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THE PDX INFRARED TV CAMERA SYSTEM

BY

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THE PDX INFRARED TV CAMERA SYSTEM

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Abstract

An infrared TV camera system has been developed for use on PDX. This system is capable of measuring the temporal and spatial energy deposition on the limiters and divertor neutralizer plates; time resolutions of 1 ms are achievable. The system has been used to measure the energy deposition on the PDX neutralizer plates and the temperature jump of limiter surfaces during a pulse. The energy scrapeoff layer is found to have characteristic dimensions of the order of a cm. The measurement of profiles is very sensitive to variations in the thermal emissivity of the surfaces.

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An infrared TV camera system has been developed for the measurement of the temporal and spatial energy deposition on the PDX limiters and neutralizer plates. The TV camera itself is an Inframetric Model 210, the specifications of which are tabulated in Appendix A.

In the limiter viewing position, see Fig. 1, the camera was mounted on the equator of the PDX device and viewed the limiters through a germanium window. The inner limiter fell directly in the camera's field of view, the outer being viewed via a mirror mounted on the inner wall adjacent to the inner limiter. This arrangement did not permit viewing of the top and bottom limiters.

The neutralizer plates in the upper dome of the PDX vacuum chamber were viewed as shown in Fig. 2. Mirrors mounted in the dome were arranged such that all four neutralizer plates appeared simultaneously within the field of view of the camera. Mounted on the neutralizer plates were a series of targets as shown in Fig. 3. These targets were constructed from 0.08" titanium plates which were chemically etched over their centers so that when they were clamped together to form the targets, 0.003" gaps occurred between adjacent plates. Since the energy flux is expected to have toroidal symmetry, the effect of the gaps is to force one dimensional heat flow in the targets. The 0.080" plate thickness represents the resolution limit of the camera system in the given configuration. Wedge shape titanium edge shields were mounted on either side of the targets so as to force the energy flux to be incident only on the front face.

For temperature measurements the camera was used in the so called line scan mode. In this mode a single horizontal line in the field of view is scanned repeatedly at a 4 kHz rate. Any line in the field of view can be chosen by a simple electronic adjustment. As most of the energy deposition resulted it profiles which varied vertically, one would ideally like to mount the camera on its side - an act precluded by the LN_2 dewars incorporated into the camera. To overcome this, a field-of-view rotator was constructed which optically interchanged the horizontal and vertical in the field of view.

The detector output, together with the sync. signal generated at the start of each line scan, was fed via a buffer memory to the DAS data acquisition system where it was archived. On recall the temperature profile with a 1 ms temporal resolution was yielded. The energy flux incident upon the surface was then computed from the temperature profiles by the use of a Green function formulation, the complete technique and the resulting code being given in Appendices B and C.

A representative data sample is shown in Fig. 4. The left hand column gives the measured temperature profiles on one of the neutralizer plate targets (the 2/4 outer which occurs at R = 1.05 m in Fig. 2). The energy deposition profiles are given in the right hand column; the numbers within each box are the times in ms from the start of the PDX discharge. In this pulse 3 MW of neutral beams were switched on at 400 ms and off at 720 ms. The impulse length used in the Green function unfolding was 50 ms which is why a sizable energy flux is still recorded at 748 ms.

Of interest is the width of the energy flux deposition profile in the vicinity of the separatrix. The width at half height is measured to be 12.2 mm, which corresponds to a similar dimension on the machine equator.

The temperature profile occurring on the outer limiter along the vertical line corresponding to the limiter center is shown in Fig. 5. The limiter top half (the R.H.S.) appears to be hotter than the bottom half. Inspection of the limiter showed the bottom to be more discolored by arc tracks and getter deposited titanium; thus, it is felt that the temperature along the observed line was more or less constant, the observed temperature variation being mostly a result of local changes of thermal emissivity of the limiter surface. To a large degree this was confirmed by observing the small temperature profile changes which occured during cooldown, at times at which the limiter could be regarded as being in thermal equilibrium.

As can be seen calibration is an important aspect of the measurement. It was decided to calibrate the system absolutely with respect to thermocouples imbedded in the limiters and neutralizer plate targets. This was repeated regularly by observing the cooling down of the various surfaces (after an experimental run) with both thermocouples and the infrared camera system. The neutralizer plate targets showed little surface damage, and the cooling down profiles changed as would be expected if the emissivity were a constant over the target face.

