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LABORATORY PLASMA PROBE STUDIES

Walter J. Heikkila

Plasma laboratory experiments and data reduction continued during this reporting period. This report summarizes some of the data obtained on electrostatic resonances observed in the plasma generated at The University of Texas at Dallas.

Dr. Rainer Kist* and UTD personnel utilized a UTD developed digital Langmuir probe plus RF probes to study resonances generated in a collisionless laboratory CO_2-plasma. Laboratory instrumentation, including the Langmuir probe output, were connected to the PDP 11/45 digital computer which automatically recorded and reduced probe data.

The main body of this report is presented in the following two papers written by Dr. Kist.

Appendix A: Plasma Probe Measurements in a Collisionless Laboratory CO_2-plasma.

Appendix B: Operation of a Digital Langmuir Probe on Line with a PDP 11/45 Digital Computer

*On leave at UTD, sponsored by the European Space Research Organization (ESRO), now European Space Agency (ESA).

Plasma Probe Measurements in a

Collisionless Laboratory CO_2-Plasma

by Rainer Kist +

This memo describes diagnostic experiments performed in a collisionless plasma using CO_2 as working gas. In particular simultaneous measurements that have been performed by means of Langmuir- and RF-probes are presented. A resonance occuring above the parallel resonance in the frequency characteristic of a two electrode system is interpreted as being due to the resonant excitation of electroacoustic waves. The memo represents a part of the accomplishments achieved in the course of a laboratory plasma investigation at the University of Texas at Dallas (UTD).

+ On leave at UTD, sponsored by the European Space Research Organization (ESRO), now European Space Agency (ESA).

Introduction:

Studies with diagnostic probes in laboratory plasmas have several important advantages as compared to space plasma investigations:

1) Systematic variation of the parameters involved with the possibility of measuring over large time intervals and of repeatin the measurements .

2) Extensive testing of the performance of space plasma probes in a plasma environment prior to a space mission.

3) Systematic investigation of specific plasma phenomena with the aim of improving existing or developing new diagnostic methods.

4) Extensive investigation of various phenomena such as plasma wave mode generation and propagation, instable plasma states and nonlinear effects.

5) Relatively low cost and short time period needed for realizing a plasma experiment.

The results of such laboratory plasma investigations may provide data for checking on particular theories in plasma physics or have impact upon the understanding in fields like space plasmas (planetary ionospheres, magnetosphere, solar wind etc.) or even (after scaling up the results properly) fusion plasmas.

For the space plasma physicist the laboratory plasma is and will remain a very valuable tool even though in the coming spacelab age the ionosphere itself may be used for particular investigations as a large scale "laboratory" plasma of low density and temperature.

In the piece of work presented here the influence of the electron temperature on the frequency characteristic of the plasma impedance of a two electrode system was investigated. Of particular interest was the resonant excitation of electro-acoustic waves within two RF electrodes for different geometries and plasma conditions.

Experimental System

A stainless steel vacuum chamber, 70 cm long and 50 cm in diameter, has been equipped with a plasma source which uses CO_2 as working gas. A turbomolecular pump together with a copper shroud which was cooled down to liquid nitrogen temperature provided a background vacuum of about 10^{-6} Torr. Fig. 1 shows the source schematically. The general concept was to produce a discharge plasma in a separate volume V_1 (bell jar) and let it expand into the volume V_2 (chamber) through a diaphragm. During operation typical pressure values were 10^{-2} Torr in volume V_1 and 10^{-4} Torr in volume V_2. In order to control the pressure gradient and the plasma source performance the diaphragm was an iris which could be varied by means of a feedthrough mechanism. A heated tungsten cathode provides primary electrons for the discharge as well as neutralizing electrons for the ions moving from the discharge region into the tank. A paddle proved very useful in baffling high energetic electrons coming from the discharge.

A set of different plasma probes were installed in the tank, in particular

a) a conventional Langmuir probe (LP)

b) a retarding potential analyzer (RPA) and

c) electrode systems for RF impedance measurements.

Fig. 2 shows schematically the arrangement of the plasma source and the probes in the vacuum system. The probes were mounted on movable high vacuum feedthroughs in order to change their position and/or orientation within the tank.

The RF-measurements presented in this memo were performed with a cylindrical and a spherical two-electrode system (E_1, E_2), as shown in Fig. 3. The principle of the RF-measurement is also shown. A swept frequency RF generator provides a signal of constant amplitude within the frequency interval of typically 1 to 25 MHz. The RF-reference voltage $\underline{U}_R$ at E_1 as well as the test voltage $\underline{U}_T$ at E_2 are measured and compared as to their complex ratio

$$\underline{U}_T / \underline{U}_R = E + jF$$

by means of a network analyzer hp 8407.

The signals provided by the network analyzer are magnitude

$$\alpha = \left| \frac{\underline{U}_T}{\underline{U}_R} \right| = \sqrt{E^2 + F^2} \quad \text{in dB}$$

and phase φ = arctan (F/E) in degrees. Magnitude and phase together are a measure for the complex plasma impedance Z = X + jY between E_1 and E_2. In case of the spherical system half spheres were used as E_1 and E_2. Additional half spheres were operated as guard electrodes in order to reduce the influence of the tank walls.

In Fig. 4 are shown current-voltage characteristics of a spherical (diameter: 10 mm) stainless steel Langmuir probe.

The parameter of this set of curves is the bias voltage U_1 of the plasma source heating circuit. It can be seen that the velocity distribution and temperature T_e of the electrons is markedly influenced by U_1. In the present case the distribution function is maxwellian in good approximation for U_1-values of - 2 V, - 3 V and - 4 V. The corresponding T_e-values are 0.55, 0.53 and 0.52 eV, respectively. For each of these Langmuir curves the magnitude α measured as function of frequency was plotted on a X-Y-recorder. Fig. 5 shows the corresponding set of curves, which reveals the following essential features:

a) above the parallel resonance f_P, which is in our case (no magnetic field) equal to the plasma frequency f_N, occurs an additional resonance f_Z, and

b) f_Z is pronounced most clearly for the case of maxwellian distribution of the electrons with low electron temperature T_e (U_1 = - 2 V, - 3 V, - 4 V).

This resonance f_Z can be understood in terms of electroacoustic waves (also called electron pressure or Landau waves) which are launched by an RF-source above the plasma frequency. Excitation of this electrostatic type of plasma wave, which is damped with increasing frequency by collisionless or Landau damping, is predominantly responsible for the real part of the impedance of an electrode system immersed into a plasma. For a single electrode this real part would decrease monotonically with increasing frequency. For a two electrode system (E_1, E_2) as used in our experiment, however, a characteristic electrode distance d can be defined (distance between inner and outer cylinder or between two spheres). In this case the electroacoustic wave can produce a standing wave pattern between E_1 and E_2. This is expected to occur essentially at eigenfrequencies of the system {electrodes-plasma} for which the wavelength λ_{ea} (or integer multiples of it) matches the distance d.

To check this interpretation we start with the Bohm/Gross (1959) dispersion relation for these plasma waves

$$\omega^2 = \omega_N^2 + (3KT_e/m_e)\cdot k^2 \qquad (1)$$

Here ω is the angular RF-frequency, ω_N the angular plasma frequency, K is Boltzmann's constant, m_e the electron mass and $k = 2\pi/\lambda_{ea}$ the electroacoustic wave number. Equation (1) gives the wavelength λ_{ea} at the resonance frequency $f_Z = \omega_Z/2\pi$:

$$\frac{\lambda_{ea}}{m} = 0.7263 \frac{\sqrt{KT_e/eV}}{\frac{f_N}{MHz}\sqrt{\frac{f_Z^2}{f_N^2} - 1}} \qquad (2)$$

Applied to the measurements of Fig. 5 we get the following table 1:

Table 1

U_1/V	T_e/eV	f_Z/f_N	λ_{ea}/mm
- 1	.61	1.40	56
- 2	.55	1.34	54
- 3	.53	1.31	56
- 4	.52	1.30	52
- 5	.65	1.32	54
- 6	.85	1.38	54

The distance of the cylindrical electrodes is d = 38 mm. Due to the cylindrical geometry (equation (1) is strictly valid for plane waves), to the ion sheath, and possible inhomogeneous plasma distribution within the electrodes one cannot expect an absolute agreement between λ_{ea} and d. But we have as an essential result, that the ratio λ_{ea}/d is constant within a few percent for all combinations (f_N, f_Z, T_e) that occur in the set of curves of Fig. 5.

Theoretical work done by Whale (1963), Balmain (1965) and Lin/Mei (1970) shows that excitation of electroacoustic waves is reduced by the presence of an ion sheath. On the other hand collapsing the ion sheath by changing the electrode bias potential to the plasma potential leads to electron absorption so that damping of the electroacoustic wave is to be expected, too. Thus varying the electrode DC-potential U_{DC} from negative (ion sheath extended) to positive (ion sheath "collapsed"), a value for U_{DC} should occur for which the resonance at f_Z is best pronounced.

The curves of Fig. 6, where the potential U^T_{DC} of the test electrode E_2 was varied, exhibit exactly this behaviour and thus seem to confirm the interpretation for the f_Z-resonance suggested above.

Measurements with the spherical electrode system also show the resonance $f_Z = f_{Z1}$ as can be seen from Fig. 7. In this case the distance d of the two spheres was varied. In case of the large distance d = 92.8 mm a second resonance f_{Z2} above f_{Z1} occurs. These measurements were analyzed on grounds of a theory by Chasseriaux et al. (1972), in which the potential of an oscillating point charge in a warm isotropic plasma is calculated using kinetic plasma theory. The results predict resonances of the potential and hence of the plasma impedance of a spherical system essentially at those frequencies, at which the wavelength λ_{ea} (or integer multiples) equals the distance d between the spheres. As to our experiment we thus have to check, if the measured values for d, f_{Z1} (and f_{Z2}) and f_N lead to the same electron temperature. The result of this analysis is presented in table 2.

Table 2

$d/_{mm}$	f_{Z1}/f_N	T_e/eV
92.8	1.11	.44
83.8	1.11	.43
74.8	1.14	.45
65.8	1.20	.53

Again the essential result is that all cases lead in fact within a few percent to the same mean temperature T_e = 46 eV. In case of d = 65.8 mm the error in T_e is relatively large due to the larger error in reading the resonance frequency f_Z. The mean value for T_e is indicated by the straight line drawn into the corresponding Langmuir characteristic of Fig. 8. The additional resonance at f_{Z2} leads, applying the theory of Chasseriaux et al., to the value T_e = .51 eV. This value still seems to be reasonable in view of several error sources like reading error for f_{Z2}, deviation of the velocity distribution of the electrons from maxwellian, presence of an ion sheath around the electrodes etc.

The experiments presented here show that a system of two RF-electrodes lead to additional resonances of the impedance characteristic above the plasma frequency which can be understood in terms of resonant excitation of electroacoustic waves.

Systematic and more detailed investigations of the plasma impedance of two electrode systems will be performed in the big plasma chamber at IPW+/Freiburg. The importance of the additional resonance f_Z relies on two aspects:

1) knowing the distance d and the plasma frequency f_N, f_Z allows in principle to deduce the electron temperature T_e.

+ IPW = Institut für Physikalische Weltraumforschung.

2) This method would allow to determine T_e with high temporal resolution (10^{-1} to about 10^{-2} sec) which would be of particular value for diagnostic measurements in space plasmas as well as non stationary laboratory plasmas.

Acknowledgement:

The author wishes to thank Prof. W. Heikkila and Dr. D. Winningham for valuable discussions and B. Milam for his engineering assistance.

References

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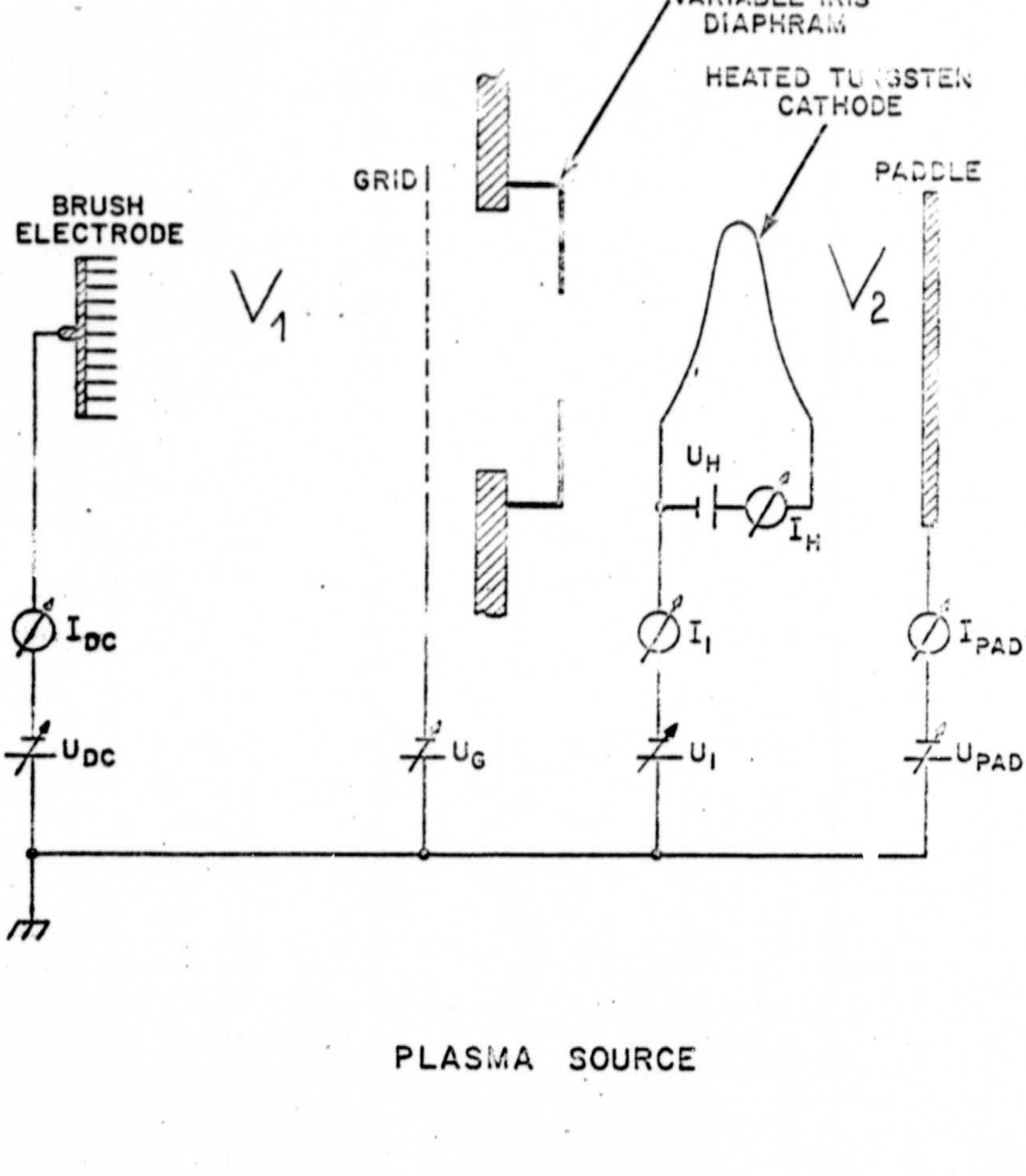
2) H.A. Whale, J. Geophys. Res. 68, No 2, 415 (1963);

3) K.G. Balmain, Radio Sci. J. Res. NBS 68 D, (4), 559 (1965);

4) S.H. Lin, K.K. Mei; IEEE Trans. Ant. Propag. AP-18, No 5, 672 (1970);

5) J.M. Chasseriaux, R. Debrie, C. Renard; Report der "Groupe de Recherches Ionosphériques" (1972);



