TN-63-60
R. P. Borghi
D. H. Jeong
August 1963

GRADIENT MEASUREMENTS FOR THE SLAC ACCELERATING STRUCTURE

Following the decision to use a .230-in. disk for the SLAC Structure,[1] an effort was begun to obtain specific and detailed information on the characteristics of this "thick disk" structure and to examine proposals for arriving at final dimensions for the disk coupling holes and cavity diameters. These examinations are being made on completed ten-foot sections which are fabricated with the methods proposed for pipe production. While this approach has delayed the final determination of dimensions, important assurance has been gained with regard to the quality of the final product.

The purpose of this report is to list the dimensions proposed to date, and to describe a method for checking and correcting gradient behavior. Direct measurement of the gradient can provide, in addition, a sensitive indication of the internal behavior of the sections including internal and coupler mismatches, and provide a direct measurement of impedance in the constant gradient structure. Evaluation of proposed dimensions is under way and will be reported as it becomes available. It should be noted that the differences among the various dimension sets are small and thus any may be considered equivalent to final SLAC dimensions for most purposes.

A. SUMMARY OF PROCEDURE APPLIED TO THE SLAC STRUCTURE

Corrections for the gradient were obtained by comparing the field variation and total attenuation in an existing structure with the field variation and attenuation required for a constant gradient structure at the desired beam loading. The resulting differences were translated to changes in dimensions of the coupling aperture between cavities.

Following the determination of corrected coupling aperture (disk hole diameter) the effect of the changes on phase velocity was found. This and other considerations affecting phase velocity were used to obtain corrections for the

[1]Quarterly Status Report, July 1 to September 30, 1962. "Two-Mile Accelerator Project," SLAC Report No. 8, November 1962, p. 5.

structure cavity diameter. The assumption is made that changes in cylinder diameter will not have a significant effect on the group velocity in each cavity.

1. Specification of Field Variation

The gradient is related to the dissipated power by[2]

$$V_n = \left(r_n P_{Dn}\right)^{\frac{1}{2}} \text{ volts/cavity} \tag{1}$$

where

r_n = shunt impedance of the n-th cavity[3]

P_{Dn} = power dissipated in the n-th cavity

A structure having a constant gradient with a given beam loading will have a constant energy absorption by the beam and a constant power dissipation in each cavity. Under constant gradient operation all the terms in the following equation are constant.

$$P_{Tn} = P_{Bn} + P_{Dn} \tag{2}$$

where

P_{Tn} = total power lost to beam and circuit in cavity n

P_{Bn} = power lost to beam in cavity n

P_{Dn} = power lost to circuit in cavity n

The attenuation in each cavity under these conditions is

$$\alpha_n = \frac{1}{2} \ln \frac{1}{1 - 2A_n} \text{ nepers} \tag{3}$$

[2] See e.g., R. B. Neal, "Design of Electron Accelerators With Beam Loading," J. Appl. Phys., V. 29, No. 7, July 1958, Eq. (2.2).

[3] We are assuming in this discussion that r_n is constant. The technique of forcing correspondence of the field variation and total attenuation tends to compensate for variations in Q_n and r_n.

where

$$A_n = \frac{1}{2}\frac{P_{Dn}}{P_n} = \frac{1}{2}\frac{1}{\frac{P_o}{P_{Tn}} - n}\left\{\frac{r_n i^2}{2P_{Tn}} + 1 - \left[\left(\frac{r_n i^2}{2P_{Tn}}\right)^2 + \frac{r_n i}{P_{Tn}}\right]^{\frac{1}{2}}\right\} \qquad (4)$$

and

P_n = power flux into cavity n

P_o = input power

n = 0,1,2

i = average beam current during pulse

This expression for A_n is essentially that given by Neal.[4] It is derived in the same fashion, with the additional assumption that the power dissipated in a cavity is not changed by the presence of a bunch in that cavity, that is, we may write

$$P_{Tn} = 2A_n P_n + \left(i_n^2 r_n P_{Dn}\right)^{\frac{1}{2}} \qquad (5)$$

where A_n is 1/2 the fractional power loss in the n-th cavity regardless of the presence of the beam, and $P_{Dn} = 2 A_n P_n$. Since under constant gradient operation, all factors are constant, we may solve for A_n obtaining Eq. (4).

The total attenuation through the section is

$$\sum_{n=o}^{N-1} \alpha_n = \tau \text{ nepers} \qquad (6)$$

where N, the number of cavities in a section, is an independently specified quantity. The value of the current used in the above expression is that

[4]R. B. Neal, "Theory of the Constant Gradient Linear Electron Accelerator," ML Report No. 513, May 1958, p. 4, Eq. (3.6).

giving the desired beam loading. This is determined from,[5]

$$i = (\text{Fractional Beam Loading}) \left[2 \frac{\left(P_o \sum_{n=o}^{N-1} r_n\right)^{\frac{1}{2}} \left(1 - e^{-2\tau}\right)^{\frac{1}{2}}}{\sum_{n=o}^{N-1} r_n \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{2\tau}}\right)} \right] \tag{7}$$

The power lost in each cavity to the beam and by dissipation is given by Eq. (2).

P_{Bn} is the total beam energy gain in a section divided by the number of cavities.[6]

$$P_{Bn} = \frac{1}{N} \left\{ \left(P_o \sum_{n=o}^{N-1} r_n\right)^{\frac{1}{2}} \left(1 - e^{-2\tau}\right)^{\frac{1}{2}} - \frac{i \sum_{n=o}^{N-1} r_n}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right) \right\} \tag{8}$$

Using Eq. (1) and

$$P_{Bn} = i\, V_n \tag{9}$$

we have

$$P_{Dn} = \frac{P_{Bn}^2}{i^2 r_n} \tag{10}$$

Eqs. (8), (9), and (10) allow P_{Tn} to be determined for use in Eq. (4).

Thus the required attenuation per cavity, α_n, may be determined for a constant gradient structure with a specified total attenuation, beam loading, input power, and number of cavities. The average value of the shunt impedance is required.

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[5] R. B. Neal, M Report No. 259, March 1961, p. 5, Eq. 7.

[6] Ibid.

To determine the required field variation in absence of the beam, we use Eq. (1), noting that in this case there is no beam loading and the power dissipated in a given cavity is simply the input power reduced by the attenuation to that cavity.

$$P_{Dn} = 2A_n P_n \quad , \quad \ln \frac{P_o}{P_n} = 2 \sum_{n=o}^{n-1} \alpha_n$$

$$\therefore \quad P_{Dn} = 2A_n \frac{P_o}{\ln^{-1} 2 \sum_{n=o}^{n-1} \alpha_n} \tag{11}$$

where the A_n and α_n have been determined using Eqs. (3) and (4).

2. Comparison of Actual and Ideal Behavior, and Application of Corrections to the Coupling Apertures.

Perturbation measurements give the relative field strength in each cavity.* These, plus a measurement of the total attenuation, allow a comparison of the actual structure with the ideal behavior described in Section 1. For convenience, the comparison is made in terms of A_n, one-half the fractional energy loss caused by dissipation in each cavity. The A_n in the actual structure are determined successively using Eqs. (11) and

$$\frac{P_{Dn}}{P_o} = 2A_o \left(\frac{E_n}{E_o}\right)^2 \quad , \quad A_n = A_o \left(\frac{E_n}{E_o}\right)^2 \ln^{-1} 2 \sum_{n=o}^{n-1} \alpha_n \; . \tag{12}$$

E_n^2/E_o^2 is given by the perturbation measurement of the structure fields. A_o is determined from the total section attenuation as follows:

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*A non-resonant perturbation technique is used, a brief description of which is contained in Quarterly Status Report, January 1 to March 31, 1962. M Report No. 298, April 1962, p. 18.

$$A_o = \frac{A_T}{\sum_{n=o}^{N-1}\left(\frac{E_n}{E_o}\right)^2} \tag{13}$$

The summation is obtained from the E_n^2/E_o^2 data, where A_T = one-half the fraction of the input power dissipated in the entire section in the absence of the beam.

The measured A_n are compared with the ideal A_n from Section 1 to obtain corrections for the coupling aperture. To distinguish the two we shall designate measured values with primes.

Changes in coupling aperture are related to A_n by the group velocity and the change in group velocity with coupling aperture, both of which are known. The group velocity is given by

$$v_{gn} = \frac{\omega}{2Q_n A_n} \tag{14}$$

then

$$v_{gn} - v'_{gn} = \Delta v_{gn} = v'_{gn}\left[\frac{Q'_n}{Q_n}\frac{A'_n}{A_n} - 1\right] \tag{15}$$

Assuming that the Q and $\partial v_g/\partial(2a)$ remain constant for the corrections being considered, we obtain

$$\Delta(2a)_n = \frac{\Delta v_{gn}}{\left.\frac{\partial v_g}{\partial(2a)}\right|_n} = \frac{\left(\frac{v_g}{c}\right)'_n\left[\frac{A'_n}{A_n} - 1\right]}{\left.\frac{\partial(v_g/c)}{\partial(2a)}\right|_n} \tag{16}$$

where $2a$ = coupling aperture diameter* and $(v_g/c)'n$ = measured group velocity

*Figure 1 shows the dimension designations at n prior to correction. The group velocity and its partial with respect to (2a) have been measured separately. This data is given in Figs. 7 and 8.

In applying the corrections, a given disk hole diameter is altered by an amount equal to the average $\Delta(2a)$ of the cavities lying on either side of it.

The effect of local aberrations on the correction terms was minimized by smoothing the data or intermediate terms prior to selection of final dimensions.

3. Corrections for Cavity Diameter

The cavity diameter is used to control the phase velocity of the structure. The factors considered in obtaining corrections for this dimension were:

1. Change in coupling aperture
2. Tuning margin
3. Temperature
4. Frequency
5. Dielectric constant of medium filling the section
6. Consistently observed phase aberrations

The corrections are applied to the dimensions of completed sections in the same fashion as described for the coupling aperture. Some comments concerning these follow.

Changes in the coupling aperture affect the phase velocity and are compensated by corresponding changes in cylinder diameter (2b) by

$$\Delta(2b) = \Delta(2a) \; \frac{\partial f/\partial(2a)}{\partial f/\partial(2b)} \qquad (17)$$

Both partials are known and plotted in Figs. 11 and 12.

A tuning margin must be provided to insure that all cavities may be brought to the proper phase velocity by indenting the cavity walls. Initially, a margin of .001 inch has been chosen for all cavities. This corresponds to a phase margin of 1.92 degrees at the input and 5.85 degrees at the output.

It appears at present that the magnitude of the tuning margin will be determined by dimensional variations introduced during the brazing of the sections. The one mil figure represents a somewhat optimistic evaluation of the limited data we have to date. Choosing a uniform oversize in 2b will tend to require a uniform amount of indenting by the tuning machine over a section length.

The temperature at which the parts were machined and inspected must be considered as well as the temperature at which rf measurements are made and the intended temperature of operation. The latter is 113°F. The scaling factor used is the linear thermal coefficient of expansion for copper, namely[7]

$$(9.2961 + .005252t)10^{-6} \text{ where } t \text{ is in } ^\circ\text{F}.$$

The operating frequency is 2,856,000 KC

All testing to date has been carried out in atmosphere. Humidity, pressure, and temperature have been considered in determining what the operating frequency of the section would be when evacuated.

Consistent phase aberrations have been observed, but their effect to date appears to be small.

A phase change of about 2° per section results from the pressure differential occurring on evacuation. This relatively small error will be accommodated in the tuning margin. Present plans call for the tuning of the section while evacuated and at 113°F.