Figure 6 summarizes the results obtained in an experiment in which the outer limiter was slowly inserted into the outer edge of a PDX standard D diverted discharge (the discharge being constrained to interact with the 2/4 neutralizer plates only). It is seen that at a limiter radius of 45 cms there is a sudden increase in the front surface temperature, and as it is further inserted, it begins to absorb more of the energy which would normally have been deposited on the 2/4 outer neutralizer plate. Temperature jumps approaching 1000°C are seen to occur as the limiter approaches the separatrix. The zone in limiter radius between 40 and 44 cms corresponds to the zone of more or less constant electron density and temperature, measured by Budny [1] and Owens [2], which is thought to be part of a poorly confined plasma associated with the 6/8 divertor coils (which are still activated). As one leaves this zone the energy falloff is seen to occur over characteristic lengths of 1 cm.

The infrared TV camera system provides a very useful tool for the measurement of energy deposition on limiters, walls, and neutralizer plates in plasma devices. Temporal energy resolutions of 1 ms are easily achievable with faster times being possible. This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

APPENDIX A

INFRAMETRICS MODEL 210 SPECIFICATIONS

Spectral Bands	Channel 1	3 to 5 microns
	Channel 2	8 to 12 microns
Temperature Measurement Range		-20°C to 200°C
	with Filter	0°C to 2000°C
Minimum Detectable Temperature Jump		0.2°C
Resolvable Elements Per Line	Channel 1	75
	Channel 2	150
Detectors		Hg Cd Te
Detector Coolant		Liquid Nitrogen
Coolant Hold Time		3 hours
Scan Rate in Line-Scan Mode		4 kHz
Frame Rate in TV Mode		30 Hz with 2:1 Interlace
Lines Per Frame		180
Optics		Coated Germanium
Framing Mirrors		Copper
Camera Size		5-1/2" x 8" x 8.5 (HWL)
Camera Weight		11 lbs.

APPENDIX B

OBTAINING THE ENERGY FLUX

The temporal variation in the measured temperature profiles is unfolded to yield the energy flux. The technique used makes use of the Green function given by Ref. [3], for the 1-D heat flow problem of an infinite plate of finfte thickness, at initial uniform temperature, subject to a plane heat source on its surface. The formulation of the problem is done in Ref. [4] and is repeated here.

The Green function for the surface of the neutralizer plate of thickness L at time t due to an instantaneous heat flux of unit strength incident at $t = 0$ is

$$G(t) = \frac{1}{L} + \frac{2}{L} \sum_{n=1}^{\infty} \exp \left[\frac{-(n\pi)^2 \lambda t}{L^2 \rho c}\right] . \qquad (1)$$

where ρ = density, c = specific heat and λ = thermal conductivity. The change in surface temperature is

$$\Delta T = \frac{1}{\rho c} \int_0^t q(\tau)\ G(t-\tau) d\tau$$

$$= \frac{1}{\rho c L} \int_0^t q(t) \left\{1 + 2 \sum_{n=1}^{\infty} \exp \left[\frac{-(n\pi)^2 \lambda\ (t-\tau)}{\rho c L^2}\right]\right\} d\tau , \qquad (2)$$

which is solved to give the heat flux.

The equation is solved numerically using the measured surface temperature ΔT as input. The incident heat flux is assumed to be composed of many square pulses of width $\Delta\tau$ and height q_i. From Eq. (2) it follows that the surface temperature at $t = t_N$ due to the pulse from $t = \tau_i - \Delta\tau$ to $t = \tau_i$ is given by

$$\Delta T_N = \frac{q_i}{\rho c L} \int_{\tau_i - \Delta\tau}^{\tau_i} \left\{1 + 2 \sum_{n=1}^{\infty} \exp\left[\frac{-(n\pi)^2 \lambda (t_N - \tau_i)}{\rho c L^2}\right]\right\} d\tau$$

$$= \frac{q_i \Delta\tau}{\rho c L} F_{N,i} \quad . \qquad (3)$$

Where

$$F_{N,i} = 1 + 2 \sum_{n=1}^{\infty} \frac{\rho c L^2}{(n\pi)^2 \lambda \Delta\tau} \exp\left[\frac{-(n\pi)^2 \lambda (t_N - \tau_i)}{\rho c L^2}\right]\left\{1 - \exp\left[\frac{-(n\pi)^2 \lambda \Delta\tau}{\rho c L^2}\right]\right\} .$$

