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DESIGN AND FABRICATION OF THE ACCELERATING STRUCTURE
FOR THE
STANFORD TWO-MILE ACCELERATOR

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by

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SUMMARY

This report describes the principal factors affecting the design and fabrication of the accelerating structure that will be used for the Stanford two-mile linear electron accelerator. The structure will be an all-copper, cylindrical, disk-loaded waveguide, approximately four inches in diameter, and 10,000 feet long. When powered by 240 klystron amplifiers, each operating at a peak power of 24 megawatts, the accelerator will produce a 20-Bev electron beam at an average beam current of 30 microamperes (10% beam loading). By increasing the number of klystrons to 960, should this eventually be warranted, the beam energy could be increased to 40 Bev, and the average beam current to 60 microamperes.

Although the traveling-wave accelerating structure described here is in general similar to that used with previous Stanford machines, a number of the structure's principal parameters are different. The operating frequency, 2856 Mc/sec, remains the same as earlier machines, as does the 10-foot interval between rf-power feed points along the machine. The rf pulse length of 2.5 μ sec and the pulse repetition rate of 360 pps result in a beam duty cycle approximately ten times greater than that of the present Stanford 1-Bev machine. Other differences from earlier machines are the selection of the $2\pi/3$ operating mode rather than $\pi/2$; a constant-gradient structure rather than one with constant-attenuation; and a lower value of the attenuation parameter in the structure ($\tau = 0.57$ nepers).

In addition to these parameters, the report describes the selection of accelerator length in relation to the total rf power required for a given beam energy.

Final design of the accelerating structure is based on a synthesis of analytic and empirical findings together with consideration of the cost and practicality of fabrication and adjustment techniques. These latter factors are also described. A special furnace has been developed to assemble ten-foot sections of the accelerator by brazing. Final tuning of the individual accelerator cavities (which are machined slightly oversize) will be accomplished by pressing permanent "dimples" into the cavity volume; the reliability of this dimpling technique is one of the principal factors making the brazing method of fabrication feasible. A second satisfactory method of fabrication, electroforming, is also described.

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I. INTRODUCTION

A. Historical Review

In April, 1957, Stanford University proposed the construction of an electron linear accelerator approximately two miles long designed to produce an electron beam of high intensity in the energy range from 10 to 40 Bev for purposes of particle-physics research. This accelerator was authorized in September, 1961 and is now being constructed on a site on Stanford land. Stanford is carrying out this work under a prime contract with the U. S. Atomic Energy Commission. The estimated total construction cost of this accelerator is \$114 million, and the construction schedule calls for completion by July 1, 1966.

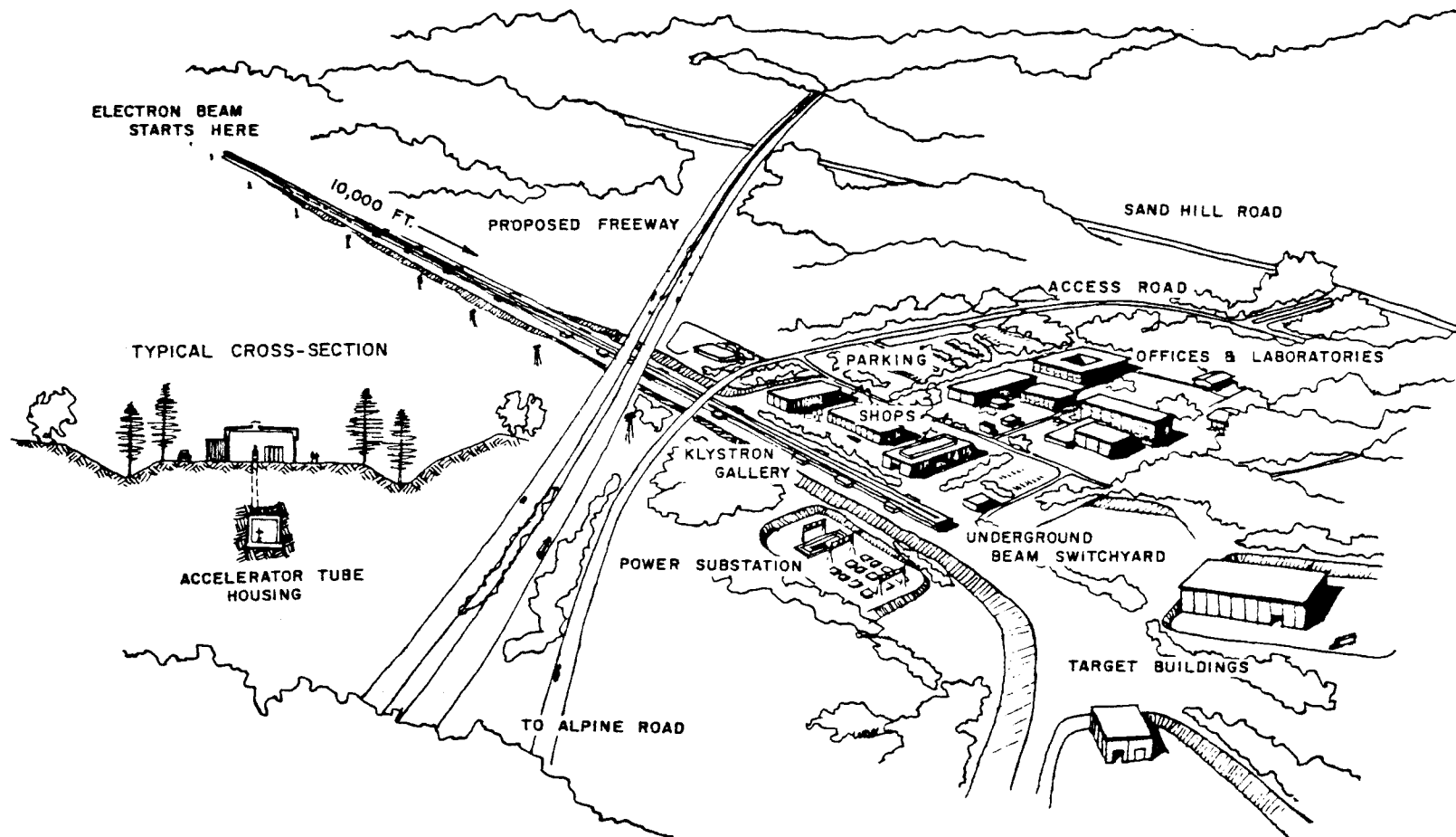
The design of the two-mile accelerator is a logical extension of the accelerator development that began at Stanford University in 1947.¹ Up to the present date, the largest of the Stanford accelerators (the 300-foot Mark III)² has operated at energies up to about 1 Bev. The purpose of this report is to discuss the design and fabrication of one of the principal components of the two-mile accelerator, the disk-loaded waveguide which serves as the accelerating structure.

B. General Description

Before discussing the detailed design of the accelerating structure it may be helpful to give a brief general description of the two-mile accelerator. A general view of the accelerator and target area is shown in Fig. 1.

The accelerator proper will consist of a disk-loaded cylindrical waveguide supplied with microwave power at a frequency of 2856 Mc/sec. The accelerator will be made in sections approximately ten-feet long, and each of these sections will be independently fed with power through a suitable S-band waveguide and waveguide-to-accelerator coupler. A total of 960 ten-foot sections will comprise the entire accelerator. The accelerator will be supplied with power by 240 klystron amplifiers, each capable of producing up to 24 megawatts of peak power at 360 pulses per second and 2.5 microseconds pulse length. The power output from each klystron will be divided four ways and will be used to supply power to four successive ten-foot sections, as shown in Fig. 2. With this initial

¹All references and footnotes are given at the end of the text, page 80.



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FIG. 1--General view of accelerator and target area.

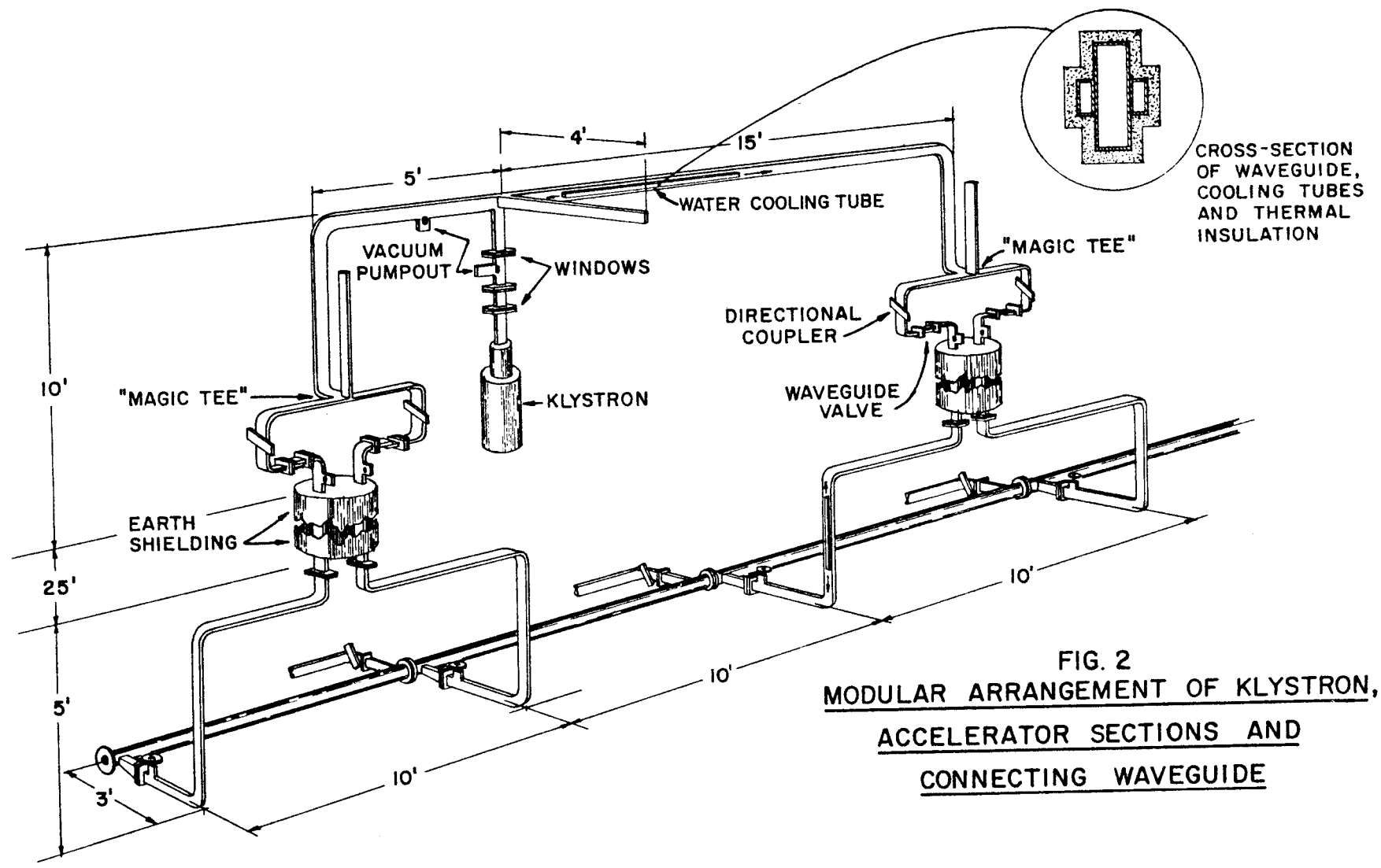


FIG. 2
MODULAR ARRANGEMENT OF KLYSTRON,
ACCELERATOR SECTIONS AND
CONNECTING WAVEGUIDE

complement of tubes, each operating at the conservative level of 6 megawatts, the accelerator will be able to supply an average electron current of 15 microamperes at an energy of 10 Bev. The energy can be increased to 20 Bev and the current to 30 microamperes by increasing the power output from each klystron to 24 megawatts. Operation with a complement of 240 tubes is referred to as Stage I.

