COMPANY CONFIDENTIAL January 1957

STRETCH CIRCUIT MEMO # 8

Dr. H. P. Wolff

SUBJECT: Measurement of Small Signal Fourpole Parameters of Transistors

SUMMARY: Results of a search for suitable equipment for small signal fourpole measurements on transistors over a wide frequency range are presented.

Only part of the equipment ordered has been received to date. Jigs for supply of d-c to the transistors to be measured have been designed for the Wayne Kerr Bridge 601. Problems involved in the design of the jigs are discussed.

Measurements on IBM drift transistors have been and are being taken with the Wayne Kerr Bridge 601 over a frequency range from 15kc to 5 mc. Measurements must be made in Common Base connection of the transistors. Results of the measurements can be converted into common emitter parameters by computation. The conversion formulas are presented.

Other formulas for conversion of measurements on transistors with load into short circuit parameters are also presented.

Results of measurements are given in form of graphs.

The correlation between computed values of the y-parameters of a T equivalent circuit and actual measurements are also shown.

1. Purpose of Measurements

A transistor regarded as a black box (fourpole) is fully determined by measurements of its fourpole parameters.

The results of these measurements are being used

1. for the development of an equivalent circuit of the transistors by means of computation.
2. for the determination of the effect of the selected operating point on the transistor parameters.
3. for investigation of the transistors with respect to their deviation from an average and the determination of an average transistor. These measurements would also be useful for determining transistor variations with life.

2. Choice of Parameters to be Measured

A survey of available equipment shows that most of the equipment is designed for measurements of admittance in terms of a parallel connection of resistance and reactance. It furthermore is felt that it is easier to design an effective short circuit than an open circuit at higher frequencies. It therefore has been decided to measure the short circuit y parameters of the transistor.

3. Measuring Equipment

3.1 Suitable equipment

A search for suitable equipment for small signal measurements on transistors has the following results:

The equipment listed is the most suitable equipment with respect to ease of operation, sensitivity, admittance range and capability of measuring input and output admittance as well as transfer parameters. All the equipment listed has been ordered, except receiver DZ-1, a surplus receiver, which is not for sale. Only part of the equipment has been received to date.

<table>
<tr><th>Frequency Range</th><th>Bridge</th><th>Generator</th><th>Receiver</th></tr>
<tr><td>15Kc - 5 mc</td><td>Wayne Kerr 601</td><td>GR 1001 A</td><td>DZ -1
HRO 60</td></tr>
<tr><td>1 mc - 100mc</td><td>Wayne Kerr 801</td><td rowspan="2">hp 608D</td><td>hp 417A with
hp 460A amplifier</td></tr>
<tr><td>30mc - 300mc</td><td>Diagraph ZDU</td><td>internal</td></tr>
<tr><td>300mc - 2400mc</td><td>Diagraph ZDD</td><td>hp 612A to
1200 mc</td><td>internal</td></tr>
</table>

Received to date have been:

Bridge	Generator	Receiver
Wayne Kerr 601	GR 1001 A hp 608 D	DZ - 1 (on loan) HRO 60
Diagraph ZDU		hp 417 with hp 460A
	hp 612 A	

3.2 Jigs for d-c Supply to the Transistors

The design of jigs necessary for supply of the d-c bias to the transistors proved to be difficult. Considerable effort had to be made in order to develop jigs which do not disturb measurements over a broad band of frequencies.

Blocking capacitors turned out to be effective short circuits only over a very limited frequency range. A separate component research had to be undertaken in order to find optimum capacitors and combinations of them for the frequency range of the bridge. Very careful considerations had to be given to the design of the jigs with respect to minimizing lead inductances. Heavy copper buses had to be used instead of wires in the jigs. Special sockets have been made so that the copper buses lead directly to the transistor.

After all these precautions had been taken it still proved to be impossible to design a jig which covers the whole frequency range of one bridge. Instead, two different jigs covering the lower and the higher range of frequencies respectively of one bridge had to be built for the measurement of each of the parameters y11, y22, y12, and y21.

The performance of the jigs has been carefully checked by comparing measurements of suitable resistors first connected directly to the terminals of the bridge and then connected to the terminals of the jigs. Page A of the appendix shows the measurement of the reactive part of a test resistor with and without jig in order to demonstrate the accuracy of the present jigs.

The jigs for the Wayne Kerr bridge 601 are ready. Jigs for the Diagraph ZDU are being designed. Negotiations with manufacturers of capacitors had the result that a number of specially made capacitor discs of high capacitance, small size and suitable form, will be sent to us. It is planned to have the ZDU jigs ready by the end of January 1957.

The sensitivity of the Diagraphs originally was too low to meet the requirements of small signal measurements. Negotiations with the manufacturer led to a redesign of the Diagraph, which will be shipped in the future with sufficiently increased sensitivity.

Shipment of the Wayne Kerr bridge 801 is expected to be made by the end of January 1957. Preliminary measurements on capacitors in order to get information on suitable capacitors and capacitor combinations for the 801 jigs have been made. Actual design of the jigs can be started only after receipt of the bridge. It is estimated that the 801 jigs will be ready approximately four weeks after receipt of the bridge.

4. Measurements

As set forth above the only equipment ready for measurements to date is the Wayne Kerr Bridge 601. Measurements on IBM drift transistors over the frequency range of this bridge, 15 kc to 5mc have been made.

4.1 By measuring the same transistor several times under identical conditions, information is obtained on reproducibility of the measurements and on the stability of the transistor.

4.2 By measuring several transistors under identical conditions, information is obtained on the deviation of the single transistors from an average and the average is determined.

4.3 By measuring transistors at different operating points, information may be obtained on the change of the transistor parameters over the operating range of the non-saturated transistor.

Data from 4.2 and 4.3 is being used for the computation purposes and for the development of an equivalent circuit.

Results of the measurements with the Wayne Kerr bridge actually are

$\frac{1}{y11}$, $\frac{1}{y22}$, $\frac{-1}{y12}$, $\frac{-1}{y21}$ in terms of a parallel connection of R_p and jX_p. For convenience the results are converted into $g_p + jy_p$ and $R_s + jX_s$.

5. Results of Measurements

Results to date have been obtained on measurements according to 4.1 through 4.3. Curves of the y parameters of IBM drift transistors have been measured by Miss S. V. Clements and are presented in the appendix. (pages B through I)

The graphs of data obtained from the measurements illustrate that:

1. A given transistor does not vary over a period of three weeks unless the unit is subjected to a shock or similar adverse conditions. The curves shown (ppB - E) are for measurements on an IBM drift transistor.

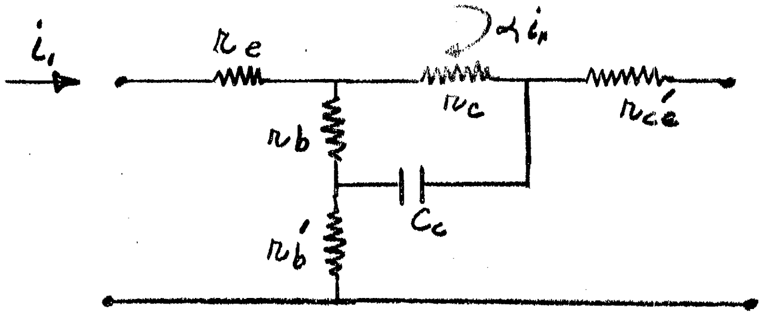
2. Of the seven drift units measured to observe the deviation of parameters from one transistor to another, all of the parameters follow the same shape curve with only variation in magnitude. A greater difference in magnitude is noted between one transistor and the other six. (See pages F through M).

3. In changing the operating point over the operating range of the non-saturated transistor, greater change of the transistor parameters is observed when changing the emitter current than when changing the collector voltage. Holding the collector voltage constant at -5volts, the input admittance, forward and reverse transfer characteristics and the output admittance increases with increasing emitter current over the range from 1 ma to 4 ma. Holding the emitter current constant at 2 ma, the input and forward transfer conductances increase when the collector is biased more negatively while the other parameters decrease in magnitude when the collector voltage is made more negative. (These curves are shown on page N.

6. Computation and Equivalent Circuit

Starting from an equivalent T-network of the transistor which we believe to be acceptable as a first approach, the formulas for the Z-parameters of a fourpole representation have been computed and programmed for the IBM 704. The numerical values of these Z parameters are automatically converted into values of the respective Y parameters by the 704. The reason for this split procedure is that the formulas for the Z parameters derived from the equivalent T-network are relatively simple in comparison to equivalent formulas for the Y parameters and that a routine matrix conversion program is readily set up.

A preliminary investigation of the influence of the single network components on the Y parameters has been made. With this experience it has been tried by stepwise changing the value of the components of the presumed network to duplicate the measured curves of 4.2 within a reasonable tolerance. The correlation between the measured curves and the curves computed by J. Standeven from the following equivalent circuit is reasonable.



Further work on this project must be delayed. The curves and the values of the components of the equivalent circuit are shown in the appendix as page 0.

A more detailed report on this project will be submitted at a later time.

7. Conversion of Parameters

7.1 Conversion of Y_B to Y_E

Measurements of the Y parameters of the transistor with the Wayne Kerr bridge can be made only in common base configurations as far as Y12 and Y21 are concerned. The reason is that the phase reversal of the common emitter configuration will not allow the bridge to be balanced.

Results of the measurements in terms of Y_B can be converted into Y_E parameters by computation according to the following formulas.