In summary then, the procedure for alteration of the gradient and subsequent changes in phase velocity is as follows.

1. Begin with a structure (possibly a uniform structure) for which the shunt impedance, group velocity, and the $\partial v_g/\partial(2a)$ are known. To compensate for the effect of changes in aperture on phase velocity we also require $\partial f/\partial(2b)$.

2. Measure the total attenuation and gradient variation (the latter is not necessary if starting with a uniform structure). Using Eqs. (11), (12) and (13) determine the A_n' for the structure at hand.

3. Using the desired values of beam loading and total attenuation determine the operating current, Eq. (7). Also determine the total power absorbed by the beam and circuit, Eqs. (8), (9) and (10). With these find the ideal A_n by using Eq. (4).

4. Determine the corrections to coupling aperture using the A_n', A_n, the group velocity, and $\partial(v_g/c)/[\partial(2a)]$ in Eq. (16).

5. The phase velocity may be compensated for the changes in coupling aperture by altering the cavity diameter as indicated by Eq. (17).

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[7] "Technical Survey of OFHC Brand Copper," The American Metal Co. Ltd., 1957.

B. SPECIFIC MEASUREMENTS AND CORRECTIONS

The approach described above has been used to arrive at a set of .230-in. disk constant gradient dimensions (Mod C). The starting point was the Mod 0 sections described in Part C, for which considerable data is available.

Ten percent beam loading was considered the nominal operating value and used initially. It was found, however, that this required a minimum coupling aperture having a rather small area (see Fig. 2). Based on earlier considerations in connection with the thin disk structure, .750 inch appeared to be about the minimum acceptable aperture diameter. A beam loading of 5% was found to give a diameter a trifle greater than this, and was chosen as the design loading.

1. The Ideal Gradient

Using Eq. (7), we obtain the current for a given beam loading. For our parameters, namely[8]

$$\begin{aligned} P_o &= 24 \times 10^6 \text{ watts} \\ \tau &= .57 \text{ neper} \\ r_n &= 1.98 \text{ megohms/cavity} \end{aligned} \tag{18}$$

the fractional beam loading is .749 per ampere. For 5% beam loading $i = .0667$ amps.

Using Eq. (8) we obtain for the energy absorbed by the beam

$$P_{Bn} = (.6131 - .4594\, i^2) \times 10^6 \text{ watts/cavity} \tag{19}$$

For 5% beam loading $P_{Bn} = 38.864$ KW/cavity. The total energy lost by the rf wave per period is given by Eqs. (8) and (10).

$$P_{Tn} = P_{Bn} \left(1 + \frac{P_{Bn}}{i^2 r_n} \right) \tag{20}$$

[8]The value used for r_n is the approximate average value over the section given in reference 12, p. 49.

For 5% beam loading,

$$P_{Tn} = 210,175 \text{ watts/cavity}$$

We can now compute the A_n required per cavity using Eq. (4). Table 1 gives the A_n for 5% beam loading.

2. Comparison of Actual and Ideal Behavior

A perturbation measurement for a typical tuned section is shown in Fig. 3. The average of attenuation measurements for the original (Mod 0) section was 4.62 db = .532 nepers.

$(E_n/E_o)^2$ is obtained by normalizing perturbation measurements shown in Fig. 4. From the latter

$$\sum_{n=0}^{N-1} \left(\frac{E_n}{E_o}\right)^2 = 96.434 \tag{21}$$

giving a value of A_o' [Eq. (13)] of .006791. The A_n' determined using Eq. (12) are shown in Fig. 5, along with the theoretical values for 5% beam loading.

Use of Eq. (16) gave the corrections for coupling aperture given in Fig. 5. The $\partial(v_g/c)/[\partial(2a)]$ and the group velocity necessary for use in Eq. (16) are shown in Figs. 7 and 8. These were applied to the Mod 0 dimensions to obtain the Mod C dimensions given in Table 1.

The expected group velocity and phase variation for Mod C structures are shown in Figs. 14 and 13. The latter is given at a frequency for which the total phase error is approximately zero, (a commonly used convenient checking point). The bowing of the phase toward the large side is typical for a structure with a tuning margin. The somewhat erratic behavior, particularly toward the output end, results from round-off of the dimensions to .0001 inch and an increased phase sensitivity toward the output.

3. Corrections for Cavity Diameter

The factors listed in Part A-3 were applied to the cavity diameter (2b). Table 2 lists the correction in degrees and mils for each factor and the total correction for each cavity. In determining the dielectric constant of air, references 9 and 10 were used.

C. SUMMARY OF STRUCTURE DIMENSIONS

Four sets of dimensions have been used to construct constant gradient sections of the thick disk variety. These have been called Modifications O, A, B, and C. Briefly, they have been derived as follows.

Modification O is the original set of dimensions obtained by Loew and Altenmueller for a constant gradient structure. Five sections were made to these dimensions, the data from which was used as a basis for Modifications A and C. To date the largest number of completed sections, 5, have used these dimensions.

Modification A was an initial attempt by the authors to bring the group velocity of the Modification O sections closer to the specified linear variation between $(.0204 < v_g/c < .0065)$. No attempt was made to consider beam loading or variations in Q, or in shunt impedance.

Modification B dimensions were the result of additional work by Loew[11] to obtain better results, primarily through use of a computer for smoothing and interpolating experimental results. Three of these sections are now in final assembly stages. The measurements and considerations used in the design of Modifications O and B are given in greater detail in reference 12.

The Modification C derivation has been described in detail in Parts A and B. Two of these sections are now being completed.

A summary of dimensions of Mod O, Mod A, and Mod B, all of which have been used to fabricate ten-foot sections, is included for convenience in Table 3. To facilitate comparisons, disk and cylinder dimensions for all Modifications are plotted in Figs. 9 and 10.

The review and criticism of Dr. E. L. Chu and the encouragement of A. L. Eldredge are gratefully acknowledged.

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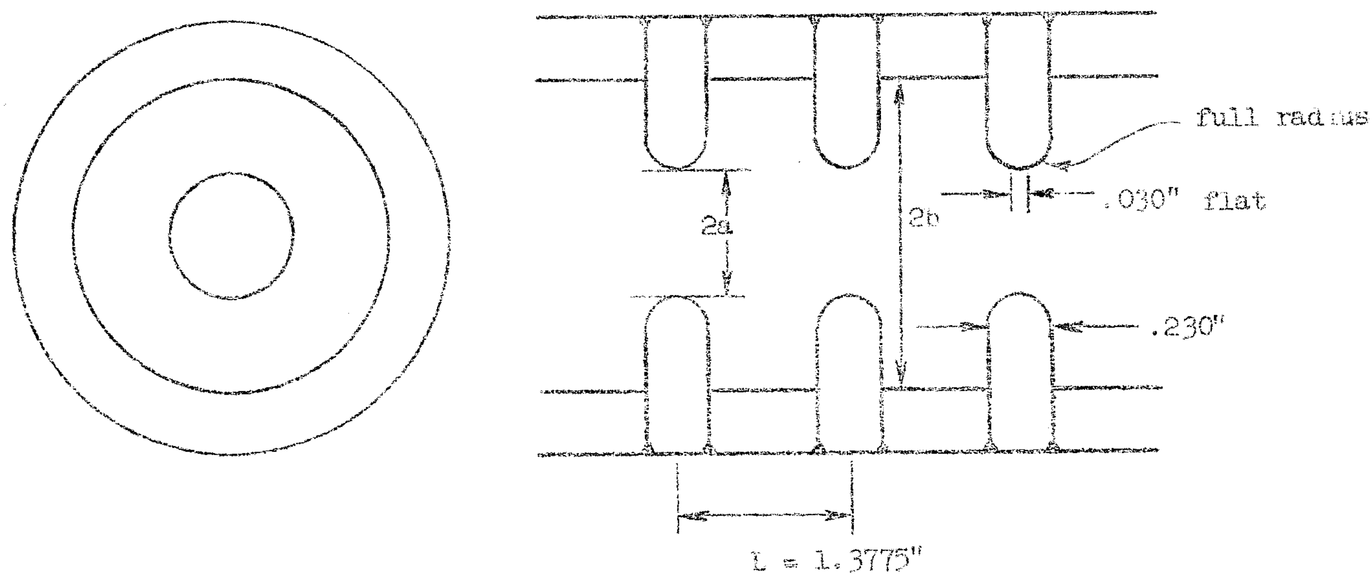
[9] "Technique of Microwave Measurements," edited by C. C. Montgomery, Rad. Lab. Series, Vol. 11, p. 391.

[10] E. H. Bean, "The Radio Refractive Index of Air," Proc. IRE, Vol. 50, No. 3, March 1962, pp. 260-273.

[11] O. A. Altenmueller, B. Kendall, G. Loew, "Cavity Dimensions for Constant Gradient Accelerator Sections," SLAC Technical Note TN-62-46, September 1962.

[12] A. L. Eldredge, G. A. Loew, R. B. Neal, "Design and Fabrication of the Accelerating Structure for the Stanford Two-Mile Accelerator," SLAC Report No. 7, November 1962.



$\beta L = 2\pi/3 \qquad f = 2856,000$ kc

FIG. 1--The accelerator slow-wave structure.

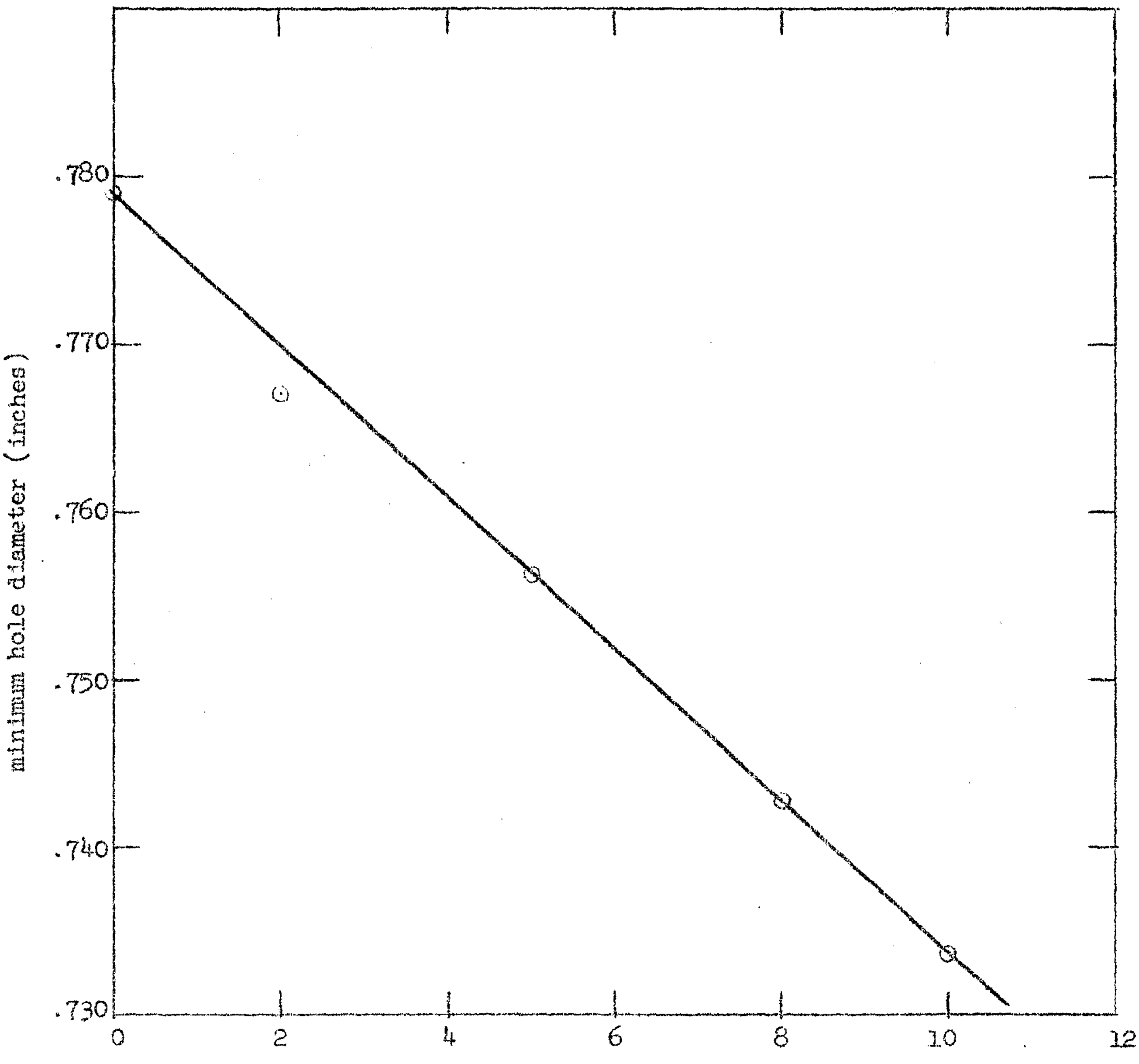


FIG. 2--Minimum coupling aperture (2a) vs beam loading for a constant gradient structure. (Disk thickness = .230 in., $\beta L = 2\pi/3$, f = 2856 Mc).

