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IRRADIATION EFFECTS OF 40 AND 440 MEV PROTONS ON TRANSISTORS

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Langley Station, Hampton, Va.

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IRRADIATION EFFECTS OF 40 AND 440 MEV PROTONS ON TRANSISTORS

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SUMMARY

Several types of transistors were irradiated with 40 and 440 Mev protons by utilizing the 40 Mev linac accelerator at the University of Minnesota and the 440 Mev synchrocyclotron at the Carnegie Institute of Technology. The measurement of transistor parameters before, during, and after irradiation is presented in both graphic and tabular form as a function of integrated flux. The data presented indicate that the 40 Mev protons are more effective in producing damage than the 440 Mev protons. Most of the damage due to 40 Mev protons occurred below an integrated proton flux of 10^{12} protons/cm^2. The transistors having a higher alpha cut-off frequency proved to be more resistant to radiation.

INTRODUCTION

The presence of high-energy protons in the earth's radiation belts and in solar flares poses a problem in the design of circuits utilizing transistors for space application. The flux above an energy of 25 Mev in the inner belt is approximately 2.5×10^4 protons/cm^2-sec with the differential energy spectrum varying as $E^{-3.4}$. The proton energy ranges up to approximately 600 Mev (refs. 1 and 2). The proton flux in an extreme solar flare may be as high as 10^6 protons/cm^2-sec. In some high-energy events the proton energies extend into the billion electron volt (Bev) range (ref. 3).

Damage produced in solids by charged-particle bombardment has been considered theoretically in references 4 and 5. Most of the theory for such damage has been arrived at by using pure-element models with no definite correlation existing with a transistor junction; thus, a definite need for experimental data exists. This report presents data obtained during experimental testing of several types of transistors. If transient damage effects such as ionization are neglected, the primary damage produced in pure silicon and germanium is the creation of Frenkel defects (vacancy-interstitual pairs). This is the vacancy created by knocking an atom from its normal lattice site and having it come to rest at an interstitual position within a lattice structure. The defects that are formed affect the electrical characteristics of a semiconductor by providing recombination and trapping sites which can reduce the number of carriers and result in a decrease in carrier lifetime (refs. 6 and 7).

Only a limited amount of work has been accomplished with protons in the study of radiation damage on semiconductors (ref. 8). Results of bombardment with 40 and 440 Mev protons presented in the present report show the extent to which transistors are damaged when they are subjected to a total proton flux in the order of 10^{12} protons/cm^2. With a knowledge of the proton spectrum in the radiation belts and in solar flares, an estimate can be made of the lifetime of the various transistors subjected to these environments.

The authors are indebted to Dr. Roger B. Sutton of the Carnegie Institute of Technology and to Dr. J. H. Williams of the University of Minnesota for their valuable assistance and many courtesies extended during the progress of the experiments at their respective laboratories.

SYMBOLS

BV_{CBO} breakdown voltage, collector to base junction reverse-biased, emitter open-circuited

BV_{CEO} breakdown voltage, collector to emitter, with base open-circuited

BV_{CER} breakdown voltage, collector to emitter, base connected through a specified resistance to emitter

BV_{EBO} breakdown voltage, emitter to base, with collector open-circuited

C_{ob} capacitance, collector to base, measured across the output terminals with alternating-current input open-circuited

f frequency

$f_{\alpha b}$ frequency at which magnitude of small-signal short-circuited forward-current transfer ratio is 0.707 of its low-frequency value

f_{max} maximum frequency of oscillation

f_t frequency at which $h_{fe} = 1$

h_{FE} common emitter, static value of short-circuit forward-current transfer ratio, $\dfrac{I_C}{I_B}$

h_{fe} common emitter, small-signal forward-current transfer ratio, alternating-current output short-circuited, $\dfrac{\Delta I_C}{\Delta I_B}$

I_B direct current into base

I_C direct current into collector

I_{CBO} collector current when collector junction is reverse-biased and emitter is direct current open-circuited

I_{CEO} direct collector current with collector junction reverse-biased and base open-circuited

I_E direct current into emitter

I_{EBO} direct emitter current when emitter junction is reverse-biased and collector is open-circuited

R resistance

r'_b base spreading resistance

V_{BE} voltage, base to emitter

V_C collector voltage

V_{CB} voltage, collector to base

V_{CE} voltage, collector to emitter

$V_{CE}(sat)$ saturation voltage at specified I_C and I_B

V_{EB} voltage, emitter to base, collector open-circuited

V_{PT} punch-through voltage, collector to base voltage at which the collector-space charge layer has widened until it contacts the emitter junction

Subscript:

o initial conditions

NOTATION

Ag silver

Ge germanium

Si silicon

ZnS zinc sulfide

NPN negative-positive-negative

PNP positive-negative-positive

APPARATUS AND PROCEDURE

University of Minnesota Test

A total of 75 transistors were irradiated with 40 Mev protons by utilizing the linac accelerator at the University of Minnesota. The accelerator is capable of producing a time-average beam current of 10^{-8} amperes (approximately 6×10^{10} protons/sec). The cross-sectional area of the proton beam is approximately 1.25 square centimeters.

The experimental setup used during irradiation tests at the University of Minnesota is shown in figure 1. The transistors were mounted in individual ports on an aluminum disk and were remotely positioned in the proton beam. A cam-controlled electric motor automatically positioned each transistor in the proton beam for 10 minutes at a beam flux rate of 3×10^{9} protons/cm^2-sec or a total flux of 1.8×10^{12}. A zinc sulfide phosphor (silver activated) was placed on the aluminum disk in a position corresponding to that of the transistors and was alined with the proton-beam pipe exit. The center of the proton beam was visually located by using a closed-circuit television system to determine the location of the beam-excited portion of the phosphor. By marking the excited portion on the television monitoring screen, each transistor could be properly positioned within the marked area corresponding to the proton beam. During the experiments, the beam flux was monitored by means of a Faraday cup mounted behind the transistors. Periodic checks were made on the beam flux level through a vacant space in the aluminum disk

During irradiation the transistors were operated in an active circuit which is shown schematically in figure 2. The transistor parameters which were monitored and recorded on a direct-writing oscillograph recorder included collector current, I_C; small-signal current gain, h_{fe}; and leakage current, I_{CBO}. The base current I_B was held constant during the irradiation. Pretest and post-test measurements on each type of transistor were made both at the Langley Research Center (LRC) as well as by the manufacturer, with the exception of the 2N146 and 2N337 transistors for which no manufacturers' data were obtained.

Carnegie Institute of Technology Test

A total of 20 transistors were irradiated by utilizing the 440 Mev proton synchrocyclotron at the Carnegie Institute of Technology. The synchrocyclotron is capable of producing a time-average beam current of 2×10^{7} protons/cm^2-sec. The cross-sectional area of the proton beam at the external port is approximately 25 square centimeters.

The method used for exposing the transistors to the beam in this experiment differed from the method used at the University of Minnesota in that the larger cross-sectional area of the beam permitted the irradiation of several transistors at the same time with each bombardment lasting approximately 6 hours. Due to the nonuniformity of the cross-sectional area of the proton beam, a profile survey was made with a scintillation counter. The positions of the various transistors in the beam were carefully determined, and total dosages were arrived at by using the beam-profile plots. The beam current was measured before and during irradiation by using a helium-filled ionization chamber mounted between the beam exit port and the specimen and operated at 2 lb/sq in. above atmospheric pressure. The transistors exposed to the beam were mounted on a bracket supported by a junction box attached to a tripod as shown in figure 3. The transistor parameters measured before, during, and after irradiation were the same as those of the University of Minnesota experiments except that no manufacturer's data were obtained. Also, the number of transistors irradiated was fewer because of the lower beam flux and the longer irradiation time.

RESULTS AND DISCUSSION

A general description of the transistors that were irradiated with 40 and 440 Mev protons is given in table I. The data obtained during the various tests are presented in tables II and III. Measurements on the transistors irradiated with 440 Mev protons were not furnished by the manufacturers; therefore, table III includes only Langley Research Center data. To eliminate the effect of the normally large variations of small-signal alternating-current gain h_{fe} found in transistors of the same type, h_{fe} was divided by $h_{fe,o}$ and plotted as a function of integrated flux. These data are presented in figures 4 and 5. The filled-in symbols on the figures represent the postirradiation measurements made immediately after irradiation. The manufacturer's measurements were made from 2 to 4 weeks before and after irradiation. All data were taken at ambient temperatures of approximately 25° C.

The transistors tested at 40 Mev were subjected to a total flux of 1.8×10^{12} protons/cm^2 (fig. 4). The data obtained from this test showed that h_{fe} values degraded from 10 percent to 90 percent. The transistors showing the greatest damage were the germanium, low-frequency, alloy-junction, 2N224 transistors with an average of 90-percent loss in h_{fe}. The 2N337, a grown junction, silicon, medium-frequency transistor suffered similar losses, with an average loss of approximately 85 percent. The alloy-junction silicon, 2N859 transistors, and alloy-junction 2N526 transistors were degraded by an average of 80 percent. The transistors receiving the least damage were the high-frequency mesa, 2N743 transistors, and the surface barrier 2N128 transistors. The 2N743 transistors showed an average of 15-percent loss in h_{fe}, whereas the 2N128 transistors showed 10-percent gain to 4-percent loss in h_{fe} calculated from pretest and post-test values. The slope of the curve showing the variation of gain with integrated proton flux began to level off at around 10^{12} protons/cm^2 for most of the transistors tested at 40 Mev.

The radiation tolerance levels for transistors irradiated at 40 Mev are given in table IV, where the tolerance level is defined as the flux level at which h_{fe}

has deteriorated to 70 percent of its original value. Leakage currents of germanium transistors increased by one to two orders of magnitude. Leakage currents for the silicon transistors that were tested were in some cases too low to be measured accurately with the instrumentation used in these tests. The breakdown voltages (BV_{CBO} and BV_{EBO}) were generally within the normal operating tolerances.

The normalized small-signal alternating-current gain $\frac{h_{fe}}{h_{fe,o}}$ was plotted as a function of integrated flux at 440 Mev and is presented in figure 5. The change in current gain h_{fe} of the transistors irradiated at 440 Mev was less than 10 percent at the flux levels attained during this test, with the exception of the low-frequency 2N224 transistors. The 2N224 transistors reached the previously defined tolerance level at 5×10^{11} protons/cm^2, just below the maximum flux level reached. The flux levels reached by all the transistors irradiated during the 440 Mev tests are given in table III.

In comparing the transistors for their susceptibility to radiation damage, the thin-base, high-frequency mesa transistor was much less susceptible than the low-frequency types. This holds for both energies at which tests were made. Comparing the 2N1302 (NPN) transistor and the 2N1303 (PNP) transistor, similar except for opposite polarities, the 2N1303 (PNP) transistor was less susceptible to damage. Greater damage was experienced by the transistors at 40 Mev than at 440 Mev, if the flux levels were assumed to be the same.

The data given in table IV show that the silicon devices which were irradiated had a lower flux-tolerance level than the germanium devices of comparable frequency. This is shown in the comparison of the silicon 2N337 and 2N859 transistors with the germanium 2N1302, 2N1303, 2N1305, 2N169A, and 2N128 transistors. This is a result which normally would be expected because of the relative mass of the germanium and silicon atoms. The greater radiation tolerance of germanium over silicon has been reported in references 9 and 10.

The data presented here are consistent with data obtained on similar transistors irradiated with 22 and 240 Mev in that both showed a frequency dependence on damage, and both indicated greater damage at lower energies.

In designing electronic circuits for operation in a space environment, such as the Van Allen belts and solar flares, one should seriously consider the use of high-frequency units where feasible.

CONCLUDING REMARKS

The experimental data presented on transistor degradation due to proton bombardment at 40 and 440 Mev should be useful in the selection of transistors for applications in a proton environment. The transistors tested were selected to be representative of currently available types. The data in this report indicate that the damage sustained by the transistors was greater at 40 Mev than at 440 Mev.

When selecting transistors to be used in a space radiation environment, one should consider the use of the germanium high-frequency transistors. Theoretical studies and further experiments are needed to provide a better understanding of the basic damage mechanism of high-energy protons on semiconductor materials and compound devices.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 23, 1962.

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TABLE I.- GENERAL DESCRIPTION OF TRANSISTORS USED IN RADIATION EXPERIMENTS WITH 40 AND 440 MEV PROTONS

Transistor	Type	Structure	h_{Fe}	$f_{\alpha b}$, mc
2N1302	NPN Ge	Alloy junction	50	4.5
2N1303	PNP Ge	Alloy junction	50	4.5
2N1305	PNP Ge	Alloy junction	70	8
2N146	NPN Ge	Grown junction	[a]33	------
2N743	NPN Si	Epitaxial double-diffused mesa	40	[b]400
2N169A	NPN Ge	Rate-grown junction	72	9
2N337	NPN Si	Grown junction	35	30
2N526	PNP Ge	Alloy junction	70	3
2N128	PNP Ge	Surface barrier	[a]40	[c]60
2N224	PNP Ge	Alloy junction	90	0.5
2N859	PNP Si	Alloy junction	35	[b]14
2N393	PNP Ge	Microalloy	95	[c]60

[a]Small-signal alternating-current gain h_{fe}.

[b]Frequency at which $h_{fe} = 1$ or f_t.

[c]Maximum frequency of oscillation f_{max}.