The accelerator and its related equipment will be situated in two parallel housings. The accelerator proper will be located in an underground concrete housing, 11-feet wide and 10-feet high. The klystrons, modulators, vacuum pumps, and other auxiliary equipment will be located in an above-ground gallery, 30-feet wide and 16-feet high. The accelerator housing can be entered only when the electron beam is turned off, but the klystron gallery can be continuously occupied. The two housings will be separated by 25 feet of earth which will serve as radiation shielding. There will be a 38-inch-diameter transverse pipe between the housings every 20 feet, each containing two waveguide feeds.

Under the present authorization, the accelerator will be constructed with a complement of 240 tubes as discussed above. However, provisions have been made to permit later increase in the number of tubes connected to the accelerator to a maximum of 960, in which case each klystron will feed a single 10-foot accelerator section. This condition of operation is referred to as Stage II. With 960 klystrons each producing 24 megawatts of peak power, an electron energy of about 40 Bev should be obtained.

II. SELECTION OF CHARACTERISTIC PARAMETERS

A. Choice of Operating Frequency

Since almost all of the basic accelerator parameters have frequency dependence, it is first essential to study the implications of using the various frequency bands and to choose an operating frequency. It is not possible to make the choice of frequency by purely analytical methods; the final selection requires the application of engineering judgment and reference to previous experience.

As a guide to the choice of frequency, the frequency dependence of the principal machine parameters is listed in Table 1. This table is based upon direct scaling of the modular dimensions of the accelerating

TABLE 1
FREQUENCY DEPENDENCE OF PRINCIPAL MACHINE PARAMETERS

Parameter	Frequency Dependence	Frequency Preference		Notes
		High	Low	
Shunt impedance per unit length (r)	$f^{1/2}$	X		(1)
RF loss factor (Q)	$f^{-1/2}$		X	(1)
Filling time (t_F)	$f^{-3/2}$	X		(1), (2)
Total rf peak power	$f^{-1/2}$	X		(1), (2), (3)
RF feed interval (ℓ)	$f^{-3/2}$		X	(1), (2)
Number of rf feeds	$f^{3/2}$		X	(1), (2), (4)
RF peak power per feed	f^{-2}	X		(1), (2), (3)
RF energy stored in accelerator	f^{-2}	X		(1), (2), (3)
Beam loading (- dV/di)	$f^{1/2}$		X	(1), (2), (4)
Peak beam current at maximum conversion efficiency	$f^{-1/2}$		X	(1), (2), (3), (6)
Diameter of beam aperture	f^{-1}		X	(1)
Maximum rf power available from single source	f^{-2}		X	(5)
Maximum permissible electric field strength	$f^{1/2}$	X		(7)
Relative frequency and dimensional tolerances	$f^{1/2}$	X		(1), (2)
Absolute wavelength and dimensional tolerances	$f^{-1/2}$		X	(1), (2)
Power dissipation capability of accelerator structure	f^{-1}		X	(1), (2), (4)

- Notes:
1. For direct scaling of modular dimensions of accelerator structure.
 2. For same rf attenuation in accelerator section between feeds.
 3. For fixed electron energy and total length.
 4. For fixed total length.
 5. When limited by cathode emission.
 6. When limited by beam loading.
 7. Approximate; empirical.

structure. This assumption has been adopted to simplify the comparison. In a practical accelerator it is likely that certain compromises would be advisable which would change Table 1 in certain details but not in its general implications.

The energy of electrons from a linear accelerator with negligible beam loading is given by

$$V = K \left(P_T L r_o \right)^{\frac{1}{2}} \quad (1)$$

where P_T is the total input rf power, L is the total length, r_o is the shunt impedance per unit length, and K is a constant whose value depends upon the net rf attenuation in each independently fed accelerator section. Since r_o varies as $f^{\frac{1}{2}}$, the rf power required to produce a given final energy in a fixed length is proportional to $f^{-\frac{1}{2}}$. Thus considerations of power economy indicate that the operating frequency should be as high as possible. Other advantages of the higher frequencies are the reduced filling time, which varies as $f^{-3/2}$, and reduced energy storage, which varies as f^{-2} . A shorter filling time is advantageous since electrons can be accelerated during a larger fraction of the available rf pulse length. The use of the higher frequencies also results in greater maximum field strength (as limited by breakdown) and larger relative frequency and dimensional tolerances.

From Table 1 it can be seen that the maximum frequency which can be used is limited by the available aperture for the beam and the reduced beam-current capability. Another factor against the use of very high frequencies is the increased number of power sources and feeds required. The increased cost required for the additional rf systems, modulators, and controls, and the increased operational difficulties tend to reduce the advantages arising from the decreased power consumption at higher frequencies.

An important consideration not taken into account in Table 1 is the degree of conservatism involved in the choice of frequency band. While linear electron accelerators have been constructed and operated at L-, S-, and X-bands, the largest amount of experience is available at S-band. In fact, to this date all accelerators of this type having energies above 100 Mev have operated at S-band.

To illustrate the scaling laws given in Table 1 more specifically, design data for a 10-Bev accelerator 10,000 feet long are given in Table 2. Three cases are tabulated corresponding to operating at L-, S-, and X-bands. The specific values in Table 2 are based on relations and criteria which are developed later in this section. We shall not comment individually upon each item in Table 2, but it may be worthwhile to emphasize the following features.

(a) An important aspect of the design of the two-mile accelerator is the possibility at some suitable future date of increasing the beam energy from the initial range of 10 to 20 Bev to the higher range of 20 to 40 Bev. For reasons of economy, and to avoid prolonged machine shut-down, it is desirable to accomplish the energy expansion by increasing the rf power rather than by increasing the accelerator length. According to Table 2, the L-band structure with a fixed length of 10,000 feet cannot be expanded above about 38.4 Bev without experiencing breakdown difficulties.

(b) The average rf power requirements are in the ratio
4.1 : 1.0 : 0.4 for the L-, S-, and X-band machines, respectively.

(c) The maximum peak beam currents and beam powers are in the ratios of 1.73 : 1.00 : 0.58 for the L-, S-, and X-band machines, respectively.

(d) The aperture available for the beam in the X-band machine (0.255 in.) is small enough to cause concern about beam transmission, accelerator alignment, etc.

(e) The X-band accelerator ranks highest in terms of maximum expanded energy capability, but the higher energies require X-band sources of higher peak power than are presently available. For example, operation at 40 Bev would require 4988 sources each producing 2.5 megawatts of peak rf power.

(f) Expansion of the L-band accelerator to 40 Bev would require that each of the 185 feed points be supplied with 200 megawatts of peak power. This is much higher than the power output obtained from a single L-band source to date and could thus require parallel operation of sources at each feed.

(g) Expansion of the S-band machine to 40-Bev would require 22.2 megawatts at each of the 960 feed points. Power outputs above this level have already been obtained from single S-band sources.

TABLE 2

DESIGN PARAMETERS OF 10 BEV ACCELERATOR AT 3 FREQUENCIES¹

	Frequency		
	(L-Band) 1000 Mc/sec	(S-Band) 3000 Mc/sec	(X-Band) 9000 Mc/sec
Shunt impedance per unit length (r)	0.31×10^6	0.53×10^6	0.92×10^6 ohms/cm
RF loss factor (Q)	2.25×10^4	1.3×10^4	0.75×10^4
Filling time (t_F)	4.31	0.83	0.16 μ sec
Total rf peak power	2304	1330	768 Mw
RF feed interval	52	10	1.92 ft
Number of rf feeds	185	960	4988
RF peak power per feed	12.5	1.39	0.15 Mw
RF energy stored in accelerator	5337	593	66 joules
RF energy required for 1.67 μ sec electron beam pulse length	13,778	3325	1405 joules
Total average rf power at 360 pulses/sec	4.96	1.20	0.51 Mw
Beam loading (- dV/di)	20.5	35.5	61.5 Bev/amp
Peak beam current at maximum conversion efficiency	272.1	157.1	90.7 mamps
Minimum diameter of beam aperture	2.292	0.764	0.255 inch
Max rf peak power available from single source	216	24	2.7 Mw
Max permissible electric field strength ²	133	230	398 kv/cm
Max expanded beam energy ³	38.4	66.5	115.0 Bev
Relative frequency and dimensional tolerances ⁴	1.11×10^{-5}	1.93×10^{-5}	3.34×10^{-5}
Absolute frequency and dimensional tolerances ⁴	11 kc/sec; 0.11 mils	58 kc/sec; 0.06 mils	301kc/sec; 0.04 mils
Average power dissipated per unit area of accelerator surface ⁵	0.20	0.14	0.18 watts/cm ²
Average temperature difference across accelerator wall ⁶	0.14	0.03	0.01 degrees C

1. Assumptions: $2\pi/3$ mode in constant gradient structure; $\tau = 0.57$ nepers (rf attenuation); $L = 10,000$ feet (94.8% effective); 10% power loss in waveguides; 10% beam loading; direct scaling of modular dimensions.
2. Based on max gradient obtained to date at S-band; values for other frequencies based on scaling as $f^{1/2}$.
3. As limited by maximum permissible field strength.
4. For one percent loss in beam energy.
5. Based on 360 pulses per second and 1.67 μ sec electron beam pulse length.
6. Based on copper wall 1/3, 1, and 3 cm thick at X-, S-, and L-bands, respectively.

(h) The relative frequency and dimensional tolerances favor the use of the higher frequencies. Relative tolerances are probably more significant than absolute tolerances, since the former are a better measure of the difficulties involved in designing stable frequency sources and in critical machining operations.

(i) The average power dissipated per unit area of accelerator surface is not significantly different in the three designs because of the fact that the increased wall area at low frequency tends to compensate for the higher power required, and vice versa. However, the average temperature difference across the accelerator wall, which is a measure of the degree of detuning of the structure, is highest at L-band and lowest at X-band.