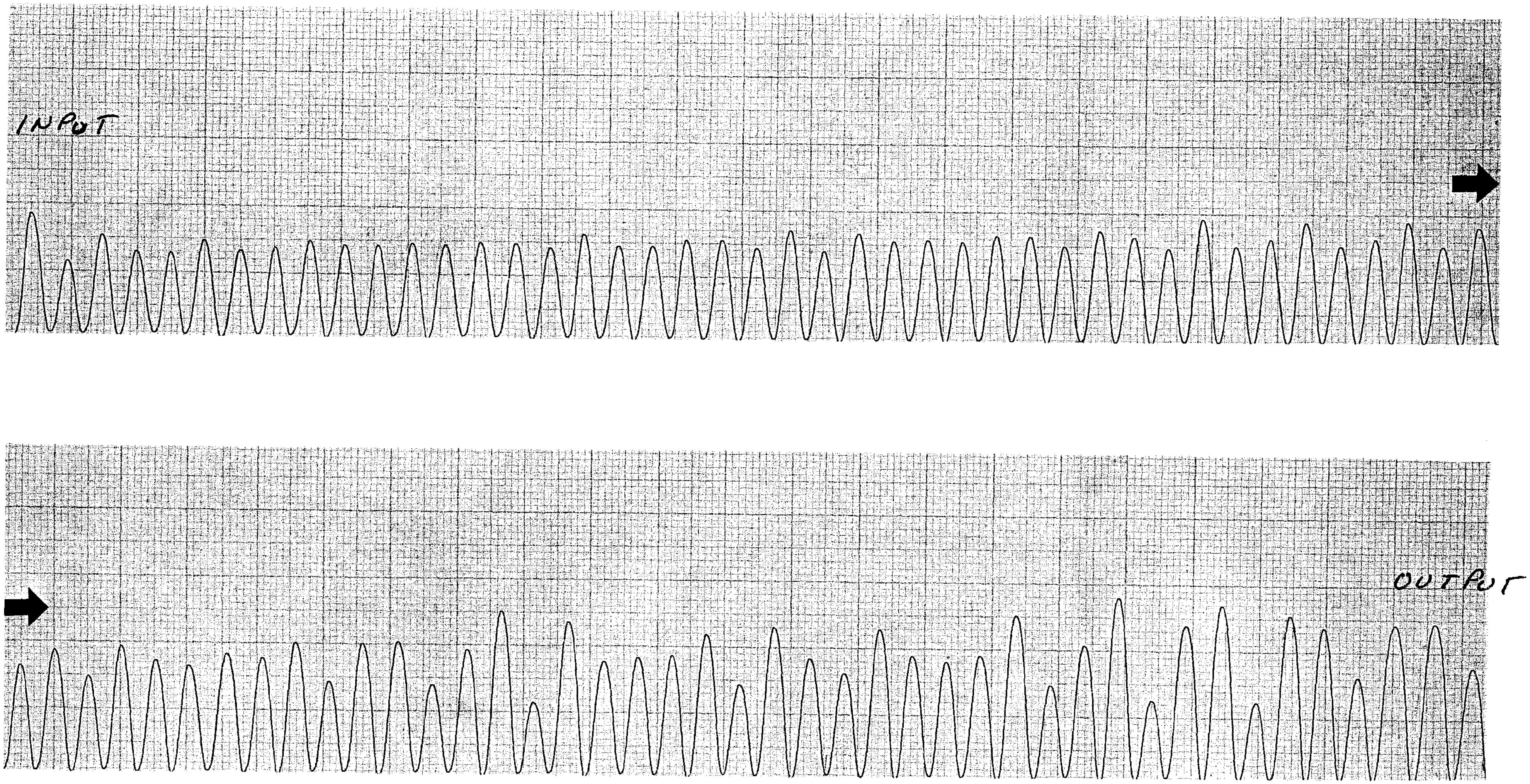


FIG. 3-- TYPICAL PERTURBATION PLOT GIVING E_n^2 ALONG THE STRUCTURE AXIS

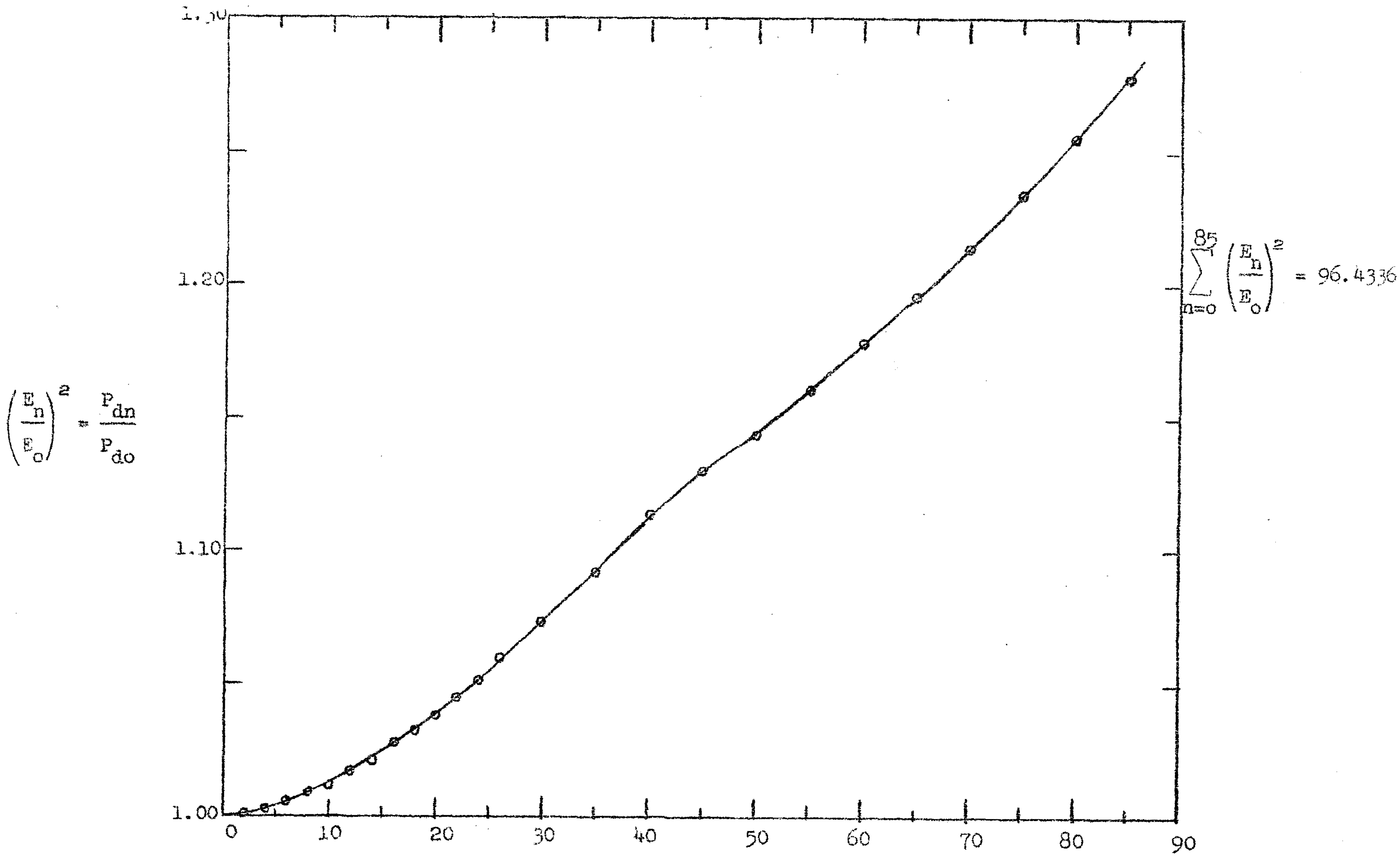


FIG. 4--$(E_n/E_o)^2$ vs cavity number for Mod 0.