PLASMA SOURCE

FIG 1

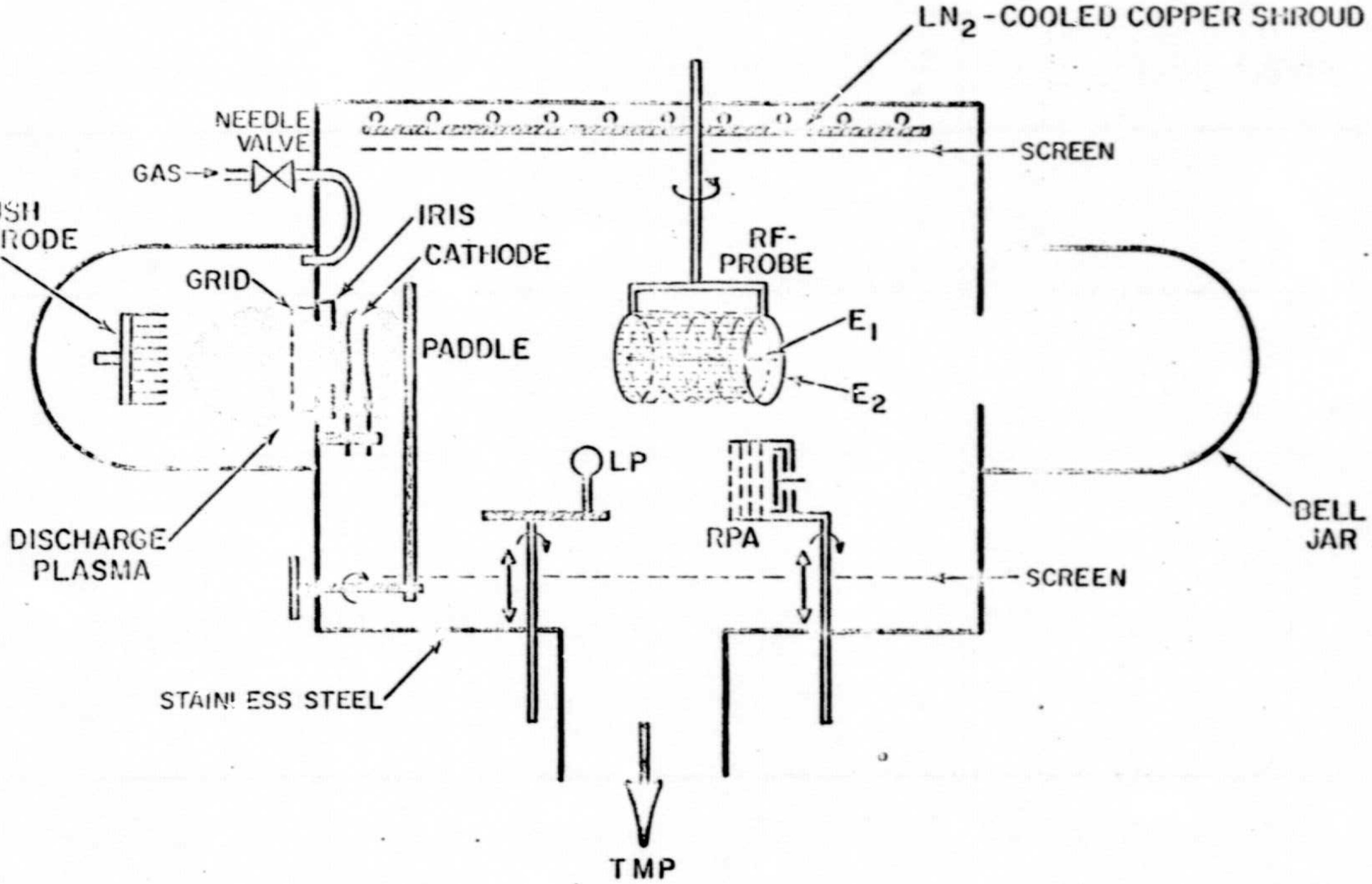
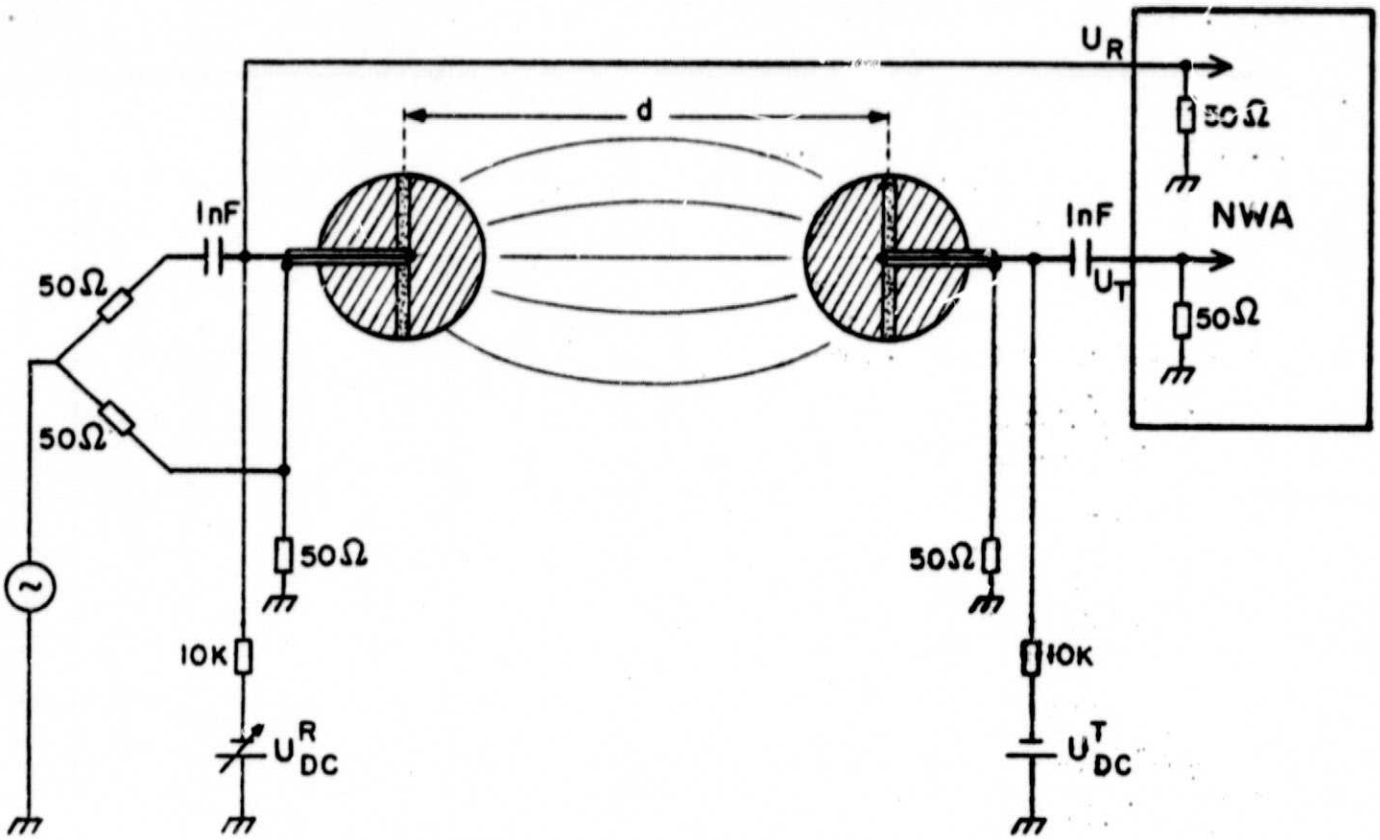
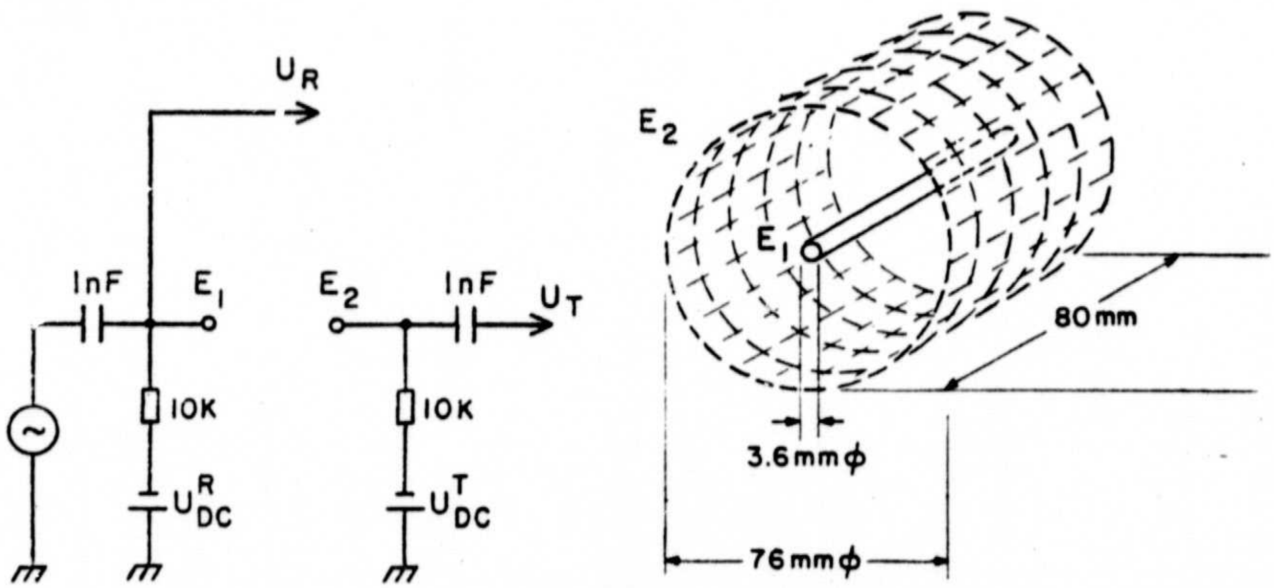

LN$_2$-COOLED COPPER SHROUD
NEEDLE VALVE
GAS
SCREEN
BRUSH ELECTRODE
IRIS
CATHODE
RF-PROBE
GRID
PADDLE
E_1
E_2
LP
RPA
DISCHARGE PLASMA
BELL JAR
SCREEN
STAIN! ESS STEEL
TMP

FIG 2



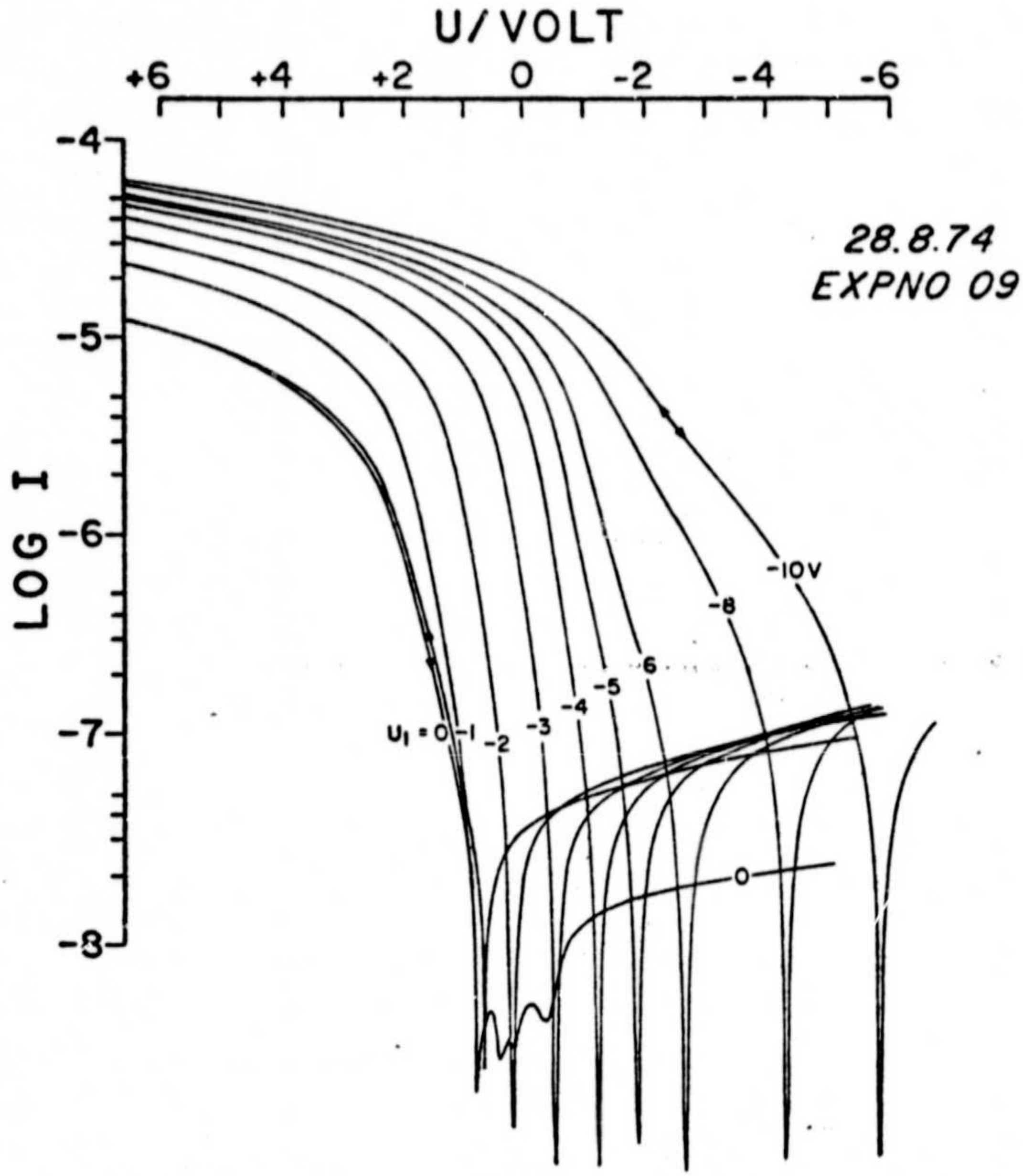
SPHERICAL RF - PROBE

DIAMETER OF BOTH SPHERES: 17.8mm



CYLINDRICAL RF - PROBE

FIG 3



SPHERICAL LANGMUIR PROBE
STAINLESS STEEL
DIAMETER 10mm
VARIATION OF U_1

FIG 4

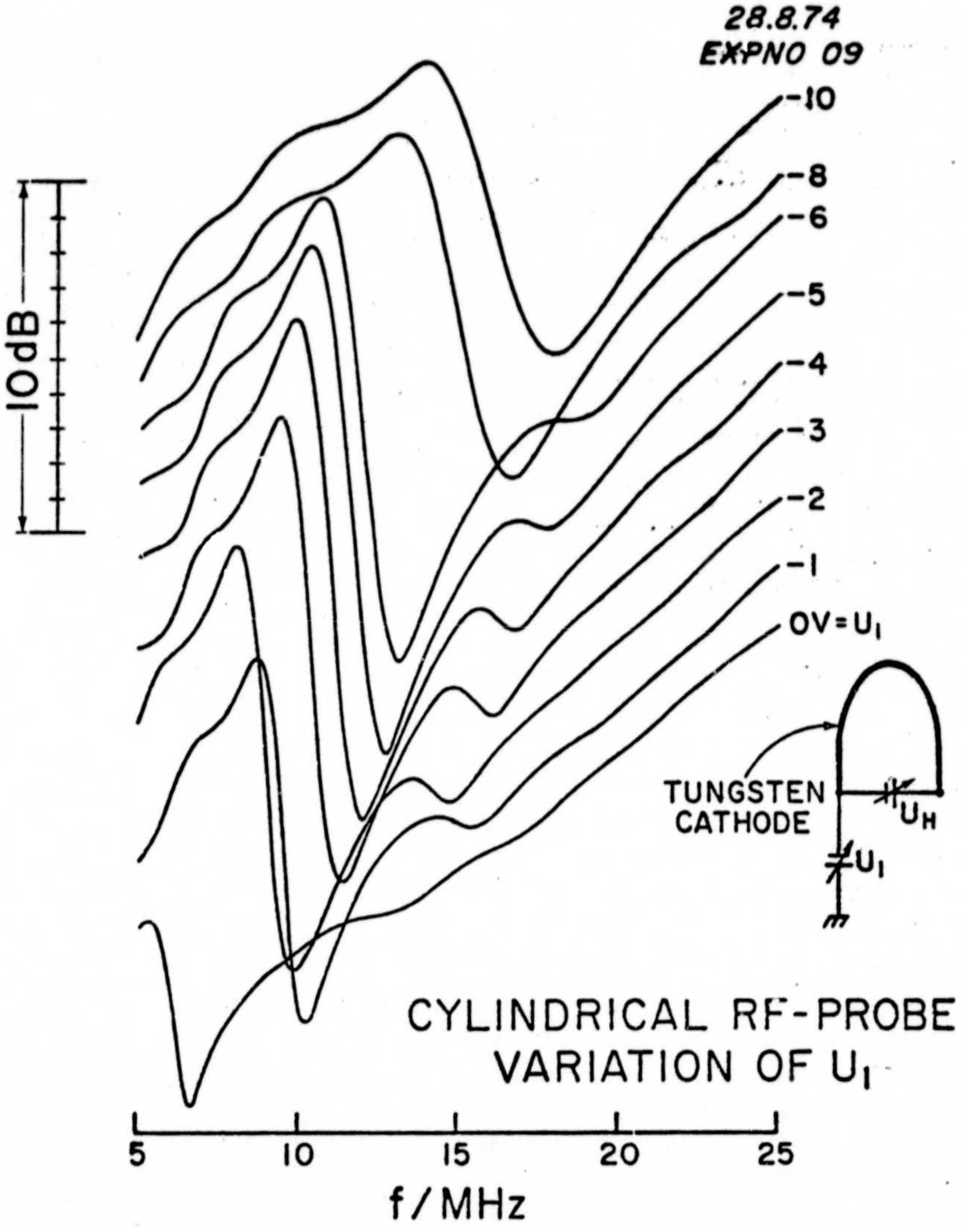

28.8.74
EXPNO 09
10dB
-10
-8
-6
-5
-4
-3
-2
-1
OV=U1
TUNGSTEN
CATHODE
UH
U1
CYLINDRICAL RF-PROBE
VARIATION OF U1
5
10
15
20
25
f / MHz