It would be possible to compare accelerator designs at the various frequencies in further detail. The designs we have chosen for illustrative purposes were based upon direct scaling of the modular dimensions of the present S-band accelerator structure. An improved design at a particular frequency from the standpoint of over-all economy or performance might result from deviating from the scaling laws we have used. For example, the L-band design might be improved by decreasing the feed interval and using a larger number of sources, and by increasing the rf and beam pulse lengths while decreasing the pulse repetition rate. However, this would not affect the total peak power requirement nor the maximum field-strength capability. Similar alterations might be made at S- and X-bands to improve certain characteristics of these designs. However, we do not believe that such changes would appreciably modify the general conclusion we have reached: the S-band accelerator is the optimum choice for the two-mile accelerator for reasons which are implicit in the scaling laws of Table 1 and the illustrative examples of Table 2.

B. Product of RF Power and Accelerator Length

The energy of electrons from a linear accelerator with negligible beam-loading was given by Eq. (1). To estimate the power-length product of the two-mile accelerator, we take $r_0 = 53 \times 10^6$ ohms/meter; moreover, we anticipate the results of Section II.H and use the value, $K = 0.82$. The minimum objective is an accelerator which will produce electrons having an energy of 10 Bev under conditions of 10 percent beam loading. The no-load energy must therefore be 11.11 Bev. To obtain a realistic

estimate, we assume that 10 percent of the rf power is dissipated in the rf transmission lines between the power sources and the accelerator, and further that 5.2 percent of the accelerator length is used for auxiliary in-line devices and does not contribute to the acceleration process.

Substituting the above assumptions into Eq. (1) we obtain

$$\begin{aligned} P_T L &= 4.06 \times 10^{14} \text{ watt cm} \\ &= 1.33 \times 10^7 \text{ Mw ft} \end{aligned}$$

Thus the product of the total rf power and the accelerator length must be 1.33×10^7 Mw-ft in order to obtain an electron-beam energy of 10 Bev with 10 percent beam loading.

C. Selection of Accelerator Length

Once the rf-power accelerator-length product has been determined, these two quantities must be determined individually. The following factors influence these selections:

1. Maximum Electric Gradient

As discussed in Section I, the design objective is a linear electron accelerator initially capable of producing energies of 10 Bev, with an ultimate capability of 40 Bev energy by addition of rf power without increase of accelerator length. This objective requires that the length of the machine must be chosen so as to permit the maximum ultimate gradient. The maximum average electric gradient obtained in an operating S-band linear accelerator to date is approximately 4.5 Mev/ft. Using this figure, we find that a length of approximately 10,000 feet is required to satisfy the ultimate energy objective.

2. Economic Considerations

The total cost of the accelerator program may be divided into three parts:

- (a) costs $\{C_P\}$ which are proportional to the total connected rf power;
- (b) costs $\{C_L\}$ which are proportional to the total accelerator length; and
- (c) fixed costs $\{C_F\}$ which include research costs and administrative costs, among others.

To be meaningful, these costs must be based on a time period that includes

the construction time plus a period judged to represent the useful life of the machine. We have used a period of 10 years useful life in cost studies. From the fact that rf power and accelerator length have equal weight in the equation for electron energy, it is easy to show that the greatest over-all economy results when $C_P = C_L$. Otherwise, the total cost is given by

$$C = \frac{1}{2} \left[\left(\frac{C_P}{C_L} \right)^{\frac{1}{2}} + \left(\frac{C_L}{C_P} \right)^{\frac{1}{2}} \right] C_{(P,L),\min} + C_F \quad (2)$$

where $C_{(P,L),\min}$ is the minimum value of $C_P + C_L$ (i.e., where $C_P = C_L$). Our cost studies have shown that an accelerator length of 10,000 feet is very close to the optimum value to minimize the total project costs over the 6-year construction period and a 10-year period of operation.

3. Land Availability

There were several potential sites available on Stanford land which seemed suitable for the accelerator project location. An accelerator length of 10,000 feet (plus another 2500 feet, approximately, for research facilities) was possible at most of these sites but no greater length without expensive land-acquisition costs.

Thus the choice of an accelerator length of 10,000 feet satisfies the several conditions discussed above, viz., it permits operation at the ultimate expanded energy-gradient; it is near optimum from the standpoint of over-all economy; and such space is available on Stanford property. Therefore, we have made the selection

$$L = 10,000 \text{ feet}$$

which, using the power-length product determined in Sec. II.B leads to the following initial total connected rf power requirement

$$P_T = 1.33 \times 10^3 \text{ Mw}$$

It should be emphasized that this value of P_T is based upon a particular choice of operating mode ($2\pi/3$) and upon a particular attenuation parameter ($\tau = 0.57$). Their selection is discussed later in this section. The value of P_T will vary slightly if another mode or another value of τ is used.

D. Selection of Number of RF Power Sources and Feed Interval

It was established in Sec. II.C that a total rf peak power of 1330 Mw must be supplied to a 10,000-foot accelerator in order to achieve an electron energy of 10 Bev with 10 percent beam loading. The next logical design decisions are the determination of the number of individual rf power sources and the spacing of the rf feeds along the accelerator length.

In general, it is more economical to obtain a large amount of microwave energy from a small number of high-power sources than from a large number of low-power sources. The basic reason for this fact is that the cost of a power source depends more strongly on the number and kind of operations involved in its fabrication and processing than upon its physical size and output rating. The cost of employment of the power sources in the accelerator system in terms of auxiliary equipment, instrumentation, controls, waveguide equipment, etc., also decreases as the total number of individual sources is reduced. Based upon laboratory and commercial experience with high-power klystron amplifiers, it seems reasonable to expect that S-band tubes can be constructed to have an average life of 2000 hours or more while producing 24 megawatts of peak rf power and 22 kilowatts of average rf power. Much higher peak power levels from single S-band tubes do not appear to be readily obtainable at this time. For reasons of conservatism, it is planned to require initially only 6 megawatts peak output per klystron, which would result in an electron beam energy of 10 Bev. At this power level, average lifetimes exceeding 2000 hours should be easily achieved. For a total rf power of 1330 megawatts, 240 klystrons producing 6 megawatts each will be sufficient. Since these tubes will have a design capability of 24 megawatts each, it will be possible to achieve electron energies up to 20 Bev with the initial complement of tubes. For operation at the Stage II level of 40 Bev, 960 tubes producing 24 megawatts each will be required.

We shall now discuss the selection of the feed spacing along the accelerator length. The limiting cases of feed spacing are (a) a single

feed for the entire accelerator, and (b) individual feeds for each of the $\approx 80,000$ individual accelerator cavities. The first extreme is obviously infeasible because the full rf power could not be transmitted through the accelerator structure. The second extreme would be prohibitively expensive because of the multiplicity of waveguides and other microwave components and the necessary controls and instrumentation. As described in Section II.H, there is an optimum, or at least a preferred value, of the net rf attenuation between feed points. The choice of attenuation parameter is a compromise among many factors. The attenuation parameter can be adjusted to the desired value by properly choosing the diameter of the aperture in the disk-loaded accelerator structure and the length of the accelerator section. Increasing the aperture size increases the group velocity and decreases the attenuation per unit length. Thus a given attenuation parameter can be obtained by either a short accelerator section of high unit attenuation (small aperture), or by a long section of low unit attenuation (large aperture), or by a compromise involving medium length and medium aperture. The main factor in favor of close feed-spacing is that the shunt impedance of the accelerator structure improves slowly as the group velocity is decreased. This is shown in Figs. 21 and 22. These figures apply specifically to the $2\pi/3$ mode, but the same general behavior is true for other modes.

Several considerations limit how closely the feeds should be spaced. These are as follows:

- (a) Increased costs because of the larger number of components, controls, waveguides, couplers, rf loads, instruments, etc.
- (b) The complexity of splitting the rf power from each source many times.
- (c) The decreased aperture available for the electron beam as the group velocity is decreased.
- (d) Increased operational difficulties because of the increased number of phasing adjustments, monitors, interlocks, etc.

In Stage I, 240 rf power sources supplying 6 to 24 megawatts each will be used, as noted above. With equal spacing, these sources will be located at 40-ft intervals along the accelerator length. In Stage II (40 Bev max), with 960 rf sources supplying 6 to 24 megawatts power level, it would not be safe (for reasons of rf breakdown) to feed the combined

power outputs of 2 or more tubes into an accelerator section. Therefore, at least one feed every 40 feet is required in Stage I and at least one feed every 10 feet in Stage II. However, the shunt impedance is reduced by about 15 percent in going from a 10-foot to a 40-foot feed interval, so that the electron energy would be about 7.5 percent less for the same total rf power input. Moreover, a very desirable design feature of the machine, as noted in Section I, is the ability to accomplish the transition from Stage I to Stage II operation without a long shut-down period. Such a delay would be required if it were necessary to install additional feeds at the time of the transition.

For reasons discussed in the previous paragraph, a feed interval of 10 feet has been chosen for the two-mile accelerator. This means that during Stage I operation, with 240 rf-power sources, the power output from each feed must be divided 4 ways so as to supply 4 successive accelerator feeds. To convert to Stage II operation, with 960 rf sources, the additional sources can be connected to the already existing feeds with minimum interference to the operations schedule.

E. Choice of RF Pulse Length and Repetition Rate

For physics-research purposes it is generally desirable to have the electron-beam duty cycle (which is defined as the product of pulse repetition rate and beam pulse length) as high as possible. The practical upper limit of duty cycle is determined by economic considerations. The rf duty cycle must be greater than the beam duty cycle because a certain time is required to fill the accelerator with rf energy prior to injection of the beam. For the case where the electron beam is injected at a time after the start of the rf pulse equal to one filling time, the ratio of beam-to-rf duty cycles is given by

$$\frac{D_b}{D_{rf}} = 1 - \frac{t_F}{t_{rf}} \quad (3)$$

where t_F is the accelerator filling time, and t_{rf} is the rf pulse length. For example, with $t_F = 0.83 \mu\text{sec}$ (the value for $\tau = 0.57$ with the $2\pi/3$ mode) and $t_{rf} = 2.5 \mu\text{sec}$, the maximum duty cycle ratio as given by Eq. (3) is 0.67. This may be compared with the value of 0.5 for

the present one-Bev Stanford Mark III accelerator. An important point to emphasize is that a given fractional change in rf duty cycle because of increasing rf pulse length permits an even larger fractional increase in the beam duty cycle. Thus increasing the rf pulse length from 2.0 to 2.5 μ sec, an increase of 25 percent, allows a 43 percent increase in the beam duty cycle (for $t_F = 0.83 \mu$ sec). The factors which place a practical limit on the maximum rf pulse length are the increasing costs of modulator components, such as the pulse transformers and the pulse-forming networks. On the basis of these considerations, we have adopted the value of 2.5 microseconds for the rf pulse length of the two-mile accelerator.

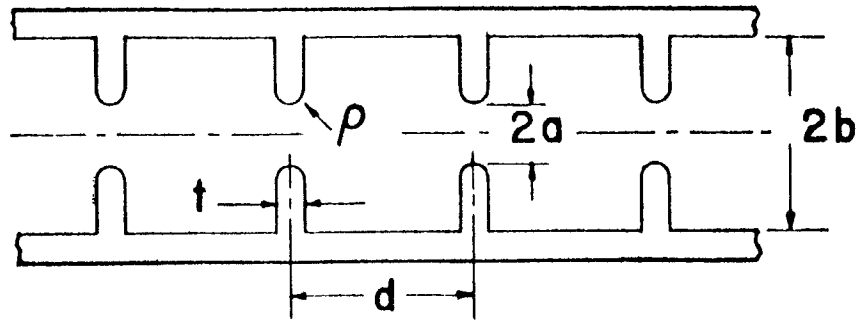
The maximum value of the pulse repetition rate is governed by three primary factors:

- (a) The initial cost of power components increases with increasing pulse repetition rate because of their higher average power ratings.
- (b) It is more difficult and expensive to design and construct high-power modulators at the higher repetition rates.
- (c) The ac power operational costs for the accelerator power sources increase almost directly with pulse repetition rate.