Thus the surface temperature rise at $t = t_N$ due to q_i $(i = 1 \ldots N)$ is

$$\Delta T_N = \frac{\Delta\tau}{\rho c L} \sum_{i=1}^{n} F_{N,i} \, q_i \; , \qquad (4)$$

or

$$\begin{vmatrix} F_{1,1} & 0 & 0 - - - - - - - 0 \\ F_{2,1} & F_{2,2} & 0 - - - - - - - 0 \\ F_{3,1} & F_{3,2} & F_{3,3} \quad 0 \;- - 0 \\ \cdot & \cdot & \cdot - - - - - - 0 \\ \cdot & \cdot & \cdot - - - - - - 0 \\ \cdot & \cdot & \cdot - - - - - - 0 \\ \cdot & \cdot & \cdot - - - - - - 0 \\ \cdot & \cdot & \cdot - - - - - - 0 \\ F_{N,1} & F_{N,2} & F_{N,3} - - - F_{N,N} \end{vmatrix} \begin{vmatrix} q_1 \\ q_2 \\ q_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ q_N \end{vmatrix} = \frac{\rho cL}{\Delta\tau} \begin{vmatrix} \Delta T_1 \\ \Delta T_2 \\ \Delta T_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \Delta T_N \end{vmatrix}$$

A computer code was written to calculate the $F_{N,i}$ and hence yield the q_i. Tests performed on this code showed that for titanium for $\Delta\tau = 50$ ms errors of 4% can be expected. This code is given in Appendix C.

APPENDIX C

CODE FOR OBTAINING ENERGY FLUX

```
      PARAMETER NN=23
C     NN=NO OF INTERVALS BETWEEN THE TEMP DATA POINTS
      REAL A(NN,NN), F(NN), T(NN), B(NN), WKAREA(NN)
C     ENERGY-UNFOLDS TEMP DATA TO GIVE ENERGY FLUX
      WRITE (5,100)
100   FORMAT ('0GIVE ME DELTA T IN SECS ')
      ACCEPT*,DT
C     AC=PLATE THICK**2/PI**2/CONDUCTIVITY*DENSITY*SP. HEAT/DT
      AC=.63533/DT
      ACC=-1/AC
C     BC=-PI**2/PLATE THICK**2*CONDUCTIVITY/DENSITY/SP. HEAT
      BC=-1.574
C     DL=DIST BETWEEN POINTS AT WHICH TEMP IS MEASURED
      DL=.339
      DO 200 I=1, NN
200   F(I)=1
600   DO 300 M=1,NN
      DO 300 N=1, 50
      X=2*AC/N/N*EXP (BC*N*N* (M-1)*DT)*(1-EXP (ACC*N*N))
300   F(M)=F(M)+X
500   DO 550 I=1,NN
550   TYPE 90, I,F(I)
90    FORMAT (3X,I3,3X,F9.5)
      WRITE (5,10)
10    FORMAT ('0FEED IN TEMP DATA T(1) TO T (NN)')
      ACCEPT*, (T(I), I=1, NN)
      ALP=1.80134/DT
      DO 20 I=1,NN
20    B(I)=ALP*T(I)
      DO 30 I=1,NN
      DO 30 J=1,NN
30    A(I,J)=0
      DO 40 J=1,NN
      DO 40 I=J,NN
40    A(I,I-J+1)=F(J)
      M=1
      N=NN
      IA=NN
      IDGT=4
      CALL LEQT1F (A,M,N,IA,B, IDGT, WKAREA,IER)
      DO 80 I=1,NN
80    TYPE 70, I, B(I)
70    FORMAT (3X,'Q('I3,')=,F9.3)
      SUM=0
      DO 82 I=1,NN
82    SUM=SUM+B(I)
      ENGY=SUM*DT*DL
      TYPE 83, ENGY
83    FORMAT (' ENERGY DEPOSITED =',F9.3,'JOULES')
      CALL EXIT
```

```
05000          CONTINUE
05100          END
```

NOTE: LEDT1F is part of the IMSL Library

REFERENCES

[1] Budny, R., unpublished.

[2] Carslaw and Jaeger, Conduction of Heat in Solids, Oxford University, 1959, 2nd ed., p. 361.

[3] Maeno, M., et al., Japan Journal of Applied Phys., Vol, 18, No. 8, Aug. 1979, pp. 1549-1555.

[4] Owens, D.K., Bull. A.P.S., Vol. 25, No. 8, Oct. 80, p. 941.