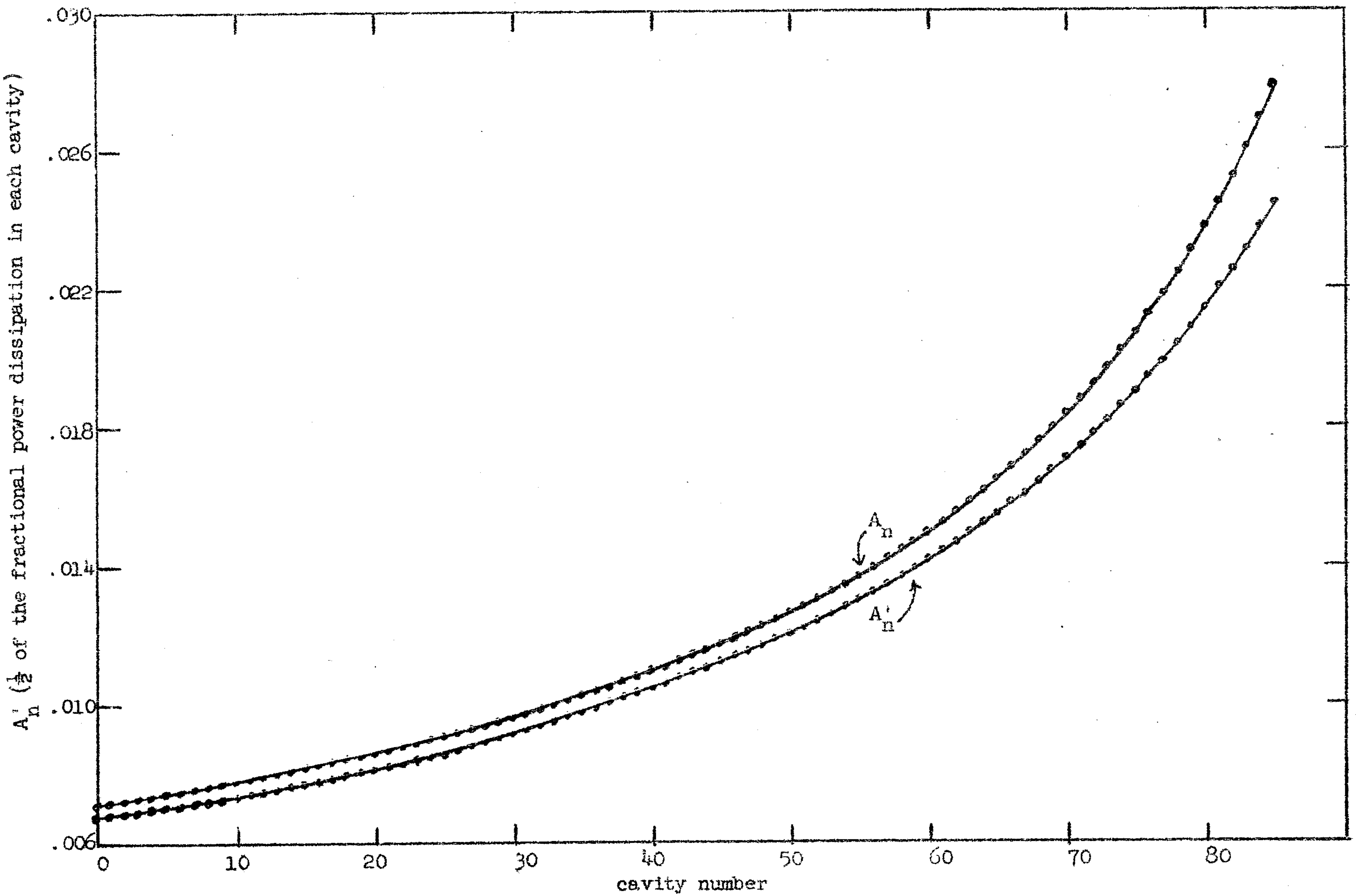


FIG. 5--A'_n determined for the Mod 0 structure and A_n for 5% loading.

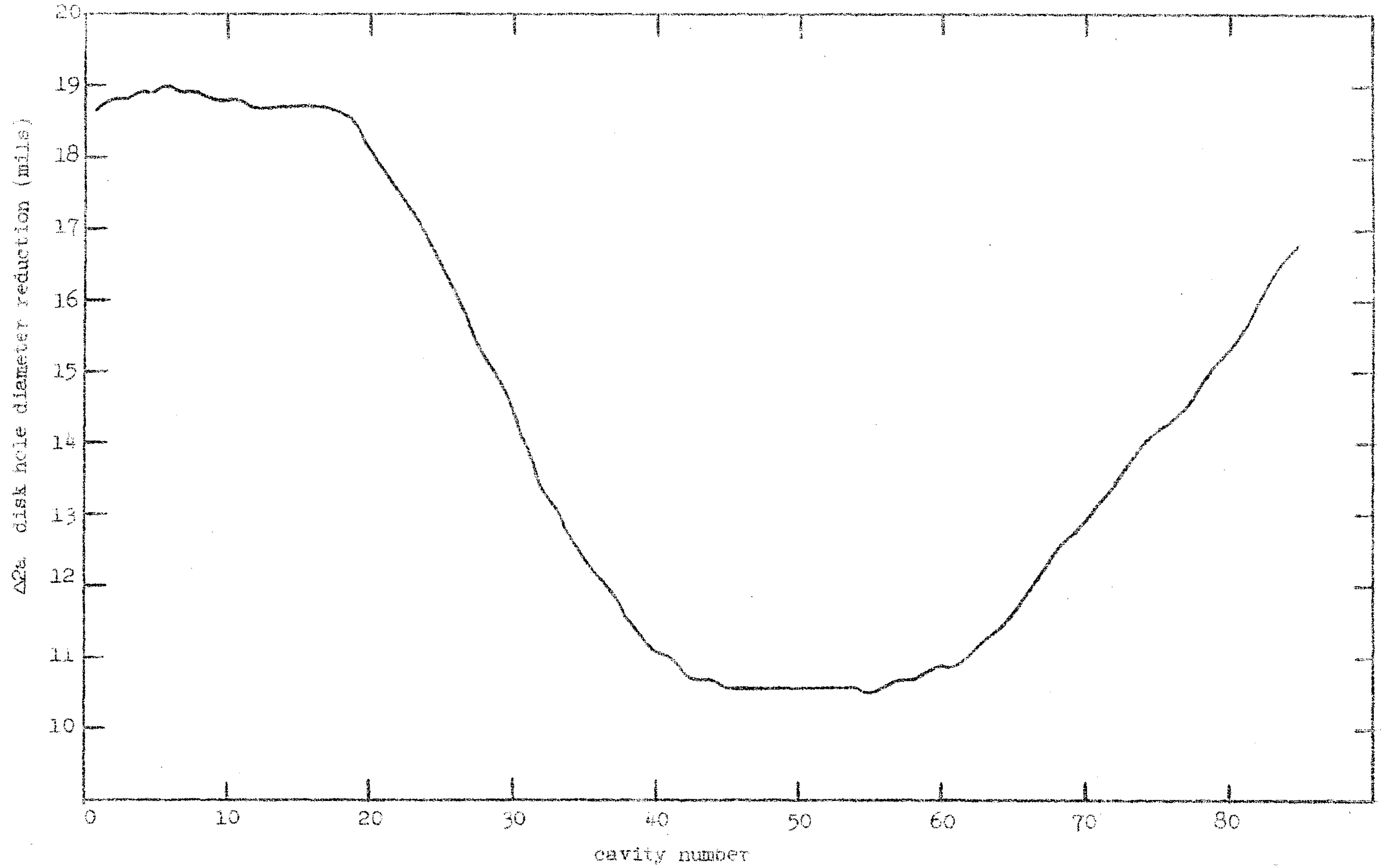


FIG. 6--Coupling aperture corrections for the Mod 0 structure.

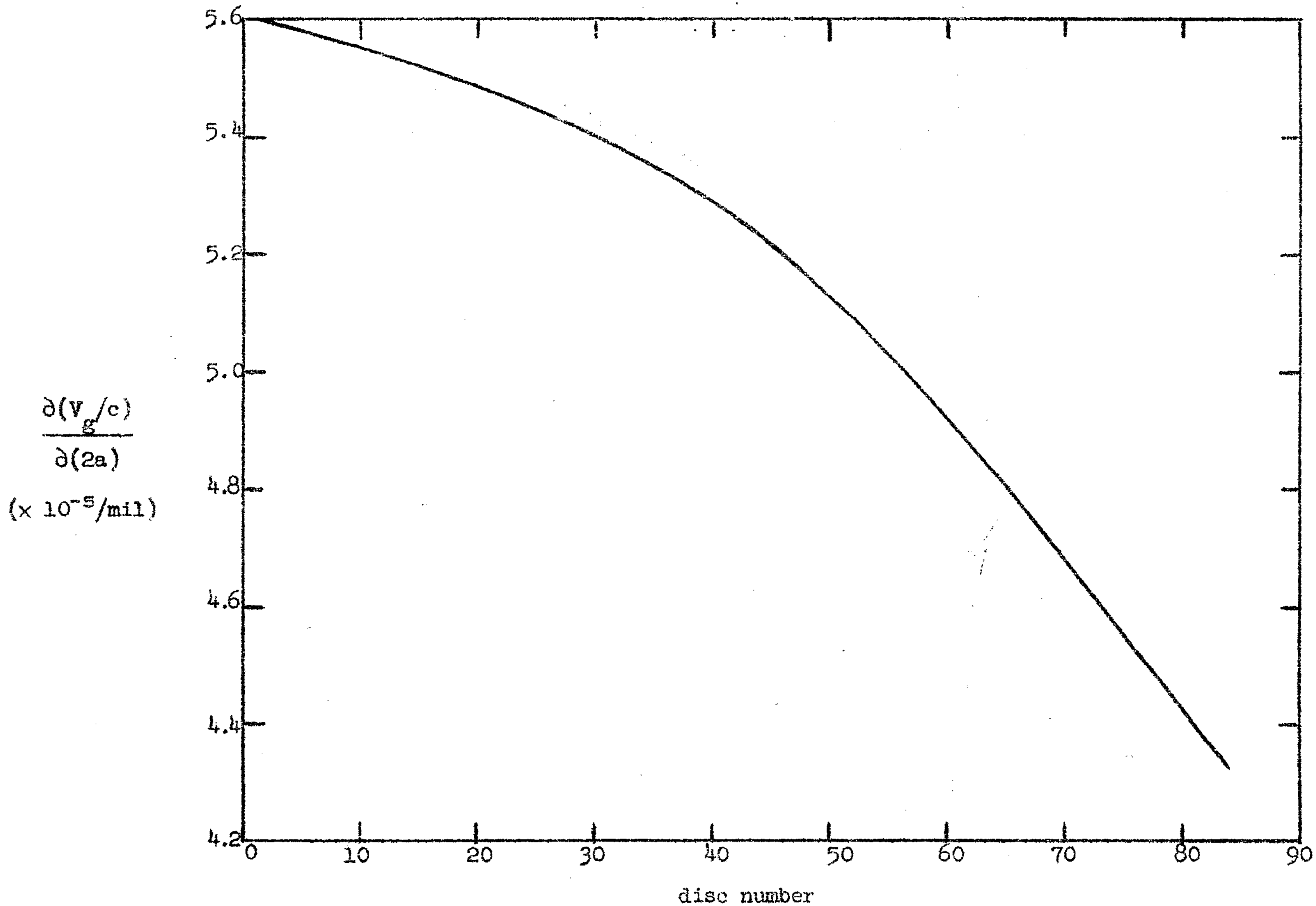


FIG. 7-- $\frac{\partial(V_g/c)}{\partial(2a)}$ vs disc number.