FIG 5

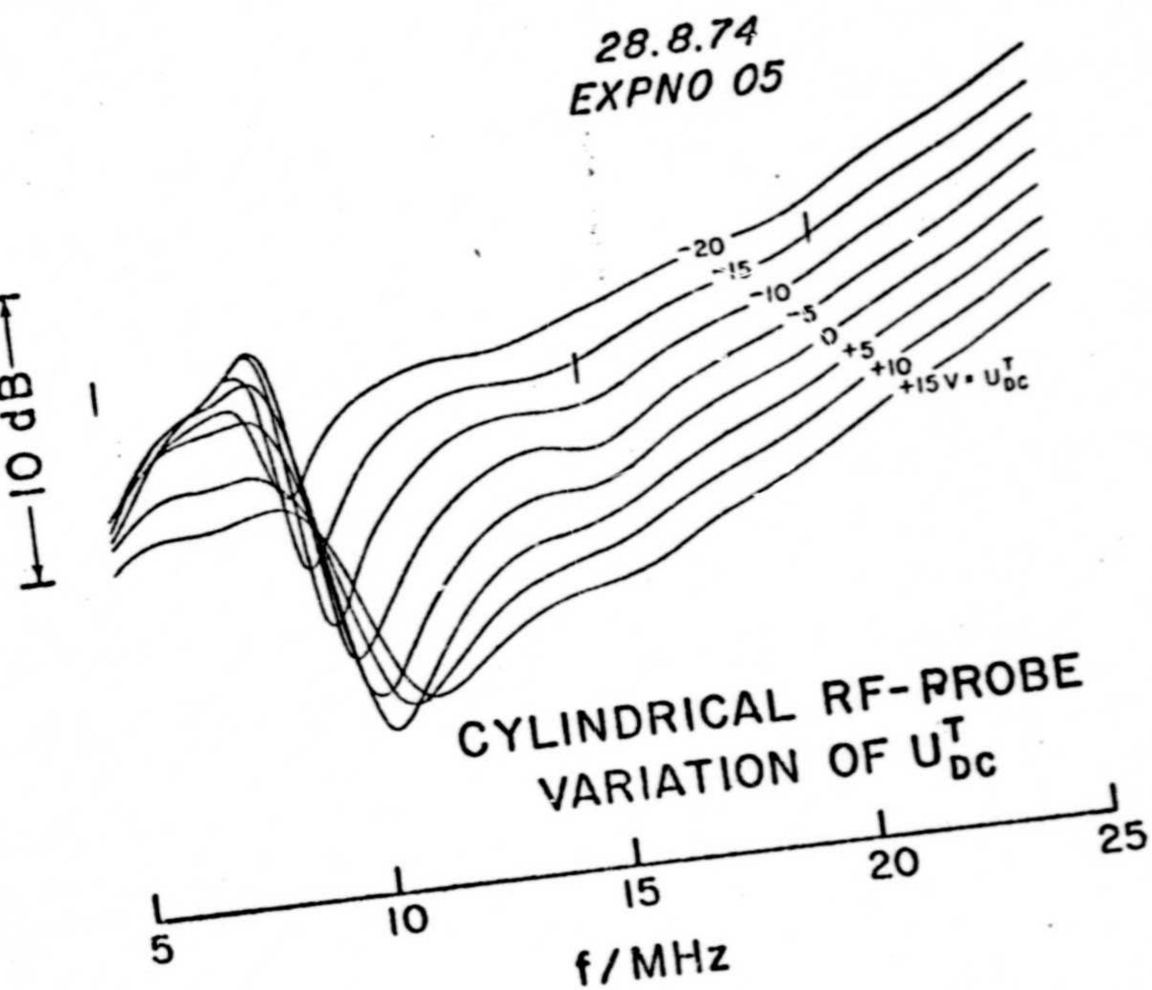

28.8.74
EXPNO 05
10 dB
-20
-15
-10
-5
0
+5
+10
+15 V = U_{DC}^{T}
CYLINDRICAL RF-PROBE
VARIATION OF U_{DC}^{T}
5
10
15
20
25
f/MHz

FIG 6

NO.	1	2	3	4	5	6	7
d/mm	92.8	83.8	74.8	65.8	56.6	47.6	38.8

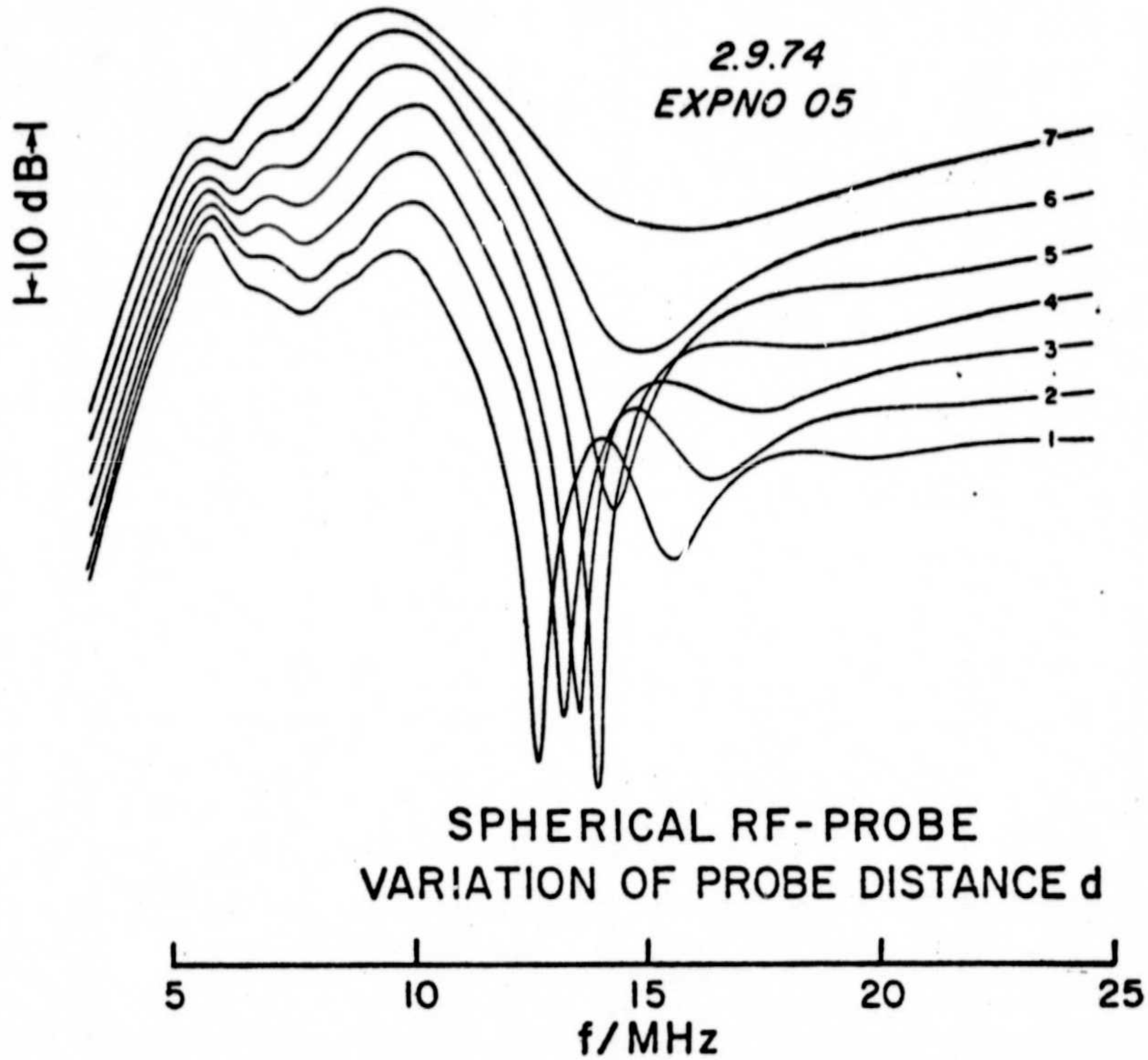
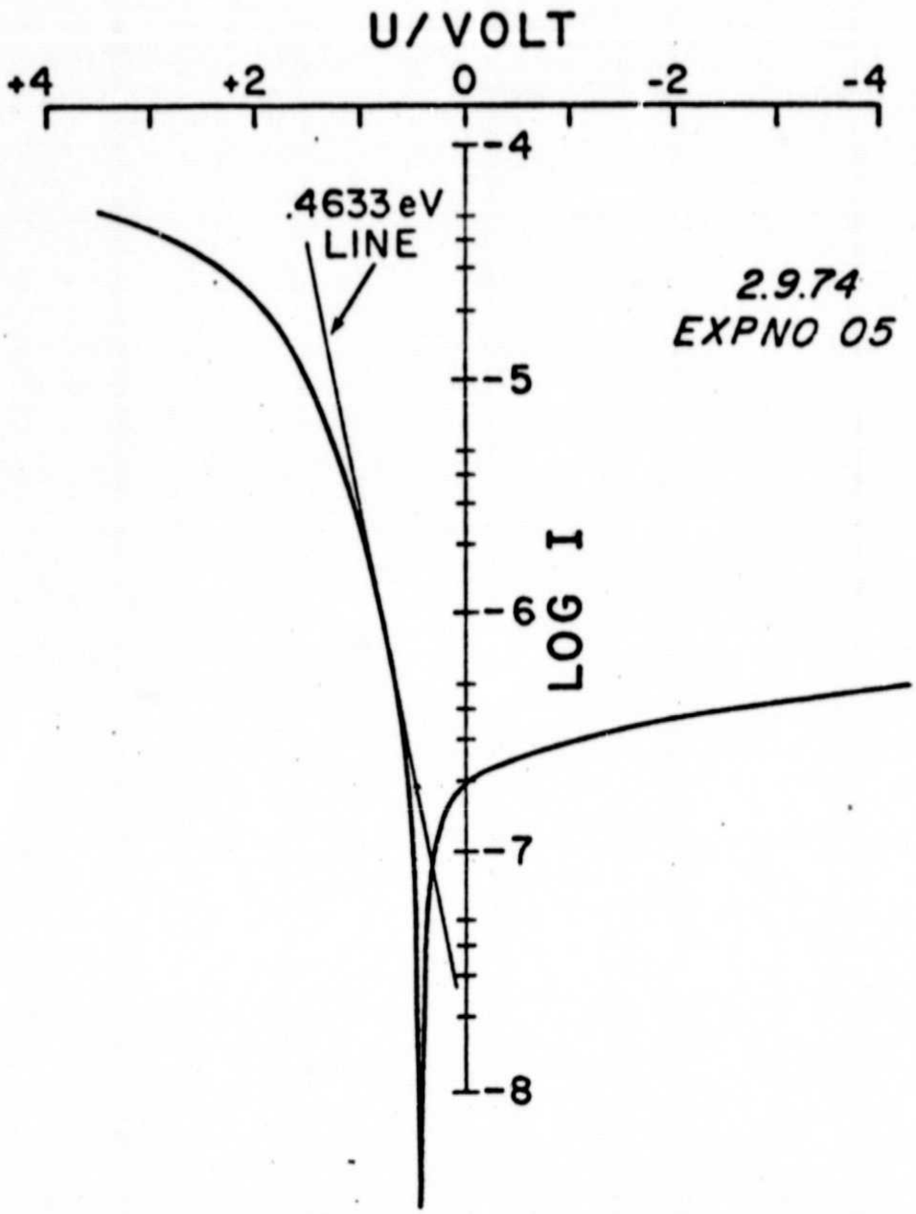


FIG 7



SPHERICAL LANGMUIR PROBE
STAINLESS STELL
DIAMETER 10mm

FIG 8

OPERATION OF A DIGITAL LANGMUIR PROBE

ON LINE WITH A PDP 11/45 DIGITAL COMPUTER

by

RAINER KIST*

This memo describes the concept and the performance of the Digital Langmuir Probe (DLP) experiment, the necessary interface electronics to the computer and the associated software. The system was set up to provide a flexible diagnostic tool for the laboratory plasma facility at the University of Texas at Dallas (UTD). The memo summarises a part of the accomplishments achieved in the course of a project which deals with production and diagnostics of collisionless laboratory plasmas at UTD.

UTD, September 1974

*On leave at UTD, sponsored by the European Space Research Organization (ESRO), now European Space Agency (ESA).

I. INTRODUCTION

Several diagnostic probes such as RF-probe, Retarding Potential Analyzer (RPA) and Langmuir Probes (LP) have been installed in the Laboratory plasma chamber at UTD. Langmuir Probes of different materials (Stainless Steel, Polymorphic carbon) and geometry (spherical, cylindrical) have been used. Fig. 1 shows the arrangement of the probes within the chamber. The detailed description and performance of the plasma source and the probes are the object of a separate memo.

A conventional Langmuir probe electronics makes use of an electrometer amplifier with either a nonlinear (diode) feedback resistor or a linear feedback resistor plus subsequent logarithmic amplifier. This allows to display the logarithm of the probe current over 3 to 4 orders of magnitude (current-voltage characteristic). This compressed form of current display, however, does not allow for a sufficient resolution of small current changes as they occur in time and/or space due to density fluctuations associated with electrostatic waves on instabilities present in a plasma.

In order to measure small electron density fluctuations in the F-region of the Equatorial Ionosphere a digital Langmuir Probe (DLP) was developed at UTD by D. Winningham and J. B. Smith for use in the EQUION rocket project. The unique feature of this experiment is to provide an absolute current resolution of $\sim 10^{-9}$ Amps and a maximum relative resolution of $\sim 10^{-4}$.

Since the investigation of electrostatic wave modes and instabilities is of special interest for laboratory plasma physics, this DLP was installed for use in the plasma chamber at UTD. In particular the digital output of the instrument allowed for a straight forward connection to the computer (PDP 11/45). Therefore an interface electronics and a set of computer programs were set up to transfer the data to the computer and from there on to magnetic tape and process them for display on a Calcomp plotter.

A general diagram of the system DLP-Computer is shown in Fig. 2. The mean parts of the system are described below in more detail.

II. Properties of the DLP - Electronics*

A triangular bias waveform is applied at G (see Fig. 3) through the electrometer amplifier (1) to the Probe P. The laboratory version of the DLP allows for using the waveform of either the internal or an external bias generator. The range for the bias voltage is from -1 to +3 volts. The period τ of the internal bias generator is controlled by the bit rate fed into the experiment and can be varied between $.5 \text{ S} \lesssim \tau \lesssim 200 \text{ S}$. The relationship between τ and the bit rate f_b is

$$\tau/S = \frac{23040}{f_b/Hz}$$

The electrometer amplifier is a 3420L BURR-BROWN with bias current of about 1 pA and frequency response better than 2 kHz.