FIGURE CAPTIONS

Fig. 1 Arrangement for viewing of inner and outer limiters.

Fig. 2 Arrangement for viewing of neutralizer plates in upper PDX vacuum vessel dome.

Fig. 3 Neutralizer plate target and edge shield.

Fig. 4 Temperature profiles measured on the 2/4 outer neutralizer plate target are given on the left, for times from 346 ms to 800 ms. On the right, are the corresponding unfolded energy profiles.

Fig. 5 Measured temperature profile on outer limiter front face. The majority of the variation is caused by changes in emissivity on the limiter front face.

Fig. 6 The temperature jump occurring during a pulse on the outer limiter front face as it is driven into a diverted PDX discharge, together with the effect this has on the energy deposited on the 2/4 outer neutralizer plate.

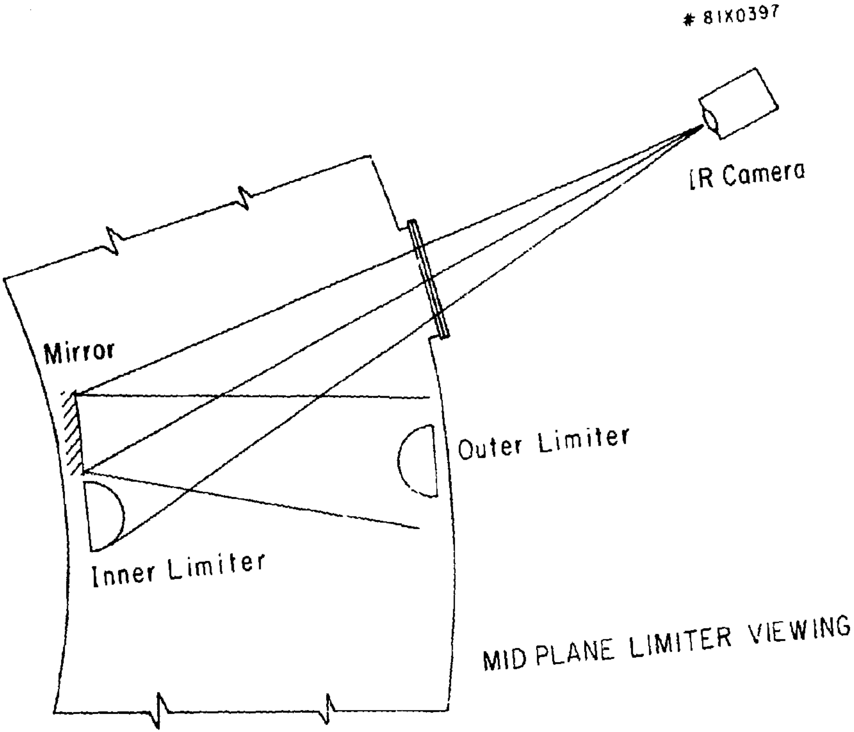
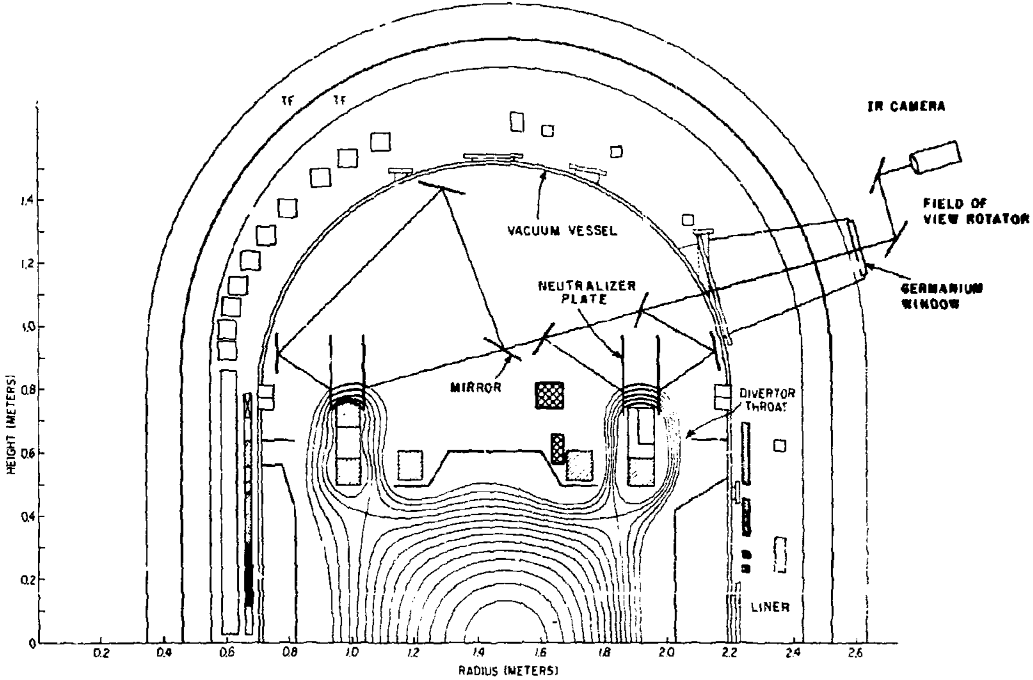