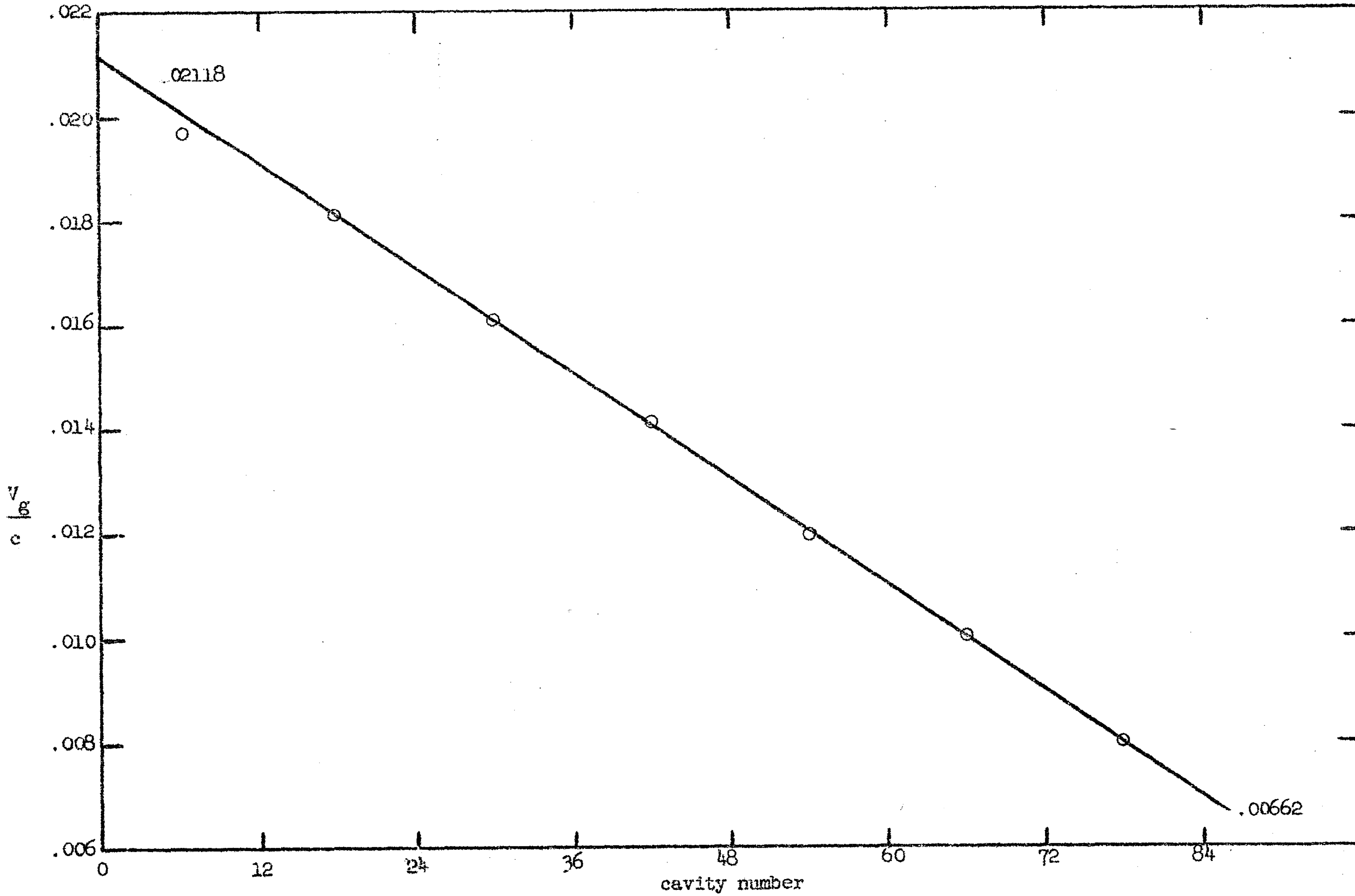


FIG. 8--(V_g/c) vs cavity number for Mod O.

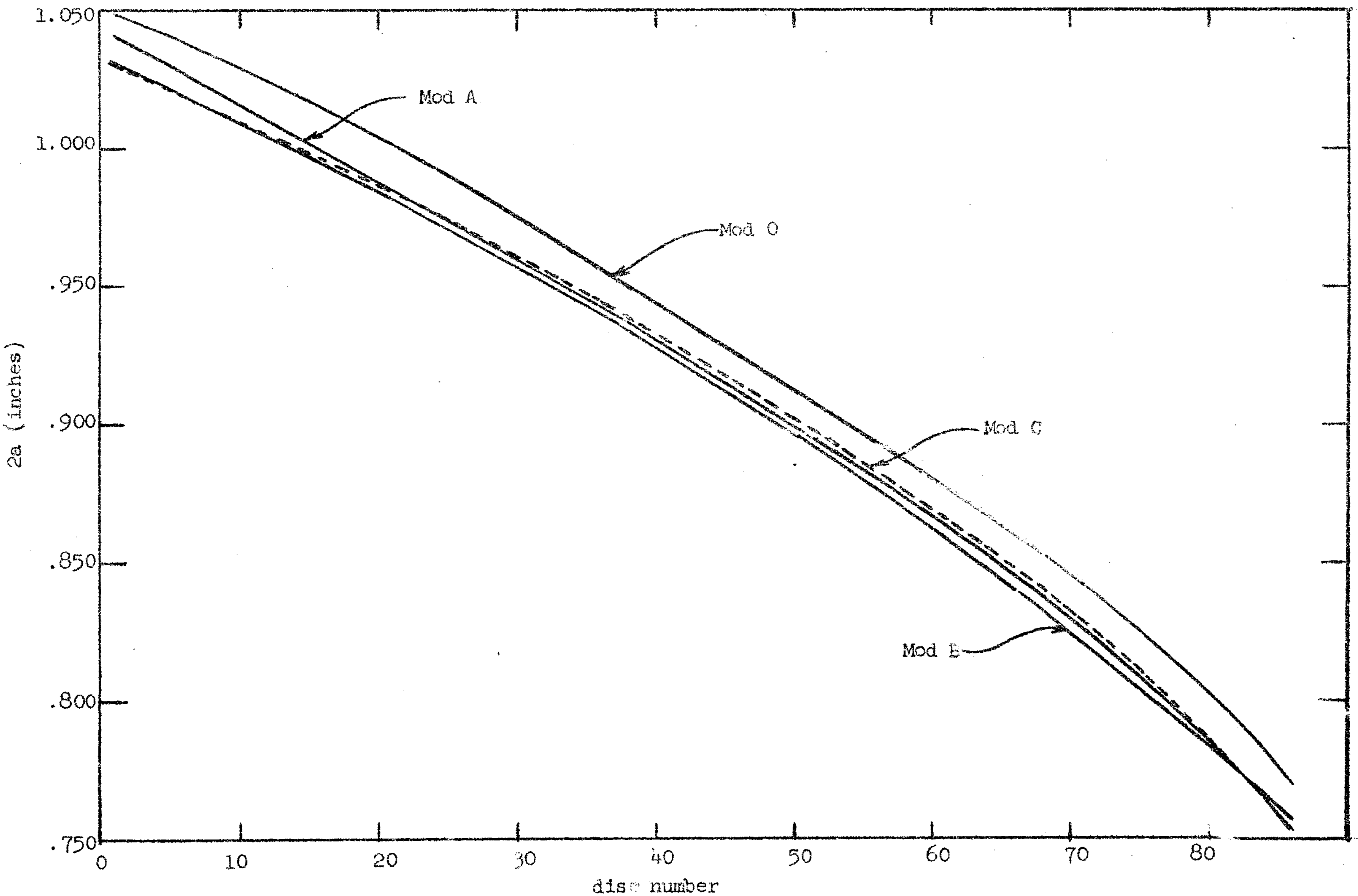


FIG. 9--Disc hole diameter vs disc number.

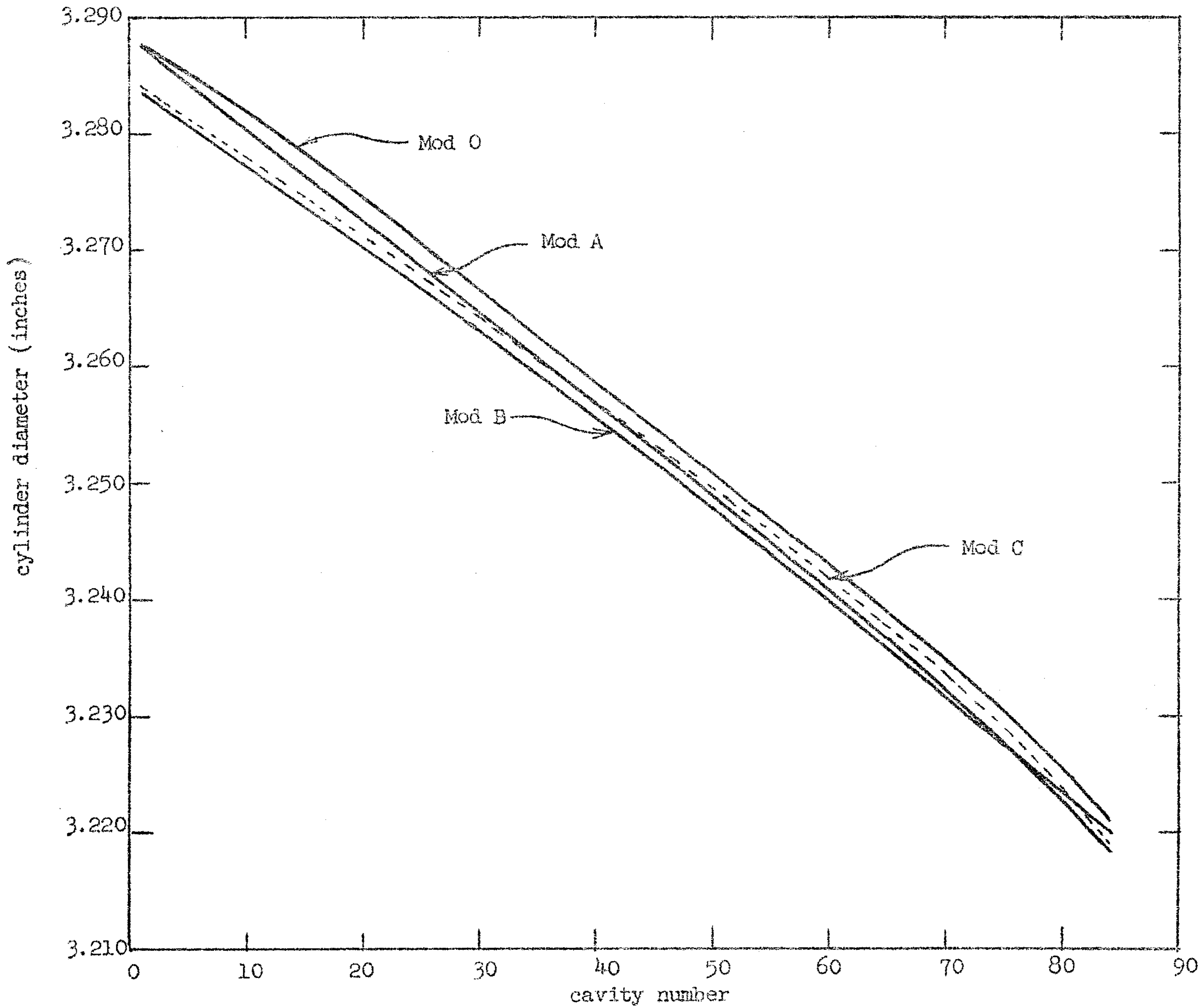


FIG. 10--Cylinder diameter vs cavity number.