The bias waveform at G also appears at A, B, and C. Therefore the bias is also introduced at J so that Amplifier 2 can see the bias as a common mode signal, and can reject it, making D independent of the bias and responsive only to the signal produced by the input current at A. One of the important system tests consists of holding the input current

*This chapter is essentially the DLP electronics description that already had been prespared by D. Winningham and J. B. Smith for the EQUION-Project.

constant and letting the bias voltage cycle while observing the output code. If the system is properly adjusted, the output code will not change by more than 1 or 2 LSB's.

The principle of operation is obvious; only a few system constants will be specified here. The A/D converter is a 0 to -10 v full scale, 8 bit unit. Of the total range of 256 increments (called minor increments) only 200 are used, leaving an unused portion at the lower and upper edges of the 10 volt range. The limits of the 200 increment range are determined by voltage comparators. Actually the comparators defined a range of 200 increments plus a hysteresis band of a few increments in order to avoid an oscillatory condition when sitting at band edge. This means that certain values of current can be represented by two different code group differing by 200 minor increments and by 1 major increment. However, when the two code groups are decoded according to a fixed algorithm, exactly the same current results.

When a voltage comparator switches it changes the D/A converter code by one increment (called a major increment). The resulting output analog increment is fed into the system at J which resets the output D by 200 minor voltage increments.

The D/A is an 8 bit unit in which the 256 increments correspond to an output voltage from -10v to +10v. This range establishes the maximum measuring limits of the system, and R_1 is chosen so that the desired maximum current will cause a $\pm$ 10v change at B. However the bias voltage must be added to this which results in a range of -11 v to +13 v at B. With a $\pm$ 15 volt supply, the +13 v limit exceeds the linear range of operation of amplifiers 1 and 2. Therefore R_1 is chosen to be 786 KΩ which results in a maximum voltage at B of 7.86 v + 3V = 10.86 v for an input current (electrons) of 10μa. This means that the positive range of the D/A will not all be used. In the negative direction (positive ion current) the maximum current will be even smaller, and is not expected to exceed 15% of the negative range capability.

The sense of the output code is arranged as follows: At the negative limit (-10v of positive ion current at B, all code bits are zero. As the current changes so as to move B in a positive direction, the code increases and at +10V all bits are 1.

At zero current (0 V at B) the code is

DAC		ADC	
MSB	LSB	MSB	LSB
0 1 1 1	1 1 1 0	1 1 0 0	1 0 0 0

Here the ADC code is 200. It cannot be 0 for zero current because the upper level comparator excludes this point from the operating region. Therefore a major increment is "subtracted" (the DAC LSB = 0) and the ADC increased from 0 to 200.

The code/current algorithm is:

$$i = [(DAC - 127)\ 200 + ADC]\ (5 \times 10^{-10}) \text{ where}$$

DAC = the decimal value of the D/a code

ADC = the decimal value of the A/d code

i = amperes (positive i means electrons flowing <u>to</u> the system. A negative i means positive ions flowing <u>to</u> the system).

5×10^{-10} = the resolution or amps/minor increment

When applied to the above code the result is:

$$i = [(126 - 127)\ 200 + 200]\ (5 \times 10^{-10}) = 0$$

If the current increases by a few minor increments, say 15, the lower level comparator will trip and the resulting code will be:

0 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1

Applying the algorithm

$$i = 15\ (5 \times 10^{-10}) = 75 \times 10^{-10}\ a.$$

The algorithm applies to all values of current.

In reading the value of the analog channel only 1 fact is necessary: The gain of Amplifier 3 is exactly -0.5. If D is -6 v, F is +3v, etc. If the ADC code is known the voltage at D and F can be computed. The ADC increment is 10v/256 = 39.0625 m.v. (40 mv is close enough). Therefore

$$V_D = -\ (ADC)\ .04\ volts$$

$$V_F = (ADC)\ .02\ volts$$

$$or\ ADC = 50\ V_F$$

from which the algorithm can be applied,

$$i = [(DAC - 127)\ 200 + 50\ V_F]\ (5 \times 10^{-10})\ amps$$

III. The Interface Electronics

The Interface Electronics (IE) provides matching of the experiment output signal to the driver assembly and allows for operation of the DLP in different modes. In more detail the following functions are realized; we partly follow the schematic diagram. Fig. 4 and the timing chart Fig. 5.

1) The bit rate is to be provided by an external pulse generator. The word and frame rates are deduced from the bit rate.
2) The serial output signal DAC-ADC of the DLP is stored in a 16 bit storage register from where it will later be transferred

in parallel to the computer via 4 each quadruple 2-line to 1-line multiplexers.

3) The voltage of the internal or external bias generator is offset by +1.33V and then fed to an A/D-Converter. The A/D-Conversion is ordered by a strobe pulse generated in the programmer.

4) The converter is also used for A/D-Conversion of the probe position monitoring voltage (position sweep). This applies for the operation mode of the experiment, in which the probe is kept at constant bias voltage and moved within the plasma.

5) A set of eight toggle switches allows for monitoring the experiment number (EXPNO) or a coded STATUS in order to identify a particular data run (measurement).

6) Upon a select signal from the programmer the DAC/ADC data or the BIAS (or position)/EXPNO (or STATUS) data is alternately switched by the multiplexers to the driver assembly and then via optical couplers to the receiver section of the computer. Sixteen bits are transferred in parallel to the computer receiver but are not actually read into the computer until a cycle request pulse is generated by the programmer. The rate at which the data points are sampled is 366 per scan. It is independent from the scantime, since both, scantime and sampling period are fixed multiples of the bit period.

7) The programmer generated cycle request pulse commands the computer to read the data at its receiver inputs and to then follow the instructions given by the computer program for data storage and/or reduction.

IV. The Computer Software

At present the software for the DLP-Computer system consists of three programs

1) Storage and Tape Transfer Program (PROBE), ASSEMBLER

2) Tape dumping Program (DLP), FORTRAN IV

3) Data Analysis Program (DIGITAL LANGMUIR PROBE), FORTRAN IV

PROBE handles the data flux that is coming from the DLP-experiment through the interface electronics IE to the receiver input of the computer. 16 bit data words are stored in the upper core memory and arranged in blocks of 8K Bytes. The part of memory used allows for storage of 22 blocks which form one file. One data block covers the data of 5.5 Scans of the Digital Langmuir Probe. As already mentioned the number of data samples taken per scan is 366 independently of the scantime. Thus with each run (measurement) practically 5 Langmuir Characteristics (each consisting of a full sweep upwards and a full sweep downwards) can be recorded. Prior to each measurement a computer attention button on the IE has to be pushed. This starts the computer to read 8 K bytes of data into the memory. A switch installed at the IE allows to interrupt the data flux.

Once up to 22 data blocks are stored they are transferred on to tape by executing PROBE with one label card for each block. The label card contains additional information (80 bytes) about the particular measurement such as file Number,block number, date and experimental conditions (pressure, probe used, etc). The data sequence on tape is thus: label card information - data block label card information - data block- A.S.O. After each 22nd block an End of File (EOF) mark is written on the tape. When executing PROBE for data transfer on to tape a 00 card inserted right after the label cards takes care of reinitializing the memory so that a new set of 22 measurements can be stored upon pushing the computer intention button.

For short compilation of the procedure in handling the program PROBE see the copy of the printer record in Appendix A.

The Program DLP reads the tape for a selected set of files and blocks and prints the data in 32 columns of octal numbers. The sequence of the data display is

EXPNO - ADC - DAC - BIAS

The selection of file Number (NF) and block (or record) number (NR) is made via a data card which contains the number of records to be read (MAXREX) in column 5, the number of records to be skipped (NRS) in column 10 and the number of files to be skipped (NFS) in column 15.

Fig. 6 shows the flow diagram for this program; a copy of the printer record of DLP is included in appendix B.

The program DIGITAL LANGMUIR PROBE in its present version meets the following objectives:

1) Skip a specified number of files and records and print label (or header) card.

2) Identify bias and find first bias peak. The bias identification relies on the fixed sequence of DAC/ADC/BIAS/EXPNO and the fact that the experiment number (toggle switch setting at the IE) is constant throughout one run.

3) Calculate current i out of DAC/ADC according to the algorithm given in Chapter II.

4) Calculate the derivative $T_G = 11606.9 \frac{\Delta U}{\Delta \log i}$

5) Print EXPNO, Bias, log i and T_G

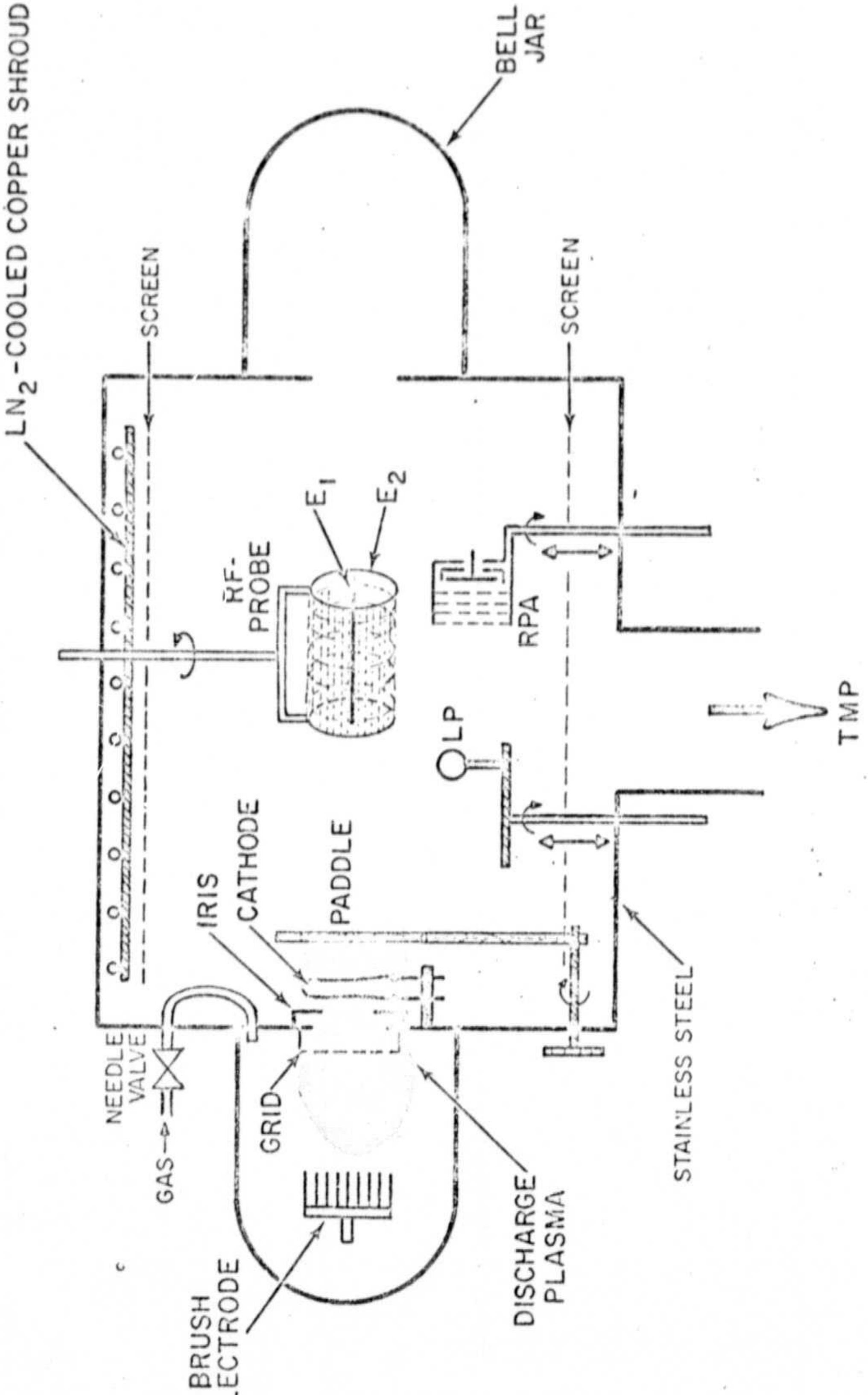
6) Plot data for one cycle (scan) on CALCOMP - Plotter

A simplified flow chart of this program is shown as Fig. 7, a copy of the program is included as appendix C.

Figs. 8 and 9 show two examples of Langmuir characteristics as semilogarithmic plots produced by the system. The current for increasing bias voltage is marked by x-es, for decreasing bias by squares. The ion current is plotted as log of its absolute value. The probe used in the plasma was a stainless steel sphere of 5 mm diameter. The surface was discharge cleaned for 10 minutes in nitrogen at about 10μ pressure. The Langmuir curves show almost no hysteresis. In Fig. 8 the floating potential is at +100 mV. In this experiment the plasma was clearly non-Maxwellian since the differential or "generalized temperature" T_G shows a monotonous increase. Here crosses are for the upward going and triangles for the downward going part of the curve. Fig. 9 shows a case where the distribution function of the electrons is close to Maxwellian. This shows up in the shoulder shaped part of the T_G - curve, occuring between 1 and 1.4 Volts and corresponding to an electron temperature T_e of about 5000 K. For an ideally Maxwellian distribution the shoulder would have a horizontal plateau. A high value of T_e corresponds to a large, a low T_e-value to a small horizontal extension of the plateau. The low T_G-values on the left side reflect the drop of the measured total current due to the ion current which becomes significant with decreasing bias voltage. The high T_G-values on the right side are due to the transition-knee from the retarding to the saturation regime of the characteristic. This knee is influenced by the inhomogeneity of the work function over the probe surface. A perfectly homogeneous work function would produce a sharper knee of the electron current curve and a correspondingly straightened shape of the T_G-plateau.

Above 2.5 V bias the data are meaningless since in this case the current exceeded the upper current limit (10^{-5} amperes) to which the electronics of the Digital Langmuir Probe was set.

ACKNOWLEDGEMENT: The author is highly indepted to Dr. D. Winningham for providing the DLP back up electronics of the EQUION-project. Many thanks go to N. Eaker and C. Thompson for designing and building the interface electronics. The outstanding help from Dr. J. Midgley, L. Wadel and D. Beck in providing parts of the necessary software is particularly appreciated. The author finally wishes to express his gratitude to B. Milam for his engineering assistance.