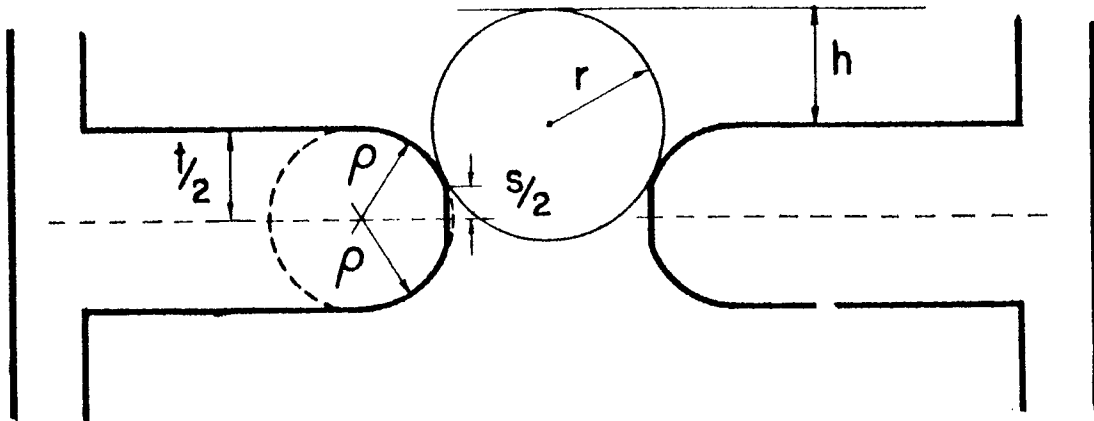
A maximum repetition rate of 360 pulses per second has been adopted for the two-mile accelerator. This may be compared with the maximum rate of 60 pulses per second for the Stanford Mark III accelerator. The combination of higher repetition rate, longer rf pulse length, and shorter filling time allows a maximum beam duty cycle for the two-mile accelerator of about .0006, or about 10 times greater than that of the Mark III accelerator.

F. Selection of Operating Mode

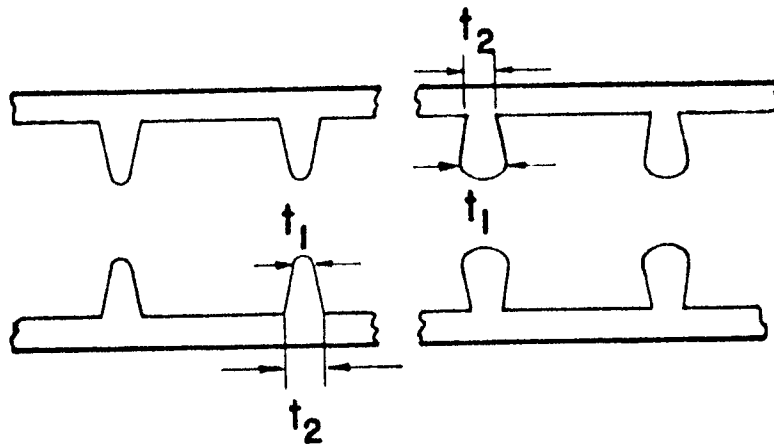
The accelerator structure is a disk-loaded cylindrical waveguide of the form shown in Fig. 3(a). The efficiency of the structure as an accelerator of electrons is measured by a quantity called the shunt impedance per unit length. This quantity, which we have already introduced in the previous discussion and designated by the symbol r_0 , may be defined as the square of the energy gained (in electron volts) by an electron per unit length for unit rf power dissipation in this same length. We have defined shunt impedance in terms of gain in particle energy to emphasize



a) TWO UNIT CELLS



b) ILLUSTRATION OF DISK DIMENSIONS



c) "CONICAL" AND "ANTICONICAL" DISKS

FIG. 3--Schematic drawing of disk-loaded waveguide.

that it is not simply the magnitude of the electric field in the accelerator structure which determines the electron energy gain per unit length; rather, it is the amplitude of the Fourier component of the axial field which travels at the electron velocity. The fundamental component is commonly used for acceleration of electrons.

The exact value of shunt impedance for a particular configuration of accelerator structure cannot be represented in simple form but can be measured to fair accuracy by microwave techniques. An approximate equation for r_0 which is suitable for studying the effects of varying the cavity dimensions is

$$r_0 = 968 \left(\frac{\beta_w}{\delta} \right) \frac{(1 - \eta)^2}{n + 2.61 \beta_w (1 - \eta)} \left(\frac{\sin D/2}{D/2} \right)^2 \quad (4)$$

where

- β_w is the phase velocity in the structure divided by c ,
- δ is the skin depth,
- η is the fraction of the length of the structure which is occupied by disks, i.e., $\eta = t/d = tn/\lambda$,
- n is the number of disks per guide wavelength, and
- D is the transit time in radians required for the electron to pass through the cavity gap, i.e., $D = (2\pi/n)(1 - \eta)$.

Equation (4) can be derived by considering an array of simple "pill-box" cavities. This equation gives too high a value of r_0 for two reasons: (a) the conductivity of the walls is never as high as the idealized value used in calculating the numerical value (968) in the equation; (b) no account is taken of the effect of the disk apertures. Nevertheless, the relative variation of r_0 with the spacing and thickness of the disks given by Eq. (4) has been confirmed by experimental measurements.

A graph of r_0 versus n for $f = 2856$ Mc/sec based on Eq. (4) is shown in Fig. 4 for four values of disk thickness t . Corresponding experimental values obtained from test cavity measurements are also shown. From Fig. 4 it is possible to draw some general conclusions. For negligible disk thicknesses ($t \approx 0$), the optimum number of disks per

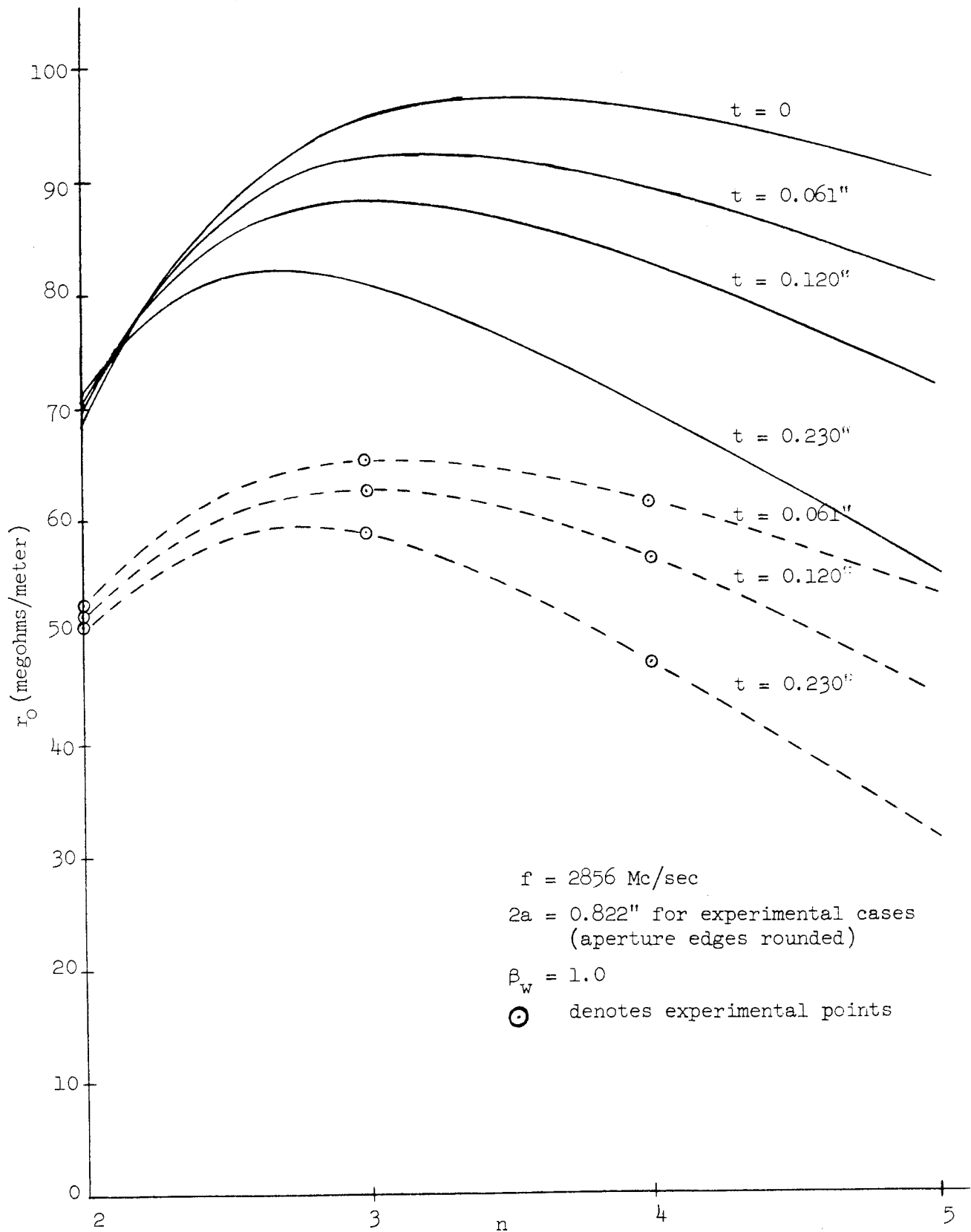


FIG. 4--Theoretical and experimental curves of shunt impedance (r_0) per unit length vs number of disks per wavelength (n) for various disk thicknesses (t).

wavelength is approximately 3.5. As the disk thickness is increased, the optimum value of n decreases. The best value at $t = 0.120$ in. is about $n = 3$. It is about 2.7 for $t = 0.230$ in., which is the chosen disk thickness. The value $n = 3$, corresponding to a phase shift of $2\pi/3$ radians per cavity, has been adopted for the two-mile accelerator. In addition to the improvement in shunt impedance, the selection of the $2\pi/3$ mode results in fewer disks and improved vacuum conductance compared to the $\pi/2$ mode used with the earlier Stanford accelerators.

The basis for the results described above may be found upon further examination of Eq. (4). There are three competing factors:

(a) The shunt impedance of the individual cavities is improved by increasing the height of the cavities, i.e., the disk spacing.

(b) The fraction of the length available for the accelerating fields to act on the electrons is increased as the number of disks per wavelength is decreased or as the disk thickness is decreased.