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2

[First value taken before irradiation; second value taken after irradiation]

(a) Transistor 2N1302; type NPN Ge

LRC pretest and post-test data						Manufacturers' pretest and post-test data													
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp	I_{CBO} at V_{CB}=25 v, μamp	I_{EBO} at V_{EB}=25 v, μamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_E=0.1 ma, v	V_{BE} at I_C=10 ma and I_B=0.5 ma, v	V_{CE}(sat) at I_C=10 ma and I_B=0.5 ma, v	h_{FE} at I_C=10 ma and V_{CE}=1.0 v	f_{ab} at V_{CB}=5 v and I_C=1.0 ma, mc	f_t at V_{CE}=5 v and I_C=1.0 ma, mc	r'_b at V_{CE}=5 v, I_C=10 ma, and f=10 mc, ohms	C_{ob} at V_{CB}=5 v, μμf	C_{ob} at V_{CB}=10 v, μμf	C_{ob} at V_{CB}=15 v, μμf
1	30	5.09	169	182	2.40	3.50	2.3	39	39	0.230	0.055	159	11.2	11.1	134	15.8	11.8	9.8
		1.40	47	44	5.76	15.0	8.4	37	38	.248	.079	62	11.1	10.5	140	15.0	11.5	9.8
2	30	2.77	92	109	2.78	3.50	2.5	48	43	.250	.060	104	11.7	12.4	162	15.0	11.2	9.3
		1.40	47	46	4.80	11.8	5.3	47	41	.270	.085	57	11.7	11.8	170	14.2	10.7	9.2
3	30	4.40	147	175	.00	2.80	1.9	43	47	.230	.050	149	14.6	15.3	126	16.8	12.4	10.6
		1.51	50	40	4.80	11.5	6.0	43	46	.248	.066	71	14.5	14.4	129	15.6	12.0	10.1
4	30	2.48	83	94	2.40	3.10	1.9	48	44	.240	.060	91	10.3	10.3	120	18.5	13.6	11.2
		1.12	37	39	10.6	17.5	7.4	47	43	.255	.095	42	10.1	9.9	124	17.7	13.5	11.6
5	30	2.64	88	108	2.25	2.90	1.9	43	43	.270	.055	105	11.3	11.8	171	14.0	10.3	8.8
		1.45	48	46	6.75	12.3	7.3	42	41	.288	.075	56	11.2	11.3	178	13.4	10.0	8.6
6	30	3.42	114	134	2.40	2.70	1.6	42	45	.250	.060	119	10.0	9.9	146	14.9	11.0	9.3
		1.04	35	32	5.28	14.0	6.4	41	44	.270	.087	48	9.9	9.6	154	14.5	10.9	9.1
7	30	2.20	73	99	2.88	3.60	1.7	46	43	.260	.080	91	6.7	6.4	136	18.0	13.2	10.8
		.84	28	27	7.70	13.1	4.4	44	41	.285	.115	40	6.5	6.3	152	17.0	13.0	11.1

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR

WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(b) Transistor 2N1303; type PNP Ge

	LRC pretest and post-test data					Manufacturers' pretest and post-test data												
Transistor number	I_B, µamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, µamp	I_{CBO} at V_{CB}=25 v, µamp	I_{EBO} at V_{EB}=25 v, µamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_E=0.1 ma, v	V_{BE} at I_C=10 ma and I_B=0.5 ma, v	V_{CE}(sat) at I_C=10 ma, and I_B=0.5 ma	h_{FE} at I_C=10 ma and V_{CE}=1.0 v	$f_{\alpha b}$ at V_{CB}=5 v and I_C=1.0 ma, mc	f_t at V_{CE}=5 v and I_C=1.0 ma, ohms	r'_b at V_{CE}=5 v, I_C=10 ma, and f=10 mc, ohms	C_{ob} at V_{CB}=5 v, µµf	C_{ob} at V_{CB}=10 v, µµf	C_{ob} at V_{CB}=15 v, µµf
8	50	3.39	68	66	1.44	1.7	1.8	52	48	0.240	0.060	56	12.2	10.4	73	10.0	7.7	6.3
		2.47	49	53	3.60	7.1	5.0	54	50	.242	.072	48	11.9	9.8	81	9.4	7.2	6.2
9	50	3.55	71	82	2.4	2.6	1.8	65	46	.260	.100	51	5.2	4.7	95	10.0	7.7	6.3
		1.92	38	48	6.24	9.5	5.2	67	50	.272	.115	38	5.1	4.6	121	9.1	6.9	5.9
10	50	7.52	150	162	2.25	1.8	2.4	50	36	.250	.070	111	16.5	14.8	89	11.6	8.8	7.2
		5.90	118	130	3.75	4.9	3.3	52	37	.253	.075	95	16.7	14.0	102	11.2	8.3	7.1
11	50	5.76	115	111	2.16	1.8	1.4	60	54	.250	.060	91	9.7	8.2	95	9.5	7.3	6.0
		4.18	84	94	4.56	5.8	2.8	61	55	.262	.078	74	9.8	7.9	114	9.1	6.8	5.9
12	50	6.75	135	132	2.16	1.6	1.2	54	55	.260	.065	100	15.3	13.2	115	8.7	6.6	5.5
		3.57	71	89	5.52	9.1	4.7	55	64	.267	.075	70	14.9	12.0	148	7.8	5.9	5.1
13	50	3.64	73	73	1.50	1.5	1.3	58	36	.250	.075	59	8.5	7.0	89	9.2	7.2	5.8
		3.52	71	55	5.50	6.0	3.7	59	37	.255	.082	50	8.4	6.7	105	8.8	6.6	5.8
14	50	2.80	56	71	1.92	1.9	1.2	76	41	.260	.090	59	5.8	5.1	89	9.8	7.6	6.3
		2.08	42	50	5.28	6.3	3.2	78	41	.265	.100	45	5.5	4.9	105	9.2	7.0	6.0
15	50	2.56	51	60	1.44	2.1	1.3	46	47	.250	.080	50	5.6	4.8	73	10.4	8.0	6.5
		1.28	26	34	4.32	6.7	4.8	45	50	.252	.085	37	5.4	4.5	76	9.6	7.4	6.3

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(c) Transistor 2N1305; type PNP Ge

LRC pretest and post-test data						Manufacturers' pretest and post-test data												
Transistor number	I_B, µamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, µamp	I_{CBO} at V_{CB}=25 v, µamp	I_{EBO} at V_{EB}=25 v, µamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_E=0.1 ma, v	V_{BE} at I_C=10 ma and I_B=0.5 ma, v	V_{CE}(sat) at I_C=10 ma, and I_B=0.5 ma, v	h_{FE} at I_C=10 ma and V_{CE}=1.0 v	$f_{\alpha b}$ at V_{CB}=5 v and I_C=1.0 ma, mc	f_t at V_{CE}=5 v and I_C=1.0 ma, ohms	r'_b at V_{CE}=5 v, I_C=10 ma, and f=10 mc, ohms	C_{ob} at V_{CB}=5 v, µµf	C_{ob} at V_{CB}=10 v, µµf	C_{ob} at V_{CB}=15 v, µµf
16	50	5.82	116	128	1.20	1.90	1.50	55	41	0.260	0.09	100	8.0	6.9	95	9.9	7.5	6.1
		.96	19	27	8.40	2.20	13.2	59	46	.271	1.30	39	7.4	6.4	142	7.9	6.0	5.2
17	50	5.26	105	89	1.68	1.50	1.30	57	44	.250	.09	95	6.0	5.2	95	10.0	7.6	6.2
		.98	20	28	6.72	13.5	7.80	61	48	.268	1.25	38	5.5	4.9	126	8.7	6.5	5.6
18	50	3.16	63	71	.48	1.50	1.00	56	41	.25	.11	61	6.7	5.5	53	11.1	18.5	6.9
		.72	14	23	4.80	11.5	6.00	60	44	.260	5.70	30	6.1	5.1	66	9.8	7.5	6.4
19	50	4.04	81	91	.48	1.40	1.10	52	46	.250	.10	71	10.7	9	75	9.7	7.4	6.1
		1.28	26	32	7.44	15.8	8.20	61	55	.262	.71	41	9.9	8.3	112	8.2	6.1	5.3
20	50	4.30	86	95	.72	1.60	1.50	55	44	.240	.10	67	8.6	7.3	75	8.7	6.6	5.4
		1.90	38	46	10.32	11.8	7.50	61	46	.254	.69	42	8.0	6.9	105	7.6	5.7	4.9
21	50	3.06	61	66	.48	.90	.90	53	43	.250	.12	54	6.4	5.4	83	8.9	6.7	5.5
		.86	17	29	1.44	14.2	9.30	58	47	.273	7.90	26	5.8	5.0	104	7.5	5.7	4.9

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(d) Transistor 2N146; type NPN Ge

LRC pretest and post-test data					
Transistor number	I_B, µamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, µamp
22	75	1.92 .51	26 6.8	25 7.9	0.48 1.44
23	75	1.33 .24	18 3.2	17 6.4	---- ----
24	75	2.00 .26	27 3.5	28 6.1	---- ----
25	75	1.59 .35	21 4.7	17 4.8	.24 2.64
26	75	4.88 1.05	65 14	45 11	.25 4.25
27	75	1.81 .46	24 6.1	21 6.9	.50 1.50
28	75	3.47 .52	46 6.9	42 7.4	.25 1.25

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(e) Transistor 2N743; type NPN Si

LRC pretest and post-test data						Manufacturers' pretest and post-test data											
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp	I_{CBO} at V_{CB}=20 v and V_{BE}=0 v, μamp	I_{EBO} at V_{EB}=5 v, μamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_E=0.1 ma, v	V_{BE} at I_B=1.0 ma and I_C=10 ma, v	h_{FE} at V_{CE}=0.25 v and I_C=1.0 ma	h_{FE} at V_{CE}=0.35 v and I_C=10 ma	h_{fe} at V_{CE}=10 v, I_C=10 ma, and f=50 mc, db	h_{fe} at V_{CE}=10 v, I_C=10 ma, and f=100 mc, db	r'_b at V_{CE}=5.0 v, I_C=5.0 ma, and f=250 mc, ohms	C_{ob} at V_{CB}=5.0 v and f=3.5 mc, μμf	C_{ob} at V_{CB}=10 v and f=3.5 mc, μμf	C_{ob} at V_{CB}=15 v and f=3.5 mc, μμf
29	50	2.00	40	83	0.0	0.012	0.93	65	6.5	0.750	15.9	41.7	18.1	12.3	21.0	3.2	3.1	3.0
		1.72	34	70	2.4	.012	2.6	64	6.5	.755	14.1	36.9	18.2	10.8	25.0	3.2	3.0	2.9
30	50	1.28	26	41	.48	.045	.45	62	6.6	.750	14.1	38.5	17.7	12.0	21.3	3.3	3.1	3.0
		1.32	26	35	.00	.010	.80	62	6.3	.755	12.8	33.3	17.8	10.8	25.0	3.1	2.9	2.8
31	50	2.10	42	53	.0	.012	.46	69	6.4	.750	15.6	43.5	18.4	11.7	21.7	3.1	3.0	2.8
		1.86	37	40	.24	.011	.80	68	6.4	.755	14.1	38.8	18.4	11.2	23.0	3.1	2.9	2.8
32	50	2.10	42	52	.24	.011	.44	63	6.6	.740	18.5	43.5	19.0	12.3	20.4	3.5	3.3	3.1
		1.88	38	42	.24	.009	.83	62	6.3	.751	16.6	39.2	19.1	12.0	22.0	3.5	3.2	3.1
33	50	2.00	40	51	.72	.012	.33	70	6.5	.750	17.2	43.5	18.0	13.0	23.0	3.1	3.0	2.9
		1.80	36	44	.24	.010	.55	68	6.4	.755	15.1	38.5	18.2	11.0	26.0	3.1	2.9	2.8
34	50	1.92	38	49	.00	.019	.73	65	6.6	.760	13.7	40.0	18.0	12.0	21.0	3.4	3.2	3.0
		1.68	34	43	.00	.019	1.70	64	6.3	.758	12.5	35.1	18.0	11.0	22.0	3.2	3.0	2.9

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(f) Transistor 2N169A; type NPN Ge

	LRC pretest and post-test data					Manufacturers' pretest and post-test data									
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp	I_{CBO} at V_{CB}=15 v, μamp	I_{EBO} at V_{EB}=5 v, μamp	BV_{CBO} at I_C=100 μamp, v	BV_{EBO} at I_C=100 ma, v	BV_{CER} at I_C=300 μamp and R=10 k,Ω, v	h_{FE} at V_{CE}=1.0 v	h_{fe} at V_{CE}=5 v, I_E=1.0 ma, and f=270 cps	$f_{\alpha b}$ at V_{CB}=5 v and I_E=1.0 ma, mc	C_{ob} at V_{CB}=5 v, I_E=1.0 ma, and f=1.0 mc, μμf
35	75	2.53 .99	34 13	27.6 11.0	0.48 1.44	0.558 2.84	0.45 1.7	59 65	15.2 15.3	57.8 65.0	36.9 14.0	38.0 14.5	9.80 9.00	1.7 2.0
36	75	3.10 1.18	41 16	29.9 14.9	.96 1.68	.448 2.91	1.43 1.94	35.1 36.5	13.0 13.5	34.9 36.0	42.6 16.9	45.0 18.2	11.50 10.45	2.2 2.9
37	75	2.72 1.52	36 20	26.5 20.1	.48 1.44	.50 2.24	.388 1.24	53.7 58	17.3 17.3	52.9 58.0	39.7 19.9	40.0 20.4	18.1 16.1	.8 1.7
38	75	2.69 1.00	36 13	34.1 16.3	.48 1.92	.525 3.40	.420 1.84	35.8 38	15.3 15.1	35.8 38.0	39.0 13.8	39.0 13.8	10.90 9.60	1.6 2.4
39	75	2.73 1.08	36 14	29.6 15.3	.00 1.68	.548 2.90	.98 3.20	30.1 30	8.10 8.10	29.7 30.0	35.9 16.0	37.5 17.0	11.0 11.1	2.0 2.9
40	75	3.30 1.52	44 20	35.0 20.4	.96 2.40	.618 3.20	.506 1.86	40.5 44	15.5 15.0	37.6 40.0	47.3 20.2	50.5 22.0	12.1 11.8	1.7 2.6
41	75	3.43 1.51	46 20	32.2 18.5	.48 1.92	.553 2.84	1.05 1.84	35 38	15.0 14.8	34.3 35.0	51.5 21.0	53.0 21.8	14.30 12.75	1.85 1.9
42	75	2.39 .98	32 13	29.0 11.5	.24 1.92	.445 2.70	.358 1.48	41.7 44	15.2 15.0	41.0 43.0	34.7 14.3	36.0 14.9	7.90 7.80	1.6 2.5

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(g) Transistor 2N337; type NPN Si

LRC pretest and post-test data					
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp
43	50	2.59 .43	52 8.6	56 11	0.0 .24
44	50	3.44 .32	69 6.4	57 6.5	.0 .24
45	50	3.88 .61	78 12	61 10.6	.48 ----
46	50	3.88 .67	78 13	61 11	---- ----
47	50	3.92 .65	78 13	65 10.3	.48 ----

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(h) Transistor 2N526; type PNP Ge