LN_2-COOLED COPPER SHROUD
SCREEN
BELL JAR
SCREEN
E_1
E_2
RF-PROBE
RPA
LP
TMP
IRIS
CATHODE
PADDLE
NEEDLE VALVE
GAS
GRID
BRUSH ELECTRODE
DISCHARGE PLASMA
STAINLESS STEEL

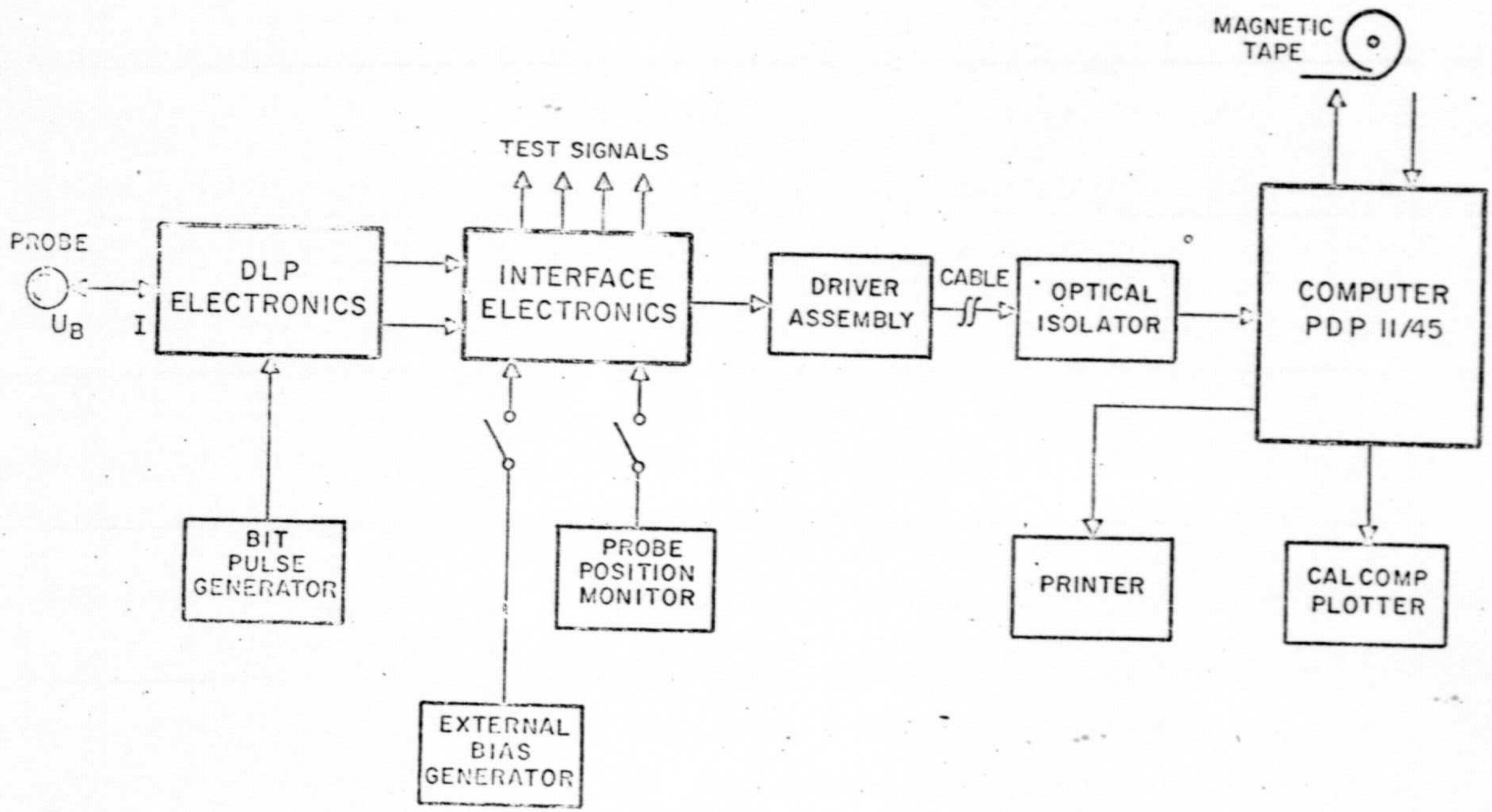


FIG. 2 SYSTEM DLP-COMPUTER

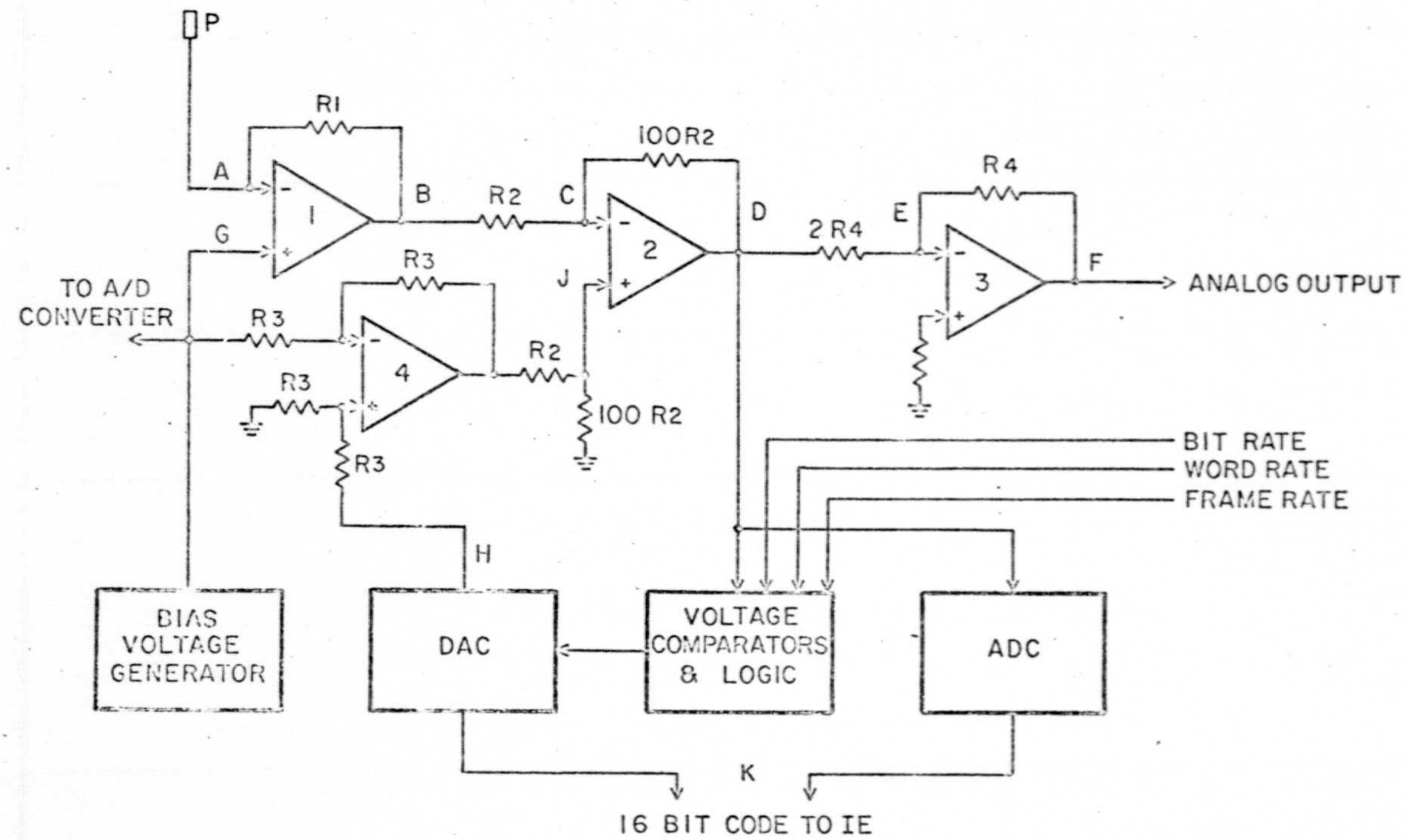


FIG. 3 DIGITAL LANGMUIR PROBE

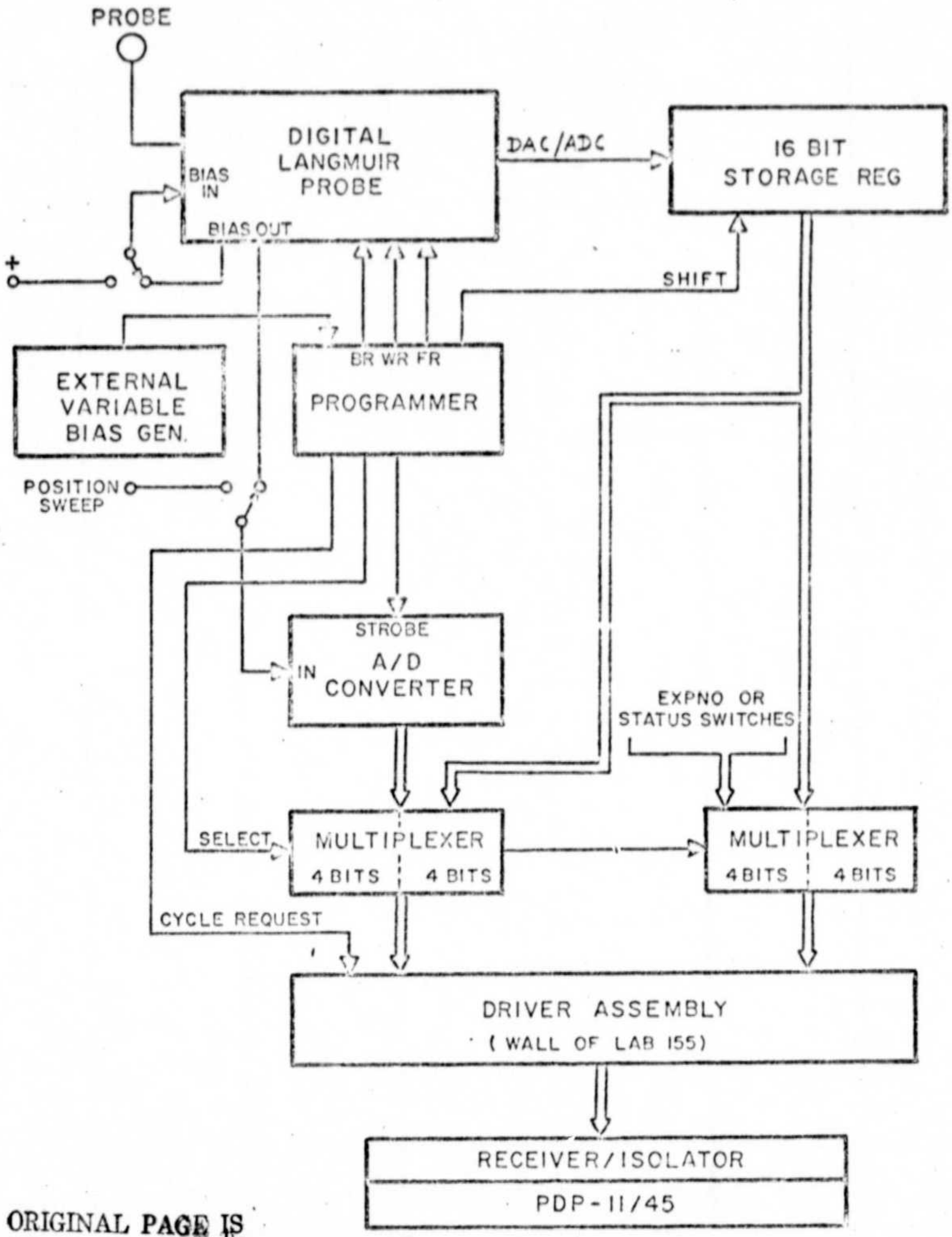


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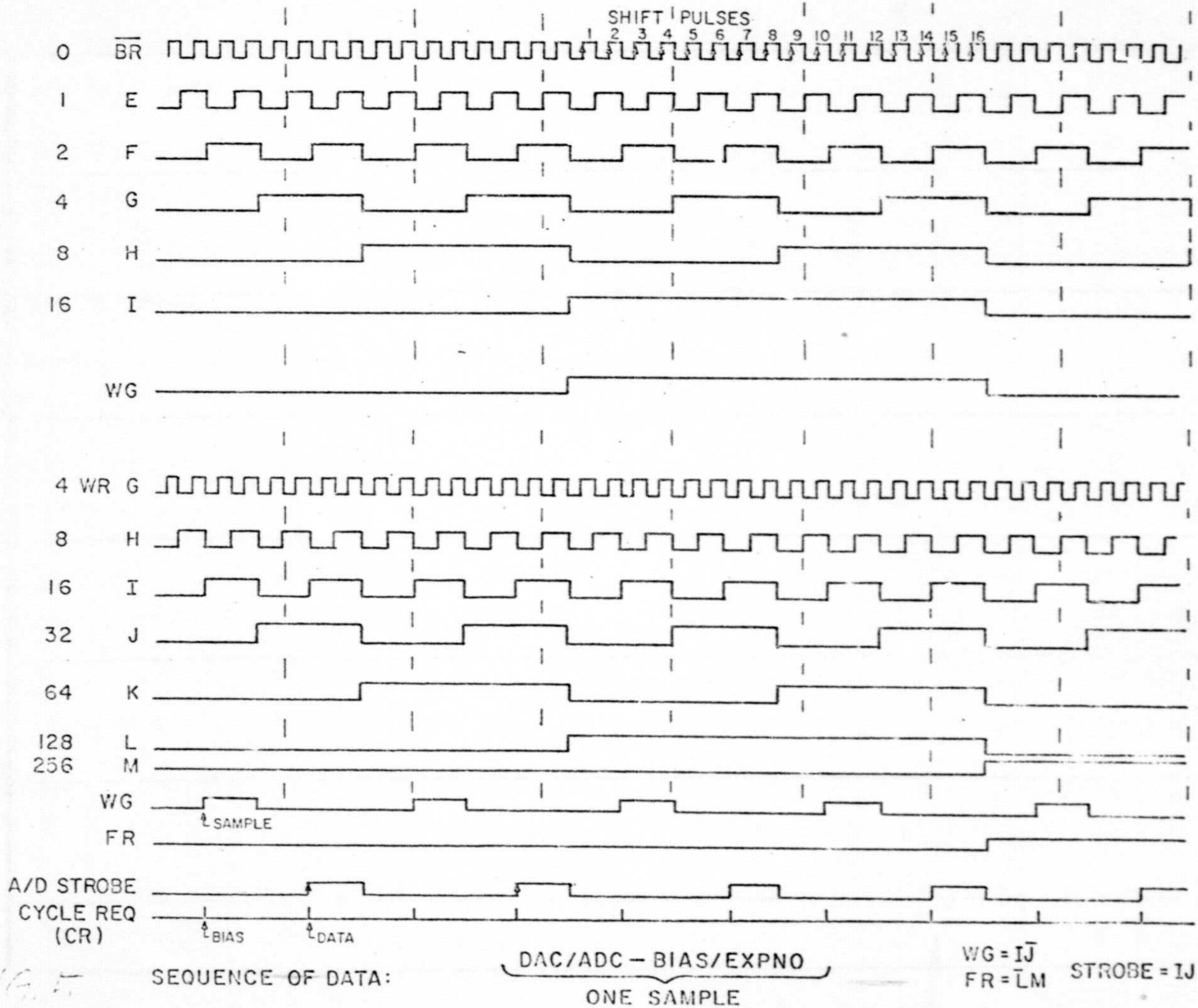
FIG. 4


SHIFT PULSES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0 BR
1 E
2 F
4 G
8 H
16 I
WG
4 WR G
8 H
16 I
32 J
64 K
128 L
256 M
WG
SAMPLE
FR
A/D STROBE
CYCLE REQ (CR)
BIAS
DATA
SEQUENCE OF DATA:
DAC/ADC – BIAS/EXPNO
ONE SAMPLE
WG = IJ̄
FR = L̄M
STROBE = IJ