Common Emitter		Common Base
$Y_{11}E$	=	$Y_{11}B + Y_{12}B + Y_{21}B + Y_{22}B$
$Y_{12}E$	=	$- \quad Y_{22}B + Y_{12}B$
$Y_{21}E$	=	$- \quad Y_{22}B + Y_{21}B$
$Y_{22}E$	=	$Y_{22}B$

7.2 Conversion of Y parameters of a transistor with load to short circuit Y parameters

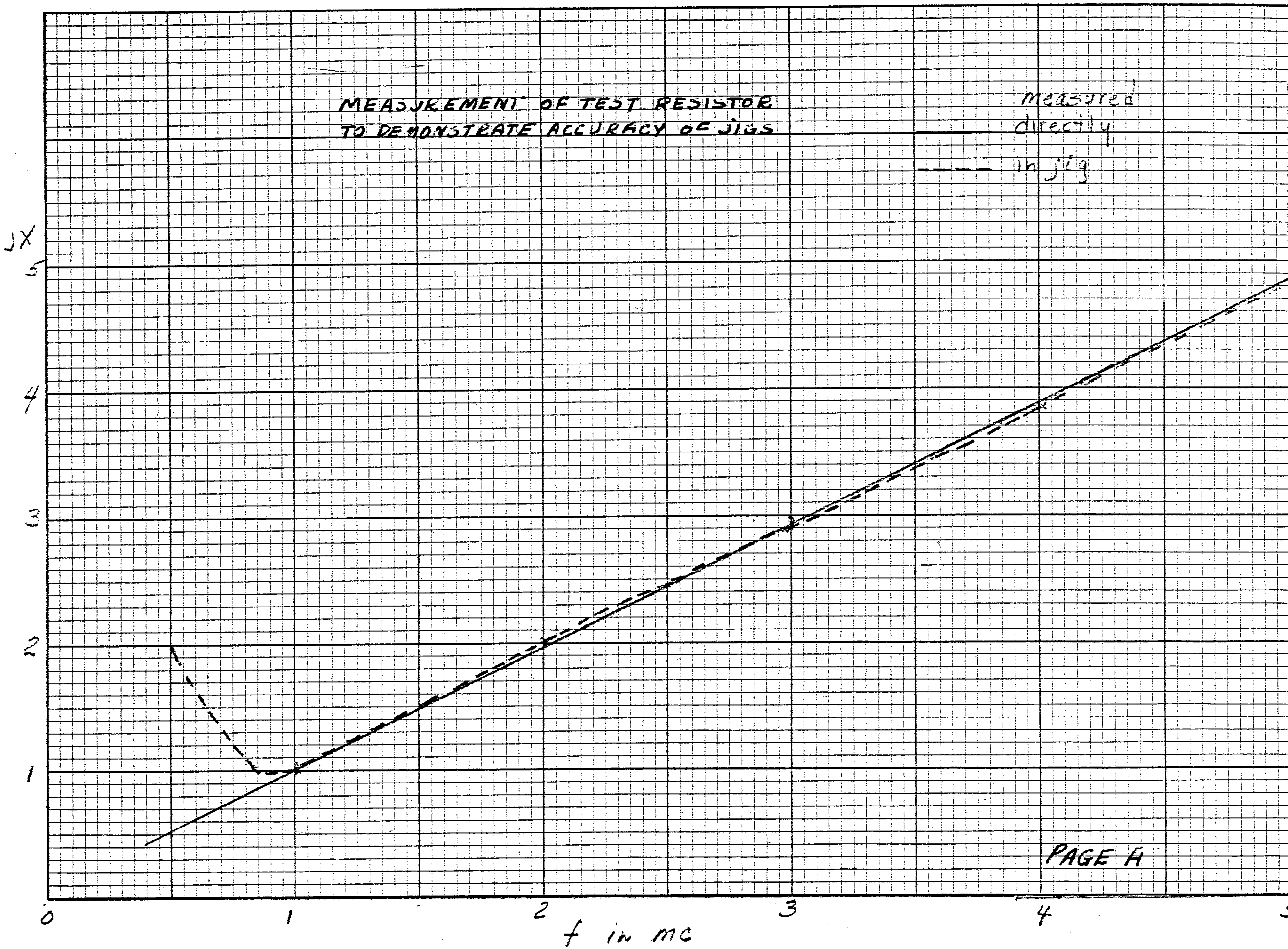
In case the Y parameters cannot be measured directly as short circuit parameters Y_s the measured parameters can be converted into short circuit parameters by application of the following conversion formulas:

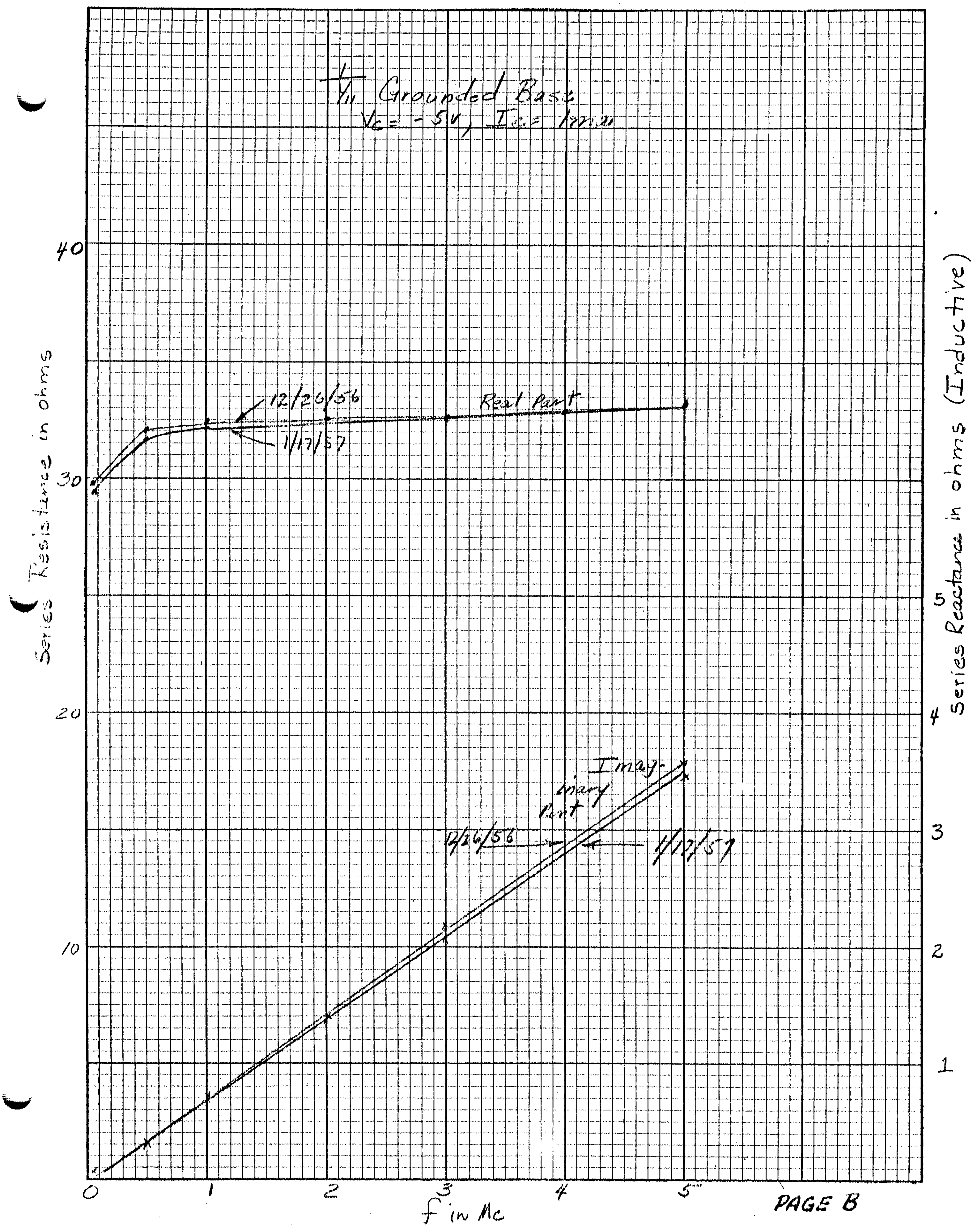
Y short circuit		Y with load Y_L
$Y_{11}S$	=	$Y_{11} \dfrac{1 + \frac{y_{12}\,y_{21}}{y_{11}\,y_L}}{1 - \frac{y_{12}\,y_{21}}{y_L^2}}$
$Y_{22}S$	=	$Y_{22} \dfrac{1 + \frac{y_{12}\,y_{21}}{y_{22}\,y_L}}{1 - \frac{y_{12}\,y_{21}}{y_L^2}}$
$Y_{12}S$	=	$Y_{12} \dfrac{1 + \frac{y_{11}-}{y_L}}{1 - \frac{y_{12}\,y_{21}}{y_L^2}}$
$Y_{21}S$	=	$Y_{21} \dfrac{1 + \frac{y_{11}}{y_L}}{1 - \frac{y_{12}\,y_{21}}{y_L^2}}$

These formulas are simplified as listed below when $y_{11}S$ and $y_{22}S$ can be measured directly and only $y_{12}S$ and $y_{21}S$ cannot be measured, which is the case for measurements with the Diagraph.