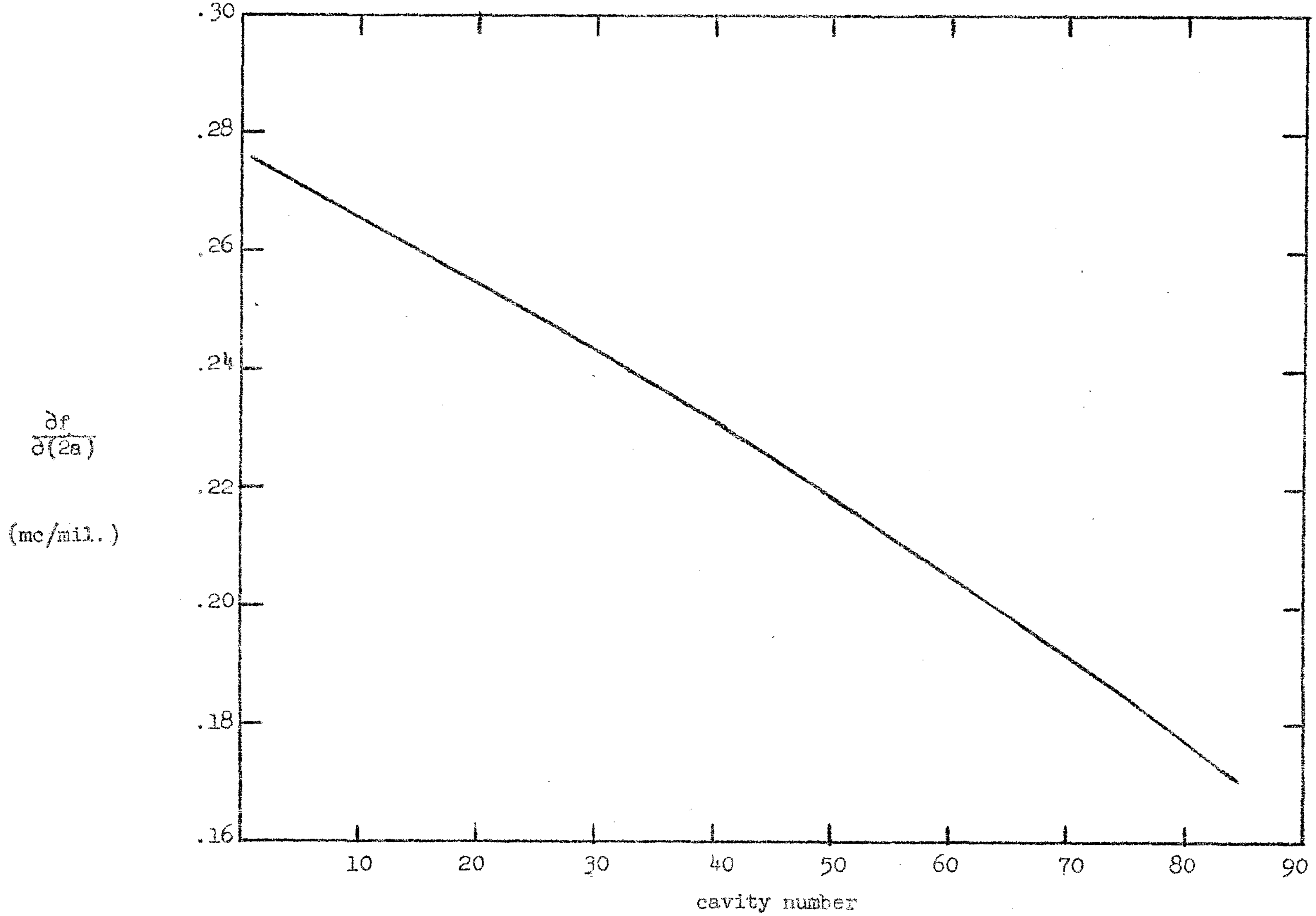


FIG. 11--∂f/∂(2a) vs cavity number.

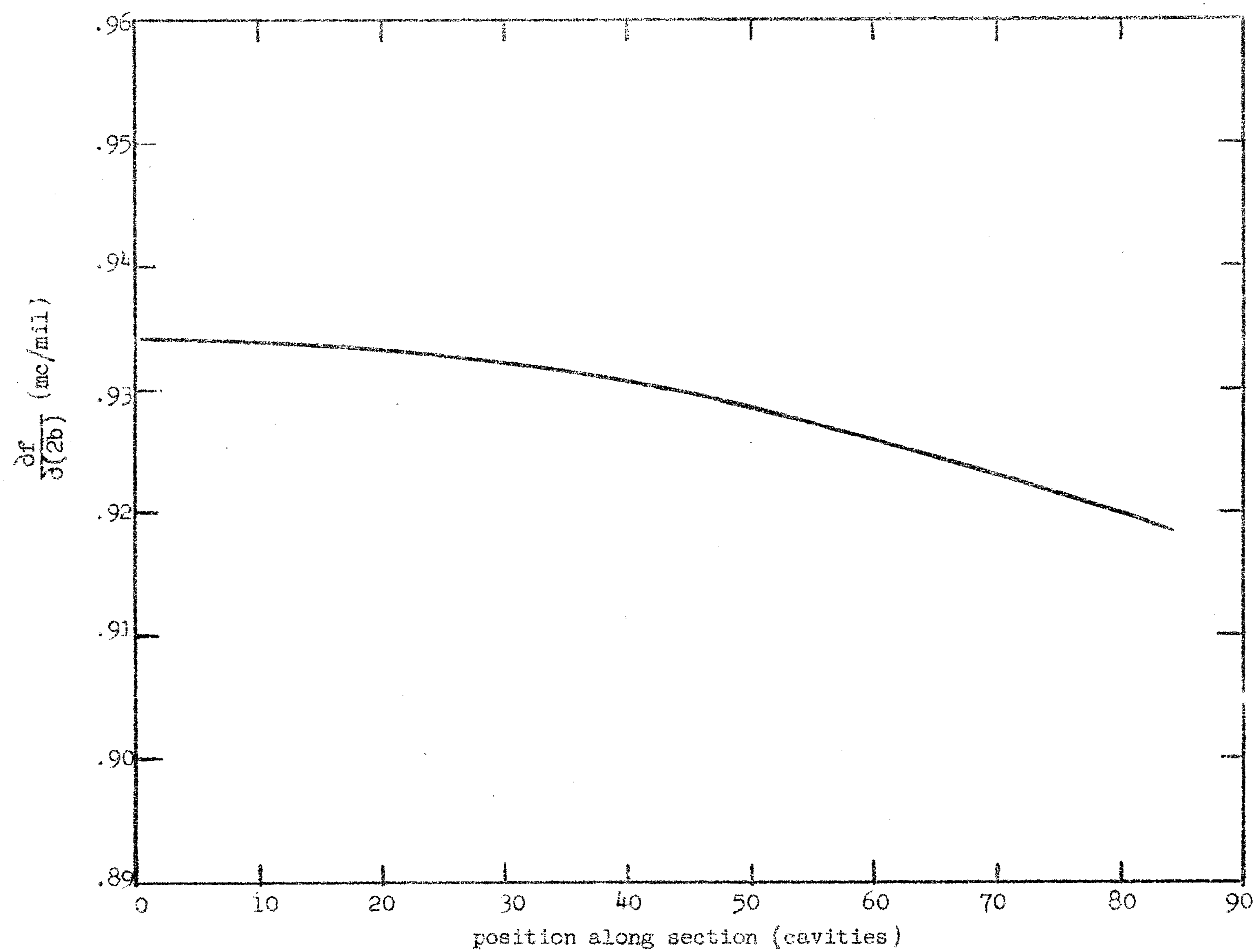


FIG. 12--$\partial f/\partial(2b)$ vs cavity no.

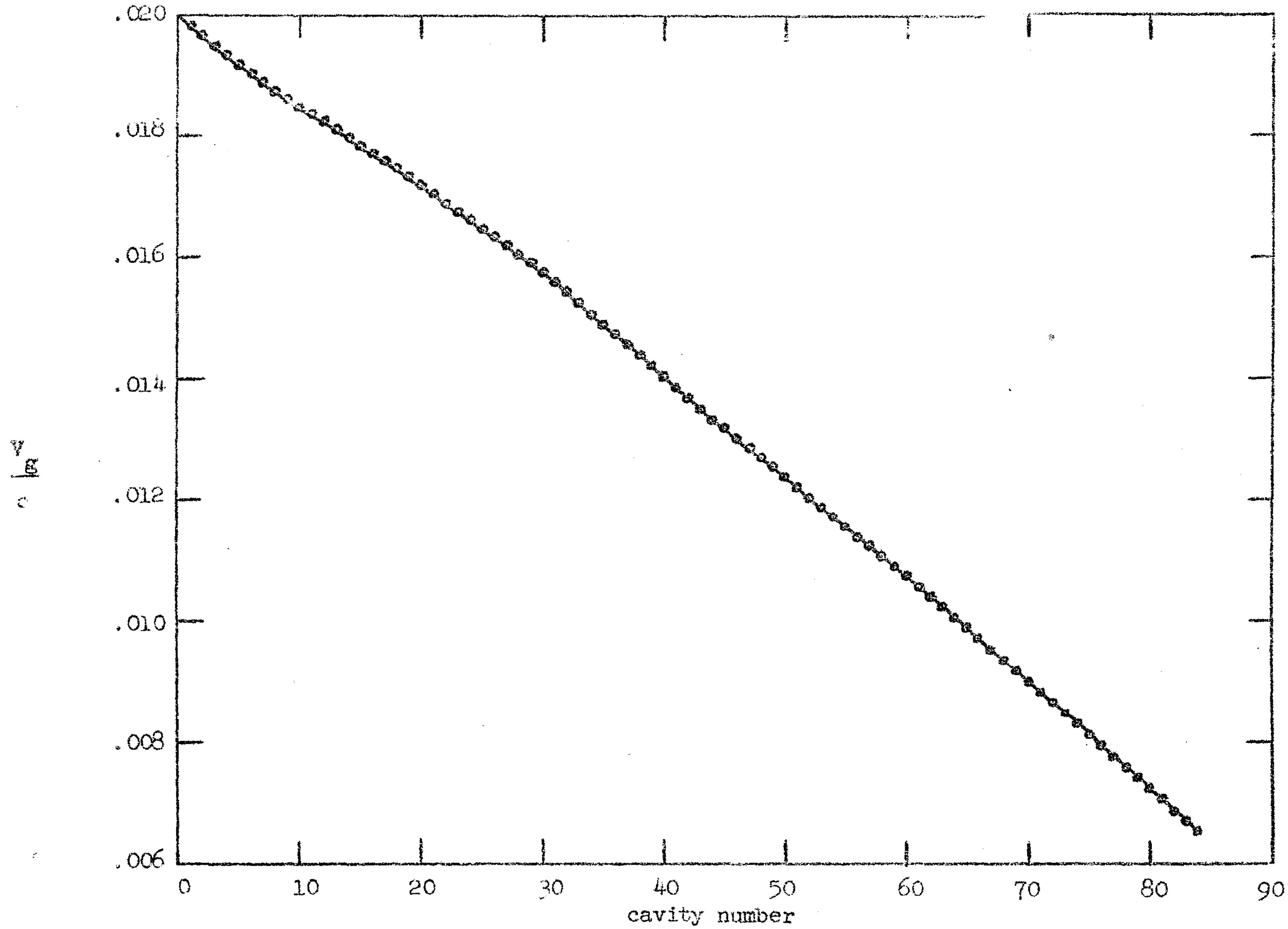


FIG. 13--Predicted group velocity for Mod C dimensions.