DLP tape dumping program

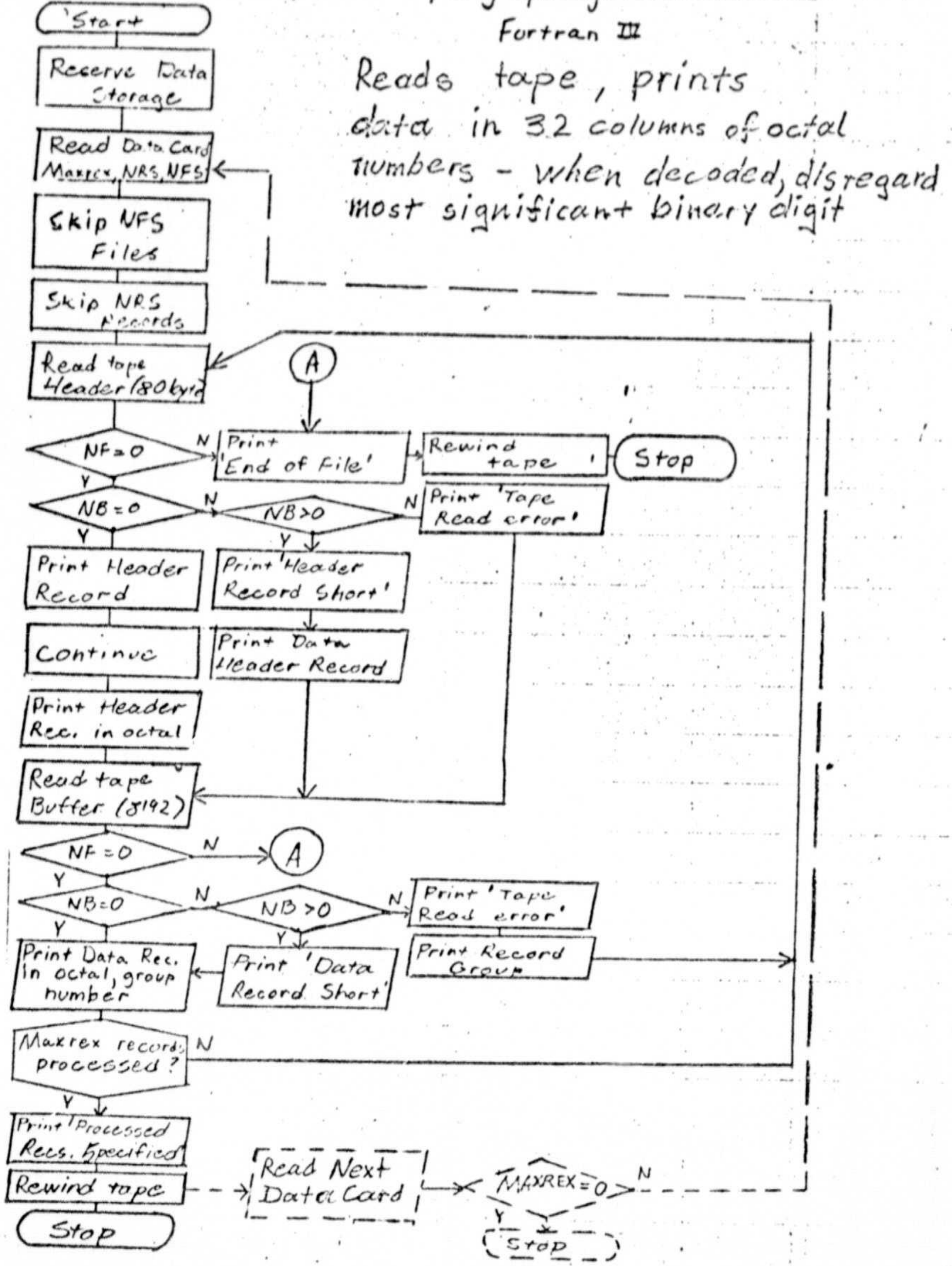
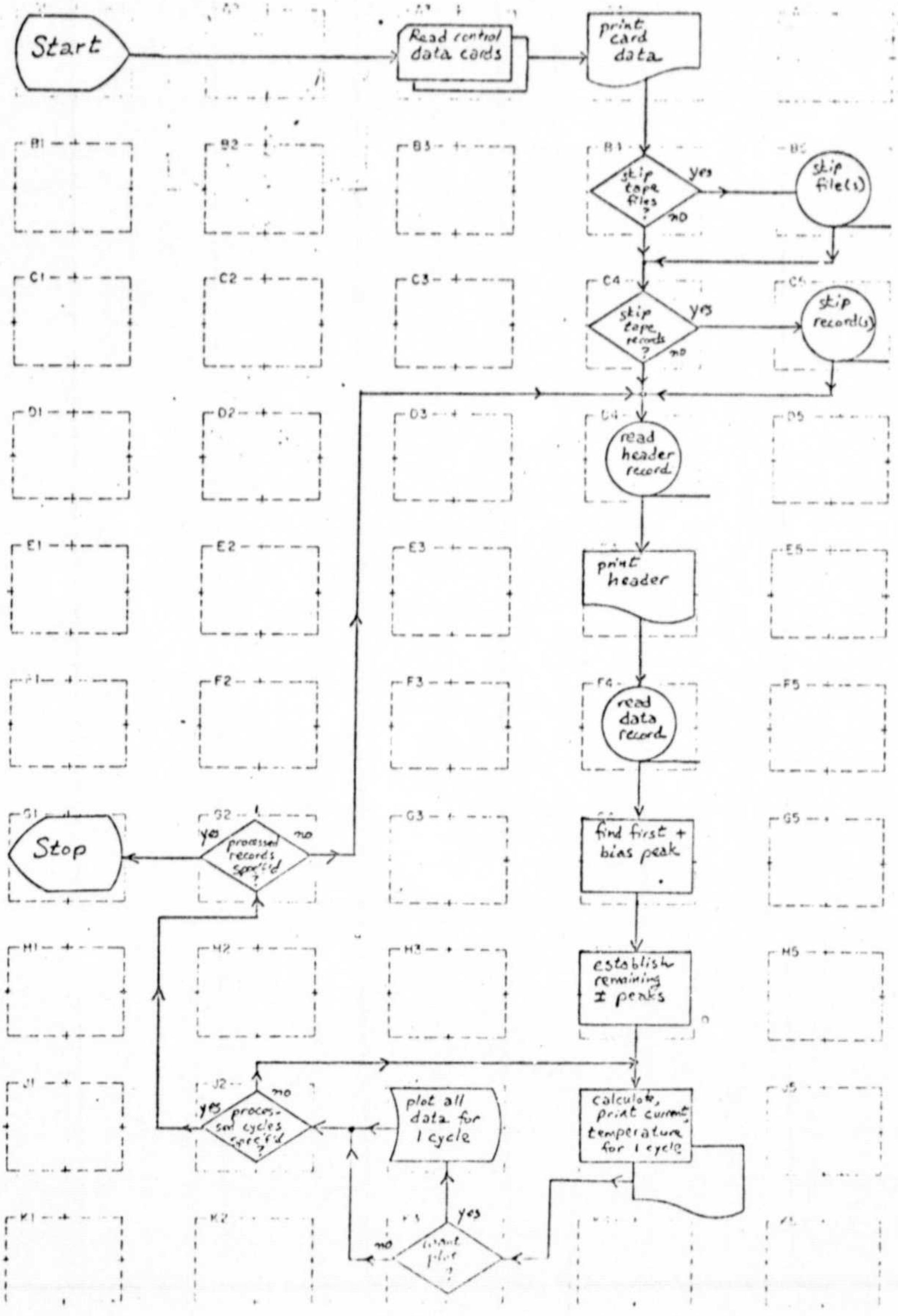


FIG. 6

IBM Flowcharting Worksheet

Programmer: L. B. Wadel Program No.: Date: 9/25/74 Page: A

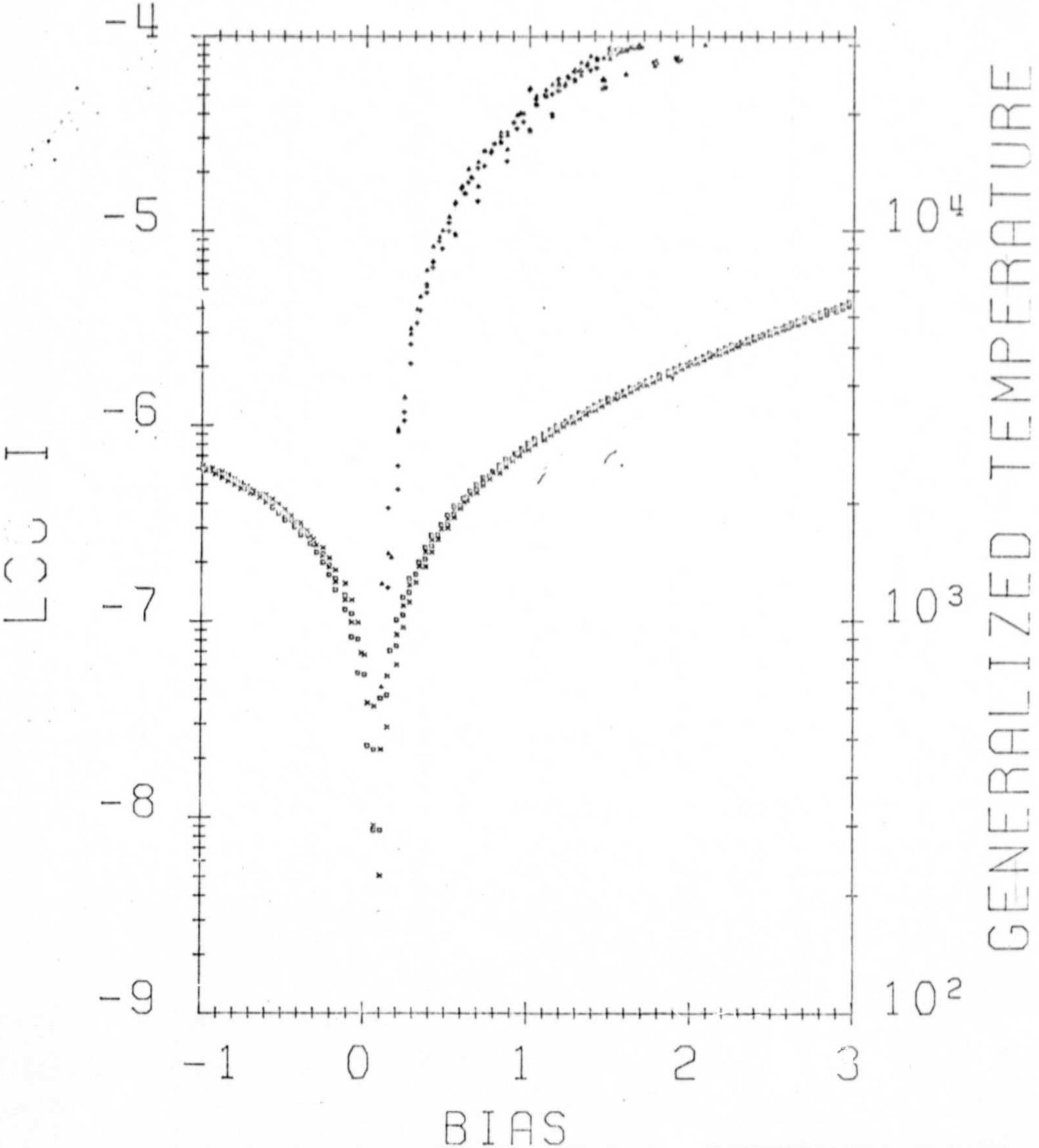
Chart ID: Chart Name: Program Name: LANGMR



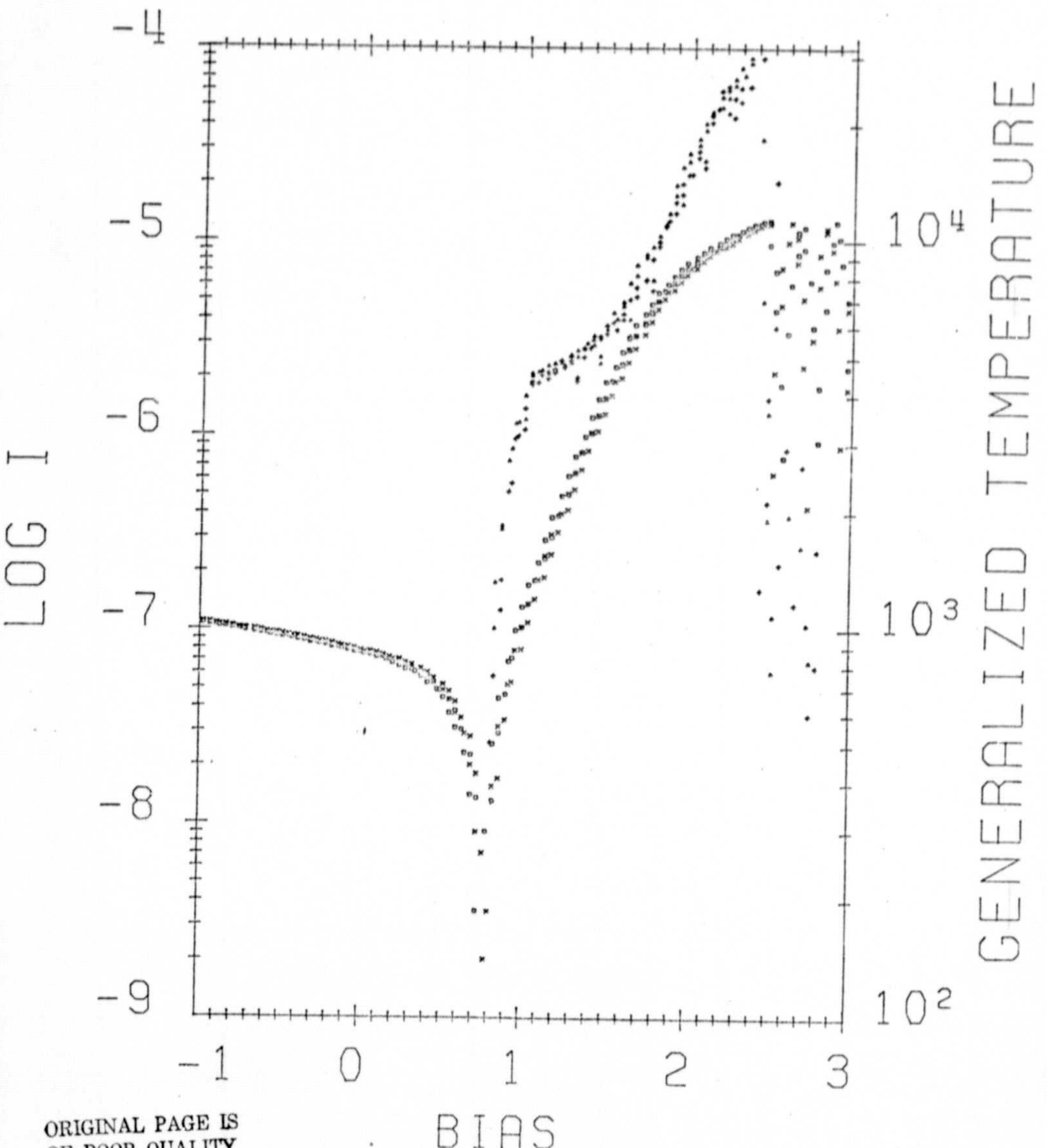
Fold under at dotted line.

Fold under at dotted line.

FIG. 7



EXP NO 192. FIG. 8



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09/26/74 EXP NO 63 FIG. 9

APPENDIX A

```
                                          .NLIST TTM
                                          .TITLE PROBE
                                 ; PROBE OPERATES SIMULTANEOUSLY WITH NORMAL BATCH PROCESSING.
                                 ; IT ACCEPTS 16 BIT AATA WORDS, IN BLOCKS OF 4K WORDS, STORING THEM
                                 ; IN UPPER MEMORY, AND (WHEN INSTRUCTED) DUMPING THEM ON TAPE AS A FILE
                                 ; A MAXIMUM OF 22 SUCH BLOKKS MAY BE STORED BETWEEN DUMPS.
                                 ; WHEN PROBE IS RUN, ONE DATA (LABEL) CARD MUST BE INCLUDED FOR EACH
                                 ; BLOCK TO BE WRITTEN.  THE CONTENTS OF THE CARD ARE WRITTEN AS AN 80
                                 ; BYTE LABEL RECORD PRECEEDING THE 8K BYTE DATA RECORD.  THE FPRST TWO
                                 ; DIGITS ON THE FIRST CARD SPECIFY THE FILE NUMBER INTO WHICH THE
                                 ; BLOCKS ARE WRITTEN.  A 00 CARD (CARD WHOSE FIRST TWO COLUMNS ARE ZERO)
                                 ; FOLLOWING THE LAST LABEL CARD CLOSES THE FILE AND REINITIALIZES
                                 ; MEMORY TO STORE ANOTHER 22 BLOCKS.
                                 ;
                                 ; PROCEDURE: 1) EXECUTE PROBE WITH ONLY A 00 CARD, TO INITIAL. MEMORY
                                 ;            2) PUSH ATTENTION BUTTON TO START A DATA BLOCK
                                 ;            3) START DATA AND STOP IT AFTER 4K WORDS OR MORE.
                                 ;            4) REPEAT 2) AND 3), BUT NO MORE THAN 22 TIMES.
                                 ;            5) EXECUTE PROBE WITH ONE LABEL CARD FOR EACH BLOCK TO BE
                                 ;               RECORDED ON TAPE, AND A 00 CARD TO REINITIALIZE MEMORY.
                                 ;            6) REPEAT 2)-5) AS OFTEN AS DESIRED, INCREASING FILE
                                 ;               NUMBER ON LABEL CARDS BY ONE AACH TIME.
                                          .GLOBL TAPE
                                          .MCALL .INIT,.READ,.WAIT,.RLSE,.EXIT
        000104                            MINT=104              ; THE ADDRESS WHERE INT IS STORED
000000                            PROBE:  .INIT   #LNKCR
000006                              1$:   .READ   #LNKCR,#CARD  ; READ ONE DATA CARD
000022                                    .WAIT   #LNKCR
000026  116701  000642                    MOVB IN,%1
000032  116700  000637                    MOVB IN+1,%0
000036  042701  177760                    BIC  #177760,%1
000042  042700  177760                    BIC  #177760,%0
000046  070127  000012                    MUL  #12,%1
000052  060100                            ADD  %1,%0            ; R0=FILE NUMBER
000054  000401                     11$:   BR   2$
000056  000422                            BR   12$
000060  001517                      2$:   BEQ  8$
000062  105267  177766                    CLRB 11$
000066  005300                            DEC  %0
000070  003414                            BLE  3$
000072  010267  000726                    MOV  %0,NF
000076  004567  000000G                   JSR  %5,TAPE          ; SKIP NF FILES
000102  000407                            BR   3$
000104  001034'                           .WORD ONE
000106  001020'                           .WORD IC
000110  000674'                           .WORD IN
000112  001032'                           .WORD ZERO
000114  001030'                           .WORD NRM
000116  001024'                           .WORD NF
000120  001457                     12$:   BEQ  6$
000122  012767  000120  000672      3$:   MOV  #120,NB
000130  042767  000060  000464G           BIC  #60,TAPE+464     ; SET MEM EXTENSION BITS
000136  042767  000060  000472G           BIC  #60,TAPE+472
000144  004567  000000G                   JSR  %5,TAPE          ; WRITE LABEL
000150  000405                            BR   4$
000152  001036'                           .WORD TWO
000154  001020'                           .WORD IC
```