LRC pretest and post-test data						Manufacturers' pretest and post-test data									
Transistor number	I_B, µamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, µamp	I_{CBO} at V_{CB}=30 v, µamp	I_{EBO} at V_{EB}=15 v, µamp	BV_{CBO} at I_E=100 µamp, v	BV_{EBO} at I_E=200 ma, v	BV_{CER} at I_C=600 µamp and R=10 k,Ω, v	h_{FE} at I_C=20 ma and V_{CE}=1.0 v	h_{fe} at I_C=1.0 ma, V_{CE}=5.0 v, and f=1 kc	$f_{\alpha b}$ at I_E=1.0 ma and V_{CB}=5 v	V_{PT}, v	C_{ob} at I_E=1.0 mc, V_{CB}=5.0 v, and f=1 mc, µµf
48	70	4.41 .70	63 10	70.0 13.7	2.16 17.52	2.66 32.0	1.88 13.2	72 80	74 78	40 30	66.1 28.5	53.0 21.5	4.00 3.49	79 58	20.3 18.0
49	70	4.06 .74	58 11	61 14	1.92 14.88	3.41 33.1	2.16 12.6	83.1 70	72.7 61	37.8 27.5	64.8 29.4	54.5 22.0	4.51 3.71	40 32	19.6 18.4
50	70	4.99 .79	71 11	82 16.5	1.92 17.04	3.40 45.0	1.60 16.2	60 58	95 100	34 23.5	75.5 27.5	63.0 21.4	4.15 3.59	46 35	20.9 18.8
51	70	4.49 .71	64 10	69 12.5	1.92 20.16	3.10 42.0	1.55 16.6	87 68	92 100	39 26.3	65.6 25.7	59.0 21.4	3.20 2.74	94 72	21.9 20.4
52	70	4.98 .80	71 11	85 13.8	1.92 7.20	2.85 41.9	1.52 14.2	74 62	84 100	37 23.7	61.1 30.0	48.0 22.1	5.13 3.31	47 55	20.6 21.0
53	70	3.56 1.12	51 16	60 21	1.68 27.84	3.13 36.5	1.78 13.8	94 78	84 100	37 20	61.1 30.1	48.0 23.0	5.13 4.51	47 38	20.6 19.0
54	70	5.73 1.24	82 18	86 25	2.16 17.76	3.50 31.8	1.82 12.8	86 82	88 100	37 25	80.6 38.1	68.0 29.9	4.27 3.80	40 32	18.4 17.6
55	70	5.26 .88	75 13	91 14	1.92 20.64	3.44 40.0	1.93 16.6	88.7 76	94.4 100	45 23	75.2 30.2	68.0 24.4	3.55 3.13	86 64	18.6 16.7

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(i) Transistor 2N128; type PNP Ge

LRC pretest and post-test data						Manufacturers' pretest and post-test data						
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_E=0.1 ma, v	h_{FE} at V_{CB}=0.5 v and I_C=3.0 ma	f_t at V_C=3.0 v and I_C=0.5 ma, mc	r'_bC_{ob} at V_C=3.0 v and I_C=0.5 ma, μμsec	V_{PT}, v	C_{ob} at V_C=3.0 v, I_C=0.5 ma, and f=4 mc, μμf
56	30	1.04 1.20	35 40	30.8 34.4	0.25 1.00	27 26	36 35	19 18	68.2 57.2	520 620	8.5 7.9	2.8 3.3
57	30	1.04 1.12	35 37	30.0 31.4	.00 .96	21 20	34 33	19 17	66.2 42.0	670 730	13 11	3.2 3.9
58	30	1.07 1.23	36 41	32.8 35.1	.48 .96	20 18	22 21	19 19	72.6 44.6	610 700	9.2 8.0	2.3 2.7
59	30	1.14 1.29	38 43	32.4 31.2	.50 1.00	20 16	25 23	19 20	63.8 78.1	645 640	10.5 13.8	2.3 3.0
60	30	1.08 1.37	36 46	37.8 39.0	1.00 2.00	22 23	27 26	19 18	66.5 31.2	525 740	9.0 8.2	2.9 3.4
61	30	1.008 1.116	34 37	31.6 31.0	.00 1.00	20 19	30 29	18 18	72.6 46.5	690 790	10.9 9.3	2.8 3.2

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Continued

(j) Transistor 2N224; type PNP Ge

LRC pretest and post-test data						Manufacturers' pretest and post-test data						
Transistor number	I_B, µamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, µamp	BV_{CBO} at I_C=0.1 ma, v	BV_{EBO} at I_C=0.1 ma, v	h_{FE} at V_C=0.6 v and I_C=100 ma	$f_{\alpha b}$ at I_C=3.0 ma and V_C=5.0 v, mc	r'_bC_{ob} at V_C=3.0 v, I_E=0.5 ma, and f=4 mc, µµsec	V_{PT}, v	C_{ob} at V_C=3.0 v, I_E=0.5 ma, and f=4 mc, µµf
62	60	7.06 4.20	117 70	118 13	----- -----	26 15	35 .4	108 1.7	1.39 .71	2,400 110	25 78	60 34
63	60	7.86 .86	131 12	126 15	5.86 42.5	24.0 1.5	42 44	110 4.7	1.05 .72	2,250 170	25 34	60 37
64	60	5.04 1.68	84 28	145 24	4.08 53.2	20 22	32 37	108 8.1	.97 .78	2,250 190	25 34	60 37
65	60	7.48 2.32	125 39	149 23	----- -----	36 42	28 32	108 36	1.07 1.01	1,950 3,100	25 80	61 37
66	60	8.80 3.04	147 51	142 18	----- -----	34 41	32.0 .4	114 11	1.00 .79	1,950 2,350	25 80	59 12
67	60	7.64 2.96	127 49	160 14.3	5.28 -----	28 41	16.0 .3	111 1.0	1.15 .53	2,450 120	25 80	61 33
68	60	8.20 3.76	137 63	163 13.8	----- -----	30 41	34.0 .1	111 2.0	1.05 .52	2,300 120	25 65	61 30

TABLE II.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE UNIVERSITY OF MINNESOTA'S 40 MEV LINAC ACCELERATOR WITH A TOTAL FLUX OF 1.8×10^{12} PROTONS/CM^2 - Concluded

(k) Transistor 2N859; type PNP Si

	LRC pretest and post-test data					Manufacturers' pretest and post-test data							
Transistor number	I_B, μamp	I_C at V_{CE}=4 v, ma	h_{FE} at V_{CE}=4 v	h_{fe} at V_{CE}=4 v and f=100 cps	I_{CBO} at V_{CB}=4 v, μamp	BV_{CBO} at I_C=0.01 ma, v	BV_{EBO} at I_C=0.01 ma, v	h_{FE} at V_C=0.5 v and I_C=5.0 ma	f_{max} at V_C=6.0 v and I_E=1.0 ma, mc	r'_b at V_C=6.0 v and f=10 mc, ohms	r'_bC_{ob} at V_C=6.0 v, f=10 mc, and I_E=1.0 ma, μμsec	V_{PT}, v	C_{ob} at V_C=6.0 v, I_E=0 v, and f=4 mc, μμf
69	50	2.35 .24	47 4.8	64 11.1	0.00 .00	67 65	78 75	32 10	15.6 18.1	30.3 ----	130.5 116.0	40 57	4.3 5.0
70	50	2.41 .49	48 9.8	66 15.5	.24 .24	74 75	82 80	33 15	22.5 22.0	33.1 ----	116.0 188.5	40 43	3.5 4.1
71	50	2.28 .33	46 6.6	41 6.8	.48 .72	62 65	70 70	32 8.5	26.9 24.2	28.3 ----	116.0 188.5	40 51	4.1 4.6
72	50	2.36 .16	47 3.2	42 6.7	.00 .00	64 63	57 55	32 7.5	27.5 27.0	37.3 ----	130.5 174.0	40 47	3.5 4.2
73	50	2.48 .26	50 5.2	44 8.2	.00 .24	59 58	56 55	32 9.1	24.7 24.8	37.2 ----	145.0 174.0	40 63	3.9 4.4
74	50	2.11 .47	42 9.4	46 15	.00 .00	65 50	76 75	32 14	25.3 30.5	35.3 ----	130.5 174.0	40 39	3.7 4.3
75	50	2.38 .15	48 3.0	43 5.6	.00 .00	70 65	74 70	33 7.7	22.5 23.5	29.7 ----	116.0 154.5	40 49	3.9 4.4

TABLE III.- PRETEST AND POST-TEST DATA ON TRANSISTORS IRRADIATED AT THE CARNEGIE INSTITUTE OF TECHNOLOGY'S 440 MEV SYNCHROCYCLOTRON

Transistor	Transistor number	Total flux, protons per cm^2	I_B, μamp	I_C at V_{CE}=4 v, ma		Δhfe, percent	I_{CBO} at V_{CB}=4 v, μamp	
				Before	After		Before	After
2N169A	1	1.90×10^{11}	75	3.56	3.12	-1.9	0.70	0.00
	2	2.63	75	2.96	2.76	-2.0	.00	.00
	3	3.46	75	3.84	3.60	-2.3	.00	.00
	4	4.10	75	3.16	2.60	-7.4	.00	.00
2N1302	5	9.96	30	6.24	5.76	-3.0	2.20	2.20
	6	2.20	30	5.90	5.60	-3.0	1.40	1.40
	7	2.63	30	6.08	5.15	-11.3	.70	.70
2N393	8	5.50	20	3.04	3.22	-1.7	.00	.35
2N146	9	3.41	75	3.84	3.72	-3.0	.70	.70
	10	4.08	75	3.80	3.04	-8.8	.00	.00
	11	5.07	75	3.16	2.31	-1.1	.00	.00
2N128	12	3.21	30	1.16	1.18	.0	.00	.37
	13	3.91	30	1.38	1.36	-3.6	.37	.74
	14	4.90	30	1.02	1.04	-1.0	.36	.72
2N224	15	5.37	75	6.17	3.79	-42.0	4.82	17.78
	16	6.36	75	7.16	4.68	-34.0	3.93	14.64
	17	7.35	75	6.33	4.10	-32.4	5.00	17.31
2N1303	18	2.42	50	3.44	3.62	.0	.72	1.45
	19	3.42	50	6.40	7.08	-3.1	.72	1.10
	20	4.42	50	6.40	6.44	-5.0	1.85	2.59

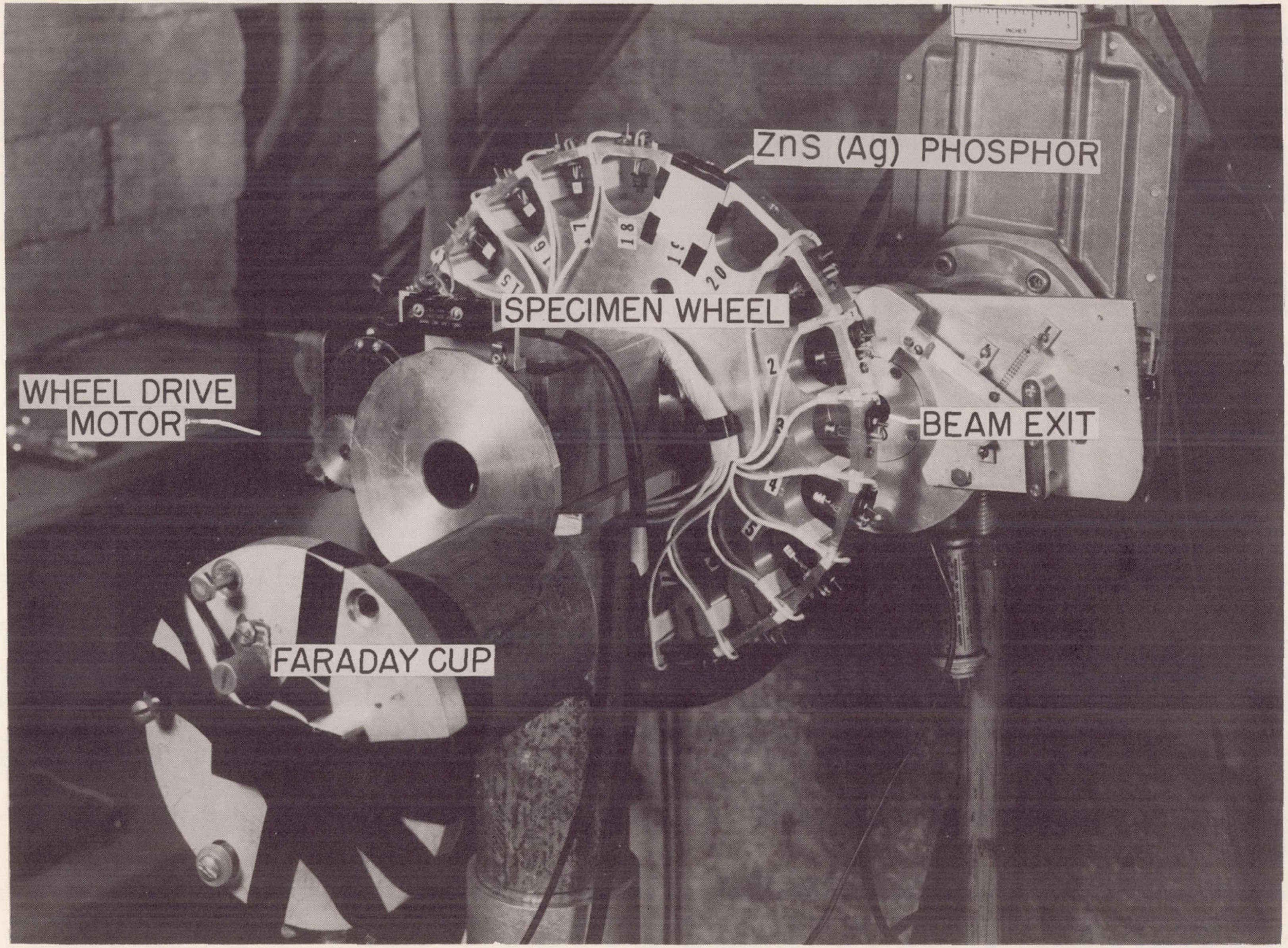
TABLE IV.- MAXIMUM TOLERANCE FLUX FOR TRANSISTORS IRRADIATED AT 40 MEV

[Maximum tolerance flux is defined as that flux at which $h_{fe}/h_{fe,o} = 0.7$]

Transistor	Maximum tolerance flux, (protons/cm^2)	Nominal frequency, mc
2N1302 (Ge)	5.0×10^{11}	4.5
2N1303 (Ge)	18.0	4.5
2N1305 (Ge)	5.0	8
2N146 (Ge)	2.0	------
2N743 (Si)	18.0	[a]400
2N169A (Ge)	7.0	9
2N337 (Si)	1.5	30
2N526 (Ge)	6.5	3
2N128 (Ge)	18.0	[b]60
2N224 (Ge)	1.5	.5
2N859 (Si)	2.5	[b]14

[a]Frequency at which $h_{fe} = 1$ or f_t.

[b]Maximum frequency of oscillation, f_{max}.



L-62-1017

Figure 1.- Experimental setup used during irradiation tests conducted at the University of Minnesota.