(c) As the disk spacing is decreased the electron transit time is decreased correspondingly, and the average or "effective" field strength acting on the electron is increased as $(\sin D/2)/(D/2)$. Thus, considerations (a) and (b) favor small n and small t , while consideration (c) favors large n and large t . As t increases, the fractional space occupied by the disks increases so that r_0 peaks at a lower value of n .

An expression similar to Eq. (4) may be given for the Q of an accelerator structure:

$$\frac{Q_0}{\lambda_0} = \frac{\beta_w(1 - \eta)}{n + 2.61 \beta_w(1 - \eta)} \quad (5)$$

where the symbols have the same meaning as before. A plot of Q versus n is given in Fig. 5. Some measured values of Q are also shown in the same figure.

The quantity Q was measured in each case by taking two cavity lengths in the ratio of 2:1 in order to cancel out the effect of the end-wall losses. The values of Q are seen to decrease from around 17,000 at $n = 2$ to about 13,000 at $n = 3$ and 10,000 at $n = 4$.

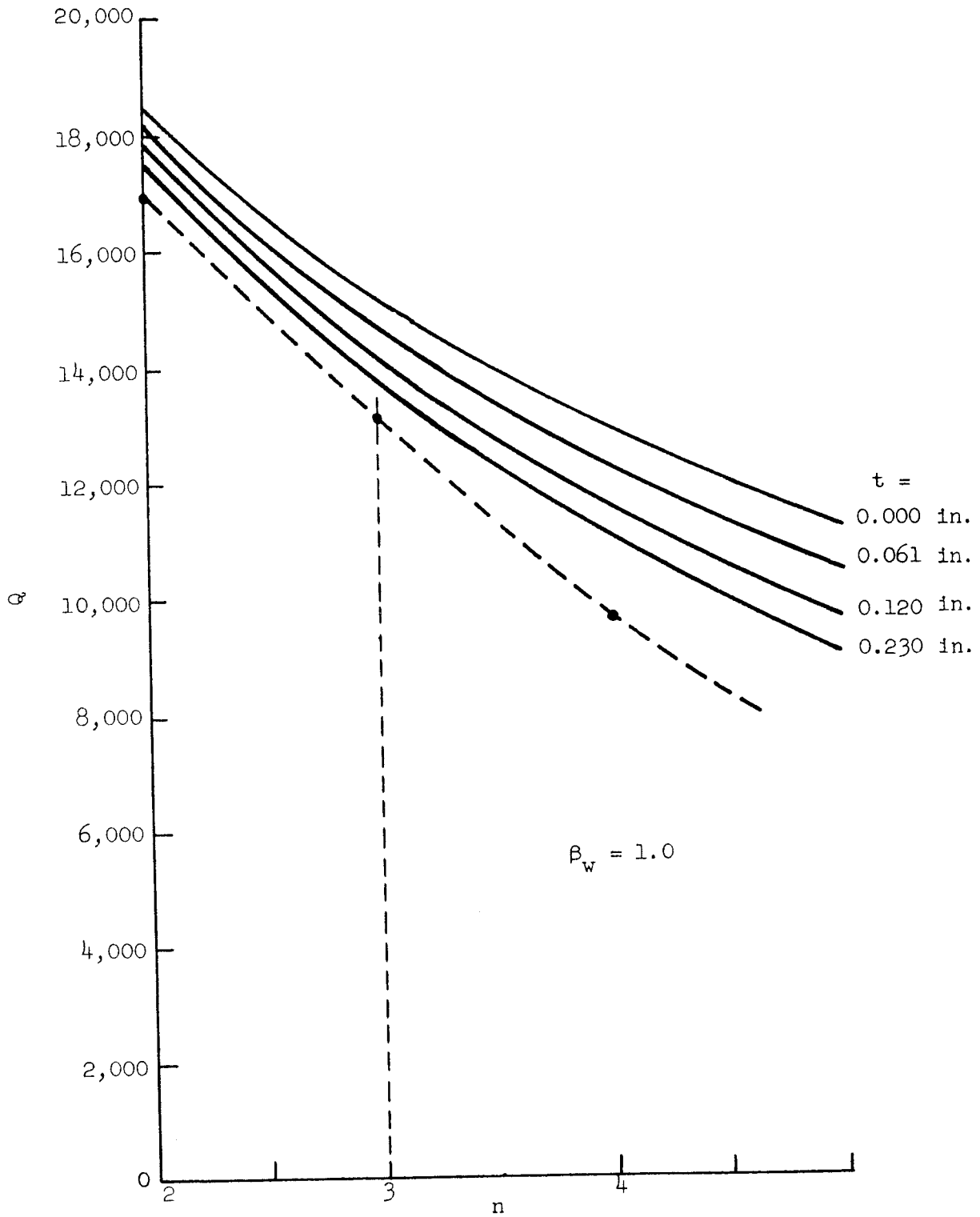


FIG. 5--Theoretical and experimental curves of Q versus number of disks per wavelength (n) for various disk thicknesses (t).

A number of experimental curves for $n = 2, 3,$ and 4 are given in Figs. 6 and 7. The data for these curves were based on disks with unrounded or "square" boundaries. For a given aperture diameter, rounding of the boundary has the effect of increasing the group velocity and decreasing the shunt impedance by about 5 to 10 percent.

Another observation which is illustrated in Fig. 7 is that the group velocity decreases with increasing disk thickness at a given value of n (except $n = 2$). This indicates that it may be quite misleading to compare the various cases on the basis of the same aperture diameter (2a). A better comparison would be on the basis of the same value of group velocity, which would thereby insure that the filling times for an accelerator section of fixed length were equal in all cases. Alternately, the comparison might be made on the basis of equal values of the product $v_g Q$, which would give equal values of rf attenuation per unit length in all cases. Adjusting $2a$ to give equal values of v_g would reduce r_o more severely in the thick-disk cases and would thus favor the adoption of thin disks. The limiting factor in reducing disk thickness is the increasing danger of arcing at the disk aperture boundary.

G. Constant-Impedance vs Constant-Gradient Structures

When an accelerator of uniform modular dimensions (constant impedance) is fed with rf power at one end, there is an exponential decay of power and electric field strength with axial distance from the input end. This means that the average axial electric field is less than the peak axial field in the structure. On the other hand, it is possible to design a structure of non-uniform modular dimensions in which the axial fields will remain constant over the entire length. Such a structure will be referred to as a constant-gradient structure.

The ratio of peak-to-average axial electric field strength is unity in the constant-gradient structure, while in the constant-impedance structure it is given by

$$\left(\frac{E_o \ell}{V_o} \right) = \frac{\tau}{1 - e^{-\tau}} \quad (6)$$

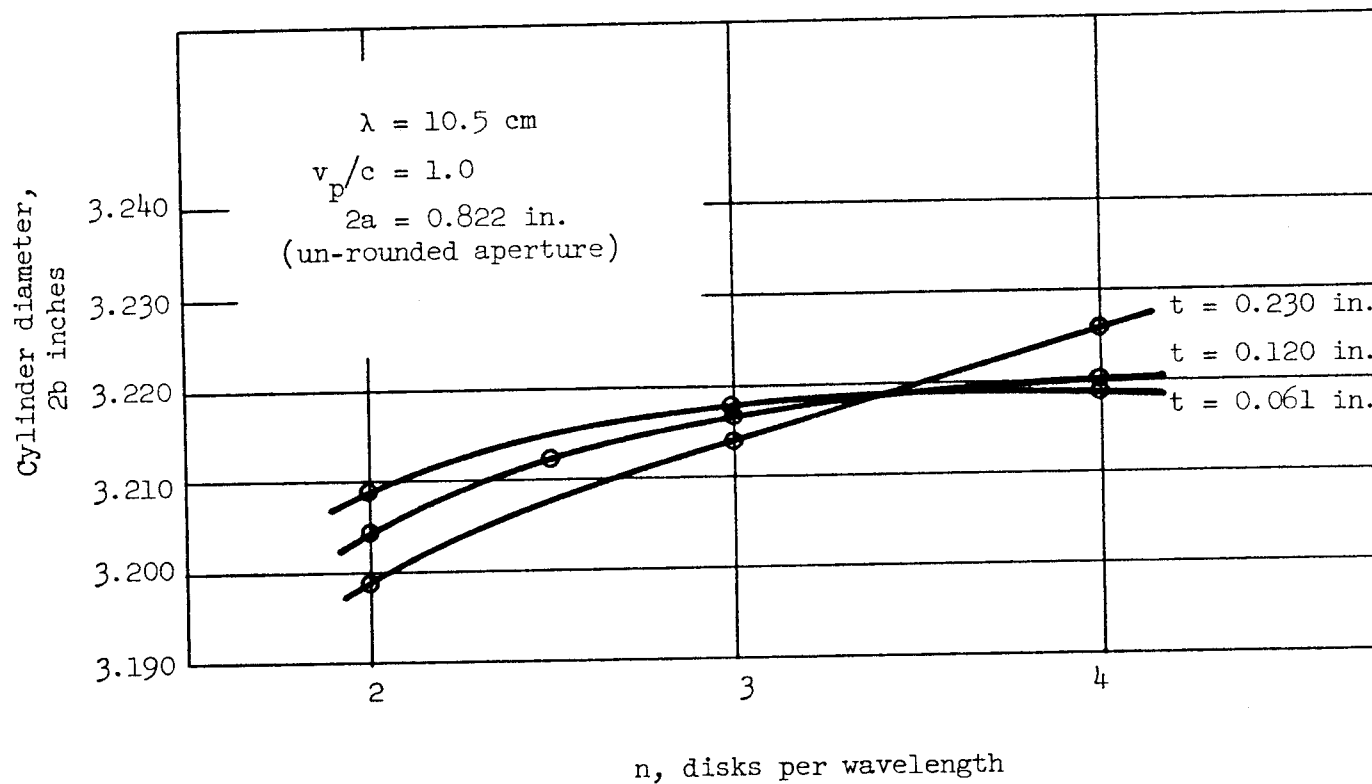


FIG. 6--Cylinder diameter of disk-loaded waveguide as a function of loading.