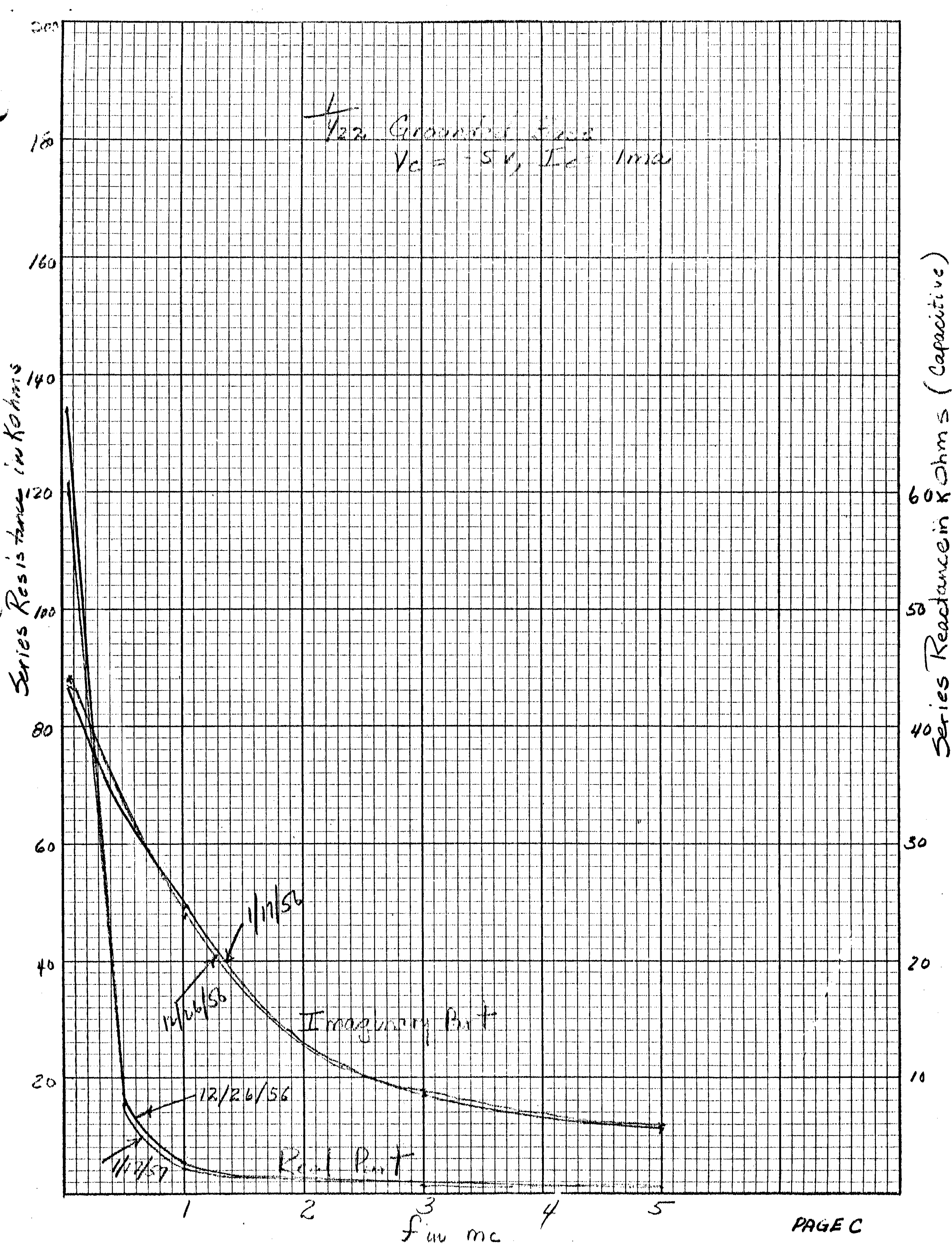
Y short circuit		Y with load Y_L
$Y_{11}S$		
$Y_{12}S$	=	$y_{12} \left(1 + \dfrac{y_{11}S}{y_L}\right)$
$Y_{21}S$	=	$y_{21} \left(1 + \dfrac{y_{22}S}{y_L}\right)$
$Y_{22}S$		

HPW:cmc

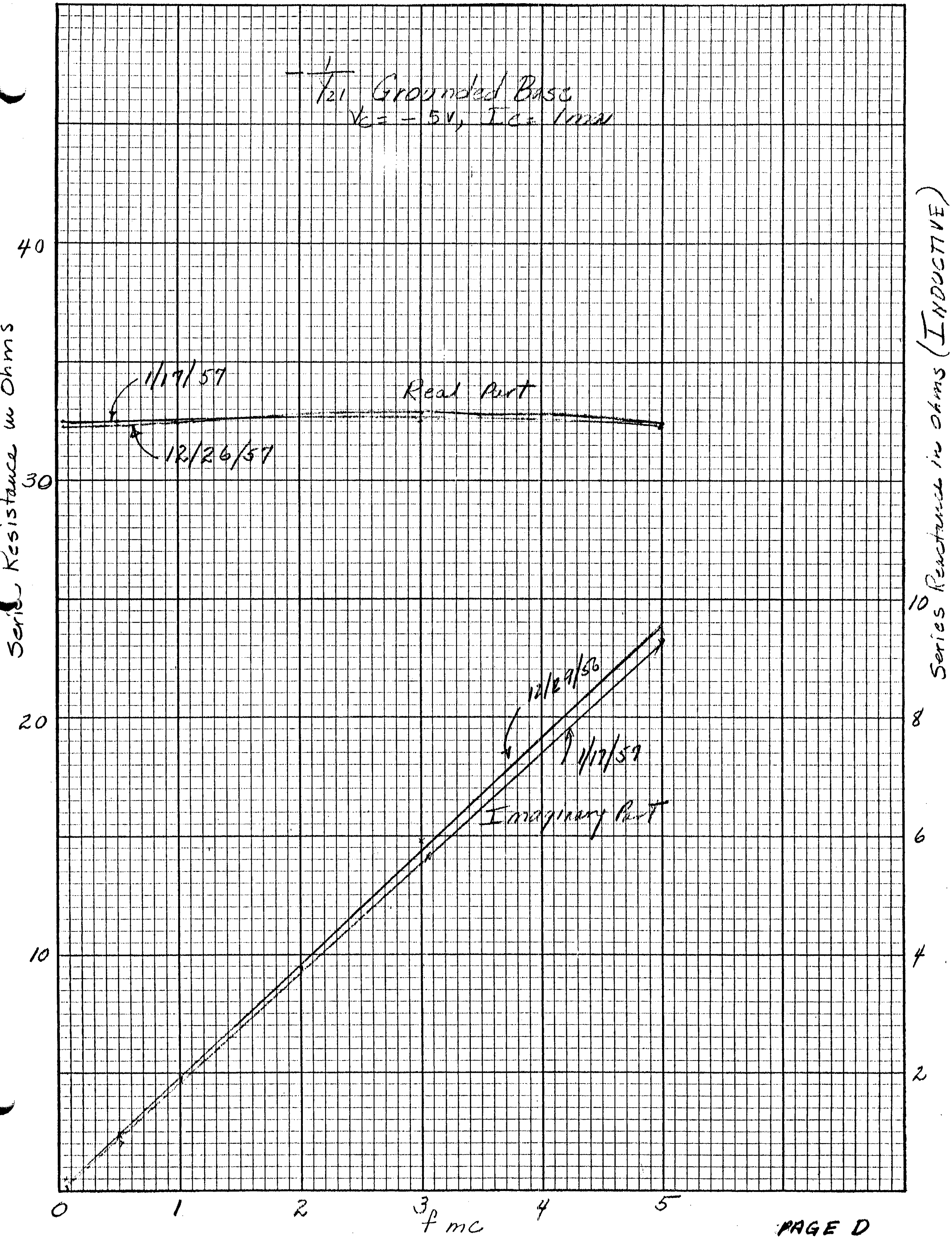

MEASUREMENT OF TEST RESISTOR
TO DEMONSTRATE ACCURACY OF JIGS
measured directly
in jig
JX
5
4
3
2
1
0
1
2
3
4
5
f in mc
PAGE A



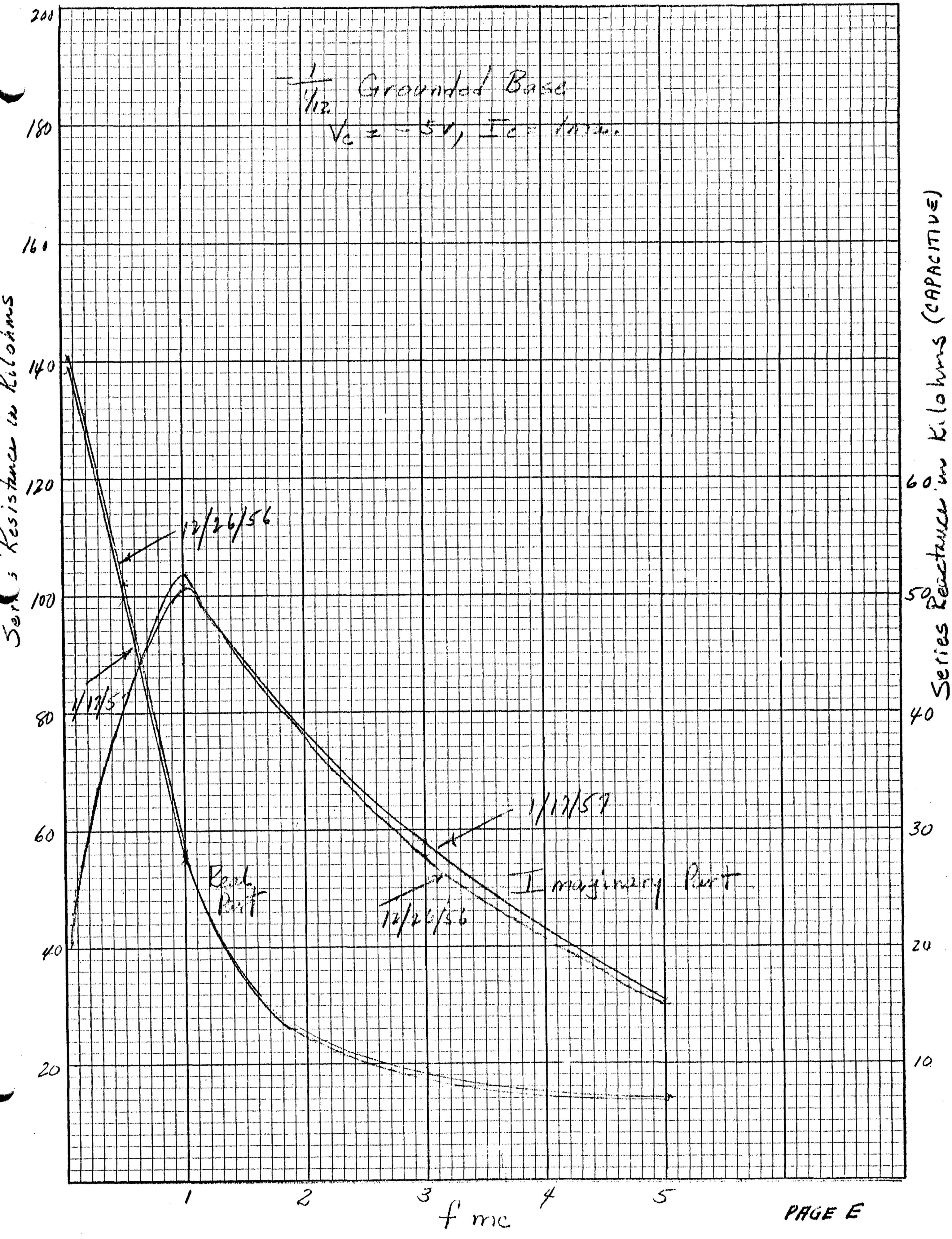
1/Y11 Grounded Base
Vc = -5V, Ie = 1ma
12/26/56
1/17/57
Real Part
Imaginary Part
12/26/56
1/17/57
40
30
20
10
0
1
2
3
4
5
f in Mc
Series Resistance in ohms
Series Reactance in ohms (Inductive)
5
4
3
2
1

