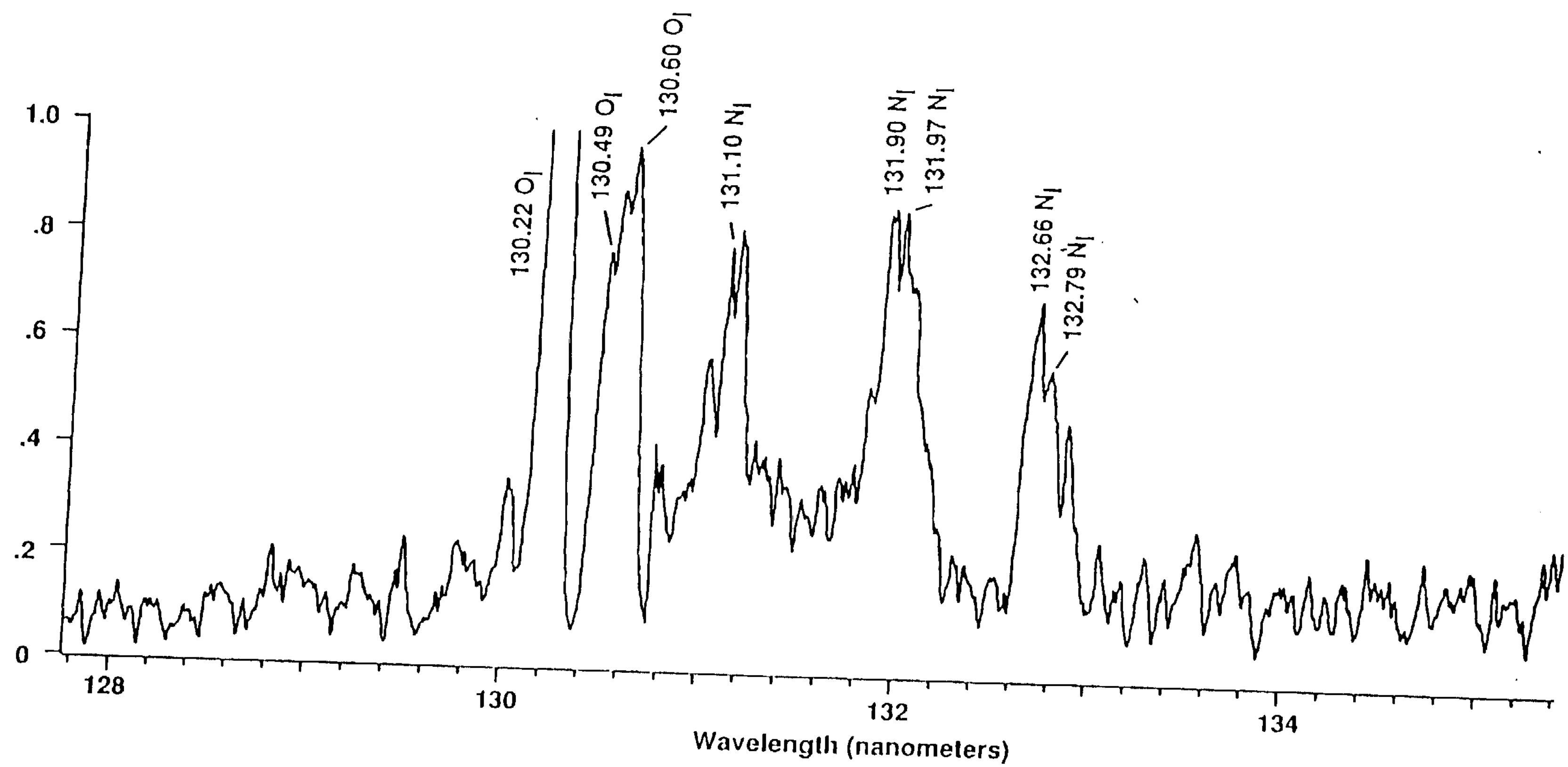


Fig. K2

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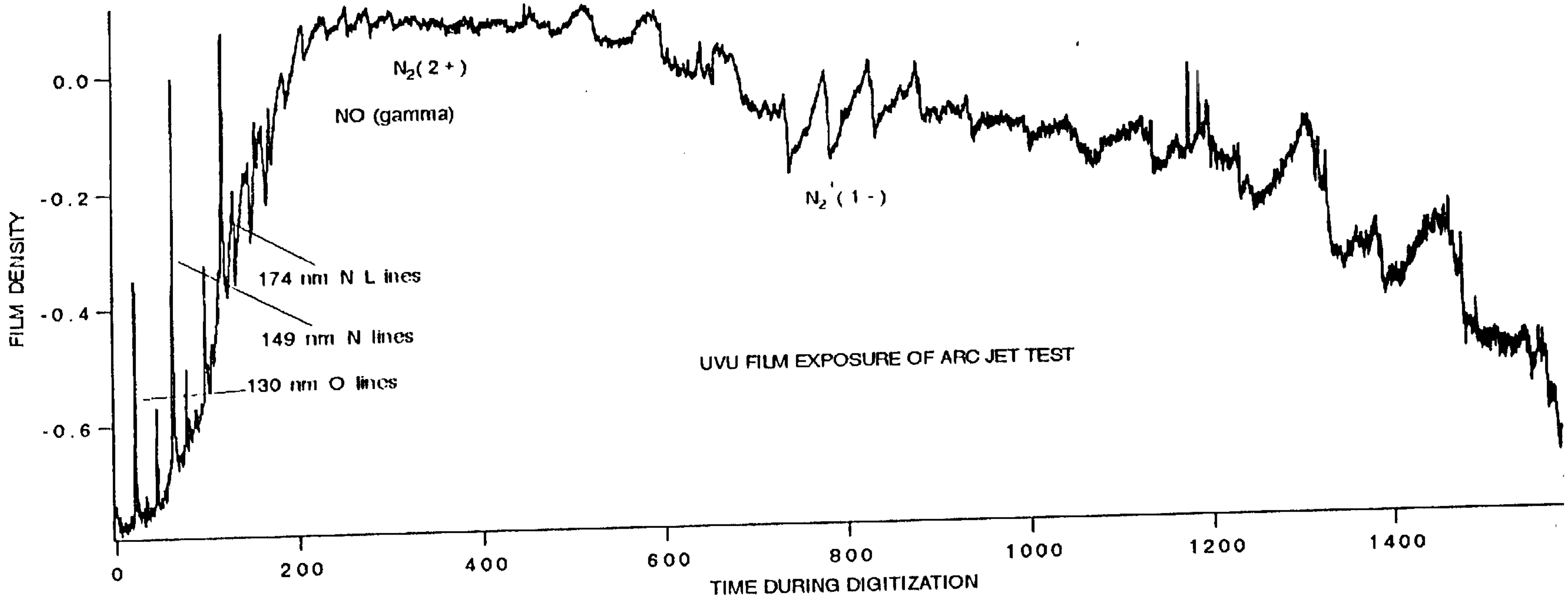

FILM DENSITY
0.0
-0.2
-0.4
-0.6
N_2(2+)
NO (gamma)
174 nm N L ines
149 nm N lines