81X0397
IR Camera
Mirror
Outer Limiter
Inner Limiter
MID PLANE LIMITER VIEWING

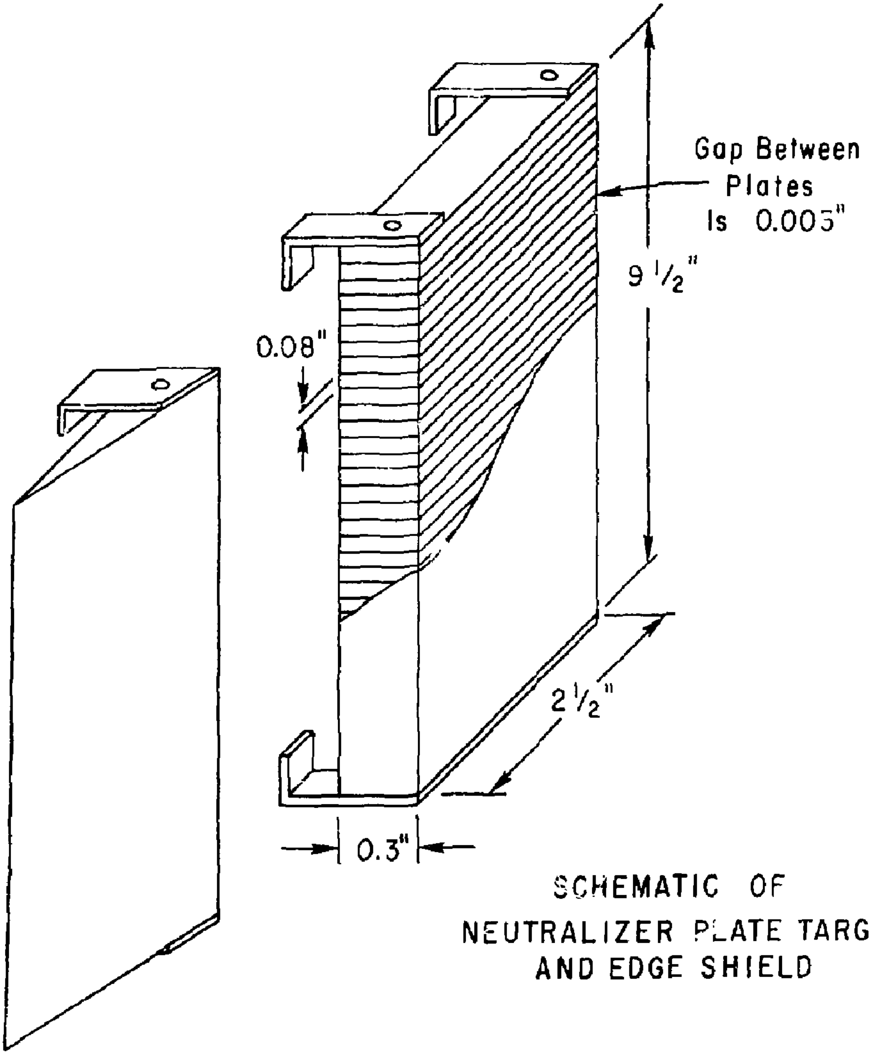
Fig. 1

81X0398



SCHEMATIC OF IR CAMERA ARRANGEMENT