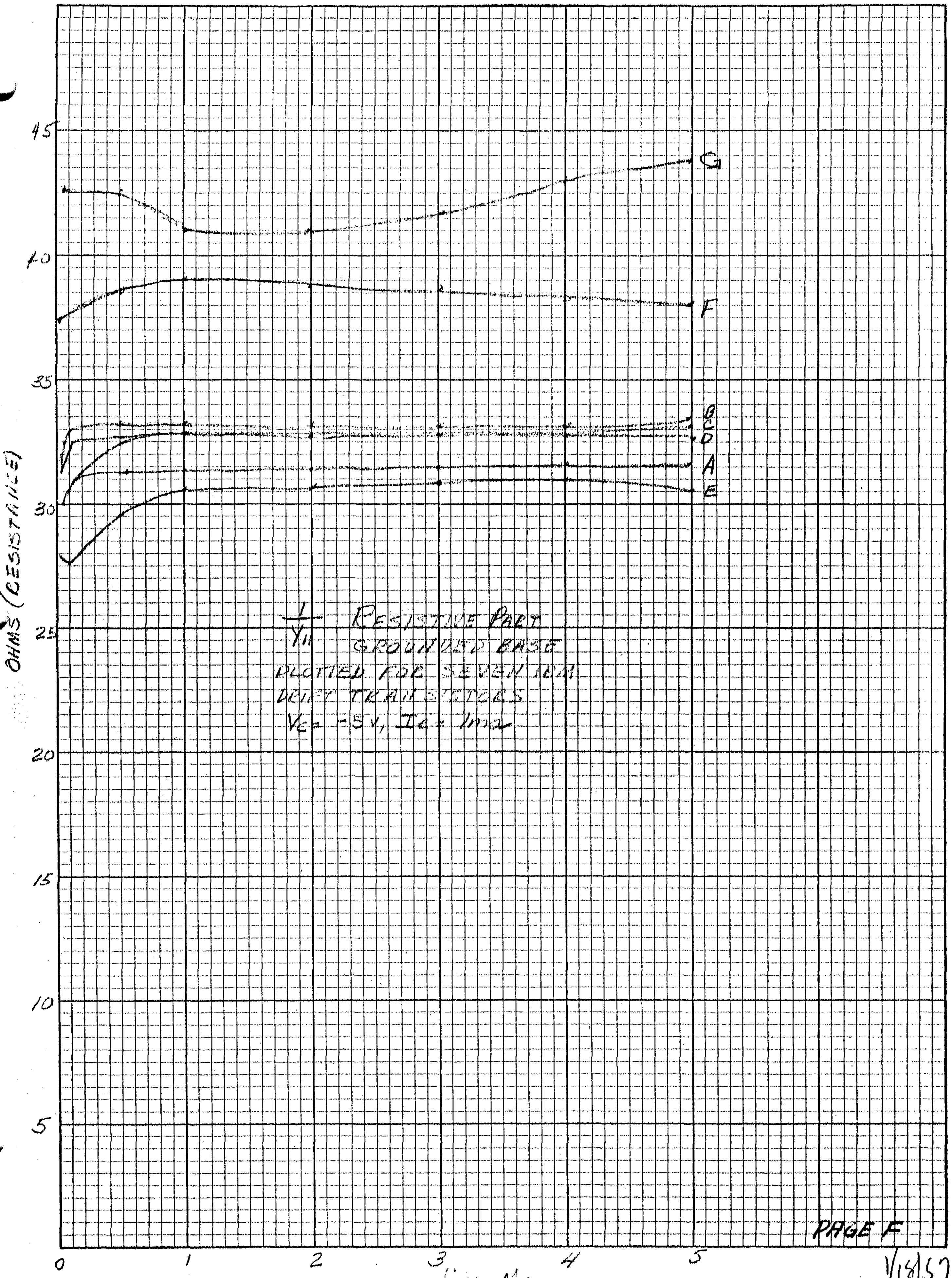


1/22 Grounded Base
Vc = 5v, Ie = 1ma
Series Resistance in Kohms
Series Reactance in K ohms (Capacitive)
f in mc
Imaginary Part
Real Part
1/17/56
12/26/56
12/26/56
1/4/57



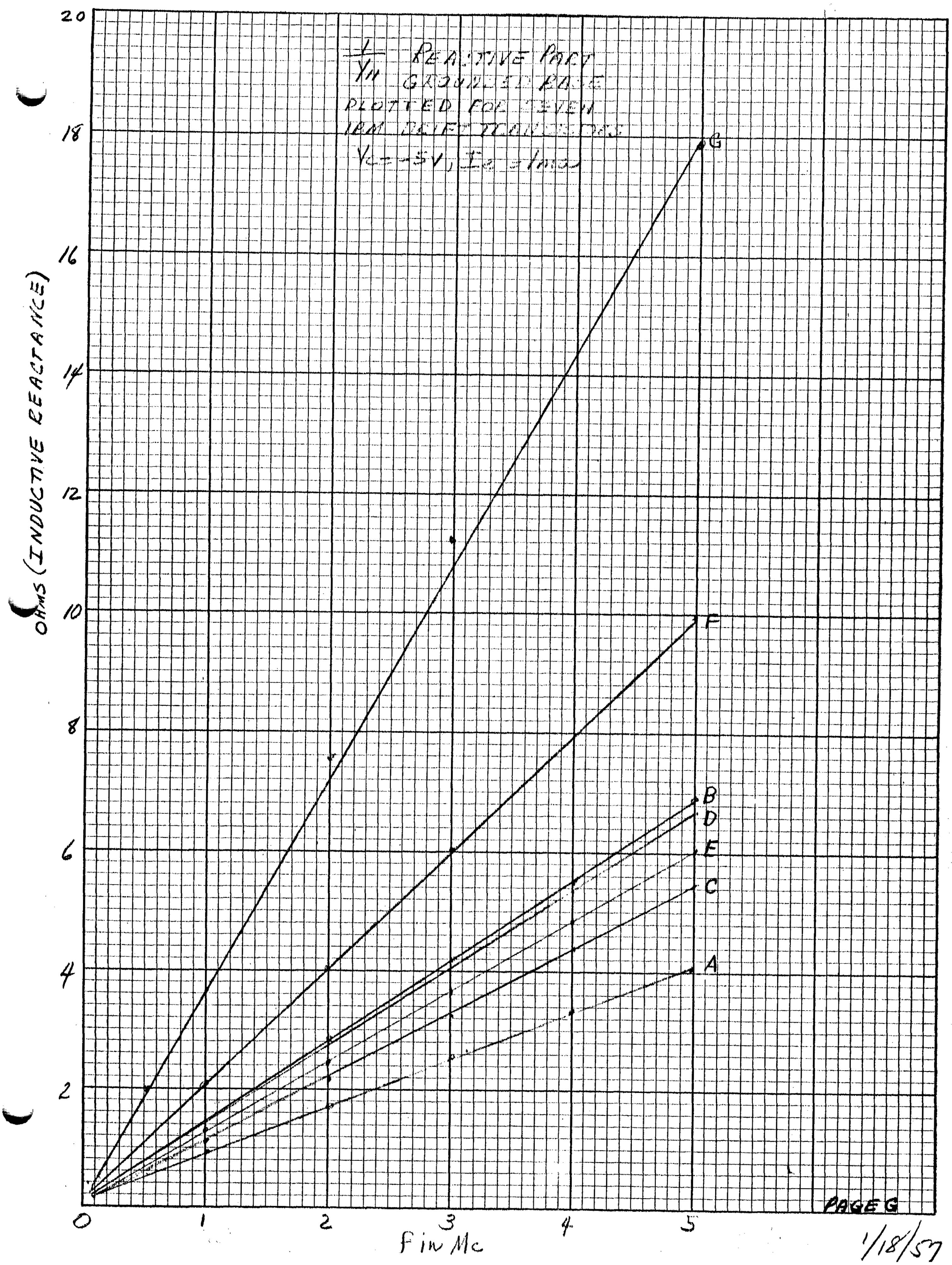
$-\frac{1}{Y_{21}}$ Grounded Base
$V_C = -5V$, $I_C = 1ma$
Series Resistance in Ohms
Series Reactance in Ohms (INDUCTIVE)
Real Part
1/17/57
12/26/57
12/29/56
1/17/57
Imaginary Part
f mc
40
30
20
10
10
8
6
4
2
0
1
2
3
4
5