130 nm O lines
N_2^+(1-)
UVU FILM EXPOSURE OF ARC JET TEST
0
200
400
600
800
1000
1200
1400
TIME DURING DIGITIZATION

FIGURE K3

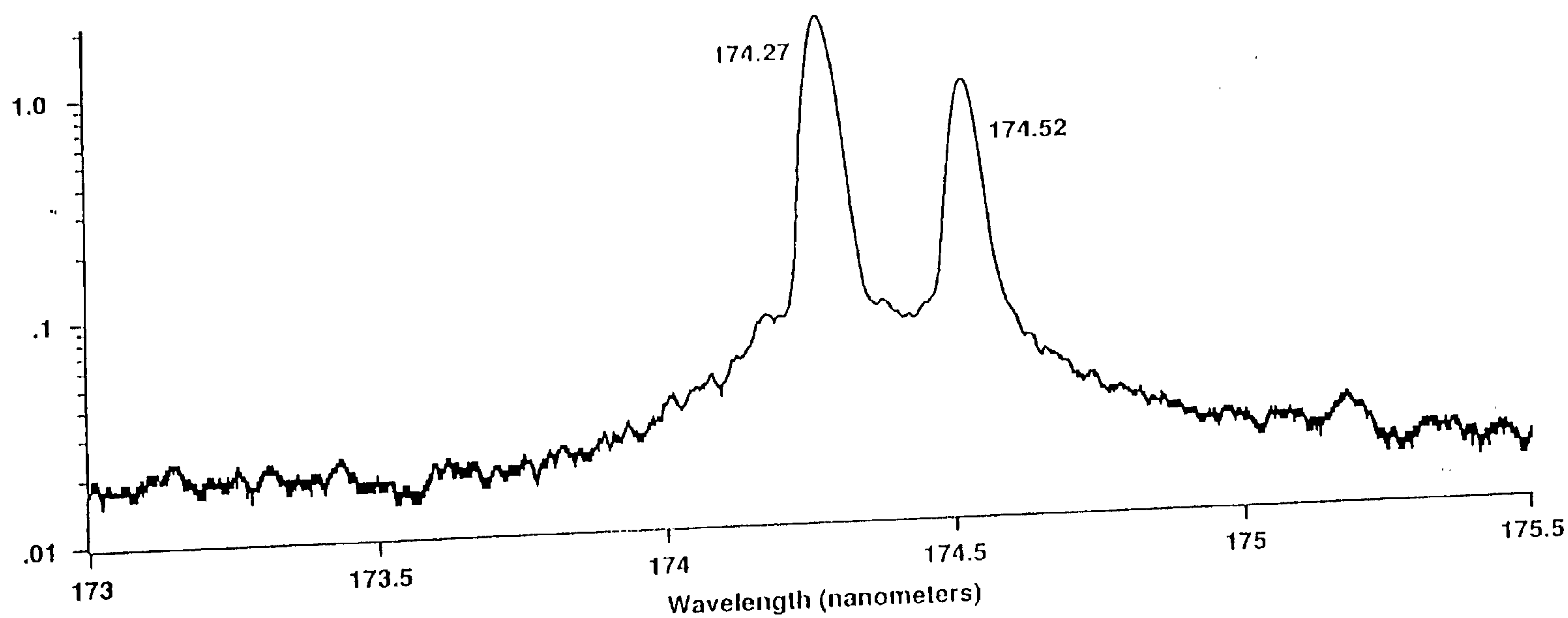

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Fig L

APPENDIX - D