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```
000156  000674'                              .WORD IN
000160  001032'                              .WORD NB
000162  001026'                              .WORD NR
000164  016700  000626              4$:  MOV   ADR,%0          ; GET BUFFER ADDRESS
000170  062767  000002  000620           ADD   #2,ADR
000176  010001                           MOV   %0,%1
000200  042700  177717                   BIC   #177717,%0
000204  050067  000464G                  BIS   %0,TAPE+464
000210  050067  000472G                  BIS   %0,TAPE+472
000214  042701  177760                   BIC   #177760,%1
000220  000301                           SWAB  %1
000222  072127  000004                   ASH   #4,%1
000226  010167  000020                   MOV   %1,9$
000232  012767  020000  000562           MOV   #20000,NB
000240  004567  000002G                  JSR   %5,TAPE         ; WRITE DATA BLOCK
000244  000415                           BR    5$
000246  001036'                          .WORD TWO
000250  001020'                          .WORD IC
000252  000000                      9$:  .WORD
000254  001022'                          .WORD NB
000256  001026'                          .WORD NR
000260  004567  000000G             6$:  JSR   %5,TAPE         ; WRITE EOF
000264  000412                           BR    7$
000266  001036'                          .WORD TWO
000270  001020'                          .WORD IC
000272  000674'                          .WORD IN
000274  001032'                          .WORD ZERO
000276  001026'                          .WORD NR
000300  005767  000522              5$:  TST   NR
000304  003240                           BGT   1$
000306  004567  000000G             7$:  JSR   %5,TAPE         ; REWIND THE TAPE OFFLINE
000312  000402                           BR    8$
000314  001040'                          .WORD OFFLIN
000316  001022'                          .WORD IC
000320                              8$:  .ELSE  #LNKCR
000326  012737  000104  000174   RESET:  MOV   #MINT,@#174     ; SET INTERRUPT ADDRESS
000334  012737  004340  000176           MOV   #4340,@#176     ; KERNEL, REG SET 1, PRIORITY 7
000342  012701  000516'                  MOV   #INT,%1
000346  012702  000104                   MOV   #MINT,%2
000352  012700  000010                   MOV   #10,%0
000356  012122                      9$:  MOV   (%1)+,(%2)+     ; MOVE THE INTERRUPT HANDLER INTO RMON
000360  077002                           SOB   %0,9$
000362  005037  172340                   CLR   @#172340        ; KA0=0
000366  012737  001600  172342           MOV   #1600,@#172342  ; KA1=1600
000374  012737  001400  172354           MOV   #1400,@#172354  ; KA6=1400
000402  012737  007600  172356           MOV   #7600,@#172356  ; KA7=7600
000410  012703  077406                   MOV   #77406,%3       ; SET PDR FOR 200 BLOCKS, READ-WRITE
000414  010337  172300                   MOV   %3,@#172300     ; KD0
000420  010337  172302                   MOV   %3,@#172302     ; KD1
000424  010337  172314                   MOV   %3,@#172314     ; KD6
000430  010337  172316                   MOV   %3,@#172316     ; KD7
000434  012701  140000                   MOV   #140000,%1
000440  012702  020000                   MOV   #20000,%2
000444  012700  010000                   MOV   #10000,%0
000450  012767  000016  000340           MOV   #16,ADR         ; RESET BEGINNING ADDRESS
000456  000237                           SPL   7
000460  012737  000001  177572           MOV   #1,@#177572     ; NNABLE MEM MGMT
```

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```
000466  012122                          10$:  MOV   (%1)+,(%2)+       ; MOVE PROGRAM TP UPPER CORE
000470  077002                                SOB   %0,10$
000472  005037  177572                        CLR   @#177572          ; CLEAR MEM MGMT
000476  000230                                SPL   0
000500  012737  001600  172354                MOV   #1600,@#172354    ; KA6=1600
000506  012737  000100  172434                MOV   #100,@#172434     ; NNABLE INTERRUPT
000514                                        .EXIT                   ; RETURN TO BATCH STREAM TO WAIT FOR ATTN.
                                              .DSABL LSB
000516  012737  000001  177572         INT:   MOV   #1,@#177572       ; NNABLE MEM MGMT
000524  000137  000536'                       JMP   @#STORE
000530  005037  177572                        CLR   @#177572          ; DISABLE MEM MGMT
000534  000002                                RTI
000536  032737  020000  172434       STORE:   BIT   #20000,@#172434   ; IS ATTN BIT SET?
000544  001005                                BNE   2$
000546  012737  000100  172434                MOV   #100,@#172434     ; IF NOT, NNALBLE INTERRUPT
000554  000137  000116                  1$:   JMP   @#MINT+12         ; AND RETURN TO WAIT
000560  032737  020000  172434          2$:   BIT   #20000,@#172434   ; KEEP TESTING ATTENTION BIT
000566  001374                                BNE   2$                ; UNTIL IT IS CLEAR.
000570  026727  000222  000072                CMP   ADR,#72           ; HAS LAST RUN ALREADY BEEN MADE?
000576  002366                                BGE   1$                ; IF SO, RETURN TO BATCH STREAM.
000600  062767  000002  000210                ADD   #2,ADR
000606  016700  000204                        MOV   ADR,%0
000612  010001                                MOV   %0,%1
000614  042701  177760                        BIC   #177760,%1
000620  000301                                SWAB  %1
000622  072127  000004                        ASH   #4,%1
000626  010137  172432                        MOV   %1,@#172432       ; SET STARTING ADDRESS
000632  012737  170000  172430                MOV   #-10000,@#172430; AND WORD COUNT
000640  042700  177717                        BIC   #177717,%0        ; GET MEM EXT BITS
000644  062700  000101                        ADD   #101,%0           ; COMBINE WITH CONTROL
000650  010037  172434                        MOV   %0,@#172434       ; START ACCEPTING DATA
000654  000737                                BR    1$
000656  000000                       LNKCR:   .WORD 0
000660  114700                                .RAD50 /XX/
000662  000001                                .WORD 1
000664  006750                                .RAD50 /BI/
000666  000122  000000  000000        CARD:   .WORD 82.,0,0
000674                                  IN:   .BLKW 82.
001016  000020                         ADR:   .WORD 20
001020  000000                          IC:   .WORD 0
001022  000120                          NB:   .WORD 120
001024  000000                          NF:   .WORD 0
001026  000054                          NR:   .WORD 54
001030  077777                         NRM:   .WORD 77777
001032  000000                        ZERO:   .WORD 0
001034  177777                         ONE:   .WORD -1
001036  177776                         TWO:   .WORD -2
001040  000004                      OFFLIN:   .WORD 4
        000000'                               .END  PROBE
```

```
PROBE   MACRO VR05A 19-SEP-74 10:19 PAGE 1+
SYMBOL TABLE

ADR       001016R        CARD    000666R        IC       001020R
IN        000674R        INT     000516R        LNKCR    000656R
MINT   =  000104         NB      001022R        NF       001024R
NR        001026R        NRM     001030R        OFFLIN   001040R
ONE       001034R        PROBE   000000R        RESET    000326R
SP     =%000006          STORE   000536R        TAPE   = ****** G
T.0       001036R        ZERO    001032R        .SYM   = 000027

. ABS.  000000     000
        001042     001

ERRORS DETECTED:  0
FREE CORE:  12529. WORDS

ERRORS DETECTED:  0
FREE CORE:  12529. WORDS
PROBE,LP:<PROBE
```

```
.
$RU LINK
LINK V11A01
*PROBE,LP:<PROBE,FTNLIB[1,1]/L/E
```

```
LOAD MAP  PROBE .LDA          10:19:59  19-SEP-74

TRANSFEP ADDRESS: 154724
LOW LIMIT: 154724
HIGH LIPIT: 157460
***********
MODULE  PROBE
SECTION          ADDRESS SIZE
<. ABS.>         000000  000000
<      >         154724  001042
***********
MODULE  TAPE
SECTION          ADDRESS SIZE
<      >         155766  001472
        TAPE     155766
```

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```
LINK V11A01
#
$RU PROBE
$FI
TIME:-10:20:21
```

APPENDIX B

```
C
C           TITLE:  DLP
C
C       DLP DIRECTIONS:
C       USE DATA CARD TO SPECIFY RECORD READING
C       PUT MAX RECS. COL.  5,  NO. RECS. SKIP COL. 10, FILES SKIP COL. 15
C        REPEAT CARDS, USE 0 FOR MAXREX IN LAST CARD.
C
        BYTE BUFFER (8192), HEADER(80)
        EQUIVALENCE (BUFFER(1), HEADER(1))
      4 CONTINUE
        N = 0
C        SKIP MODULE
        READ (8,1001)  MAXREX,  NRS,  NFS
   1001 FORMAT (3I5)
        IF (MAXREX .EQ. 0) GO TO 7000
      2 IF (NFS .LE. 0)  GOTO 5
        NB  = 0
        NR = 50
        NF  =  1
        CALL TAPE(-1,0,BUFFER,NB,NR,NF)
        NFS  =  NFS - 1
        GO TO 2
      5 CONTINUE
      6 IF  (NRS .LE. 0)  GO TO 10
        NB = 0
        NR = 2
        NF = 1
        CALL TAPE(-1,0,BUFFER,NB,NR,NF)
        NRS = NRS - 1
        GO TO 6
     10 CONTINUE
      1 NB = 80
        NR = 1
        NF = 1
        IF (N .GT. MAXREX) GO TO 55
      3 CALL TAPE (-1, 0, HEADER, NB, NR, NF)
        IF (NF .EQ. 0) GO TO 20
        IF (NB) 21, 28, 23
     20 WRITE (5, 541)
    541 FORMAT('1END OF FILE')
        GO TO 22
     21 WRITE (5,542)  N
    542 FORMAT('1TAPE READ-ERROR ON HEADER, RECORD-GROUP', I7)
        GOTO200
     23 WRITE (5,543) NB, N, HEADER
    543 FORMAT('1HEADER RECORD SHORT BY', I3, ', RECORD-GROUP', I7 /
      1 '0', 80A1)
        GOTO 200
     28 WRITE (5,555) HEADER, N
    555 FORMAT('0', 80A1, 20X,  'HEADER RECORD GROUP', I7)
C
C           TEMPORARY:  PRINTS OUT OCTAL FORM FOR DIAGNOSES OF TAPE.
C
        WRITE (5,955) HEADER
```

```
  955 FORMAT ('0', 3204)
C
  202 CONTINUE
      NB = 8192
      NR = 1
      NF = 1
      CALL TAPE (-1, 2, BUFFER, NB, NR, NF)
      IF (NF .EQ. 0) GO TO 20
      IF (NB) 221, 228, 223
  221 WRITE (5,5221) N
 5221 FORMAT('1TAPE READ-ERROR ON DATA, RECORD-GROUP', I7)
      GO TO 1
  223 WRITE (5, 5223) NB
 5223 FORMAT('0DATA RECORD SHORT BY',  I7)
  228 CONTINUE
      WRITE (5,5228) N
 5228 FORMAT('0DATA, RECORD-GROUP', I7 //)
      WRITE(5,5229)(BUFFER(I),I=1,8000)
 5229 FORMAT(' ', 3204)
      N  = N+1
      GO TO 1
   55 CONTINUE
      WRITE (5,5555)MAXREX
 5555 FORMAT('0PROCESSED NUMBER OF RECORDS-GROUPS SPECIFIED',I5)
   22 CONTINUE
      CALL TAPE (4, 0)
      GO TO 4
 7000 CONTINUE
      STOP
      END

$EOD

      ROUTINES CALLED:
      TAPE

      BLOCK       LENGTH
      MAIN,   4880   (023040)*

      **COMPILER ----- CORE**
         PHASE       USED  FREE
      DECLARATIVES 00456 13034
      EXECUTABLES  00607 12883
      ASSEMBLY     01471 14936
```

```
#
$RU LINK
LINK V11A01
#DLP<DLP,FTNLIB[1,1]/L/E

TRANSFER ADDRESS: 117764
LOW LIMIT: 117764
HIGH LIMIT: 157460
LINK V11A01
#
$EOD
$RU DLP
```

APPENDIX C

```
C        DIGITAL LANGMUIR PROBE
C
C         DATA CARD #1
C
C              NOMINAL MAX PEAK VOLTAGE        (E/F FORMAT)   COLS    1-12
C                      MIN                     (E/F       )          13-24
C              TOLERANCE                       (E/F       )          25-36
C              DATA POINTS BETWEEN POS PEAKS   (I    FORMAT)         37-41
C              DATA POINTS POS TO NEG          (I         )          42-46
C
C         DATA CARD #2
C
C              NUMBER OF FILES TO SKIP         (I    FORMAT)          1- 5
C              NUMBER OF RECORDS TO SKIP AF-
C                TER ANY FILE SKIPPING (COUNT
C                BOTH HEADER RECORDS AND DATA
C                RECORDS)                      (I         )           6-10
C              NUMBER OF RECORDS TO PROCESS
C                (COUNT ONLY DATA RECORDS)     (I         )          11-15
C              NUMBER OF CYCLES TO PROCESS
C                (LEAVE BLANK IF WANT ALL)
C                IN EACH RECORD                (I         )          16-20
C              1  IF PLOT WANTED, ELSE 0 OR BLANK                       25
C
      REAL*4  CURLOG (500), BYAS (500),  TE (500), F(500)
      INTEGER*2   IDATE(3),   IBUF(4096)
      INTEGER*2  PEAK (2)
      INTEGER*2  INTER,         ADC,      DAC,      BIAS (4), EXPNR (4)
      INTEGER*2 MAXMIN(40)
      BYTE BUFFER(8192), BUF(8192), INTERB(2), HDR(72)
      BYTE  PBUF (9000)
C
      EQUIVALENCE (BUFFER( 1), BUF(1)), (INTER, INTERB(1)),
     1 (HDR(1), BUFFER(1))
      EQUIVALENCE  (BUF(1), IBUF(1))
C
C
      DATA   NAV / 3  /
      DATA  ISW / 0/
      DATA  BSCALE / 1.95312E-2  /
      DATA   INTER /0/  KREC /0/
      DATA TSCALE /1.16069E4/
      DATA   PEAK / '  ', '**' /
      DATA OFFSET /1.33        /
C
      READ (8,8008) PMAX, PMIN, TOL, LMAX, LMIN
 8008 FORMAT (3E12.0, 2I5)
      WRITE (5,5700)  PMAX, PMIN, TOL, LMAX, LMIN
 5700 FORMAT('0BIAS MAX.=',F8.3,'  ,MIN.=',F8.3,/'0TOLERANCE =',F8.3/
     1 '0ASSUMED MAX-TO-MAX', I5, ',  MAX-TO-MIN',  I5)
      READ(8,8005)NF, NR, MAXREX, KX, IPLT
 8005 FORMAT(5I5)
      IF (KX .LE. 0)   KX = 19
      IF (KX .GT. 19)  KX = 19
      IF (IPLT .NE. 0)
     1CALL CALCMP (PBUF, 9000, 53, 0)
      WRITE (5,5707) NF
 5707 FORMAT('0FILES SKIPPED=', I4)
      IF (NF .LE. 0)  GO TO 2
      NB = 0
      MR = 32000
      CALL TAPE(-1,0,BUFFER,NB,MR,NF)
      WRITE(5,5703)NF
```