T 1/12 Grounded Base
Vc = -5V, Ic = 1ma.
Series Resistance in Kilohms
Series Reactance in Kilohms (CAPACITIVE)
200
180
160
140
120
100
80
60
40
20
60
50
40
30
20
10
12/26/56
1/17/57
Real Part
1/17/57
Imaginary Part
12/26/56
1
2
3
4
5
f mc

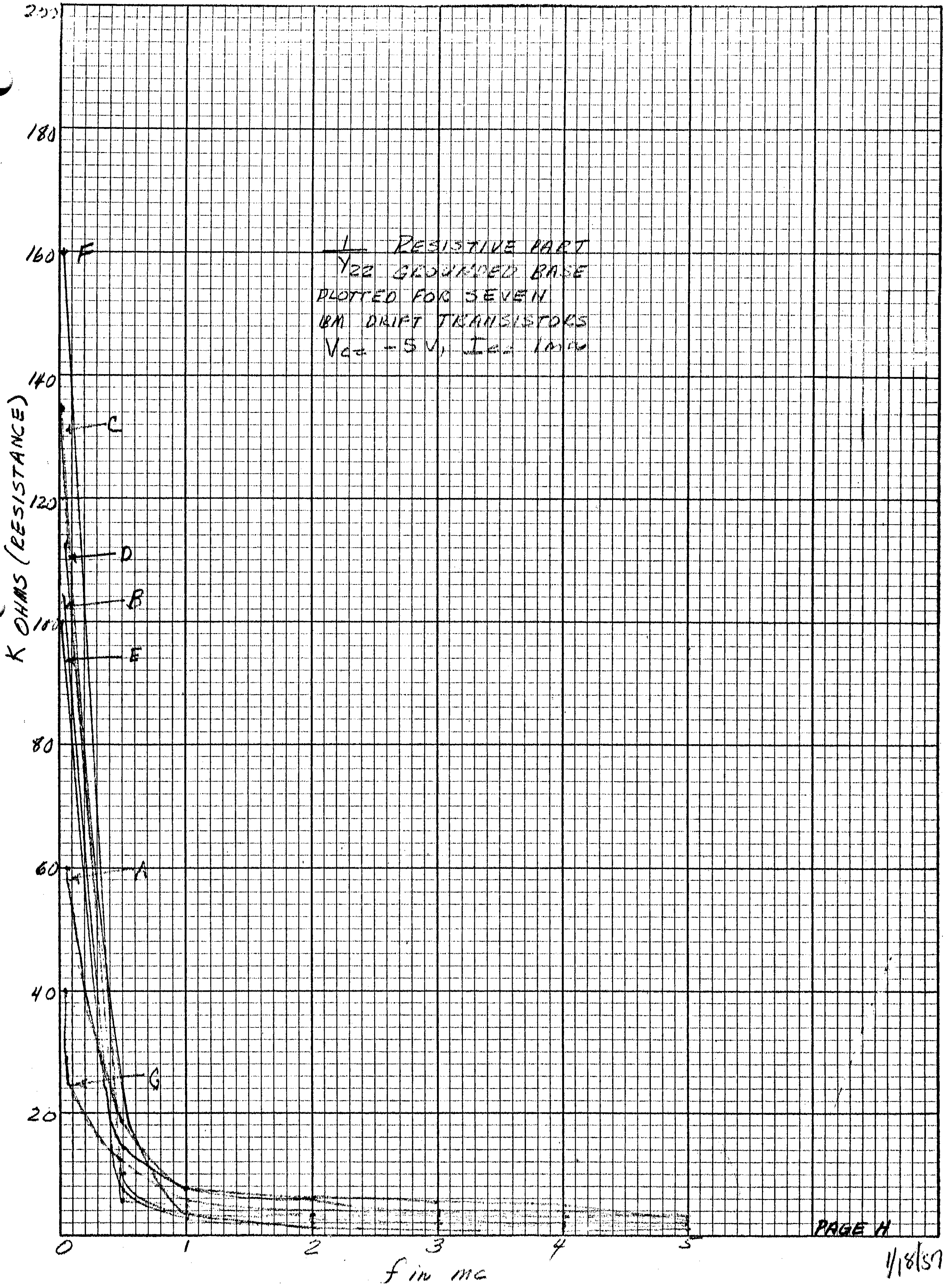


G
F
B
C
D
A
E
1/Y11 RESISTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN IBM
DRIFT TRANSISTORS
Vc= -5 V, Ie= 1ma
OHMS (RESISTANCE)
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
f in Mc
PAGE F

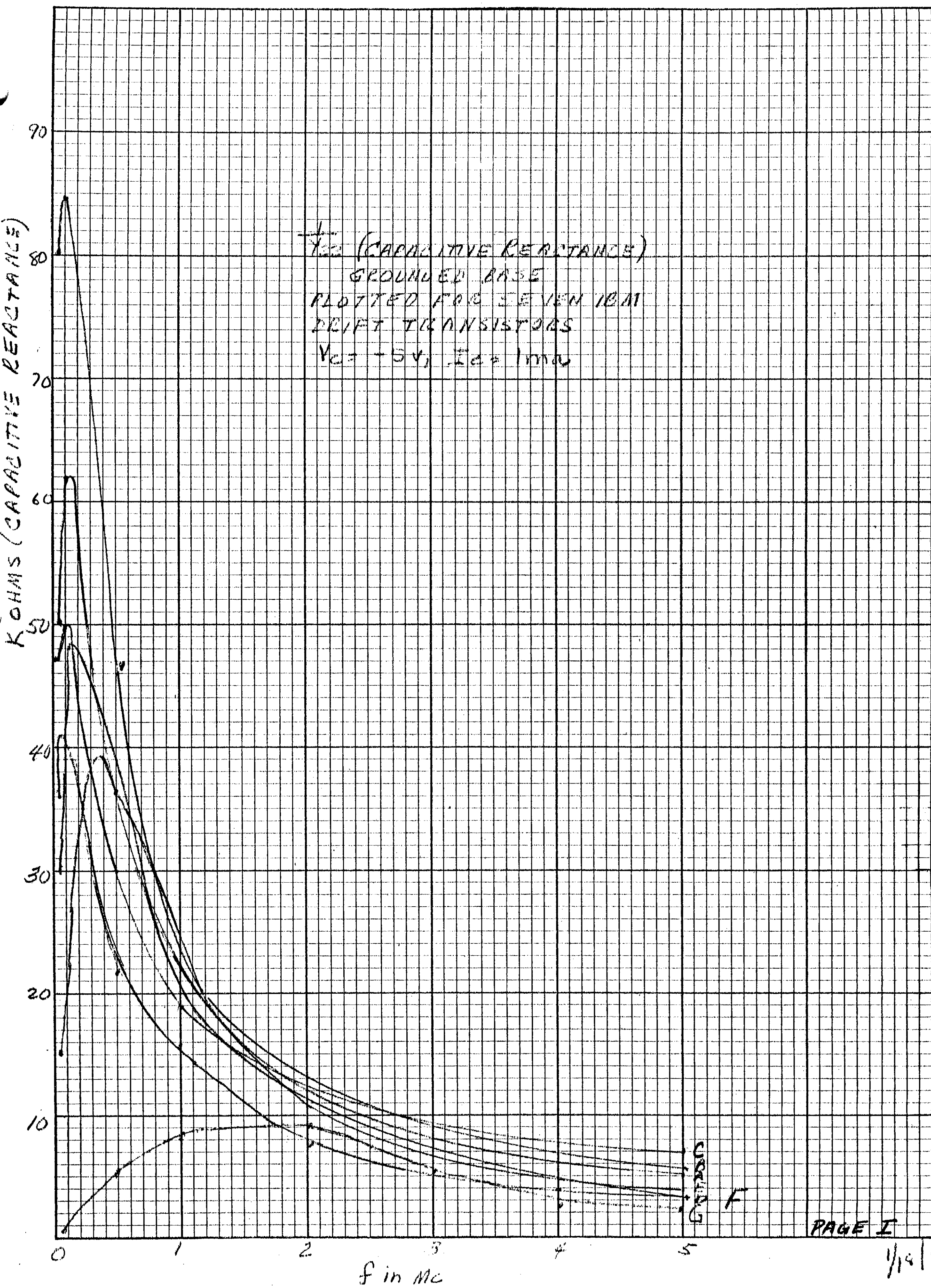
1/18/57


1/Y11 REACTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN
IBM DRIFT TRANSISTORS
Vc = -5V, Ie = 1ma
OHMS (INDUCTIVE REACTANCE)
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
F in Mc
A
B
C
D
E
F
G
PAGE G