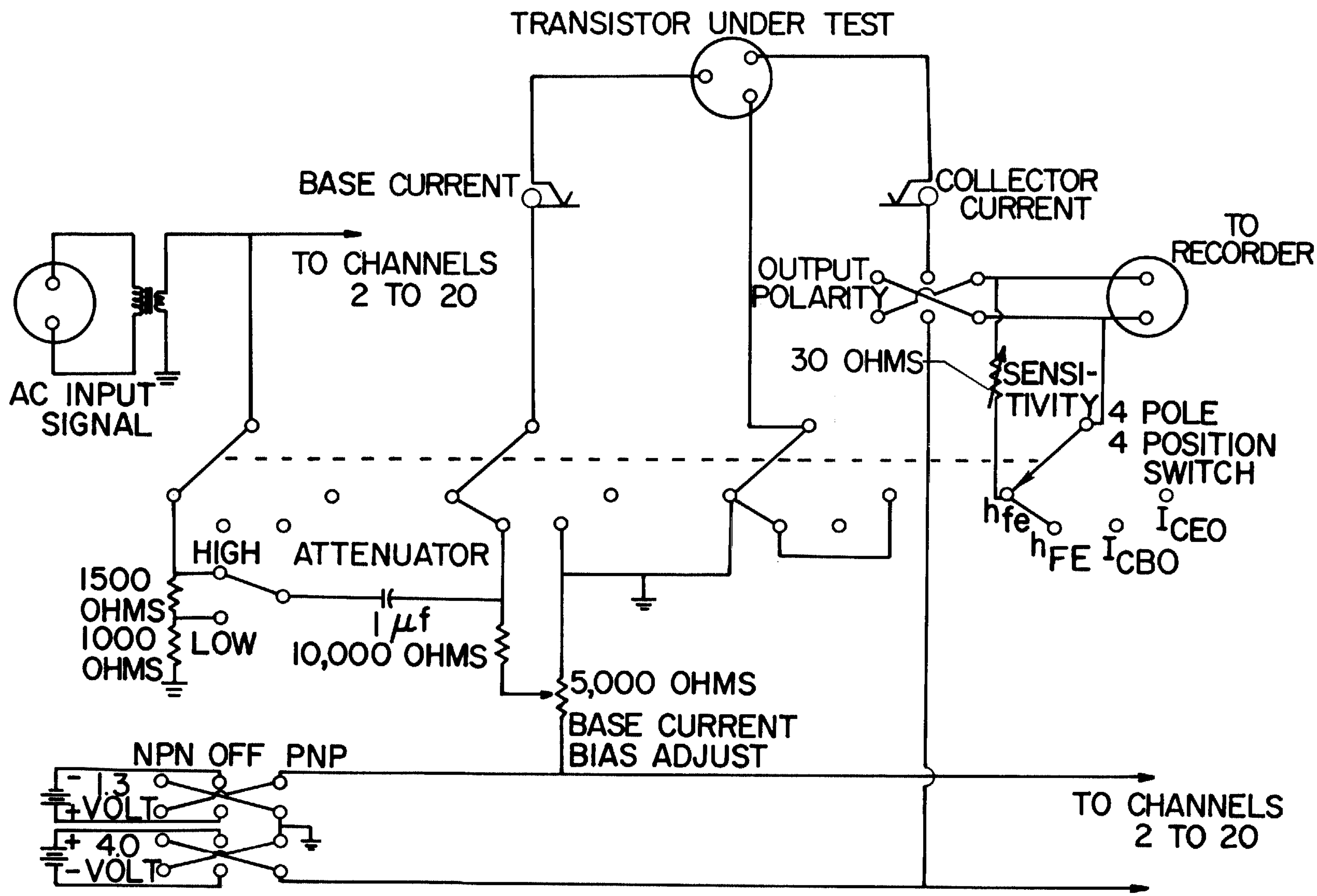


Figure 2.- Wiring diagram for transistor control unit used in University of Minnesota and Carnegie Institute irradiation experiments. Channel 1 of 20 channels.

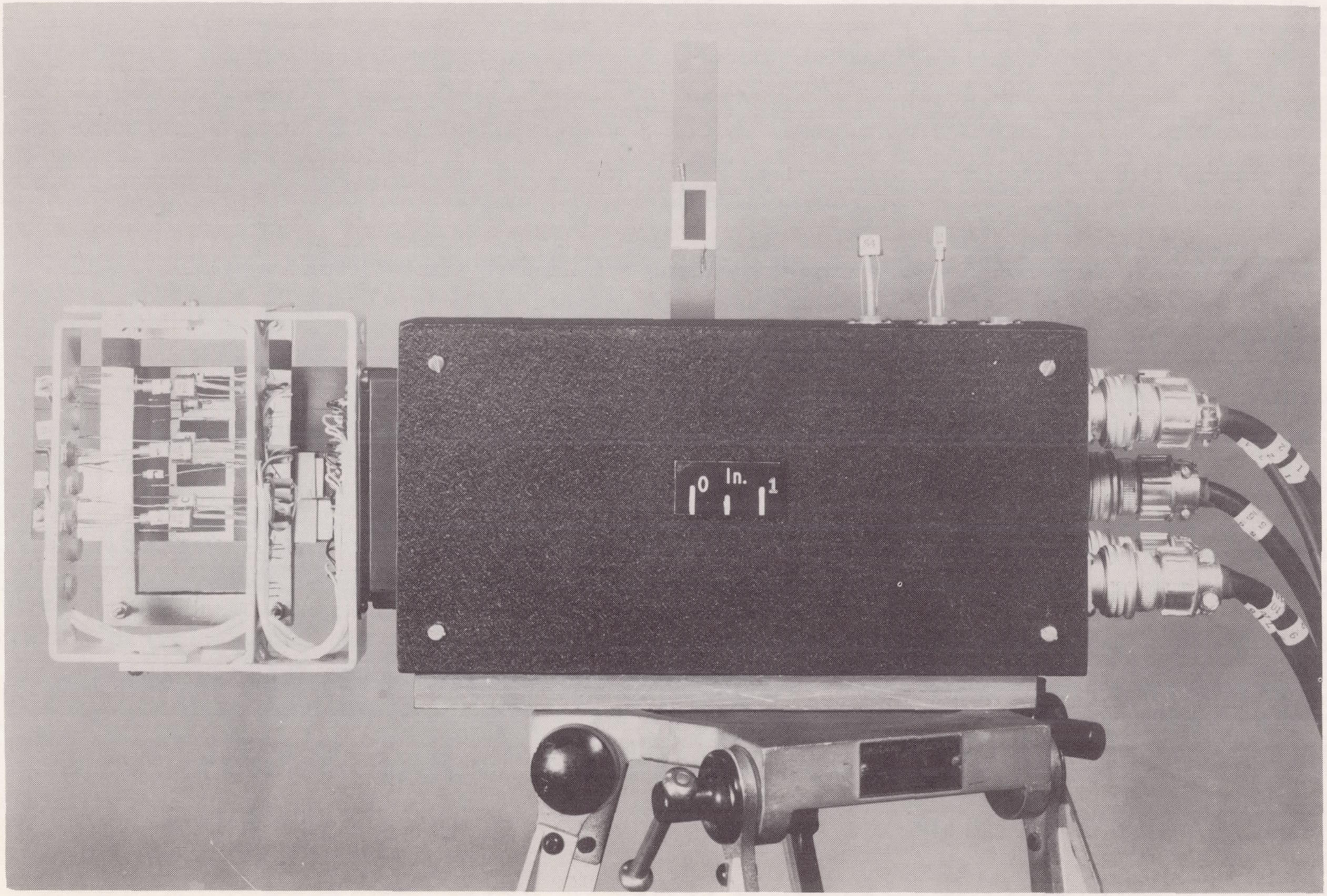


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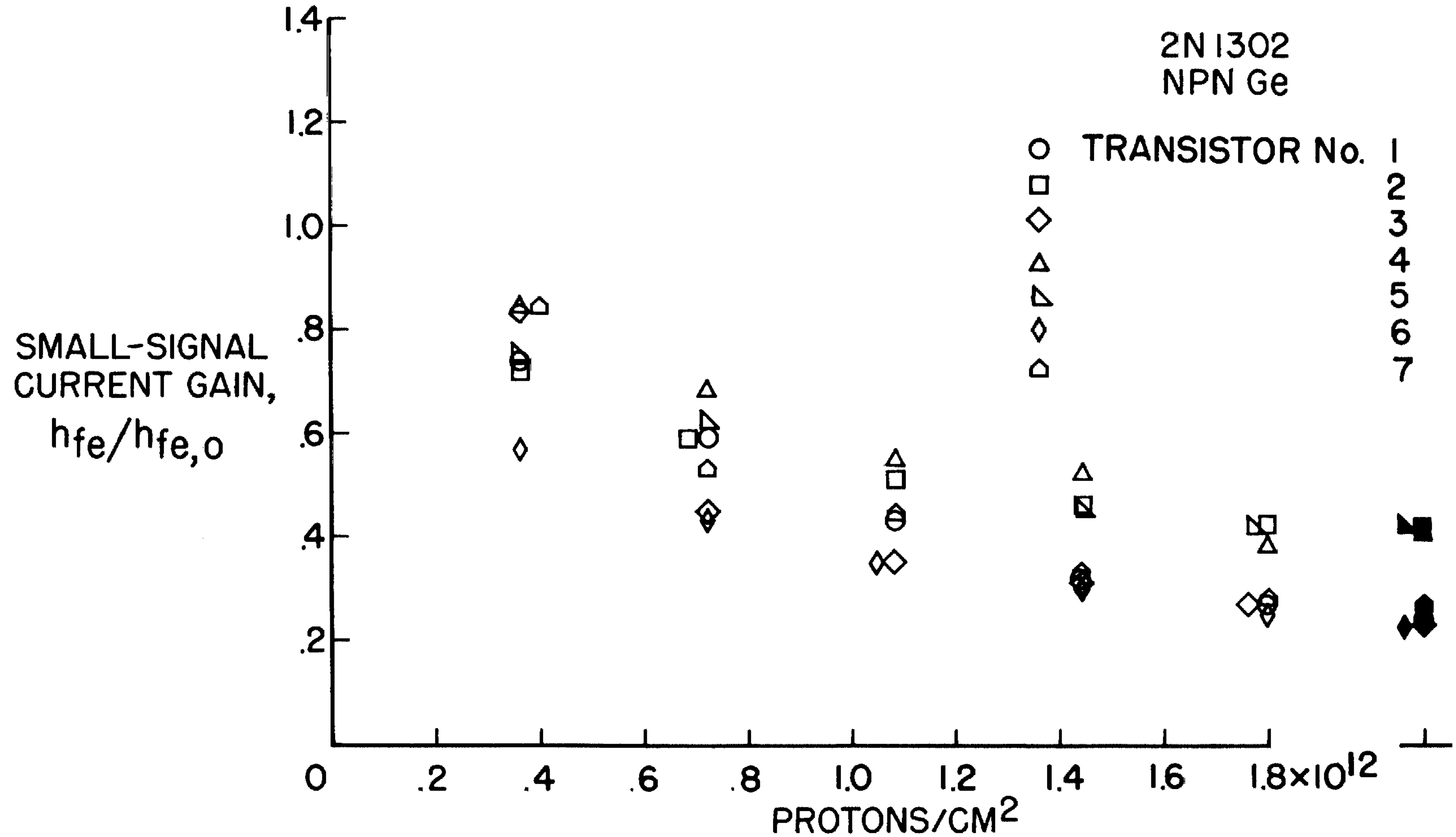
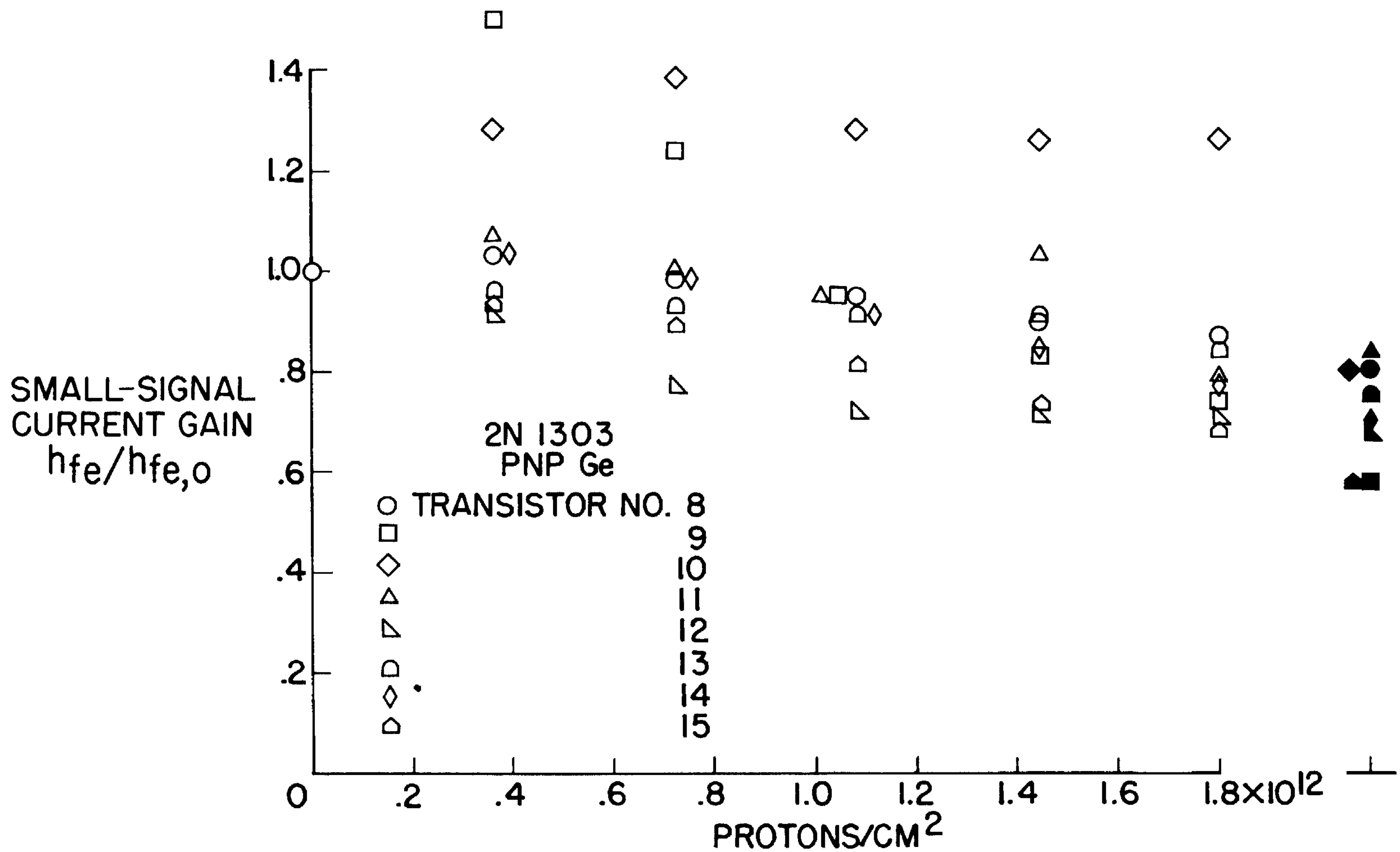
Figure 3.- Specimen mounting technique used during irradiation experiment at the Carnegie Institute of Technology.