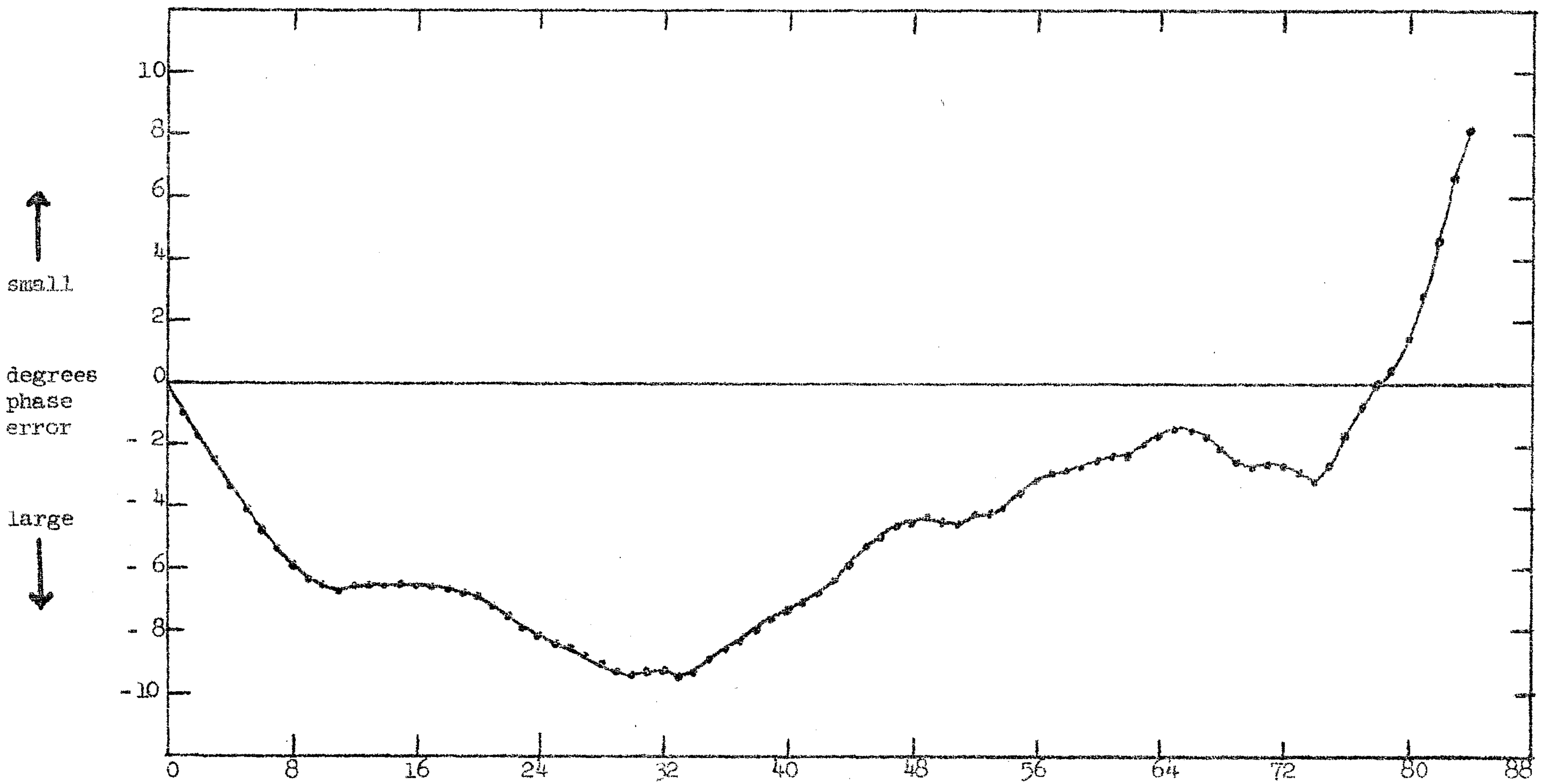


FIG. 14--Predicted phase behavior for Mod C (2855.20 mc 75°F 35% relative humidity air dielectric).

TABLE 1

CORRECTIONS AND DIMENSIONS FOR MODIFICATION C

n	Disc Hole Cor.*	Cylinder Dia. Cor.*	Mod C Disc Hole*	Mod C Cyl. Dia.*	A_n For 5% Beam Load. $\times 10^3$	A'_n $\times 10^3$
0					3.56805	3.3945
1	.0187	.0037	1.0303	3.2841	3.59955	3.4195
2	.0188	.0038	1.0280	3.2834	3.63165	3.4455
3	.0188	.0038	1.0258	3.2827	3.66430	3.4720
4	.0189	.0037	1.0235	3.2821	3.69755	3.4995
5	.0189	.0038	1.0213	3.2814	3.73140	3.5290
6	.0190	.0038	1.0190	3.2808	3.76590	3.5590
7	.0189	.0038	1.0168	3.2801	3.80105	3.5900
8	.0189	.0038	1.0145	3.2794	3.83680	3.6220
9	.0188	.0038	1.0122	3.2788	3.87330	3.6550
10	.0188	.0039	1.0099	3.2781	3.91045	3.6895
11	.0188	.0039	1.0076	3.2774	3.94835	3.7245
12	.0187	.0040	1.0053	3.2767	3.98700	3.7600
13	.0187	.0039	1.0030	3.2761	4.02640	3.7965
14	.0187	.0039	1.0006	3.2754	4.06655	3.8350
15	.0187	.0039	.9983	3.2747	4.10755	3.8745
16	.0187	.0038	.9959	3.2740	4.14940	3.9150
17	.0187	.0038	.9935	3.2733	4.19210	3.9560
18	.0186	.0037	.9911	3.2727	4.23565	3.9990
19	.0185	.0036	.9887	3.2720	4.28015	4.0425
20	.0181	.0035	.9863	3.2713	4.32560	4.0865
21	.0178	.0033	.9838	3.2706	4.37200	4.1330
22	.0175	.0032	.9813	3.2699	4.41940	4.1815
23	.0172	.0031	.9788	3.2692	4.46790	4.2295
24	.0169	.0030	.9763	3.2685	4.51740	4.2795
25	.0165	.0029	.9738	3.2678	4.56805	4.3320
26	.0161	.0028	.9712	3.2671	4.61985	4.3840
27	.0156	.0027	.9686	3.2664	4.67285	4.4390
28	.0152	.0025	.9660	3.2657	4.72705	4.4940

*In inches.

n	Disc Hole Cor.	Cylinder Dia. Cor.	Mod C Disc Hole	Mod C Cyl. Dia.	A_n for 5% Beam Load. × 10^3	A_n' × 10^3
29	.0149	.0024	.9633	3.2650	4.78250	4.5500
30	.0144	.0023	.9607	3.2643	4.83930	4.6085
31	.0139	.0022	.9580	3.2636	4.89750	4.6670
32	.0134	.0021	.9553	3.2629	4.95705	4.7270
33	.0131	.0019	.9525	3.2622	5.01810	4.7885
34	.0127	.0019	.9498	3.2614	5.08070	4.8525
35	.0124	.0019	.9470	3.2607	5.14485	4.9185
36	.0121	.0018	.9442	3.2600	5.21060	4.9865
37	.0119	.0017	.9413	3.2593	5.27810	5.0560
38	.0115	.0016	.9385	3.2586	5.34740	5.1260
39	.0113	.0016	.9356	3.2578	5.41850	5.1985
40	.0111	.0015	.9327	3.2571	5.49150	5.2715
41	.0110	.0014	.9297	3.2564	5.56655	5.3440
42	.0108	.0014	.9268	3.2556	5.64365	5.4180
43	.0107	.0014	.9238	3.2549	5.72290	5.4970
44	.0107	.0014	.9208	3.2542	5.80440	5.5720
45	.0106	.0014	.9178	3.2534	5.88830	5.6520
46	.0106	.0013	.9147	3.2527	5.97465	5.7310
47	.0106	.0013	.9116	3.2519	6.03355	5.8110
48	.0106	.0012	.9085	3.2512	6.15515	5.8930
49	.0106	.0012	.9054	3.2504	6.24955	5.9780
50	.0106	.0011	.9023	3.2497	6.34690	6.0660
51	.0106	.0011	.8991	3.2489	6.44730	6.1570
52	.0106	.0012	.8959	3.2481	6.55095	6.2500
53	.0106	.0011	.8927	3.2474	6.65800	6.3475
54	.0106	.0011	.8894	3.2465	6.76860	6.4480
55	.0105	.0012	.8862	3.2459	6.88295	6.5525
56	.0106	.0012	.8829	3.2450	7.00120	6.6595
57	.0107	.0011	.8795	3.2443	7.12360	6.7695
58	.0107	.0011	.8762	3.2435	7.25035	6.8825
59	.0108	.0011	.8728	3.2427	7.38170	6.9965
60	.0109	.0011	.8694	3.2419	7.51790	7.1185
61	.0109	.0011	.8660	3.2411	7.65920	7.2425
62	.0111	.0011	.8625	3.2403	7.80595	7.3710

n	Disc Hole Cor.	Cylinder Dia. Cor.	Mod C Disc Hole	Mod C Cyl. Dia.	A_n for 5% Beam Load $\times 10^3$	A_n' $\times 10^3$
63	.0113	.0012	.8590	3.2394	7.95840	7.5035
64	.0114	.0012	.8555	3.2386	8.11695	7.6415
65	.0116	.0012	.8519	3.2378	8.28190	7.7835
66	.0119	.0012	.8482	3.2370	8.45375	7.9310
67	.0122	.0012	.8445	3.2361	8.63285	8.0840
68	.0125	.0012	.8407	3.2353	8.81970	8.2415
69	.0127	.0012	.8369	3.2344	9.01485	8.4060
70	.0129	.0013	.8380	3.2335	9.21880	8.0755
71	.0132	.0014	.8289	3.2326	9.43220	8.7510
72	.0134	.0014	.8248	3.2317	9.65570	8.9355
73	.0137	.0014	.8205	3.2308	9.89005	9.1280
74	.0140	.0014	.8161	3.2299	10.13550	9.3290
75	.0142	.0016	.8116	3.2289	10.39465	9.5380
76	.0143	.0017	.8070	3.2279	10.66675	9.7540
77	.0145	.0017	.8022	3.2269	10.95350	9.9820
78	.0148	.0017	.7973	3.2259	11.25610	10.2200
79	.0151	.0017	.7922	3.2249	11.57585	10.4715
80	.0153	.0018	.7871	3.2238	11.91435	10.7350
81	.0156	.0019	.7818	3.2227	12.27320	11.0055
82	.0160	.0020	.7763	3.2216	12.65435	11.2935
83	.0163	.0021	.7707	3.2204	13.05995	11.5990
84	.0166	.0020	.7649	3.2192	13.49240	11.9205
85	.0168		.7590		13.95445	12.2570

TABLE 2

CORRECTIONS FOR CYLINDER DIAMETER

Cyl. No.	Freq. Change Due to Disc Hole Change (-mc)	Frequency Correction for Temp., Dielectric Const., & Orig. Freq. Error (mc)	Frequency Compensation For Consistent Phase Error (mc)	Total Frequency Correction (-mc)	Cylinder Reduction To Correct Frequency*	Total Cyl. Reduction Including Tuning Margin*
1	5.163750	.375768	.321	4.466982	4.78	3.78
2	5.158720	THIS CORRECTION IS CONSTANT OVER THE SECTION.	.321	4.461952	4.78	3.78
3	5.151705		.321	4.454937	4.77	3.77
4	5.146470		.422	4.341702	4.66	3.66
5	5.139240		.422	4.341472	4.65	3.65
6	5.118395		.422	4.320627	4.63	3.63
7	5.085990		.183	4.527222	4.85	3.85
8	5.051800		.183	4.493022	4.81	3.81
9	5.017720		.183	4.458952	4.78	3.78
10	4.997040		.193	4.428272	4.74	3.74
11	4.963125		.193	4.394357	4.71	3.71
12	4.929320		.193	4.360552	4.67	3.67
13	4.908750		.116	4.416982	4.73	3.73
14	4.888180		.116	4.396412	4.71	3.71
15	4.867610		.116	4.375842	4.69	3.69
16	4.847040		.056	4.415272	4.73	3.73
17	4.811700		.056	4.379932	4.69	3.69
18	4.765495		.056	4.333727	4.64	3.64
19	4.681140		.137	4.168372	4.47	3.47
20	4.571865		.137	4.059097	4.35	3.35
21	4.476040		.137	3.963272	4.25	3.25
22	4.379140		- .053	4.056372	4.35	3.35
23	4.284665		- .053	3.961887	4.25	3.25
24	4.176670		- .053	3.853902	4.13	3.13
25	4.058700		- .077	3.759932	4.03	3.03
26	3.927630		- .077	3.628862	3.89	2.89
27	3.799180		- .077	3.500412	3.75	2.75
28	3.694775		.137	3.182007	3.41	2.41

*In thousandths of an inch.