1/18/57

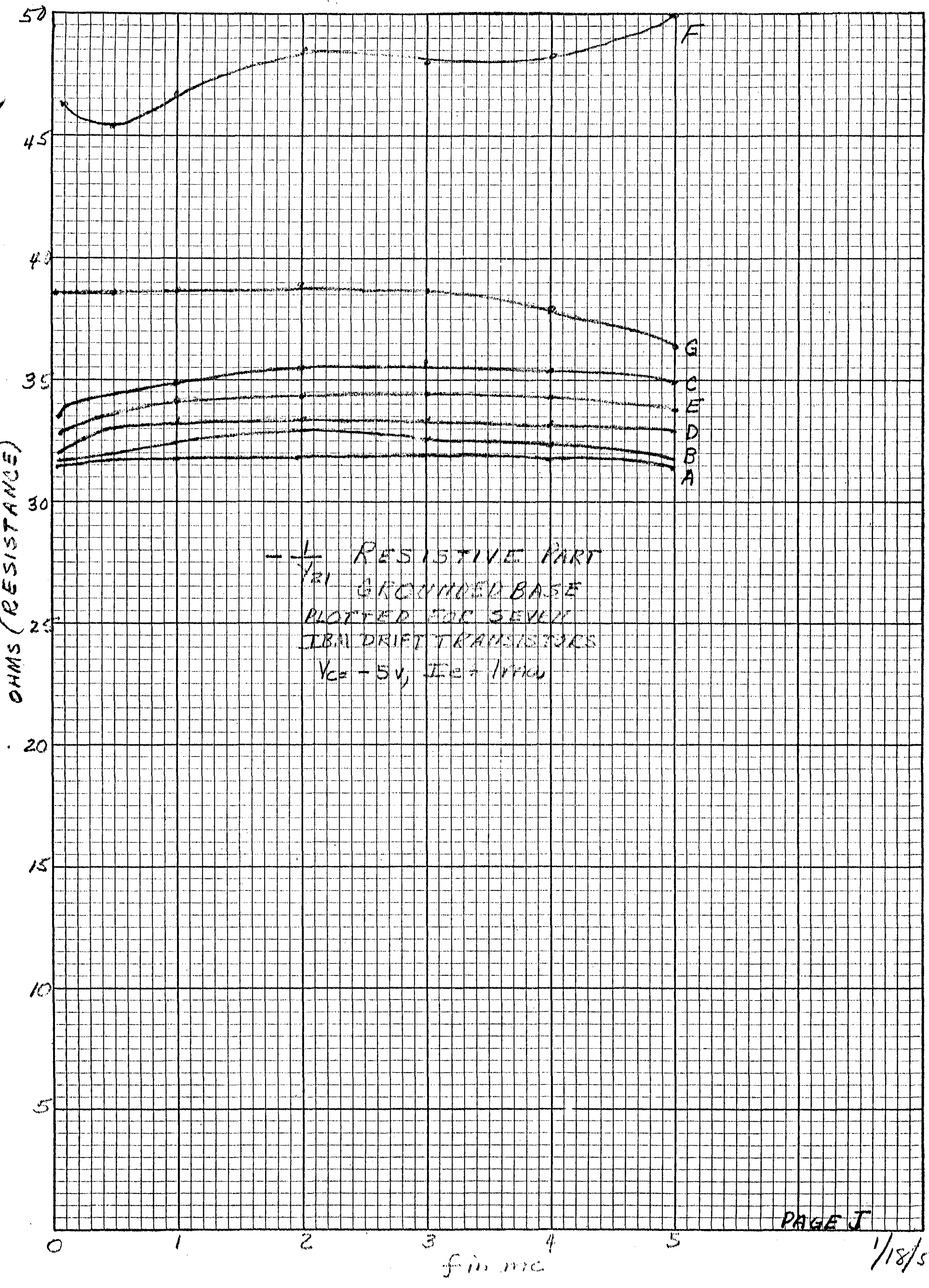

1/Y22 RESISTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN
IBM DRIFT TRANSISTORS
Vce = -5V, Ie = 1ma
K OHMS (RESISTANCE)
f in mc
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
F
C
D
B
E
A
G
PAGE H

1/18/57



1/Y22 (CAPACITIVE REACTANCE)
GROUNDED BASE
PLOTTED FOR SEVEN IBM
DRIFT TRANSISTORS
Vce = -5v, Ie = 1ma
K OHMS (CAPACITIVE REACTANCE)
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
f in Mc
F
G
PAGE I

1/14/57



50
45
40
35
30
25
20
15
10
5
OHMS (RESISTANCE)
0
1
2
3
4
5
f in mc
F
G
C
E
D
B
A
−1/y21 RESISTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN
IBM DRIFT TRANSISTORS
Vc= −5v, Ie= 1ma
PAGE J

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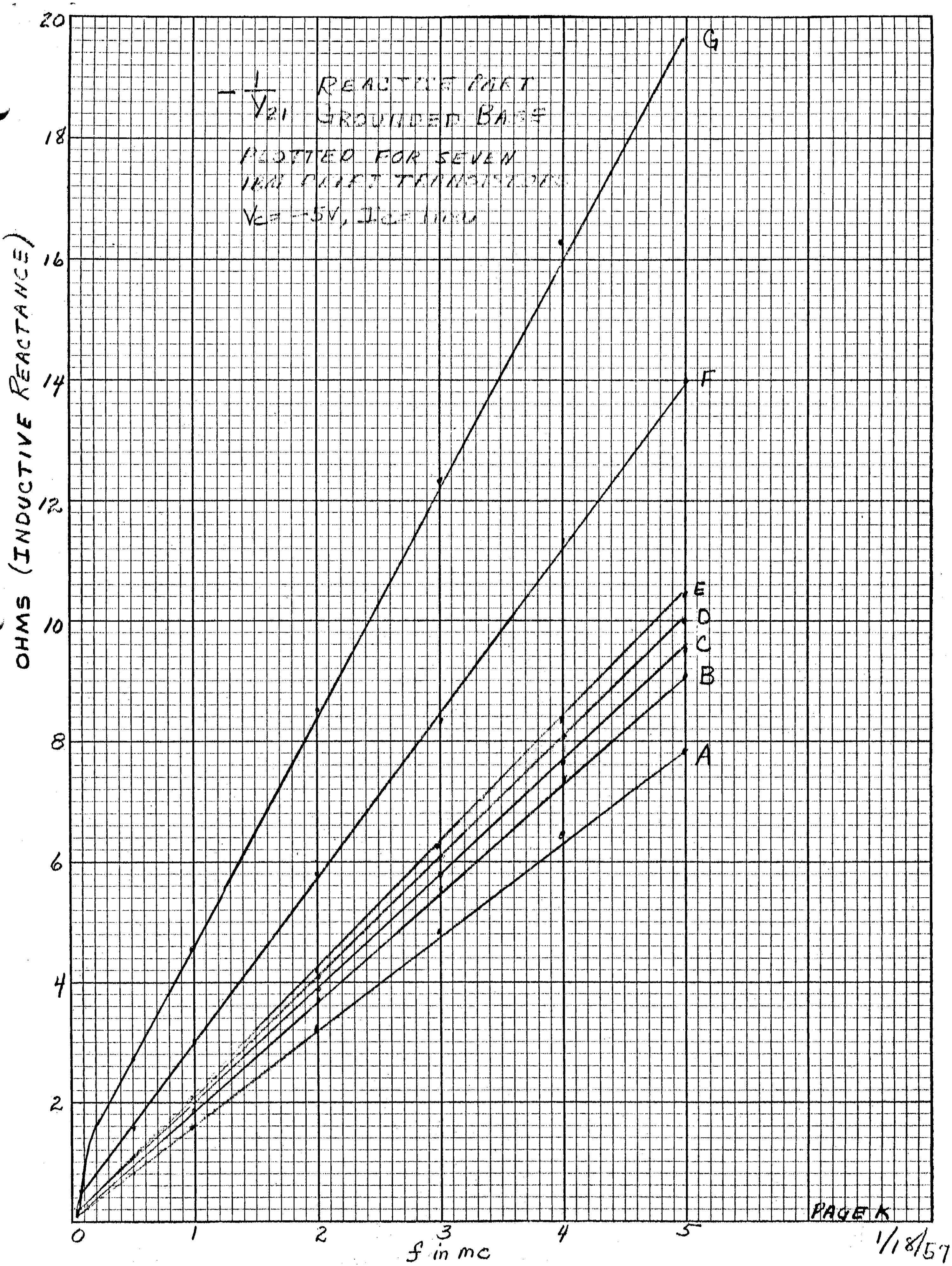
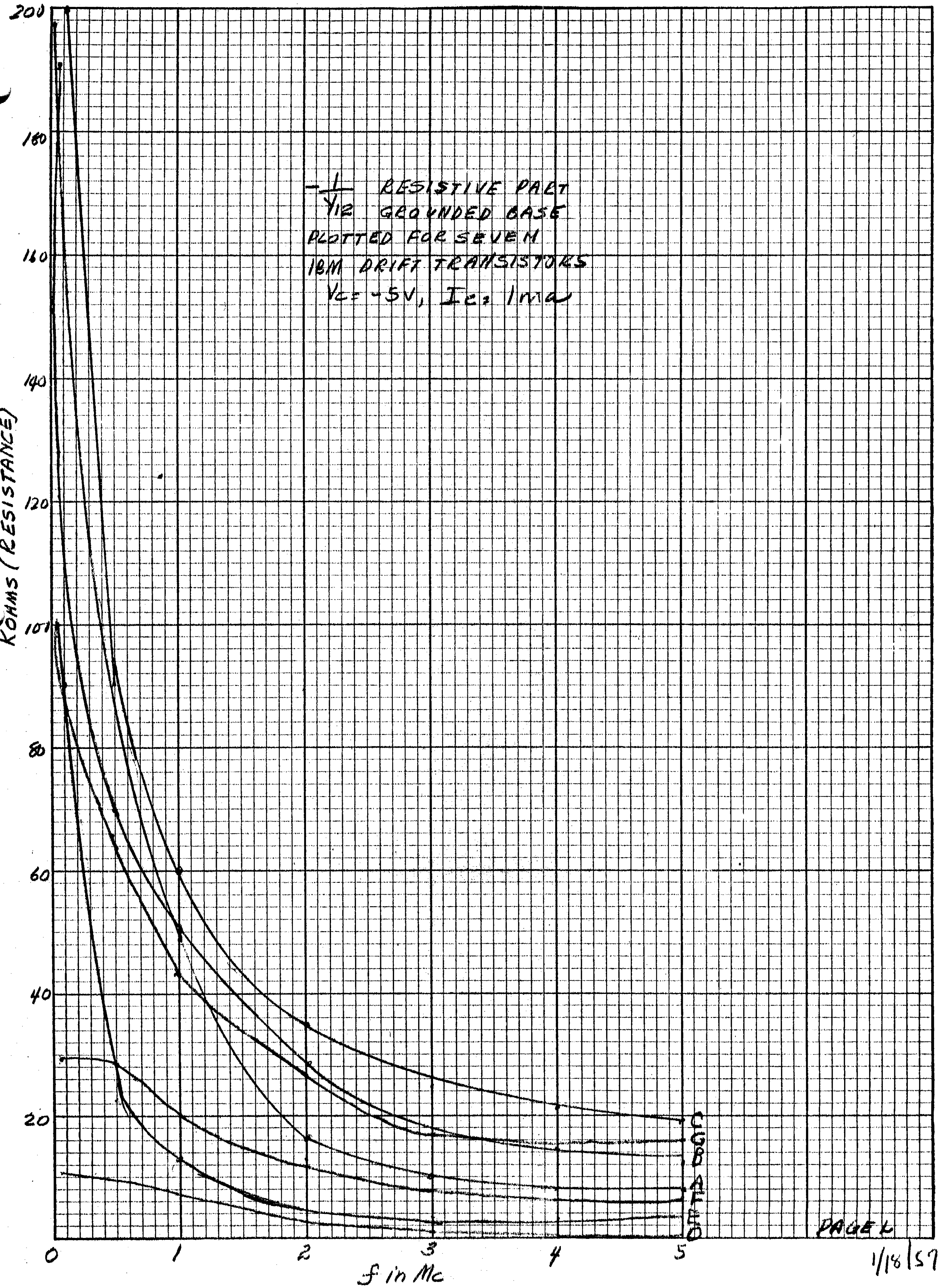
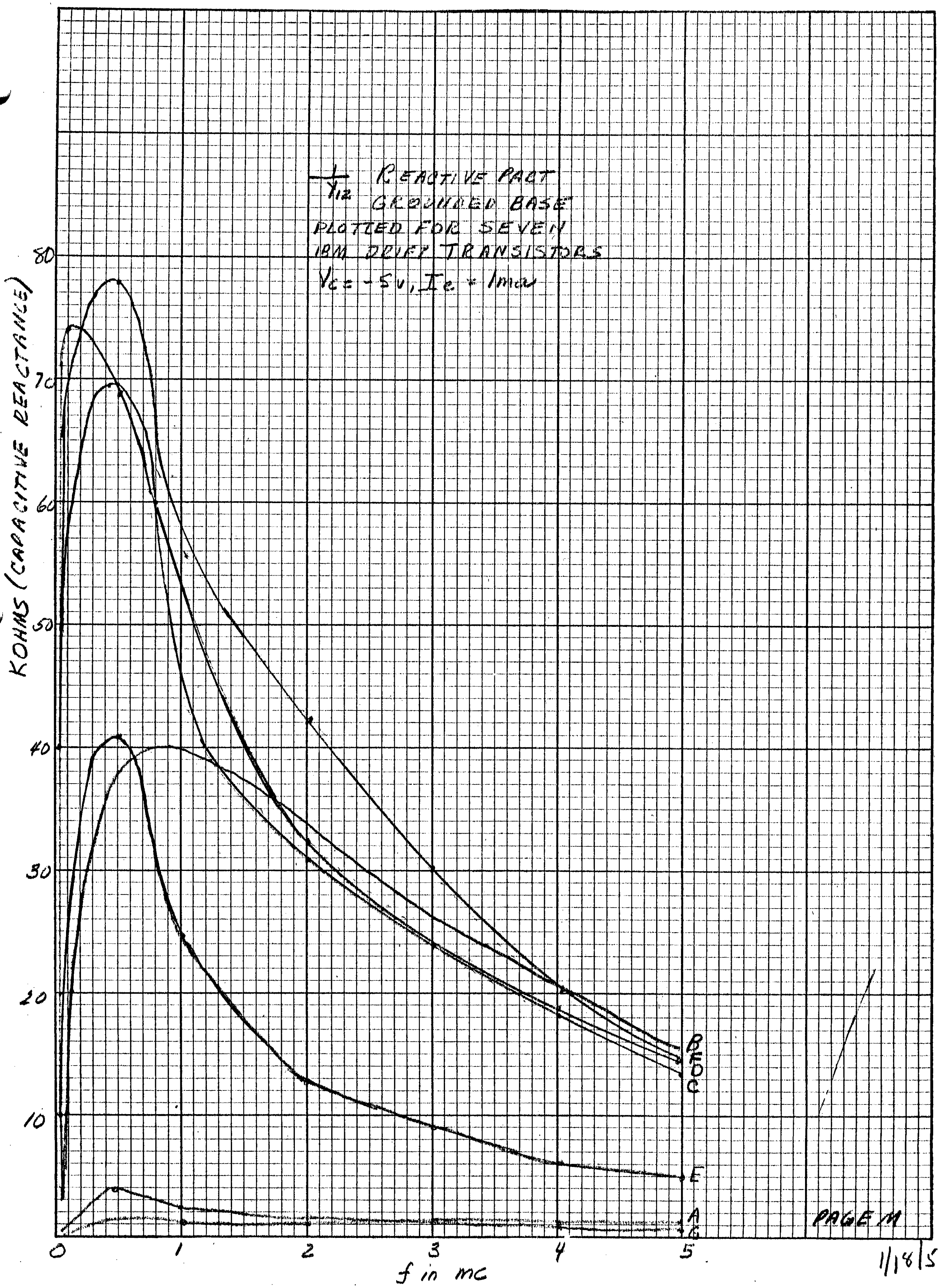