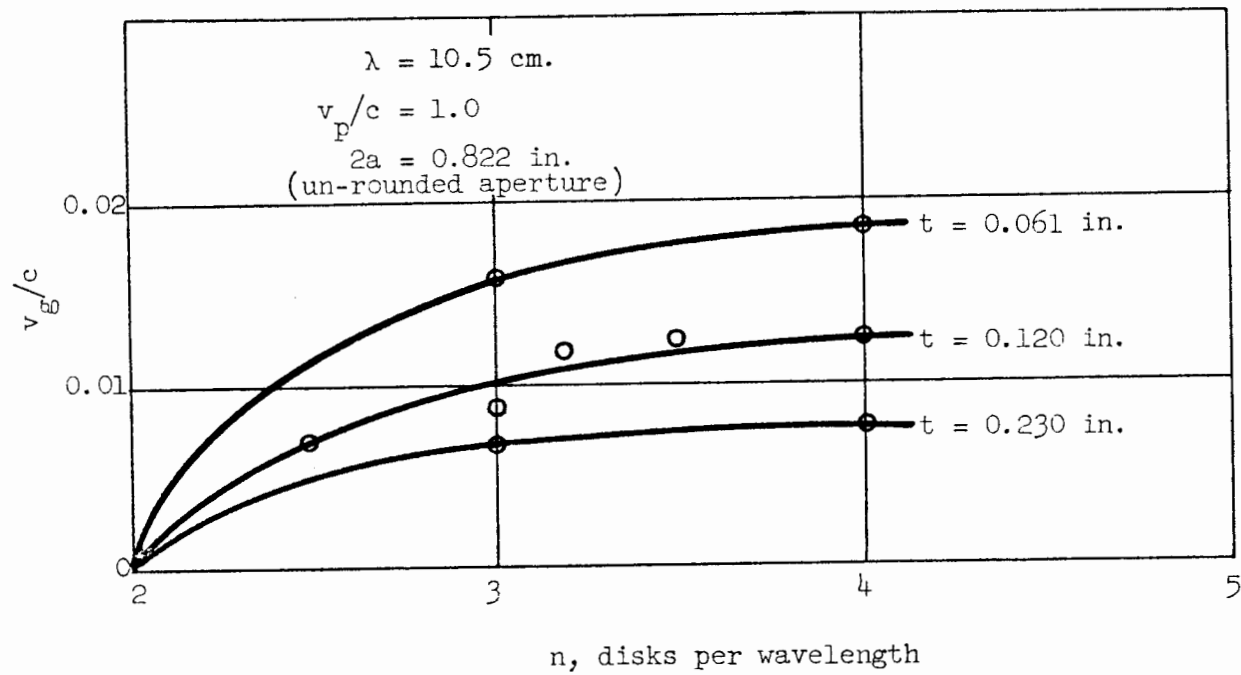


FIG. 7--Group velocity of disk-loaded waveguide as a function of loading.

where $\tau = \frac{\omega t_F}{2Q}$ is the rf attenuation parameter. [Equations (6) through (13) are given without proof. They are derived in reference 3.] These ratios are shown vs τ in Fig. 8. Thus it is clear that the constant-gradient (c.g.) structure can produce higher electron energies than an optimized constant-impedance (c.i.) structure when both are operating at the breakdown limit of electric-field strength. As indicated in Fig. 8 the relative advantage of the c.g. accelerator in achieving high gradients without breakdown depends upon the value⁴ of τ . Curves of field strength vs axial distance z for the two types of structure are shown in Fig. 9 for $\tau = 0.57$.

In addition to the advantage of reduced ratio of peak-to-average field strengths, the constant-gradient structure has several other advantages over the constant-impedance structure:

(a) The power dissipated per unit length in the c.g. accelerator is constant over the entire length of the structure. In contrast, the ratio of power loss at the input end to that at the output end of a constant-impedance structure may be as high as 12.4 to 1. (This magnitude corresponds to a value of the rf attenuation constant $\tau = 1.26$ nepers, which gives maximum no-load energy in the constant-impedance accelerator structure.) This means that the temperature rise in the c.g. structure can be perfectly compensated by a simple frequency adjustment of the rf power source, thus preventing phase shift between the electrons and the wave. Such an adjustment will be imperfect in the c.i. structure, thus leading to phase shift and loss of beam energy. A plot of the power-loss ratios for the two structures is shown in Fig. 10.

(b) The c.g. structure gives a slightly higher no-load beam energy than the c.i. structure and somewhat lower beam-loading derivative ($-dV/di$). Thus, the c.g. structure has greater relative energy advantage in the loaded case than in the unloaded case. The no-load energies for the two structures are shown in Fig. 11 and the beam-loading derivatives in Fig. 12.

(c) The c.g. structure has a higher maximum conversion efficiency (ratio of maximum electron-beam power to input rf power) and a higher corresponding maximum peak beam current than the c.i. structure. Curves of the maximum conversion efficiency, η_{\max} , and the corresponding maximum beam current, $i_{\eta_{\max}}$, are shown in Fig. 13.

(d) The c.g. accelerator is less frequency-sensitive than the c.i. accelerator, as shown in Fig. 14.

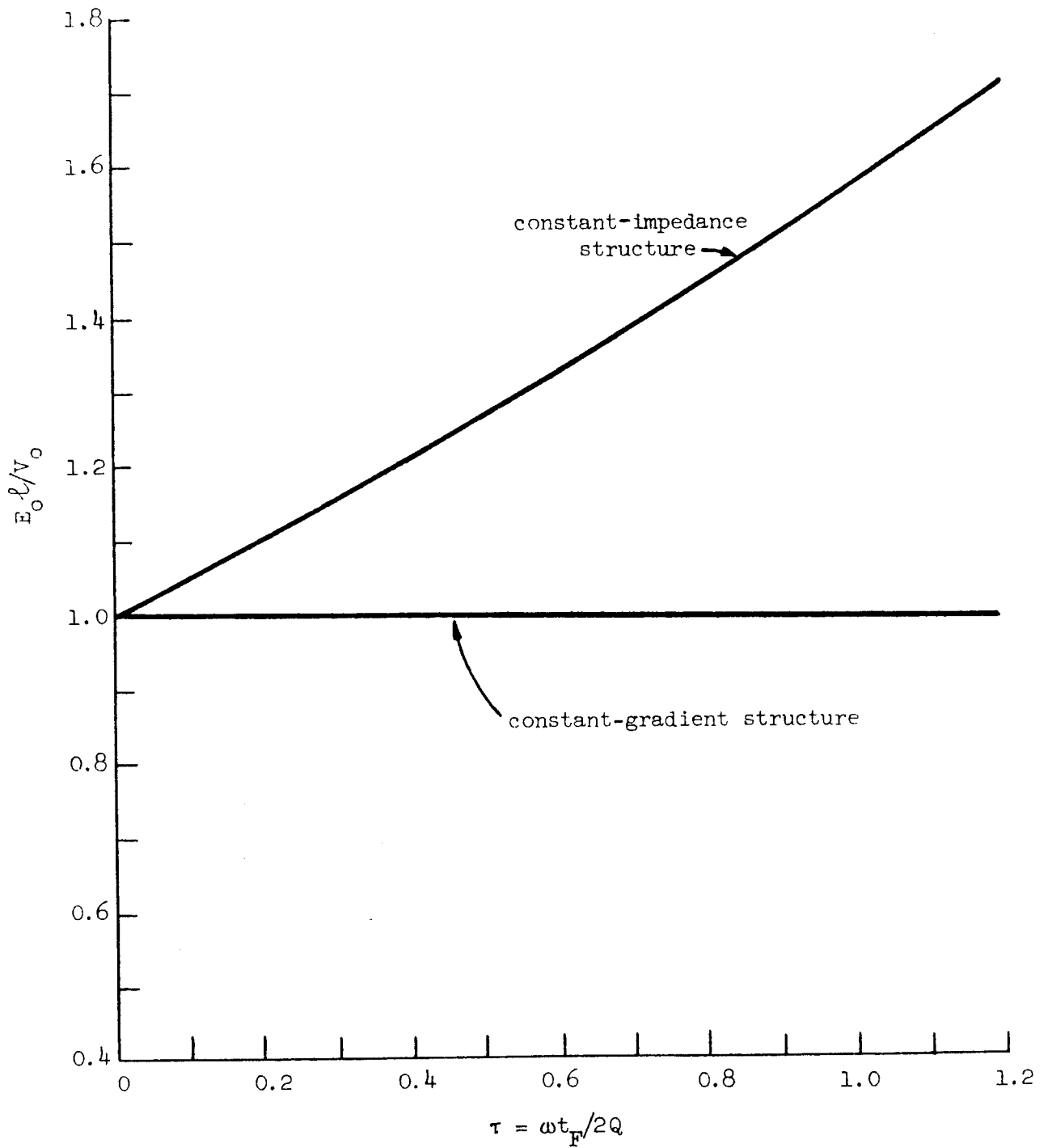


FIG. 8--Ratios of peak to average axial electric field strengths in constant impedance and constant-gradient accelerator structures versus τ .

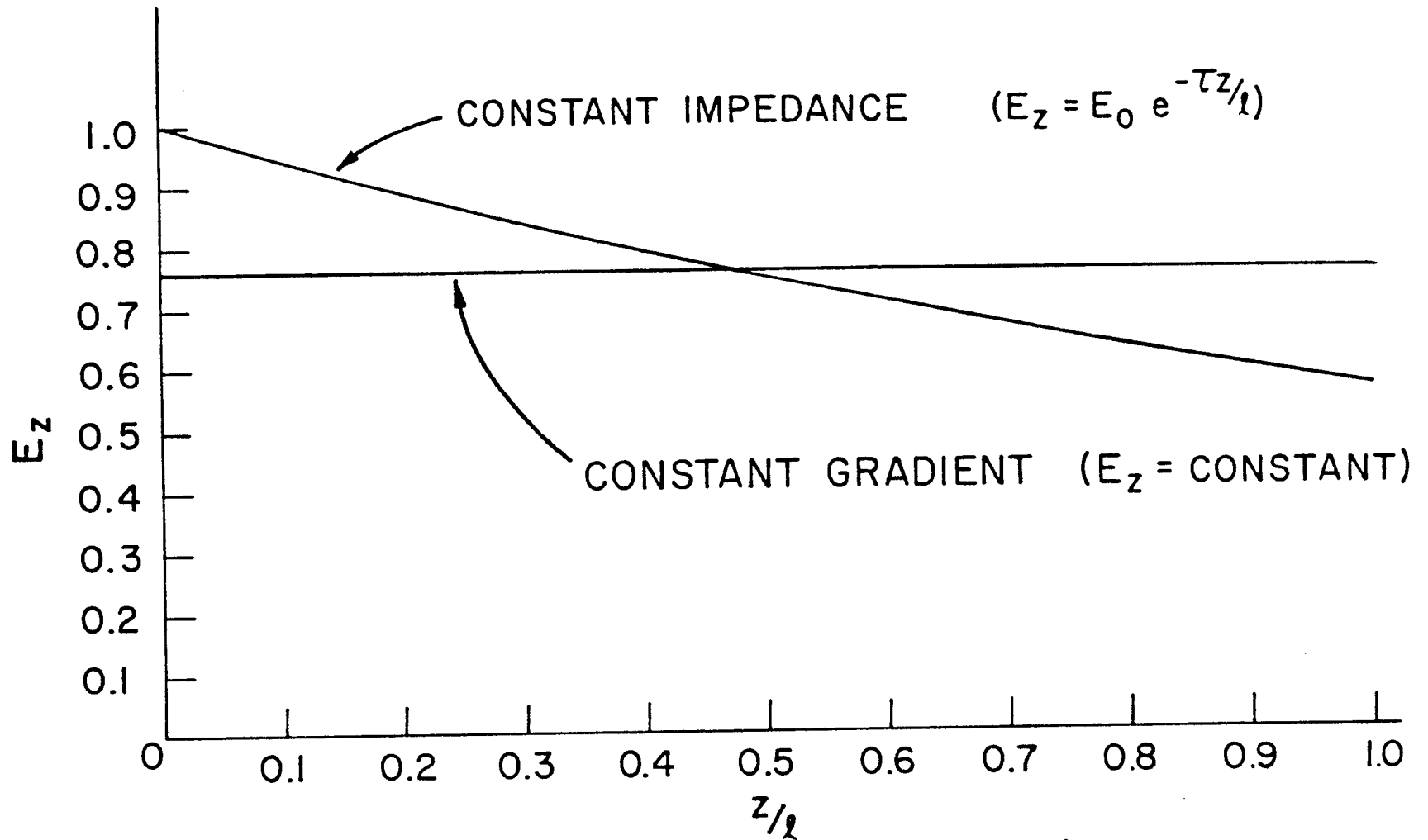


FIG. 9 AXIAL FIELD STRENGTH VERSUS z/l FOR EQUAL ELECTRON ENERGY GAIN IN CONSTANT GRADIENT AND CONSTANT IMPEDANCE SECTIONS. $\tau = 0.57$