Fig. 2



SCHEMATIC OF
NEUTRALIZER PLATE TARGET
AND EDGE SHIELD

Fig. 3

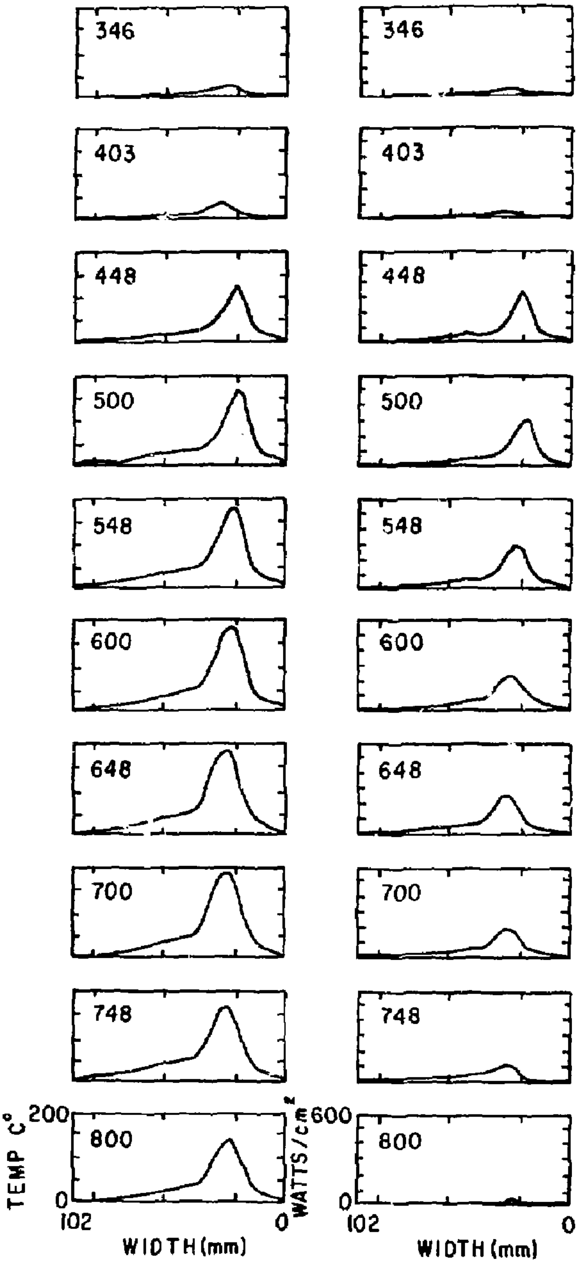
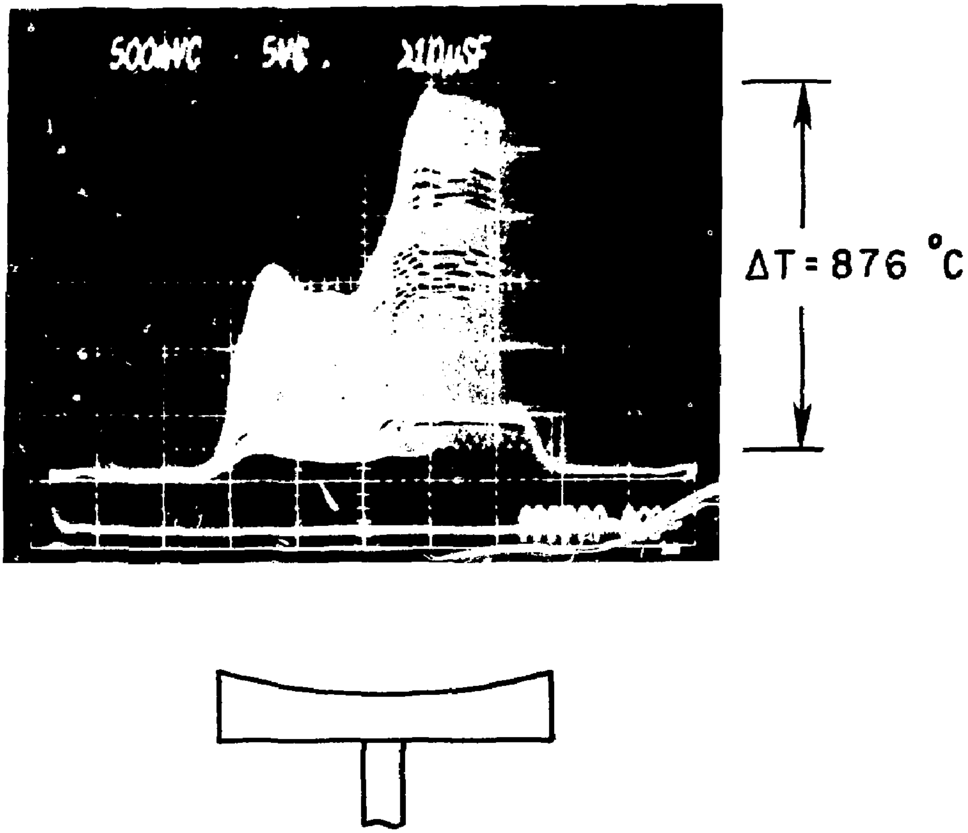