$-\frac{1}{Y_{21}}$
GROUNDED BASE
PLOTTED FOR SEVEN
OHMS (INDUCTIVE REACTANCE)
f in mc
G
F
E
D
C
B
A
0
1
2
3
4
5
2
4
6
8
10
12
14
16
18
20
PAGE K
1/18/57

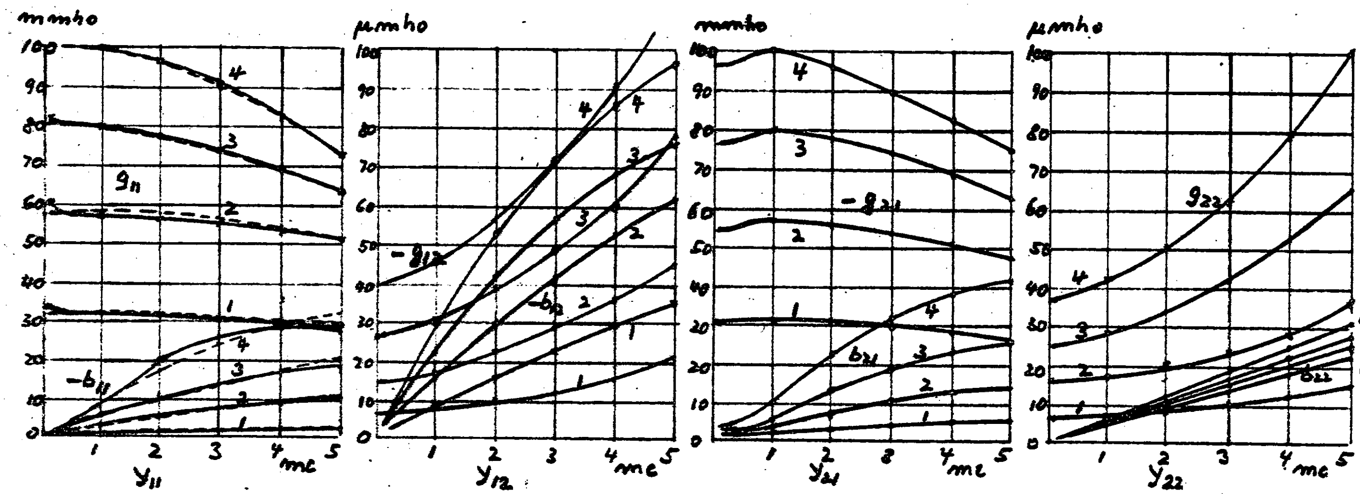


$-\frac{1}{Y_{12}}$ RESISTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN
IBM DRIFT TRANSISTORS
$V_C = -5V$, $I_E = 1ma$
KOHMS (RESISTANCE)
f in Mc
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
C
G
B
A
F
E
D
PAGE L

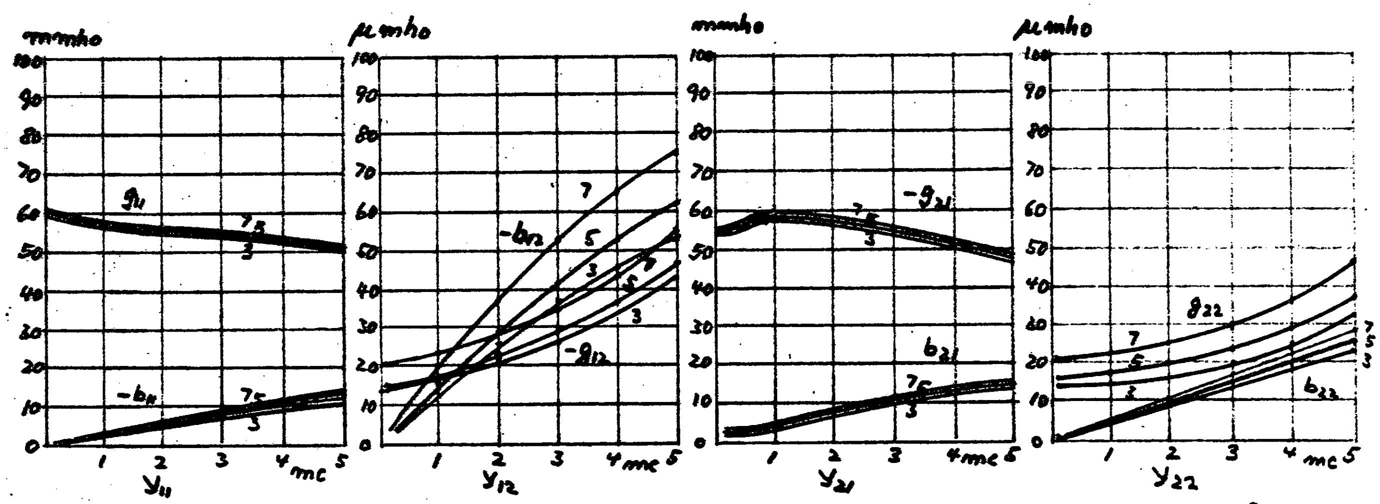
1/18/57


1/Y12 REACTIVE PART
GROUNDED BASE
PLOTTED FOR SEVEN
IBM DRIFT TRANSISTORS
Vc = -5v, Ie = 1ma
KOHMS (CAPACITIVE REACTANCE)
80
70
60
50
40
30
20
10
0
1
2
3
4
5
f in mc
B
F
D
C
E
A
G
PAGE M