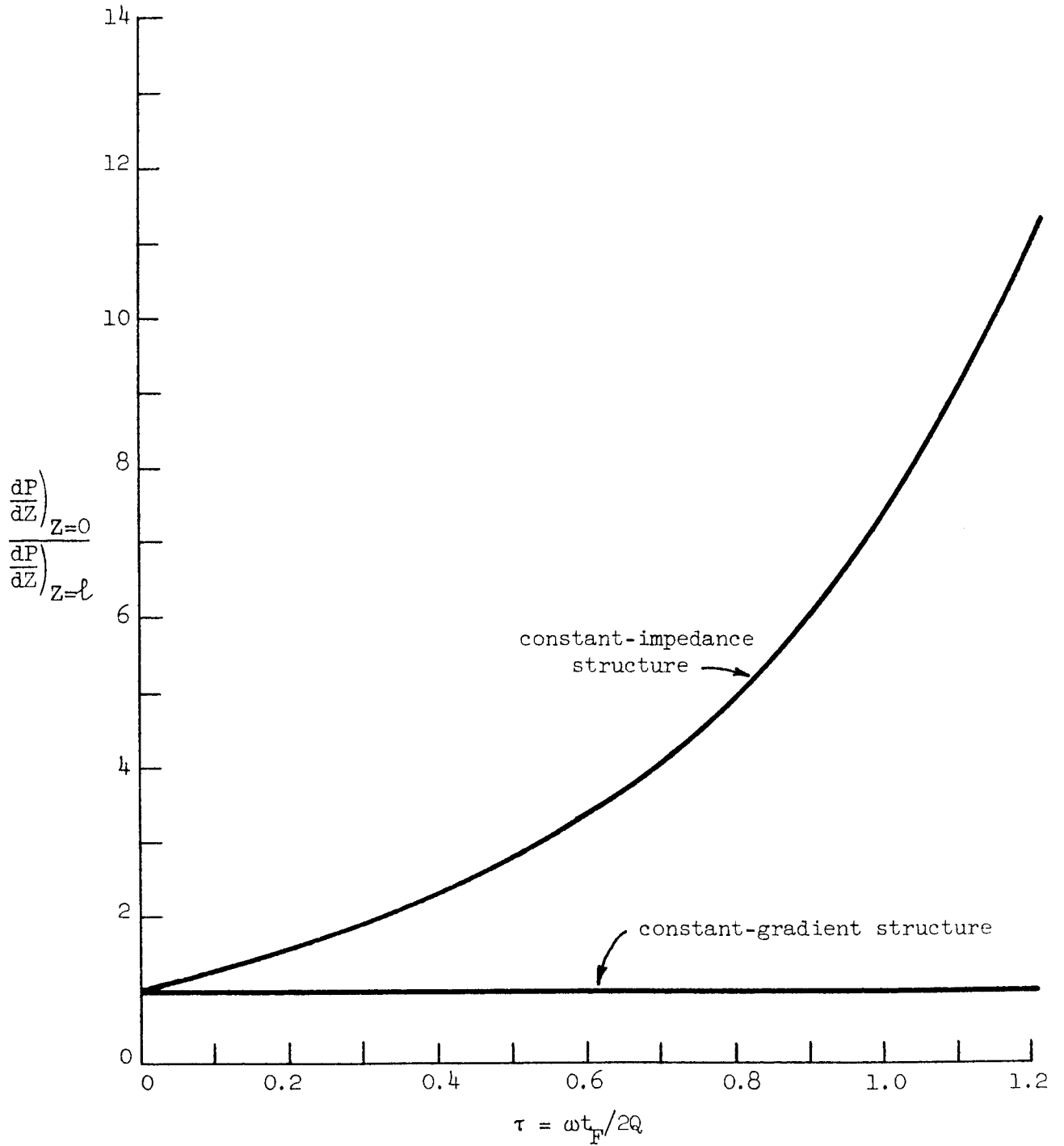


FIG. 10--Ratio of power losses at input and output ends of accelerator section for constant-impedance and constant-gradient structures versus τ .

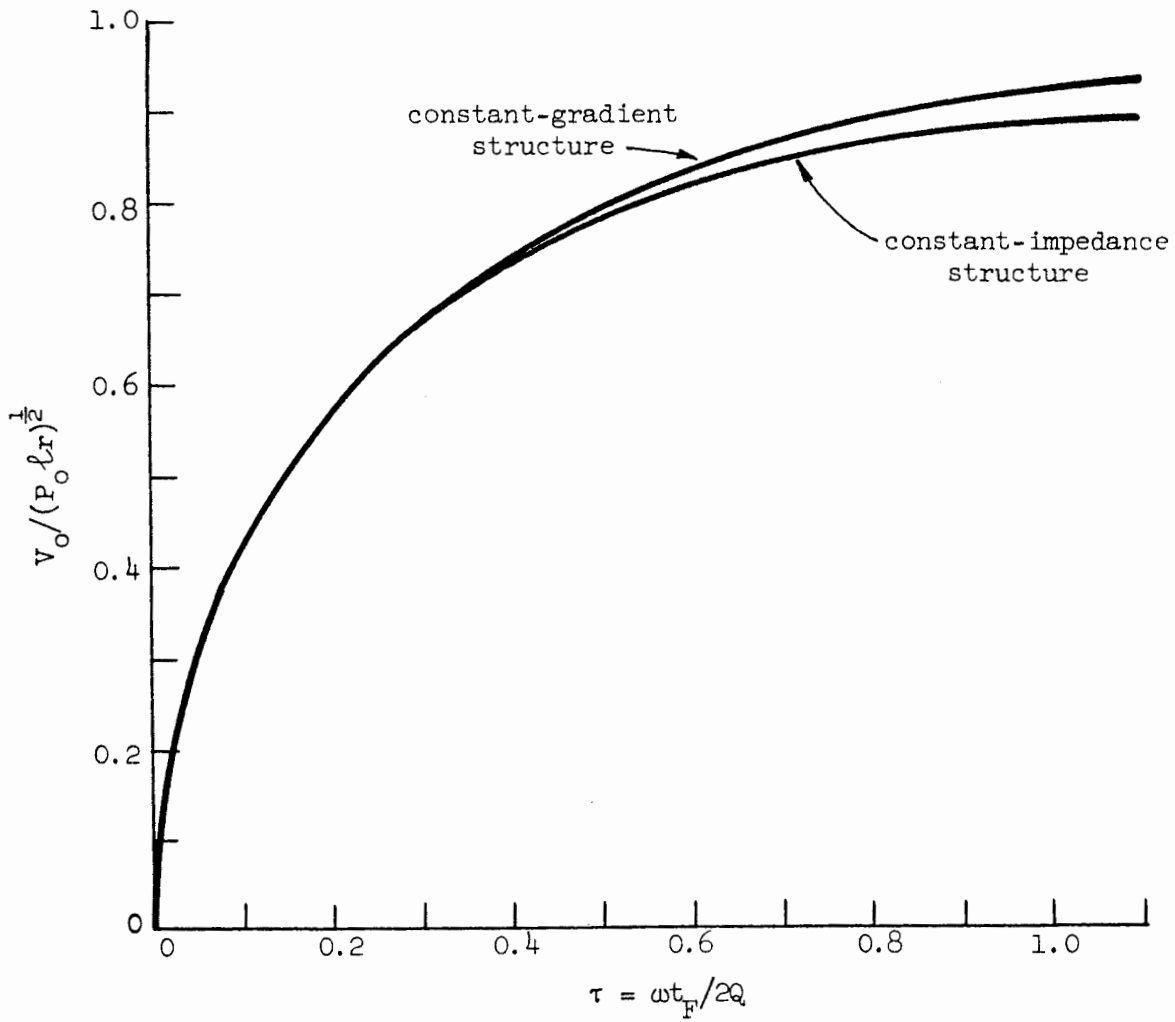


FIG. 11--Unloaded beam energies for constant-impedance and constant-gradient accelerator structures versus τ .

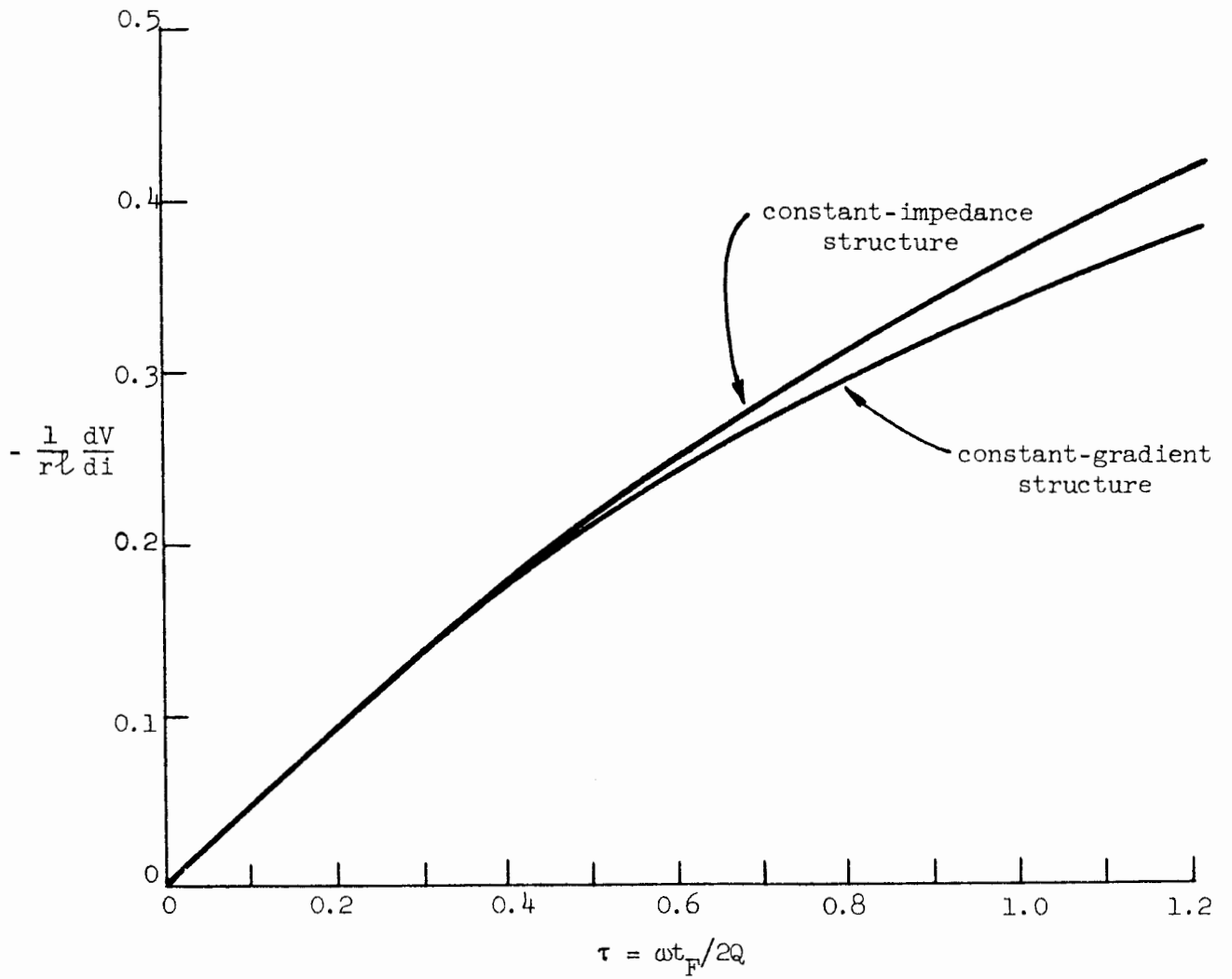


FIG. 12--Beam-loading derivatives for constant-impedance and constant-gradient accelerator structures versus τ .