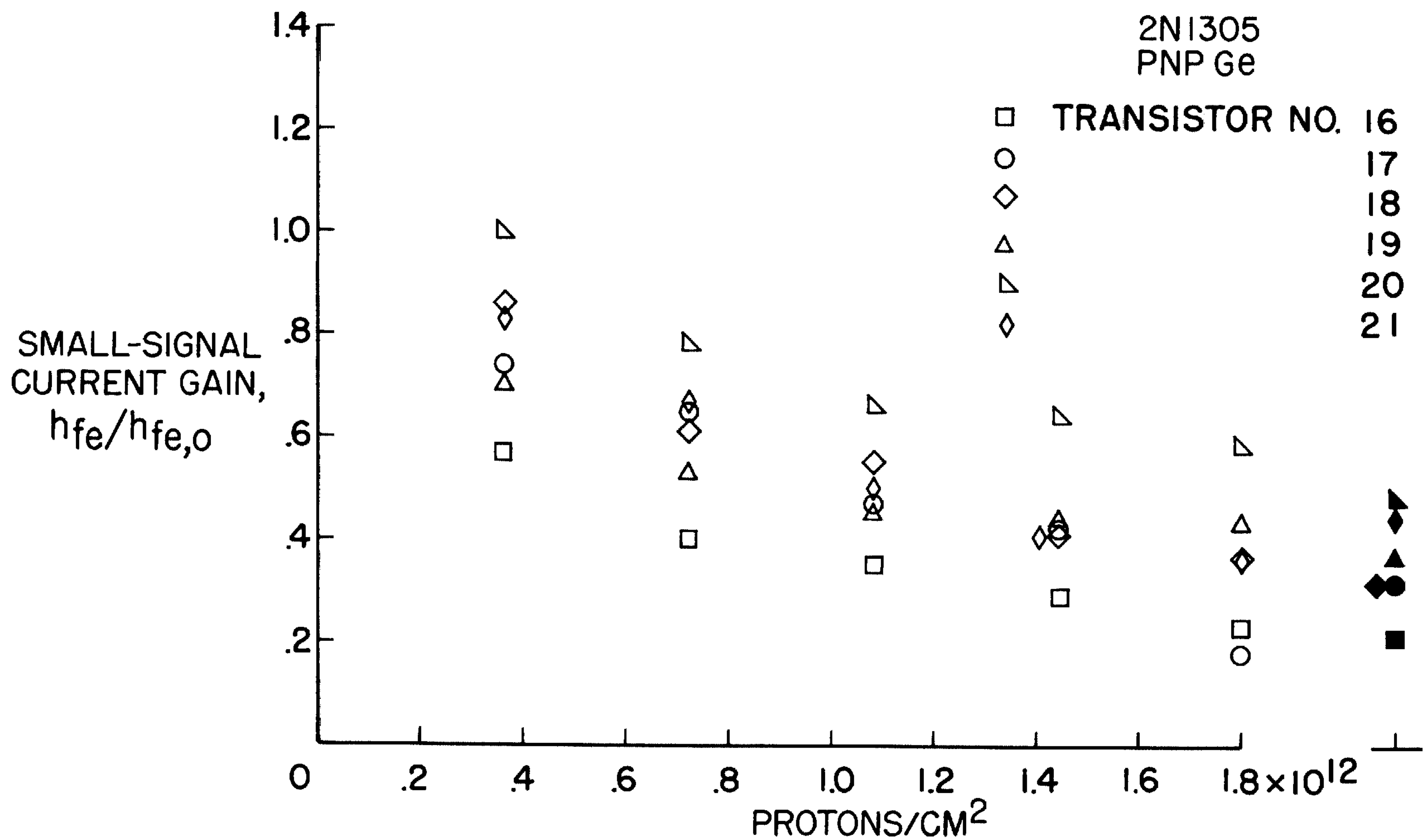
(a) Transistor 2N1302; type NPN Ge.

Figure 4.- Variation of transistor small-signal current gain with integrated flux in a 40 Mev proton beam. Filled-in symbols indicate postirradiation measurements.



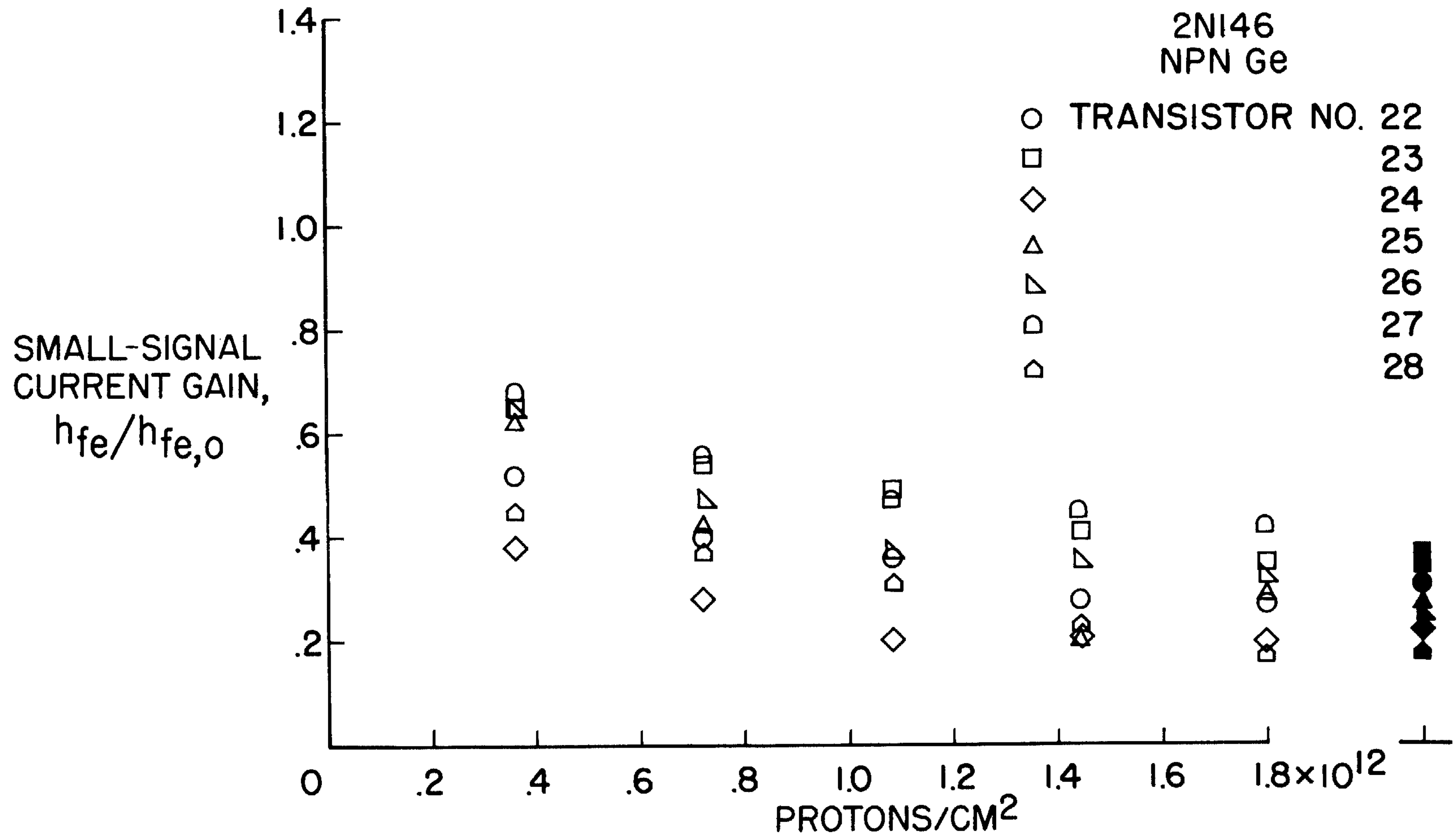
(b) Transistor 2N1303; type PNP Ge.

Figure 4.- Continued.



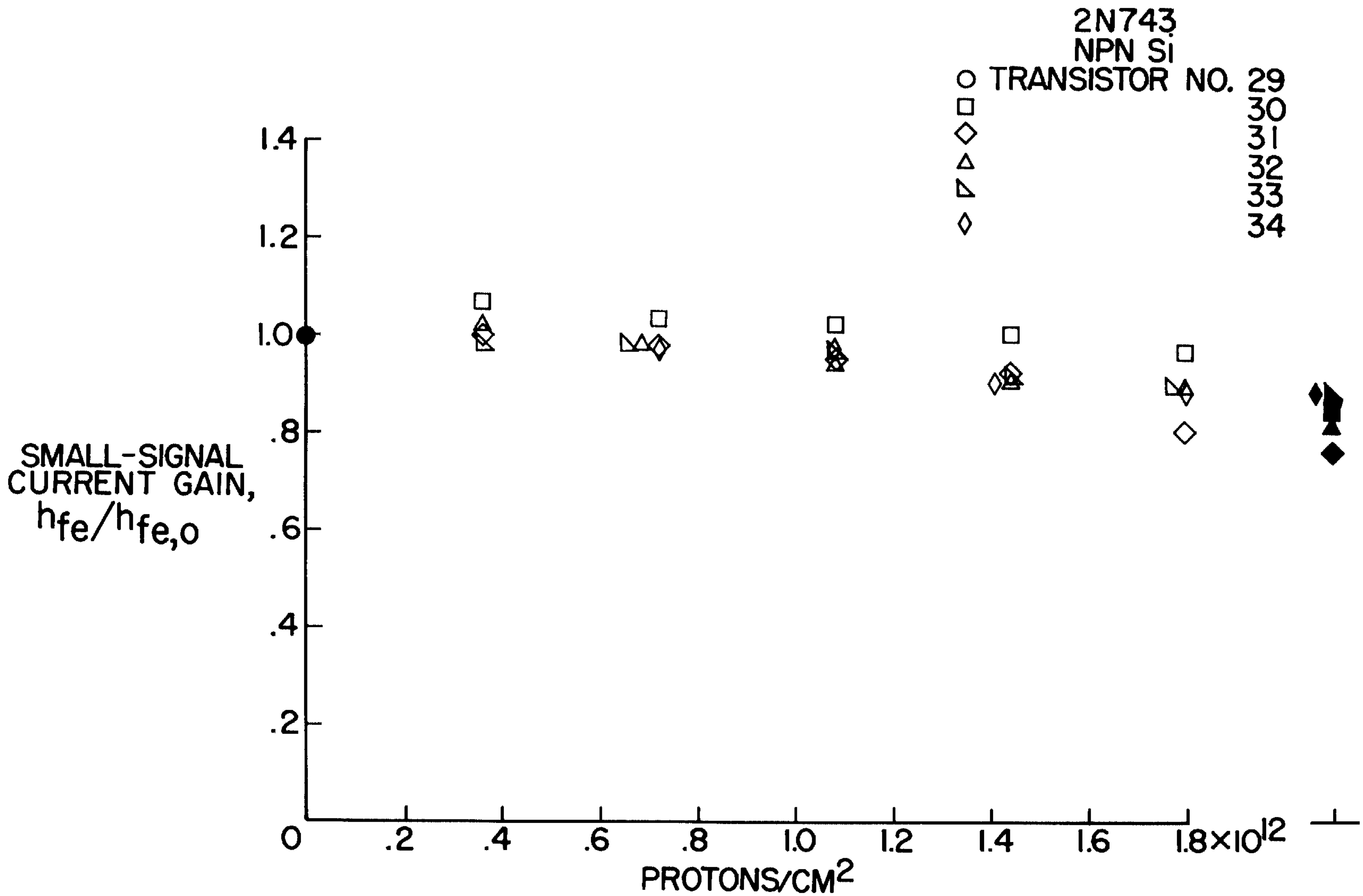
(c) Transistor 2N1305; type PNP Ge.

Figure 4.- Continued.



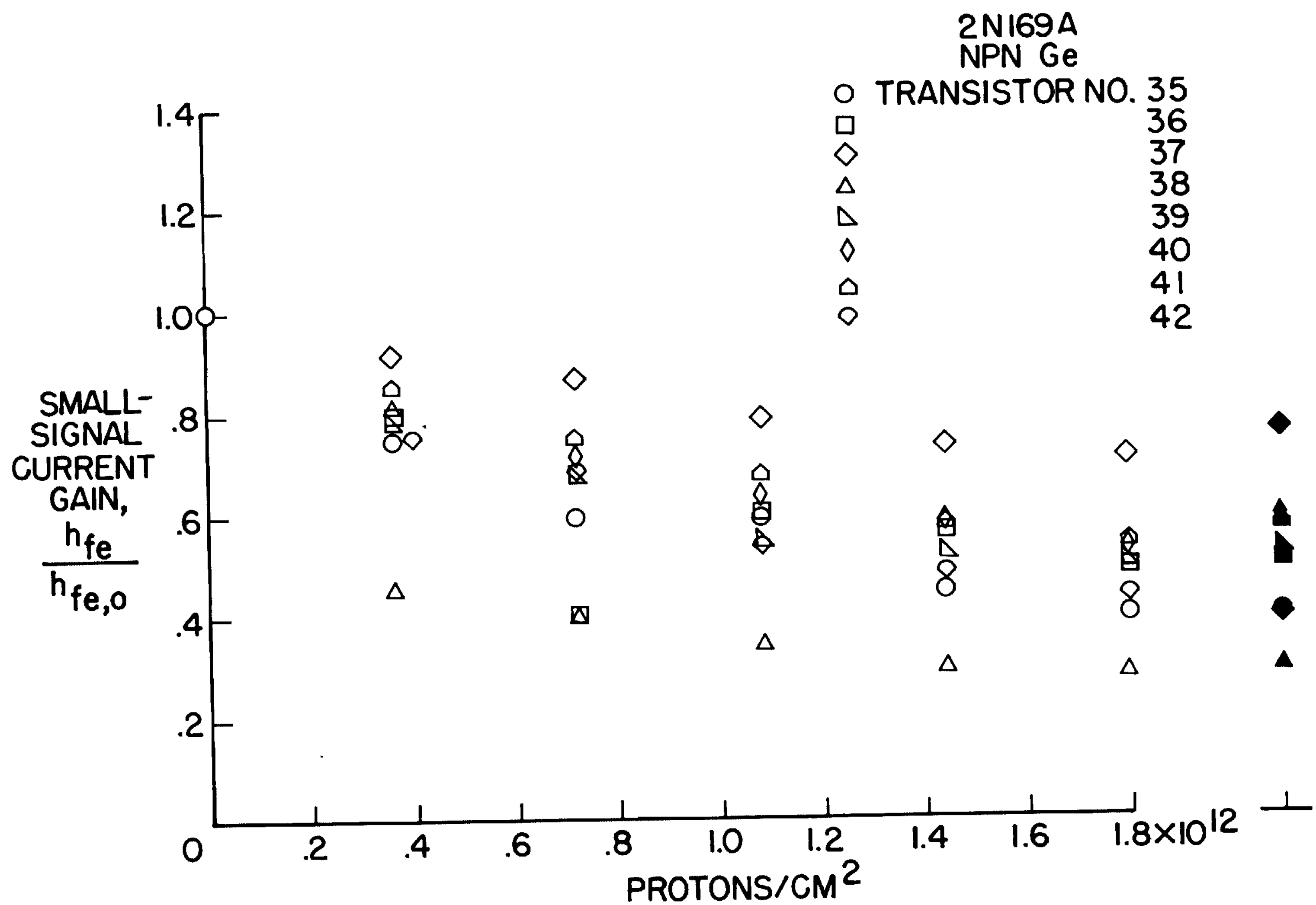
(d) Transistor 2N146; type NPN Ge.