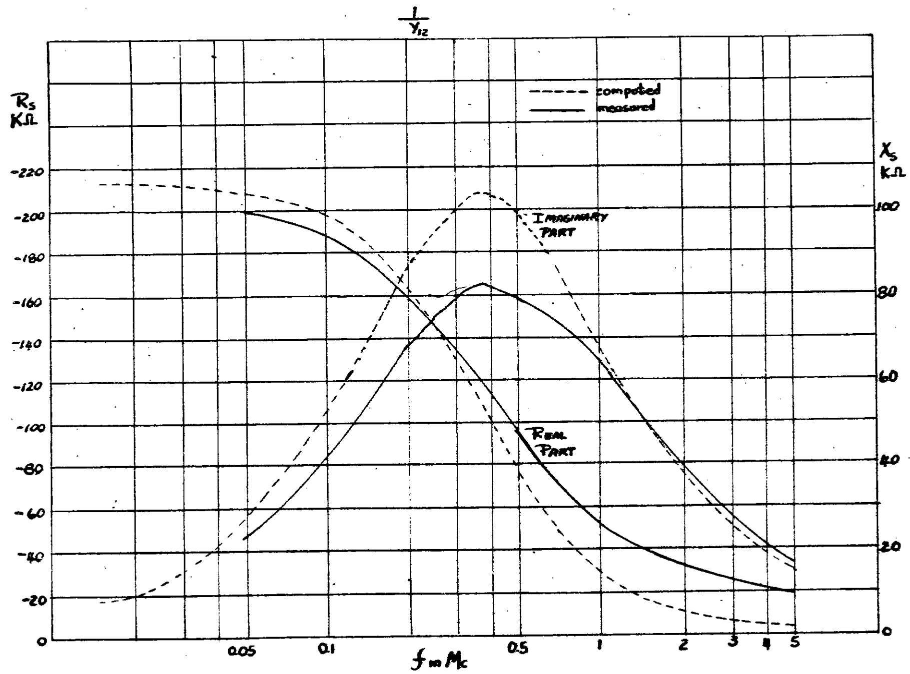
1/18/57

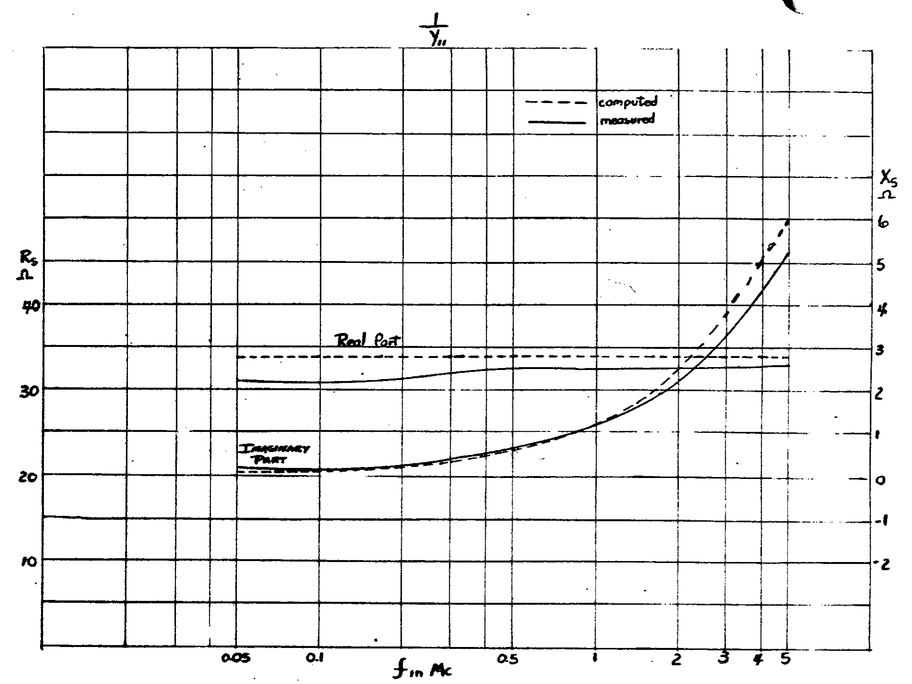


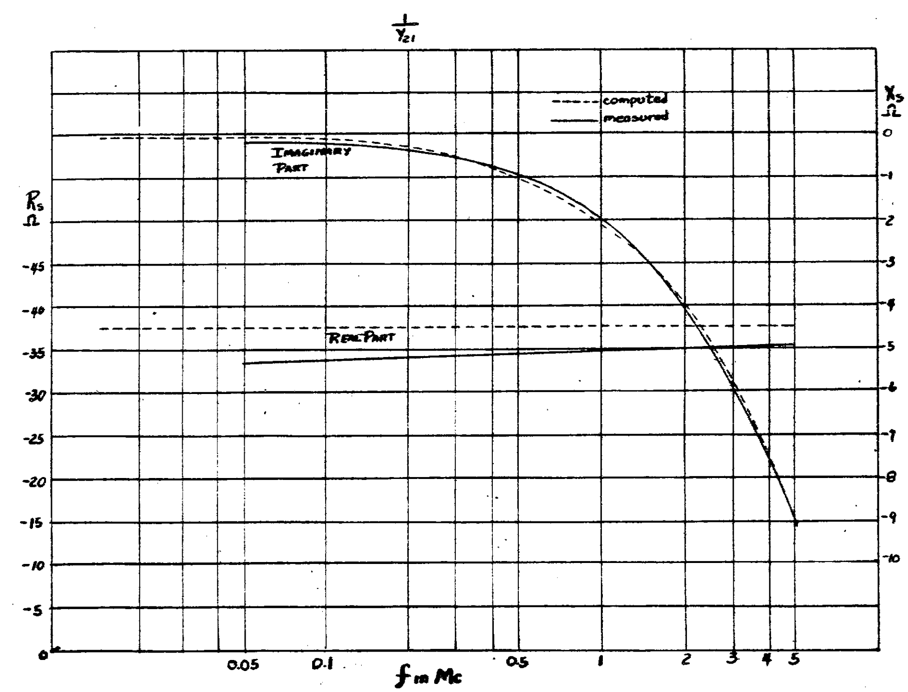
Y as function of frequency with Vc = -5V, ie = 1, 2, 3, 4 mA   Fig. 8

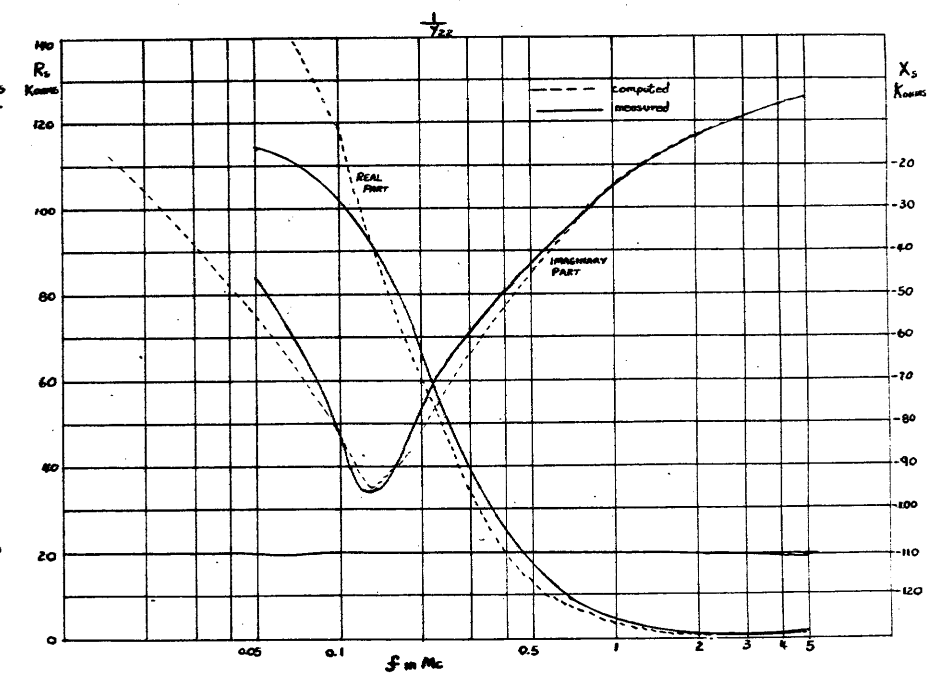


Y as function of frequency with ie = 2mA, Vc = -3, -5, -7 Volts   Fig. 9


1/Y12
Rs KΩ
Xs KΩ
computed
measured
IMAGINARY PART
REAL PART
-220
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
100
80
60
40
20
0
0.05
0.1
0.5
1
2
3
4
5
f in Mc


1/Y11
Rs Ω
Xs Ω
computed
measured
Real Part
IMAGINARY PART
40
30
20
10
6
5
4
3
2
1
0
-1
-2
0.05
0.1
0.5
1
2
3
4
5
f in Mc


1/Y21
Rs Ω
Xs Ω
computed
measured
IMAGINARY PART
REAL PART
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0.05
0.1
0.5
1
2
3
4
5
f in Mc


1/Y22
Rs Kohms
Xs Kohms
computed
measured
REAL PART
IMAGINARY PART
140
120
100
80
60
40
20
0
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
0.05
0.1
0.5
1
2
3
4
5
f in Mc

PAGE O