Cyl. No.	Freq. Change Due to Disc Hole Change (-mc)	Frequency Correction for Temp., Dielectric Const., & Orig. Freq. Error	Frequency Compensation For Consistent Phase Error (mc)	Total Frequency Correction (-mc)	Cylinder Reduction To Correct Frequency*	Total Cyl. Reduction Including Tuning Margin*
29	3.580460	.375768	.137	3.067692	3.29	2.29
30	3.441280		.137	2.928512	3.14	2.14
31	3.303300		.133	2.794532	3.00	2.00
32	3.190600		.133	2.681832	2.88	1.88
33	3.090840		.133	2.582072	2.77	1.77
34	2.991920	THIS CORRECTION IS CONSTANT OVER THE SECTION.	.199	2.417152	2.59	1.59
35	2.881980		.199	2.307212	2.48	1.48
36	2.832000		.199	2.257232	2.42	1.42
37	2.748330		.125	2.247562	2.41	1.41
38	2.664180		.125	2.163412	2.32	1.32
39	2.604000		.125	2.103232	2.26	1.26
40	2.555865		- .120	2.300097	2.47	1.47
41	2.508090		- .120	2.252322	2.42	1.42
42	2.460675		- .120	2.204907	2.37	1.37
43	2.436390		.021	2.039622	2.19	1.19
44	2.412225		.021	2.015457	2.17	1.17
45	2.387120		.021	1.990352	2.14	1.14
46	2.373340		- .122	2.119572	2.28	1.28
47	2.359560		- .122	2.105792	2.27	1.27
48	2.345780		- .122	2.092012	2.25	1.25
49	2.332000		- .156	2.112232	2.27	1.27
50	2.318220		- .156	2.098452	2.26	1.26
51	2.304440		- .156	2.084672	2.25	1.25
52	2.290660		- .180	2.094892	2.26	1.26
53	2.276880		- .180	2.081112	2.24	1.24
54	2.252425		- .180	2.056657	2.22	1.22
55	2.238710		- .153	2.015942	2.17	1.17
56	2.246085		- .153	2.023317	2.18	1.18
57	2.242720		- .153	2.019952	2.18	1.18
58	2.238150		- .163	2.025382	2.19	1.19
59	2.244865		- .163	2.032097	2.19	1.19
60	2.241040		- .163	2.028272	2.19	1.19

*In thousandths of an inch.

Cyl. No.	Freq. Change Due to Disc Hole Change (-mc)	Frequency Correction for Temp. Dielectric Const., & Orig. Freq. Error	Frequency Compensation For Consistent Phase Error (mc)	Total Frequency Correction (-mc)	Cylinder Reduction To Correct Frequency*	Total Cyl. Reduction Including Tuning Margin*
61	2.246200	.375768	- .057	1.927432	2.08	1.08
62	2.272480	THIS CORRECTION IS CONSTANT OVER THE SECTION.	- .057	1.953712	2.11	1.11
63	2.287025		- .057	1.968257	2.13	1.13
64	2.301150		.008	1.917382	2.07	1.07
65	2.335900		.008	1.952132	2.11	1.11
66	2.378670		.008	1.994902	2.16	1.16
67	2.420600		.119	1.925832	2.08	1.08
68	2.451960		.119	1.957192	2.12	1.12
69	2.472960		.119	1.978192	2.14	1.14
70	2.502990		.077	2.050222	2.22	1.22
71	2.532320		.077	2.079552	2.25	1.25
72	2.560950		.077	2.108182	2.29	1.29
73	2.598260		.186	2.036492	2.21	1.21
74	2.625420		.186	2.063652	2.24	1.24
75	2.633400		.186	2.071632	2.25	1.25
76	2.640960		- .131	2.396192	2.60	1.60
77	2.666300		- .131	2.421532	2.63	1.63
78	2.698475		- .131	2.453707	2.67	1.67
79	2.738700		- .117	2.479932	2.69	1.69
80	2.743920		- .117	2.485152	2.70	1.70
81	2.782380		- .117	2.523612	2.74	1.74
82	2.819790		- .197	2.641022	2.87	1.87
83	2.847495		- .197	2.668727	2.90	1.90
84	2.865720		- .197	2.686952	2.92	1.92

*In thousandths of an inch.

TABLE 3

DISC & CYLINDER DIMENSIONS FOR MODS O,A,B

Disc No.	Disc Hole Size (inches) Mod O	Mod A	Mod B	Cyl. No.	Cylinder Diameter (inches) Mod O	Mod A	Mod B
1	1.0490	1.0404	1.0314	1	3.2878	3.2874	3.2836
2	1.0468	1.0377	1.0290	2	3.2872	3.2866	3.2829
3	1.0446	1.0350	1.0266	3	3.2865	3.2858	3.2822
4	1.0424	1.0322	1.0242	4	3.2858	3.2851	3.2815
5	1.0402	1.0295	1.0218	5	3.2852	3.2843	3.2809
6	1.0380	1.0268	1.0194	6	3.2846	3.2835	3.2802
7	1.0357	1.0240	1.0170	7	3.2839	3.2827	3.2795
8	1.0334	1.0213	1.0145	8	3.2832	3.2819	3.2788
9	1.0310	1.0185	1.0121	9	3.2826	3.2812	3.2781
10	1.0287	1.0158	1.0096	10	3.2820	3.2804	3.2774
11	1.0264	1.0130	1.0071	11	3.2813	3.2796	3.2767
12	1.0240	1.0103	1.0046	12	3.2807	3.2788	3.2760
13	1.0217	1.0075	1.0020	13	3.2800	3.2780	3.2753
14	1.0193	1.0047	.99955	14	3.2793	3.2772	3.2746
15	1.0170	1.0020	.99698	15	3.2786	3.2765	3.2739
16	1.0146	.9992	.99441	16	3.2778	3.2757	3.2731
17	1.0122	.9964	.99181	17	3.2771	3.2749	3.2724
18	1.0097	.9936	.98920	18	3.2764	3.2741	3.2717
19	1.0072	.9909	.98658	19	3.2756	3.2733	3.2710
20	1.0044	.9881	.98393	20	3.2748	3.2725	3.2703
21	1.0016	.9853	.98127	21	3.2739	3.2718	3.2696
22	.9988	.9824	.97860	22	3.2731	3.2710	3.2689
23	.9960	.9796	.97590	23	3.2723	3.2702	3.2681
24	.9932	.9768	.97319	24	3.2715	3.2694	3.2674
25	.9903	.9740	.97047	25	3.2707	3.2686	3.2667
26	.9873	.9711	.96772	26	3.2699	3.2678	3.2660
27	.9842	.9683	.96496	27	3.2690	3.2671	3.2652
28	.9812	.9654	.96218	28	3.2682	3.2663	3.2645
29	.9782	.9626	.95938	29	3.2674	3.2655	3.2638

Disc No.	Disc Hole Size (inches) Mod C	Mod A	Mod B	Cyl. No.	Cylinder Diameter (inches) Mod O	Mod A	Mod B
30	.9751	.9597	.95656	30	3.2666	3.2647	3.2631
31	.9719	.9568	.95373	31	3.2658	3.2639	3.2623
32	.9687	.9539	.95087	32	3.2650	3.2631	3.2616
33	.9656	.9510	.94800	33	3.2641	3.2623	3.2608
34	.9625	.9481	.94511	34	3.2633	3.2616	3.2601
35	.9594	.9452	.94220	35	3.2626	3.2608	3.2594
36	.9563	.9423	.93926	36	3.2618	3.2600	3.2586
37	.9532	.9393	.93631	37	3.2610	3.2592	3.2579
38	.9500	.9364	.93334	38	3.2602	3.2584	3.2571
39	.9469	.9334	.93035	39	3.2594	3.2576	3.2564
40	.9438	.9304	.92733	40	3.2586	3.2568	3.2556
41	.9407	.9274	.92429	41	3.2578	3.2560	3.2548
42	.9376	.9244	.92124	42	3.2570	3.2553	3.2541
43	.9345	.9214	.91815	43	3.2563	3.2545	3.2533
44	.9315	.9183	.91505	44	3.2556	3.2537	3.2526
45	.9284	.9153	.91192	45	3.2548	3.2529	3.2518
46	.9253	.9122	.90877	46	3.2540	3.2521	3.2510
47	.9222	.9091	.90560	47	3.2532	3.2513	3.2502
48	.9191	.9060	.90239	48	3.2524	3.2505	3.2495
49	.9160	.9029	.89917	49	3.2516	3.2497	3.2487
50	.9129	.8997	.89592	50	3.2508	3.2489	3.2479
51	.90[illegible]7	.8966	.89264	51	3.2500	3.2481	3.2471
52	.9065	.8934	.88934	52	3.2493	3.2473	3.2463
53	.9033	.8901	.88601	53	3.2485	3.2465	3.2455
54	.9000	.8869	.88265	54	3.2477	3.2457	3.2447
55	.8967	.8836	.87926	55	3.2470	3.2449	3.2439
56	.8935	.8803	.87584	56	3.2462	3.2441	3.2431
57	.8902	.8770	.87240	57	3.2454	3.2433	3.2423
58	.8869	.8736	.86892	58	3.2446	3.2425	3.2415
59	.8836	.8702	.86542	59	3.2438	3.2417	3.2407
60	.8803	.8668	.86188	60	3.2430	3.2409	3.2399
61	.8769	.8633	.85831	61	3.2422	3.2400	3.2391
62	.8736	.8598	.85471	62	3.2414	3.2392	3.2383

Disc No.	Disc Hole Size (inches) Mod O	Mod A	Mod B	Cyl. No.	Cylinder Diameter (inches) Mod O	Mod A	Mod B
63	.8703	.8562	.85108	63	3.2406	3.2384	3.2374
64	.8669	.8526	.84741	64	3.2398	3.2375	3.2366
65	.8635	.8490	.84370	65	3.2390	3.2367	3.2358
66	.8601	.8453	.83997	66	3.2382	3.2358	3.2350
67	.8567	.8415	.83619	67	3.2373	3.2350	3.2341
68	.8532	.8377	.83238	68	3.2365	3.2341	3.2333
69	.8496	.8338	.82854	69	3.2356	3.2332	3.2325
70	.8459	.8299	.82465	70	3.2348	3.2323	3.2317
71	.8421	.8259	.82073	71	3.2340	3.2314	3.2308
72	.8382	.8218	.81676	72	3.2331	3.2305	3.2300
73	.8342	.8176	.81276	73	3.2322	3.2296	3.2292
74	.8301	.8134	.80871	74	3.2313	3.2287	3.2283
75	.8258	.8090	.80462	75	3.2305	3.2277	3.2275
76	.8213	.8046	.80049	76	3.2296	3.2268	3.2267
77	.8167	.8000	.79632	77	3.2286	3.2258	3.2258
78	.8121	.7954	.79210	78	3.2276	3.2248	3.2250
79	.8073	.7906	.78784	79	3.2266	3.2238	3.2242
80	.8024	.7857	.78353	80	3.2256	3.2228	3.2233
81	.7974	.7807	.77917	81	3.2246	3.2217	3.2225
82	.7923	.7755	.77477	82	3.2236	3.2206	3.2217
83	.7870	.7702	.77032	83	3.2225	3.2195	3.2209
84	.7815	.7648	.76582	84	3.2213	3.2184	3.2201
85	.7758	.7592	.76126	85	3.2202		
86	.7700						