Figure 4.- Continued.



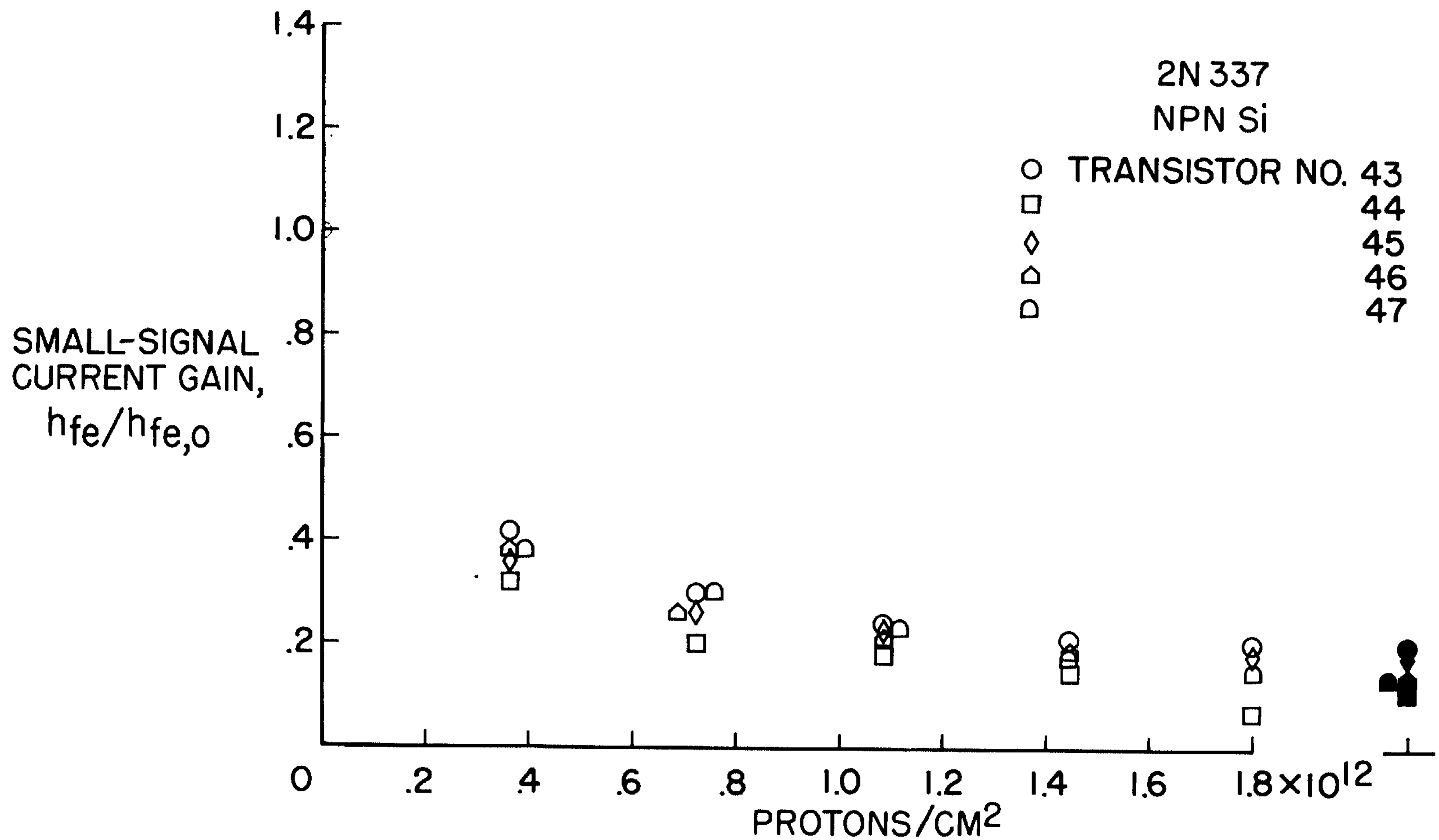
(e) Transistor 2N743; type NPN Si.

Figure 4.- Continued.



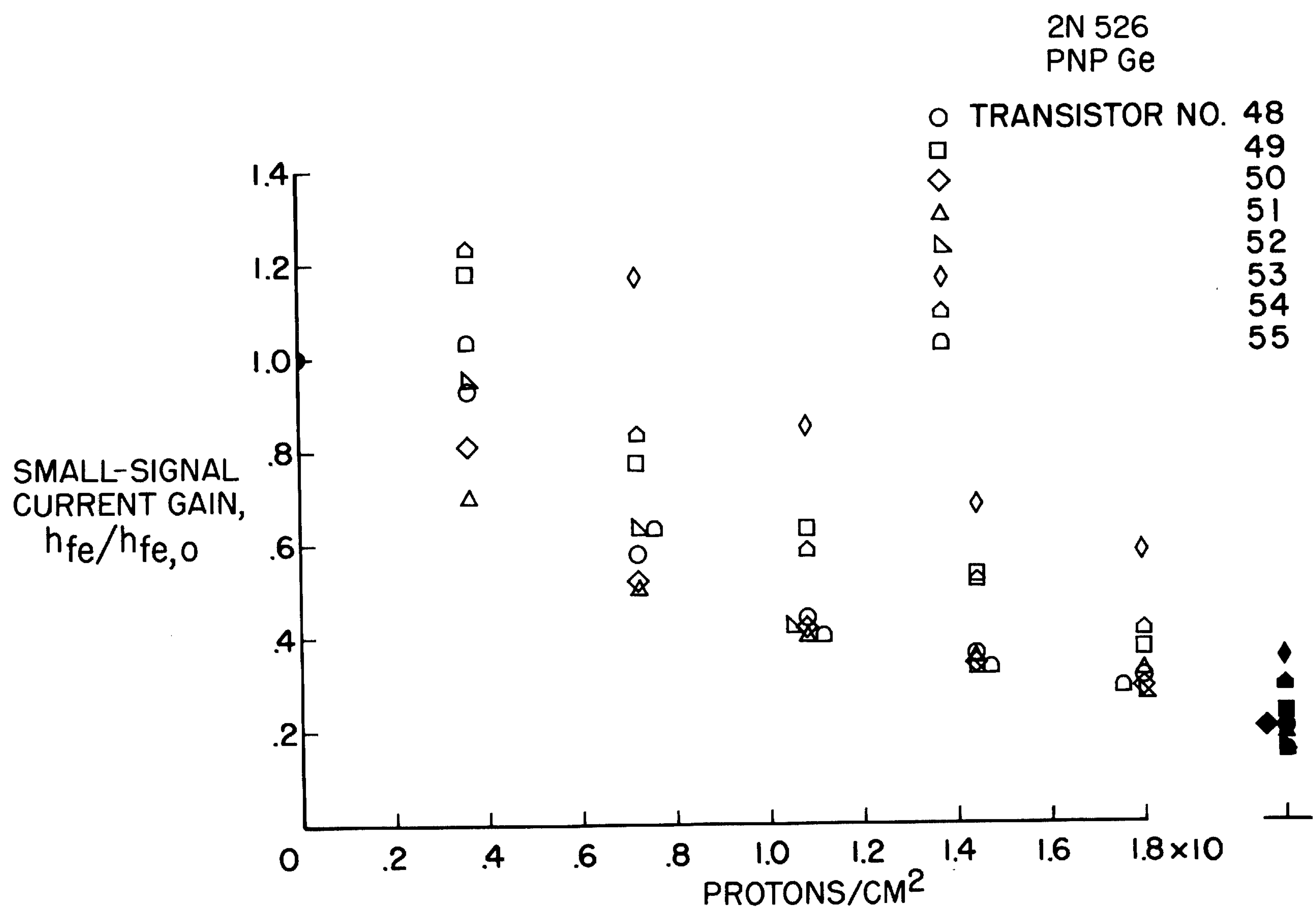
(f) Transistor 2N169A; type NPN Ge.

Figure 4.- Continued.



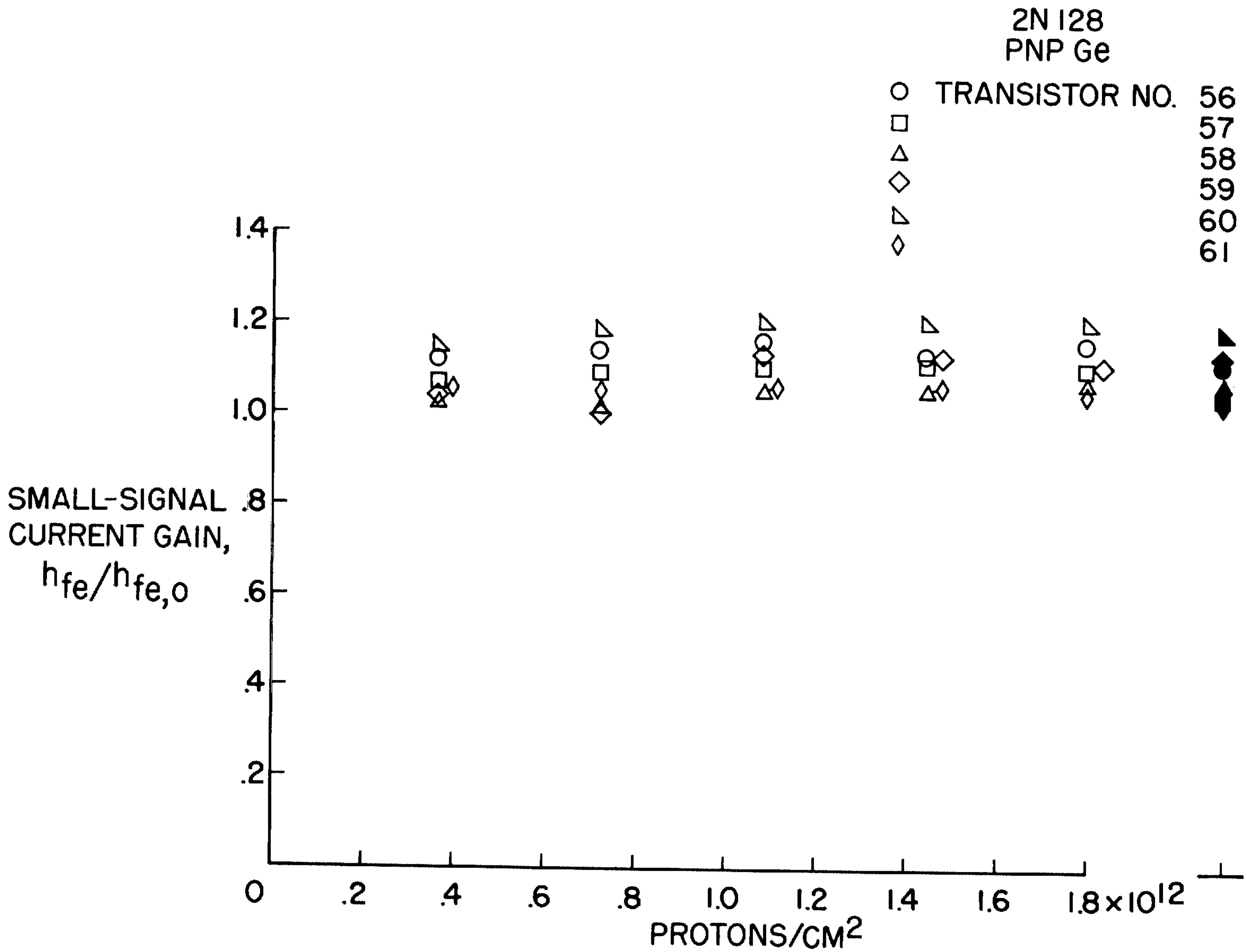
(g) Transistor 2N337; type NPN Si.

Figure 4.- Continued.



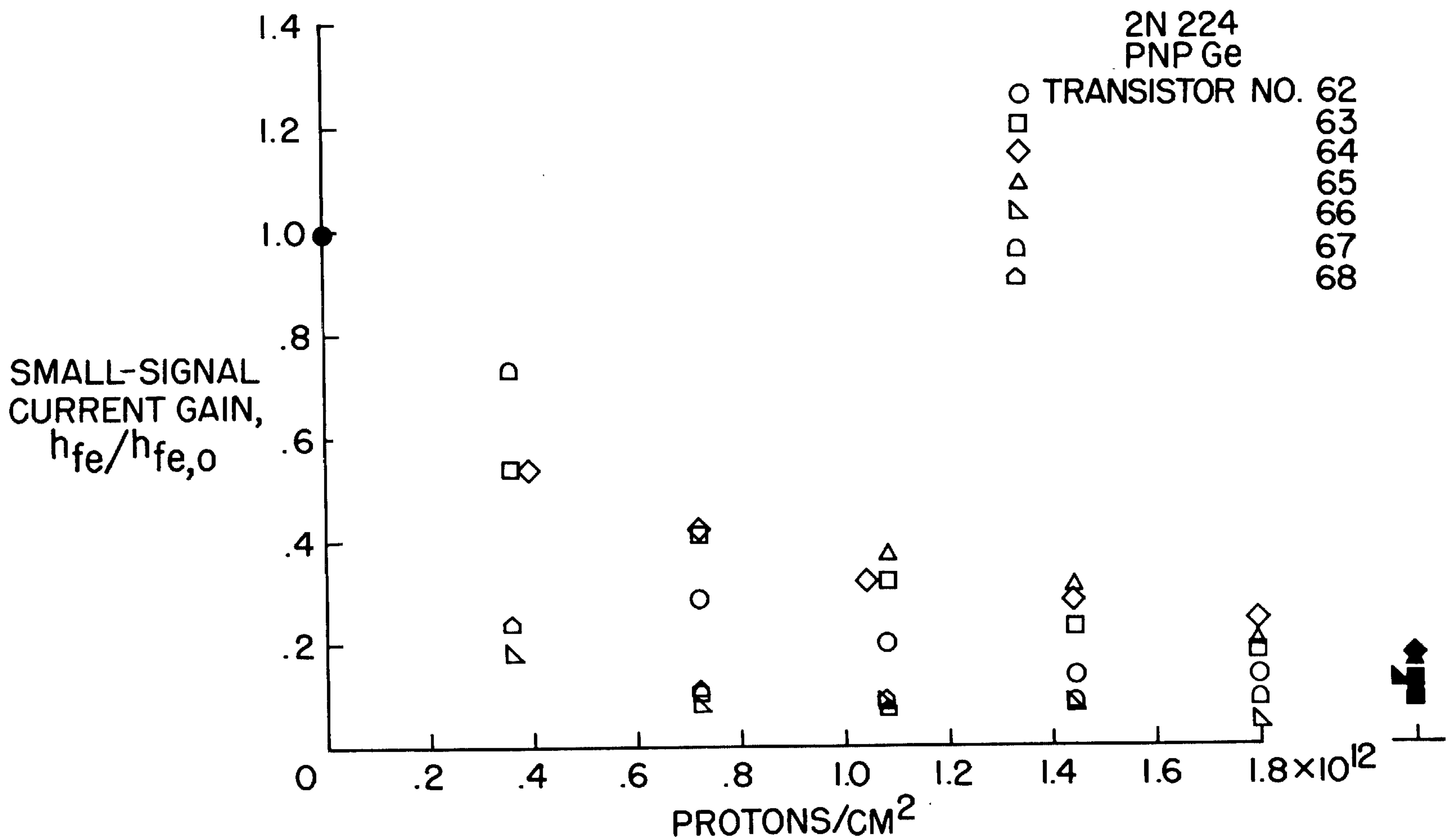
(h) Transistor 2N526; PNP Ge.