```
      IF(NF .NE. 0)  STOP
    2 CONTINUE
      WRITE (5,5701)  MAXREX, NR, KX, IPLT
 5701 FORMAT('0MAX RECORDS', I5, 5X, 'RECORDS SKIPPED', I5, 5X,
     1 'MAX CYCLES PROCESSED PER RECORD', I5, 5X, 'PLOT CODE', I3)
      KX = 2 * KX  - 1
C
      IF  (NR .LE.0)  GO TO 5
      NB = 0
      NF = 1
      CALL TAPE (-1, 0, BUFFER, NB,NR,NF)
      WRITE (5,5702)  NR
 5702 FORMAT('0AFTER SKIPPING, NR DECREMENTED TO',I3)
    5 CONTINUE
      IF (KREC .EQ. MAXREX) GO TO 888
C                 READ HDR RECORD, WAIT FOR COMPLETION
      KREC = KREC + 1
      NB = 80
      NR = 1
      NF = 1
      CALL TAPE (-1, 0, BUFFER, NB, NR, NF)
C               EOF?
      IF (NF .NE. 1) GO TO 999
C               READ ERROR OR SHORT RECORD?
      IF (NR) 10, 20, 30
C               GOOD RECORD
   20 CONTINUE
      WRITE(5,5005) HDR, KREC
 5005 FORMAT('1', 72A1, 20X, 'RECORD NO.', I5 ///)
C         SAVE DATE FROM HEADER RECORD TO PLOT
      DO 25 I = 1, 3
   25 IDATE (I) = IBUF (I+1)
C                 READ DATA RECORD , WT FOR COMP.
  300 CONTINUE
      NB = 8192
      NR = 1
      NF = 1
      CALL TAPE (-1,0,BUFFER, NB,NR,NF)
C           EOF?
      IF (NF .NE. 1) GOTO 999
C               READ ERROR OR SHORT RECORD?
      IF (NR) 310,320,330
C      GOOD RECORD
  320 CONTINUE
C               FIND PHASE
      J = 3
      DO 40 I = 6, 18, 4
      IF(BUF(2) .NE. BUF(I) ) GO TO 50
   40 CONTINUE
      DO 45 I = 402, 418, 4
      IF(BUF(2) .NE. BUF(I) ) GO TO 50
   45 CONTINUE
      GO TO 60
   50 CONTINUE
      J = 5
      DO 55 I = 8, 20, 4
      IF(BUF(4) .NE. BUF(I) ) GO TO 70
   55 CONTINUE
      DO 75 I = 404, 420, 4
      IF(BUF(4) .NE. BUF(I) ) GO TO 70
   75 CONTINUE
      GO TO 60
   70 CONTINUE
```

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 5010 FORMAT('0EXPNR MATCH NOT FOUND', / '0', 2005)
      GO TO 5
C                BUF(J)  HOLDS  FIRST ADC
   60 CONTINUE
      INTERB(1) = BUF(J-1)
      EXPNR(1)    =  INTER
      WRITE (5, 5015)  EXPNR(1)
 5015 FORMAT('0EXPERIMENT-NUMBER', O5, '   OCTAL')
C               FIND  POSITIVE BIAS PEAK
      DO 80 I = J,8117,4
      INTERB (1) =BUF(I+3)
      IF (INTER .NE. EXPNR(1) )                 GO TO 120
      INTERB (1) = BUF(I+2)
      BIAS(1)   = INTER
      BYE = BSCALE*BIAS(1)
      IF    (BYE  .GE.  (PMAX-TOL)) GO TO 100
   80 CONTINUE
  120 CONTINUE
      WRITE (5, 5020)
 5020 FORMAT('0PEAK NOT FOUND')
      GO TO 5
  100 CONTINUE
      INTERB (1) = BUF (I + 6)
      IF (INTER .LT. BIAS (1) )    GO TO 110
      BIAS (1) = INTER
      I = I + 4
      GO TO 100
  110 CONTINUE
      MAXMIN(1) = I + 2
      DO 210 I = 2, 40
  210 MAXMIN(I) = 0
      DO 220 I = 2, 38, 2
      MAXMIN(I) = MAXMIN(I-1) + 4 * LMIN
      ITEMP =       MAXMIN(I-1) + 4 * LMAX
      IF (ITEMP .GE. 8191)  GO TO 230
      INTERB(1) = BUF(ITEMP+1)
      IF (INTER .EQ. EXPNR(1) ) GO TO 240
      INTERB(1) = BUF (ITEMP + 41)
      IF (INTER .NE. EXPNR(1) ) GO TO 230
  240 MAXMIN(I+1) = ITEMP
  220 CONTINUE
  230 CONTINUE
C         TABULATE  BIAS, DAC, ADC, F    STARTING AT FIRST POSITIVE  PEAK
C            DAC IS IN BUF(I+5)          ADC        BUF(I+4)
C            BIAS       BUF(I+6)         EXPNR      BUF(I+7)
C
      DO 200 K = 1,KX,2
      KU =  MAXMIN (K+2)
      IF (KU .EQ. 0)       GO TO 5
      KM =  MAXMIN (K+1)
      KL =  MAXMIN (K)
      LCTR = 99
      N = 0
      DO 400 KK = KL, KU, 4
      N = N + 1
      IF (KK .EQ. KM)    NMID = N
      INTERB(1) = BUF  (KK-2)
      ADC = INTER
      INTERB(1) = BUF  (KK-1)
      DAC = INTER
      F(N) = ((DAC - 127) * 200 + ADC) * 5.E-10
      FABS = ABS (F(N) )
      IF (FABS .EQ. 0.)  FABS = 1.E-35
      CURLOG (N) = ALOG10 (FABS)
      INTERB(1) = BUF  (KK)
      BIAS(1) = INTER
```

```
      BYAS (N) = BSCALE * BIAS(1) - OFFSET
C        INIT TE SO CAN DETECT LATER IF ACTUALLY CALCULATED
      TE (N)  = 1.E-35
  400 CONTINUE
      NMAX = N
      N = 0
      DO  180  KK = KL, KU, 4
      LCTR = LCTR + 1
      IF (LCTR .LT. 50)  GO TO 130
      LCTR = 0
      WRITE (5, 5080)
 5080 FORMAT('1BYTE  PT BIAS EXP#     DAC  ADC       CURRENT',
     1 ' LOG(CURRENT)    DELTA_LOG      ADJ_BIAS  DELTA_BIAS',
     2 '             TE'     //)
  130 CONTINUE
      N = N + 1
      KP = 1
      IF  ( (KK .EQ. KL) .OR. (KK .EQ. KM) .OR. (KK .EQ. KU) ) KP = 2
      INTERB(1) = BUF (KK-2)
      ADC     = INTER
      INTERB(1) = BUF (KK-1)
      DAC     = INTER
      INTERB(1) = BUF (KK)
      BIAS(1) = INTER
      ITEMP = NAV + 1
      IF (N .LT. ITEMP)  GO TO 140
      ITEMP = NMAX - NAV
      IF (N .GT. ITEMP)  GO TO 140
      DO 420 J = 1, NAV
      JJ = NAV + 1 - J
      FP = F(N + JJ)
      FM = F(N - JJ)
      IF ((FP .GT. 0.) .AND. (FM .GT. 0.))   GO TO 430
  420 CONTINUE
      GO TO 140
  430 CONTINUE
      DCLOG = CURLOG (N + JJ) - CURLOG (N - JJ)
      IF (DCLOG .EQ. 0.)  GO TO 140
      DBYAS = BYAS (N + JJ)  -  BYAS (N - JJ)
      TE (N) = ABS ( TSCALE * DBYAS / DCLOG )
      WRITE (5, 5035) KK, N, BIAS(1), EXPNR(1), PEAK(KP),
     1 DAC,   ADC,   F(N),CURLOG(N), DCLOG, BYAS(N), DBYAS, TE(N)
 5035 FORMAT(' ', 2I4, I5.05,X, A1, 2I5, 1P6E13.5)
      GO TO 180
  140 CONTINUE
      WRITE (5, 5025) KK, N, BIAS(1), EXPNR(1), PEAK(KP),
     1 DAC,   ADC,   F(N),CURLOG(N),          BYAS(N)
 5025 FORMAT(' ', 2I4, I5.05,X, A1, 2I5, 1P2E13.5,  13X, E13.5)
  180 CONTINUE
      IF (IPLT .EQ. 0)  GO TO 200
      IF (ISW .NE. 0) CALL CALCMP (12., 0., 0, 2)
      ISW = 1
C        DRAW AXES
      CALL XYAXES (EXPNR(1), IDATE)
      CALL PLCUR (CURLOG, BYAS, NMID, NMAX)
      CALL PLTEM (TE, BYAS, NMID, NMAX)
C        LET INK DRY
      CALL CALCMP  ( 0.,   0.,   0, 2)
  200 CONTINUE
      GO TO 5
C
   10 CONTINUE
      WRITE (5, 5110)  KREC
 5110 FORMAT('1TAPE READ-ERROR, RECORD NO.', I5)
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   30 CONTINUE
      WRITE (5, 5130)  NB, KREC, HDR
 5130 FORMAT('1TAPE RECORD SHORT BY', I8, 10X, 'RECORD NO.', I5/
     1  '0', 72A1)
      GOTO 300
  310 CONTINUE
      WRITE (5,5110) KREC
      GO TO 5
  330 CONTINUE
      WRITE (5,5330) NB,KREC,BUF
 5330 FORMAT ('1TAPE RECORD SHORT BY',I8,10X,'RECORD NO.',
     1I5/ (' ',32O4))
      GO TO 5
C               PROCESSED MAXREX RECORDS
  888 CONTINUE
      WRITE (5, 5888)
 5888 FORMAT('1COMPLETED RECORDS SPECIFIED')
      STOP
C               EOF
  999 CONTINUE
      WRITE (5, 5999)
 5999 FORMAT('1TAPE END-OF-FILE')
      STOP
      END
      SUBROUTINE PLCUR (CURLOG, BYAS, NMID, NMAX)
      REAL*4  CURLOG(500), BYAS(500)
      DATA  C        / 1.25 /
      DATA  D        / 3.   /
      DATA  ISYMDN   / 91/
      DATA  ISYMUP   / 95/
      DATA  A        / 1.5 /
      DATA  B        / 16.5 /
C
      DO  100  I = 1,  NMAX
C         TRANSFORM ALL BYAS AS MAY NEED IN SUBRTN PLTEM
      BYAS(I)    =  C * BYAS(I)    + D
      IF((BYAS(I) .LT. 1.75) .OR. (BYAS(I) .GT. 6.75))  GO TO 100
      IF ((CURLOG(I) .GT. -4.) .OR. (CURLOG(I) .LT. -9.))GO TO 100
      CURLOG(I) =   A * CURLOG(I) + B
      ISYM = ISYMDN
      IF  (I .GT. NMID)  ISYM = ISYMUP
      CALL SYMBOL (BYAS(I), CURLOG(I), 0.05,  ISYM, 0., -1)
  100 CONTINUE
C
      RETURN
      END
      SUBROUTINE  PLTEM (TE, BYAS, NMID, NMAX)
      REAL*4    TE(500), BYAS(500)
      DATA      ISYMDN    / 93     /
      DATA      ISYMUP    / 94     /
      DATA      A         / 3.0    /
      DATA      B         / -3.0   /
      DATA    CUT /6.5    /
C        CUT MUST CHANGE IF C, D IN SUBRTN PLCUR CHANGE
C          BYAS HAS BEEN TRANSFORMED BY IMMEDIATELY PREVIOUS CALL PLCUR
      DO 100 I = 1, NMAX
      IF (BYAS(I) .GT. CUT)    GO TO 100
      IF  ((TE(I) .GT. 3.00000E4) .OR. (TE(I) .LT. 100.)) GO TO 100
      TE(I) =    A * ALOG10 (TE(I)) + B
      ISYM =  ISYMDN
      IF  (I  .GT. NMID) ISYM = ISYMUP
      CALL SYMBOL (BYAS(I), TE(I), 0.05,   ISYM,  0.,  -1)
  100 CONTINUE
      RETURN
      END
```

```
      INTEGER*2  IDATE (3)
      INTEGER*2  NCD (5)
      DATA  ISYM   / 31 /
      DATA  XL     / 1.75 /
      DATA  YB     / 3.   /
      DATA  XSCALE   / 0.125  /
      DATA  XR     / 6.75  /
      DATA  TSCALE / 3.    /
      DATA  CSCALE / 1.5   /
      DATA  TL /0.301030, 0.477121, 0.602060, 0.698970, 0.778151,
     1          0.845098, 0.903090, 0.954243  /
C
      FPN = -1.
      CALL NUMBER (XL-0.100, YB-0.500, 0.250, FPN, 0., -1)
C        DUPLICATE TO ENSURE INK START
      CALL NUMBER (XL-0.100, YB-0.500, 0.250, FPN, 0., -1)
      K = 0
      CALL CALCMP (XL, YB, 0, 1)
      DO  22 I = 1, 4
      DO  18 J = 1, 9
      K = K + 1
      X =  XL   + K * XSCALE
      CALL SYMBOL (X, YB, 0.14,  ISYM,   0., -2)
   18 CONTINUE
      K = K + 1
      X =  XL +    K * XSCALE
      CALL SYMBOL (X, YB, 0.28,  ISYM,   0., -2)
      FPN = I - 1
      CALL NUMBER (X -0.100, YB-0.500, 0.250, FPN, 0., -1)
      CALL CALCMP (X, YB, 0, 1)
   22 CONTINUE
      FPN = 10.
      CALL NUMBER (XR+0.25,    YB,   0.25,  FPN,   0., -1)
      FPN =  2.
      CALL NUMBER (999.,        YB+0.125,  0.15, FPN, 0., -1)
      CALL CALCMP (XR, YB, 0, 1)
      DO    28 I = 1, 3
      JJ = 8
      IF (I .EQ. 3) JJ = 2
      DO    26 J = 1, JJ
      Y = YB +      TSCALE *(TL(J)    + I - 1)
      CALL SYMBOL (XR, Y, 0.14,    ISYM,  90., -2)
   26 CONTINUE
      IF (I  .EQ. 3) GO TO 28
      Y = YB +  I * TSCALE
      CALL SYMBOL (XR, Y, 0.28,  ISYM,    90., -2)
      FPN = 10.
      CALL NUMBER (XR+0.25,  Y,  0.25,  FPN,    0.,  -1)
      FPN = I+2
      CALL NUMBER (999.,       Y+0.125,  0.15,  FPN, 0., -1)
      CALL CALCMP (XR, Y, 0, 1)
   28 CONTINUE
      YSV = Y
      FPN = -9.
      CALL NUMBER (XL-0.75, YB, 0.25, FPN,    0., -1)
      CALL CALCMP (XL, YB, 0, 1)
      DO  36 I = 1, 5
      DO  36 J = 1, 8
      Y  = YB + CSCALE *(TL(J)    + I - 1)
      CALL SYMBOL (XL, Y, 0.14,   ISYM,  90.,  -2)
   36 CONTINUE
      Y =  YB + I * CSCALE
      CALL SYMBOL (XL, Y, 0.28,    ISYM,  90.,  -2)
      FPN =  I - 9
      CALL NUMBER (XL-0.75,  Y, 0.25,  FPN,  0.,  -1)
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   38 CONTINUE
      K = 0
      DO 42 I = 1, 4
      DO 48 J = 1, 9
      K = K + 1
      X = XL + K * XSCALE
      CALL SYMBOL (X, Y, 0.14, ISYM, 0., -2)
   48 CONTINUE
      K = K + 1
      X = XL + K * XSCALE
      CALL SYMBOL (X, Y, 0.28, ISYM, 0., -2)
   42 CONTINUE
      CALL CALCMP (XR, YSV, 1, 1)
      CALL SYMBOL (XL-1.20,  YB+3.0,  0.30, 'LOG I', 90., 5)
      CALL SYMBOL (XL+1.9,   YB-1.0,  0.25, 'BIAS',   0., 4)
      CALL SYMBOL (XR+1.35, YB+0.5, 0.30, 'GENERALIZED TEMPERATURE',
     1  90., 23)
      CALL SYMBOL (XL,    YB-1.50, 0.250, IDATE(1), 0., 2)
      CALL SYMBOL (999., YB-1.50, 0.250, '/',      0., 1)
      CALL SYMBOL (999., YB-1.50, 0.250, IDATE(2), 0., 2)
      CALL SYMBOL (999., YB-1.50, 0.250, '/',      0., 1)
      CALL SYMBOL (999., YB-1.50, 0.250, IDATE(3), 0., 2)
      ENCODE (10, 7000, NCD)   NEXP
 7000 FORMAT('EXP NO', I4)
      CALL SYMBOL (XR-2.50, YB-1.50, 0.250, NCD, 0., 10)
      RETURN
      END
```