346
346
403
403
448
448
500
500
548
548
600
600
648
648
700
700
748
748
800
800
TEMP C°
200
0
102
0
WIDTH(mm)
WATTS/cm²
600
0
102
0
WIDTH (mm)

Fig. 4

#81X0393



TEMPERATURE PROFILE
ON LIMITER FRONT FACE

Fig. 5

#81X0396

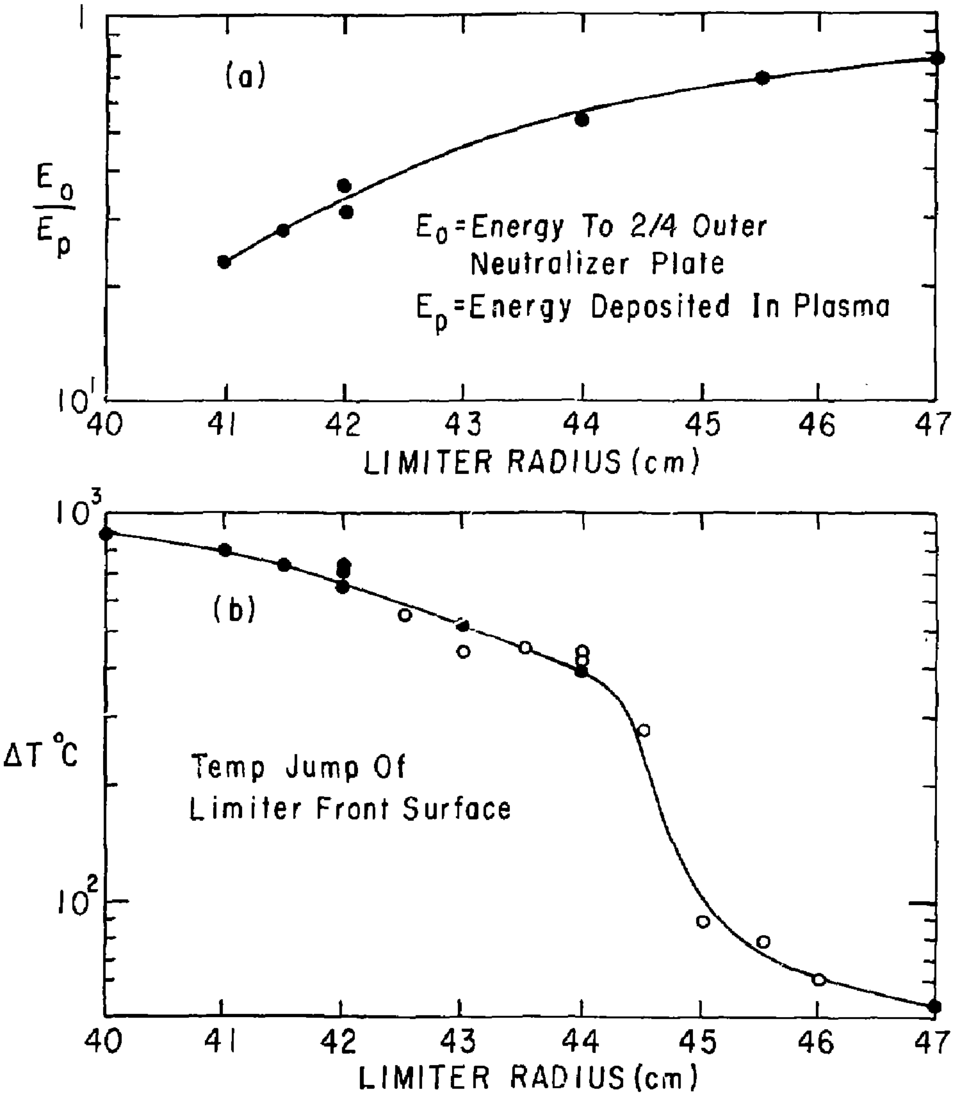


Fig. 6