Figure 4.- Continued.



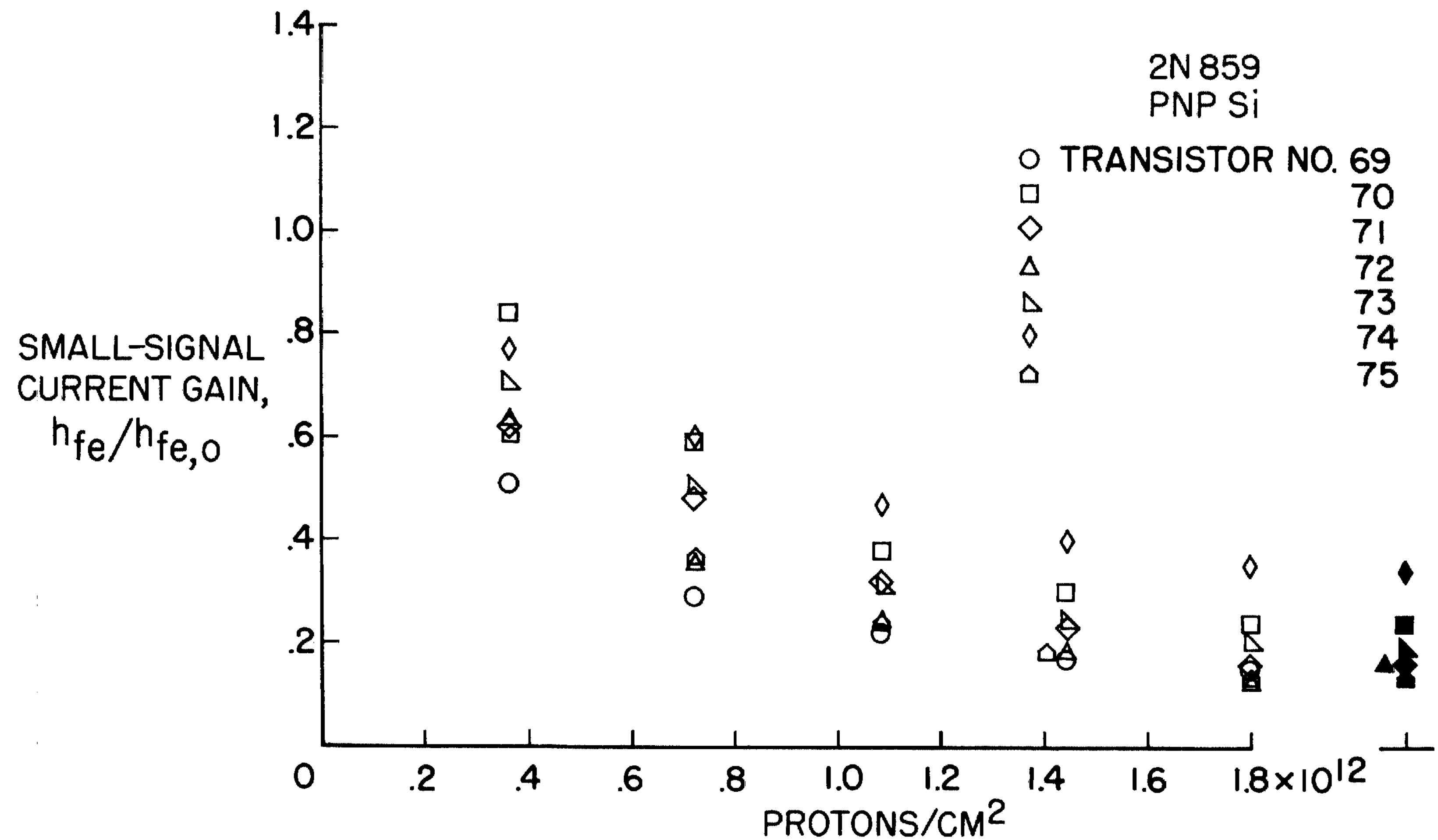
(i) Transistor 2N128; type PNP Ge.

Figure 4.- Continued.



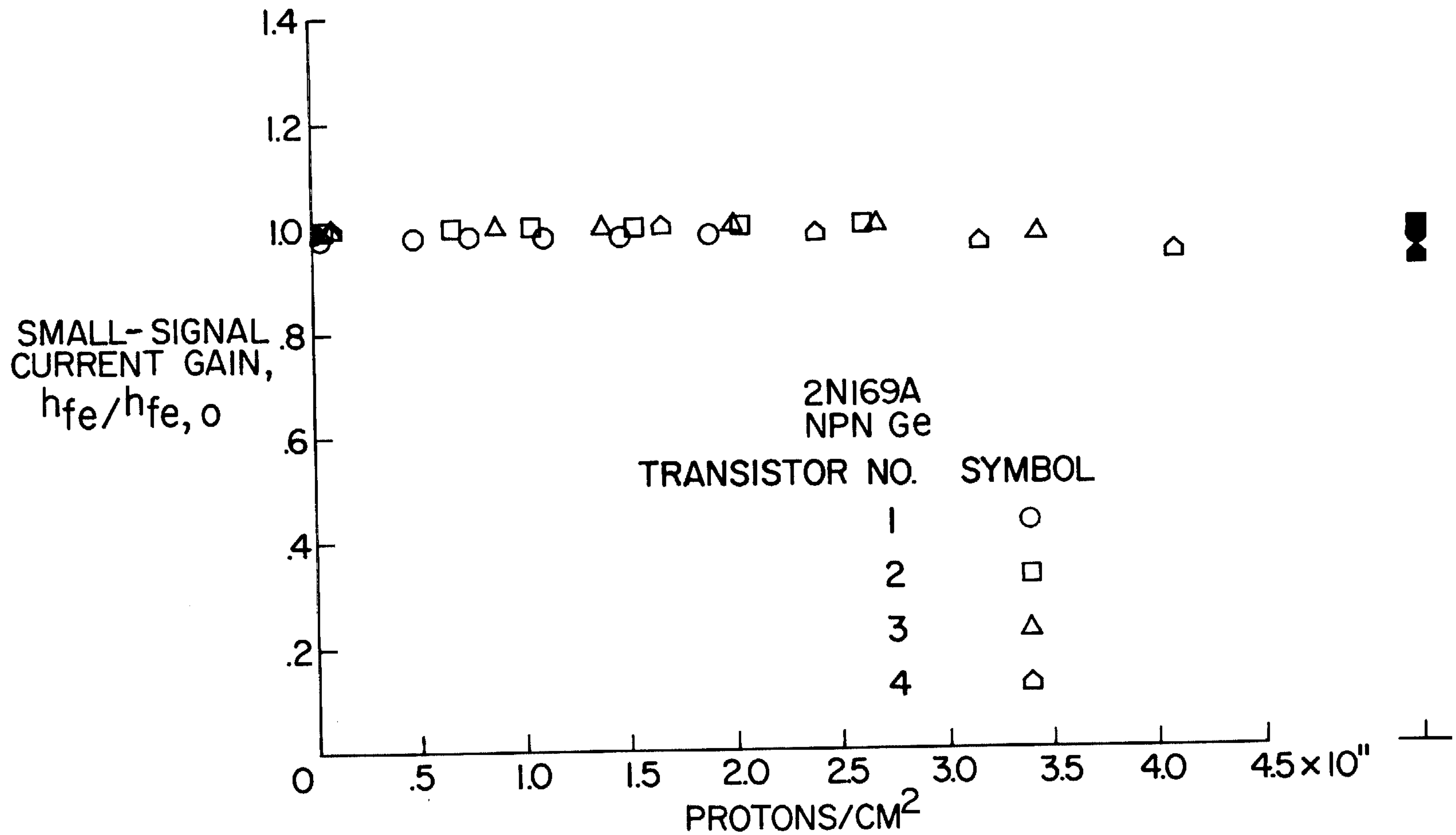
(j) Transistor 2N224; type PNP Ge.

Figure 4.- Continued.



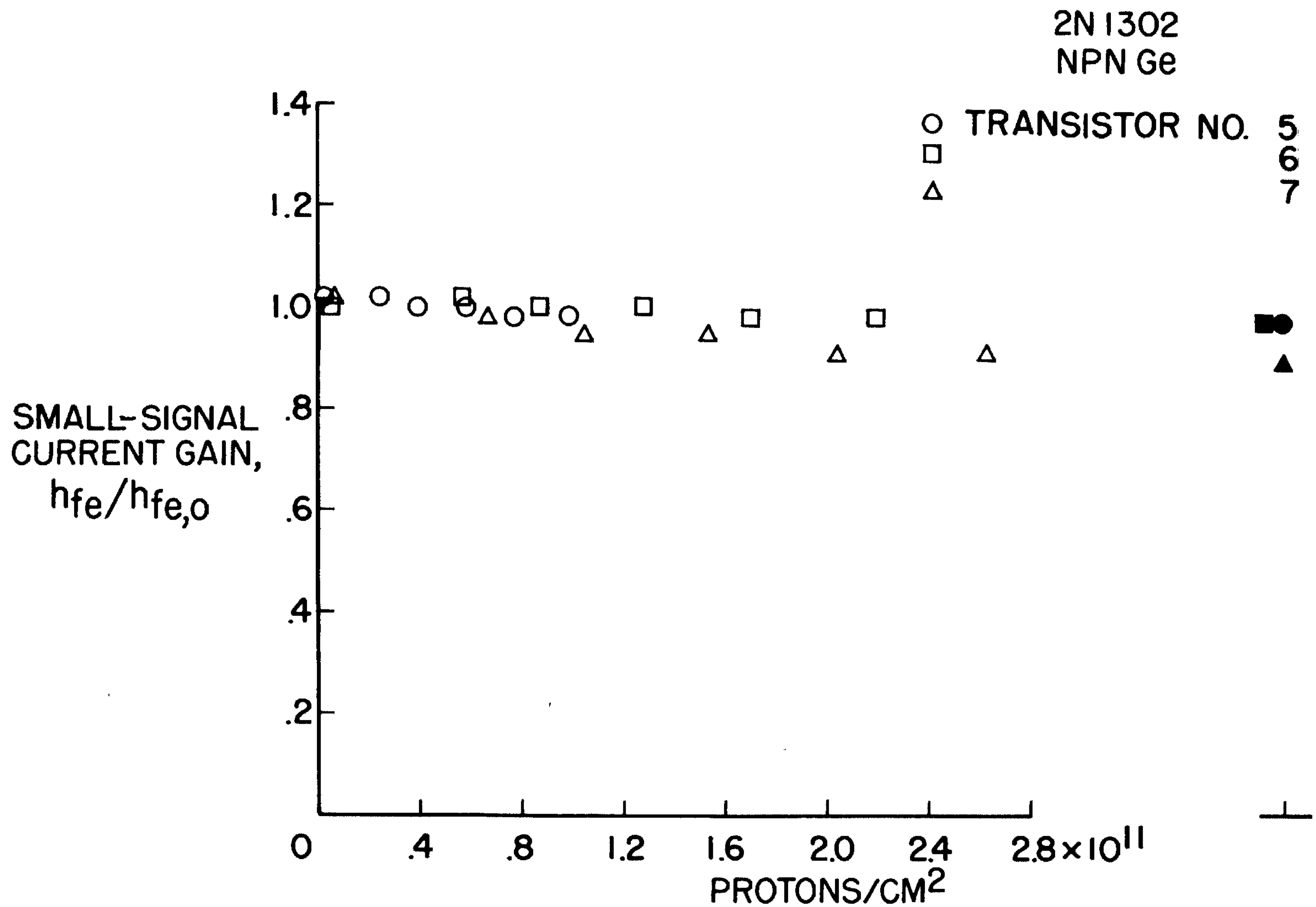
(k) Transistor 2N859; PNP Si.

Figure 4.- Concluded.



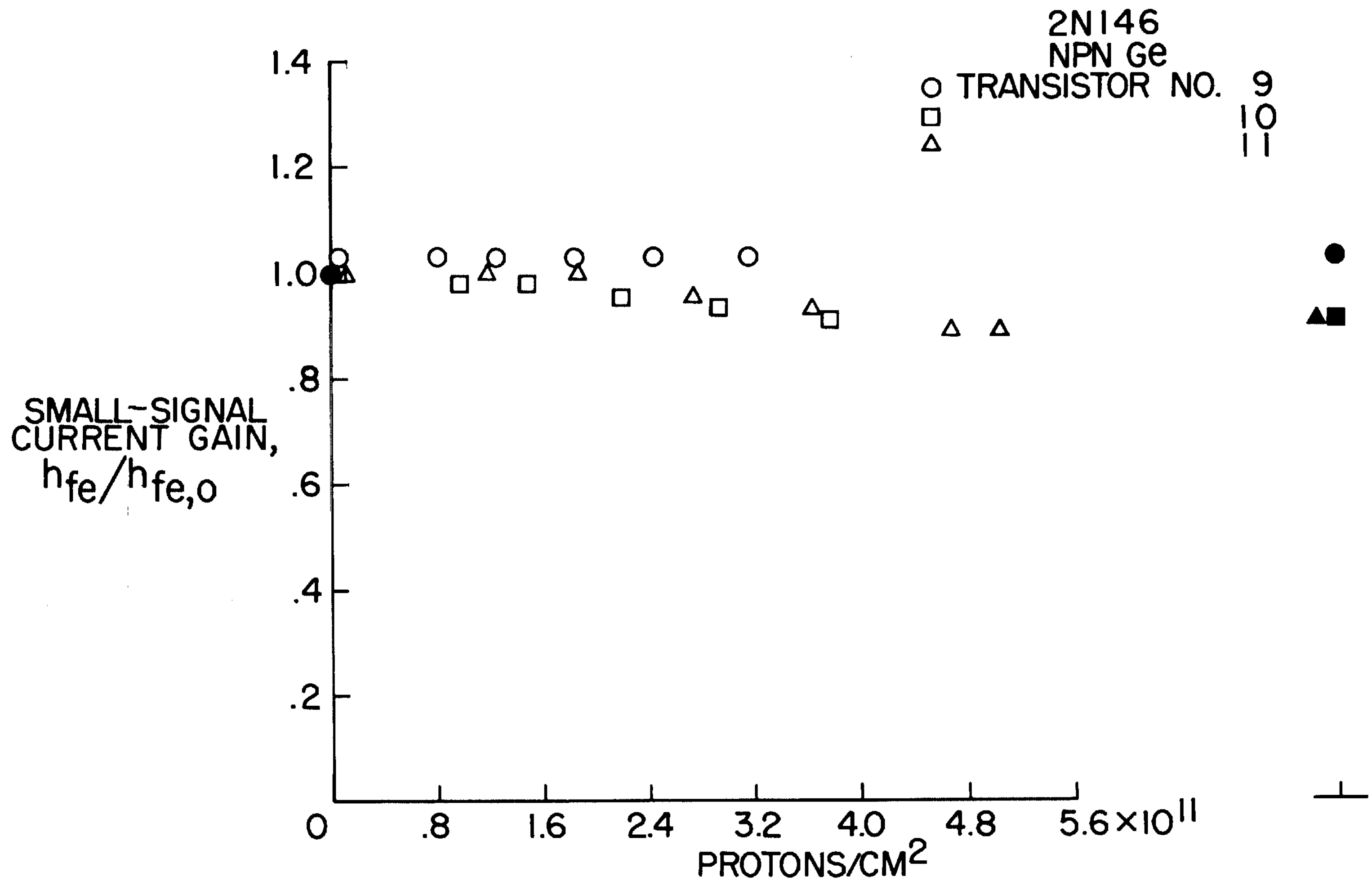
(a) Transistor 2N169A; type NPN Ge.

Figure 5.- Variation of transistor small-signal current gain with integrated flux in a 440 Mev proton beam. Filled-in symbols indicate postirradiation measurements.



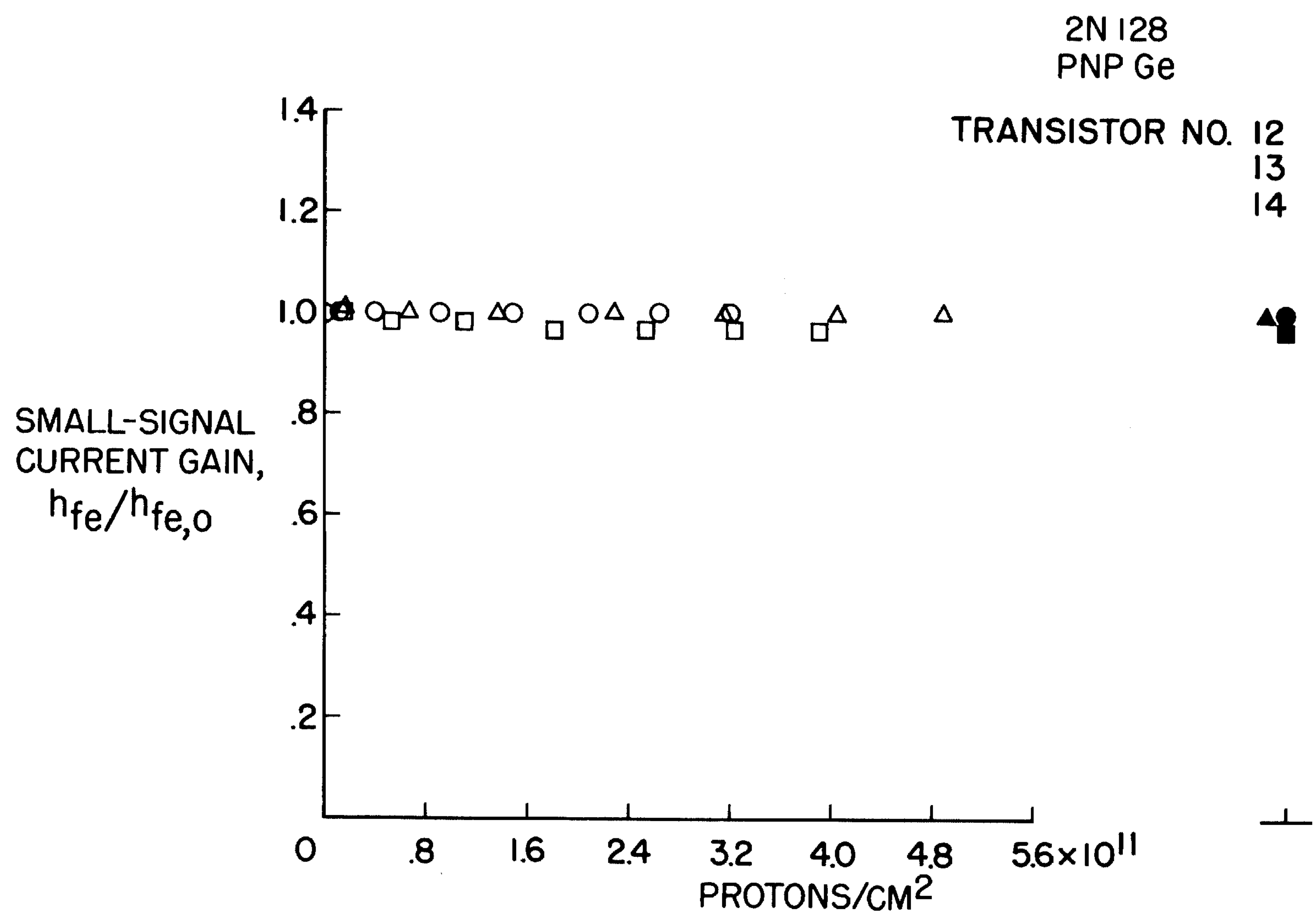
(b) Transistor 2N1302; type NPN Ge.

Figure 5.- Continued.



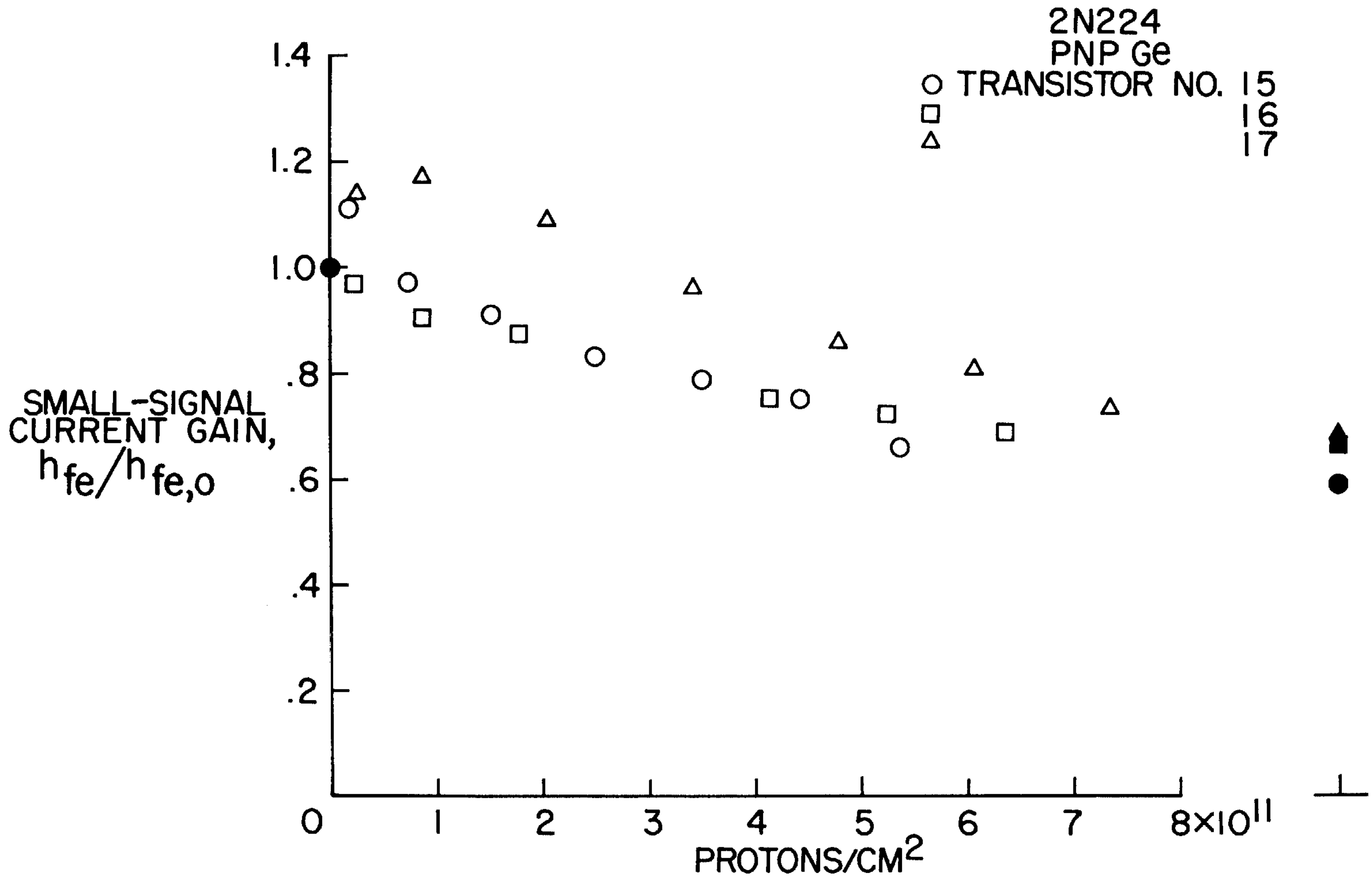
(c) Transistor 2N146; type NPN Ge.

Figure 5.- Continued.



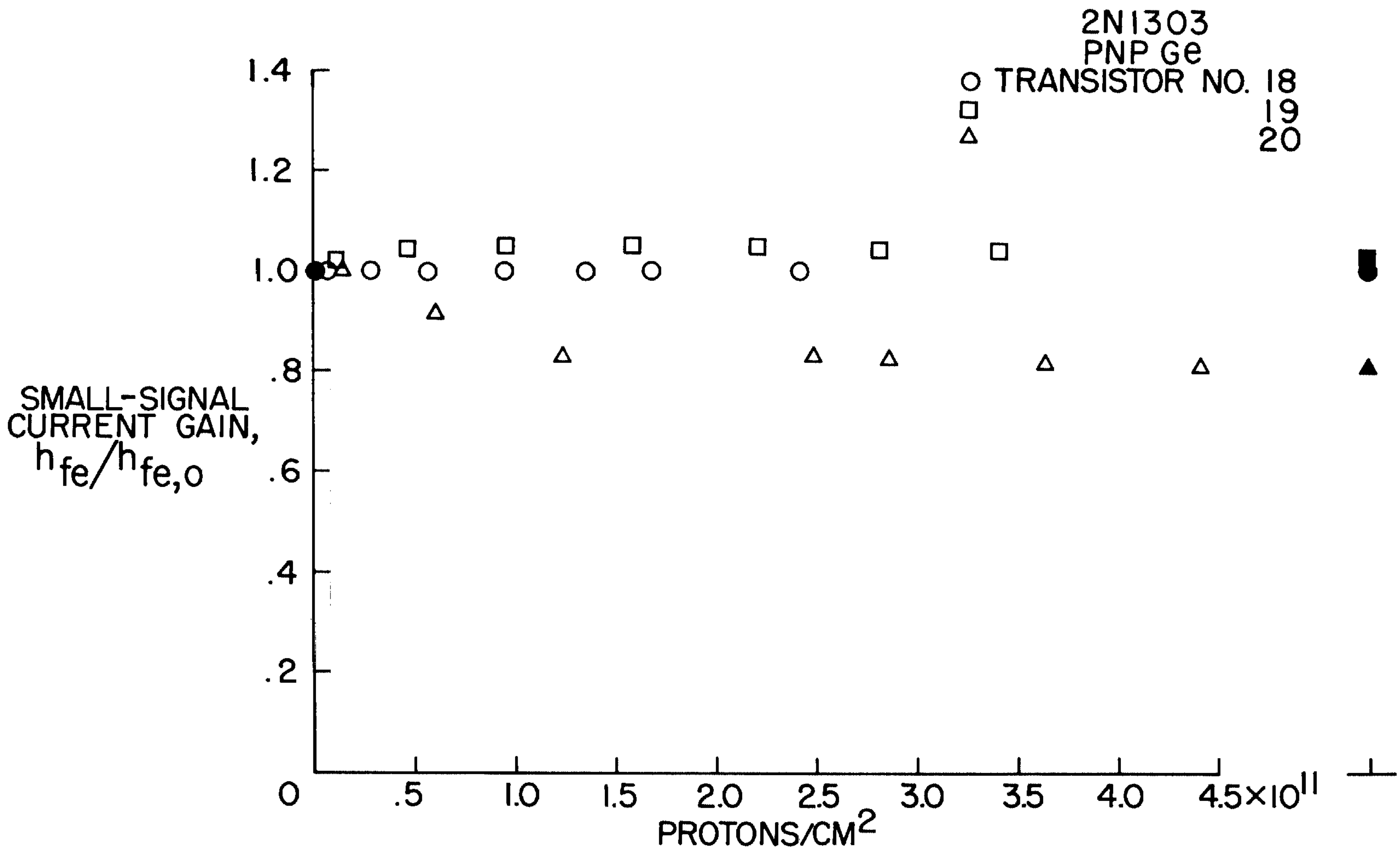
(d) Transistor 2N128; type PNP Ge.

Figure 5.- Continued.



(e) Transistor 2N224; type PNP Ge.

Figure 5.- Continued.



(f) Transistor 2N1303; type PNP Ge.

Figure 5.- Concluded.