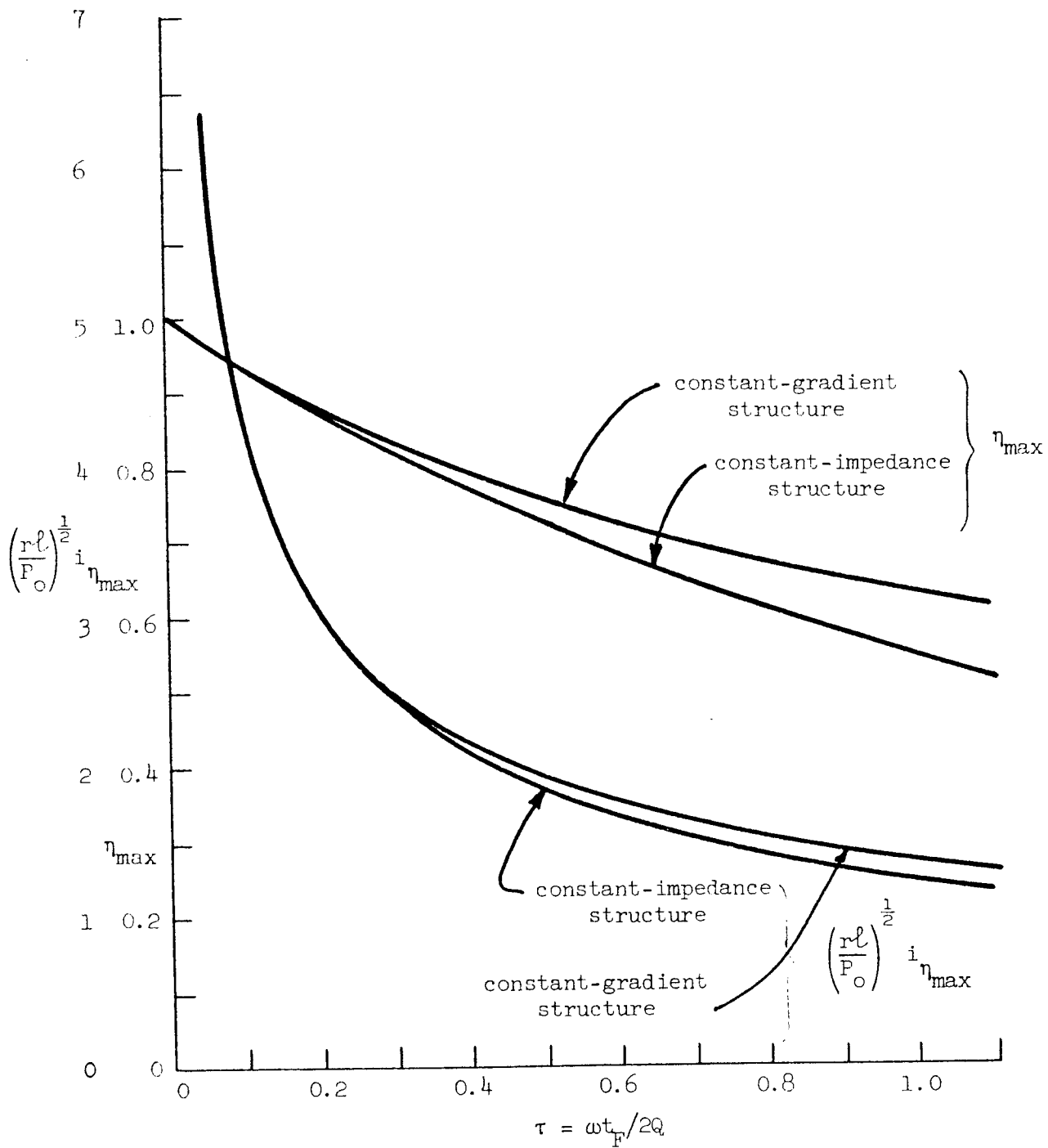


FIG. 13--Maximum beam conversion efficiencies and corresponding values of peak beam current for constant-impedance and constant-gradient accelerators versus τ .

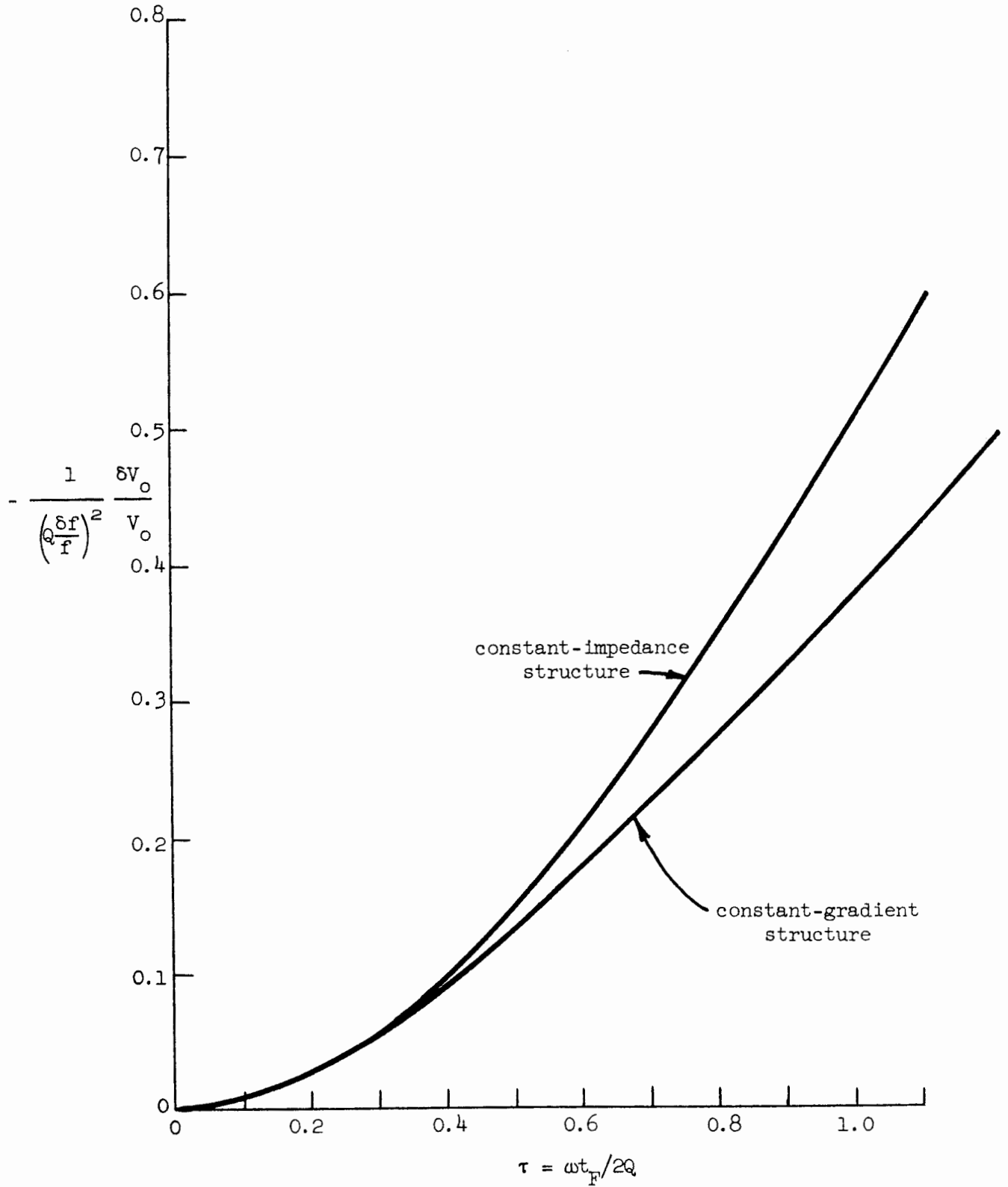


FIG. 14--Frequency sensitivities of uniform and constant-gradient accelerator structures versus τ .

The advantages discussed above depend upon τ , as shown in Figs. 8-14. To illustrate these factors numerically, the characteristics of the two structures are shown in Table 3, based upon the parameters of the two-mile accelerator.

(e) The c.g. structure is less subject to transient effects than the c.i. structure. Because of the band-pass filter characteristics of an accelerator structure, an impressed rf wave envelope of finite rise time results in amplitude and phase oscillations⁵ of the traveling wave. These oscillations result in a small increase in the width of the energy spectrum of the output electron beam. Experiments at Stanford have shown (Fig. 15) that the transient effects are more quickly damped in the c.g. structure than in the c.i. structure.

(f) Experiments elsewhere⁶ have shown that the c.g. structure is not troubled by beam "break-up" (also called "pulse shortening"⁷) phenomena which are prevalent with the c.i. structure under heavy beam loading conditions. It appears that beam interaction does not result in significant excitation of the higher order TM_{11} mode (the radially deflecting properties of which have been under study⁸ at Stanford since 1959) in the non-uniform c.g. structure as it does in the uniform c.i. structure. Figure 16 shows ω - β diagrams for the fundamental TM_{01} mode at the midpoint of a 10-foot constant-gradient section and for the TM_{11} mode at the input, midpoint, and output. Note that the $v_p = c$ line intersects each of the higher mode curves at a different frequency, thus making the build-up of a strong TM_{11} propagating wave at a particular frequency unlikely.

The advantages of the constant-gradient accelerator discussed above must be weighed against two disadvantages:

(1) The non-uniform modular dimensions of the cavities in the constant-gradient structure will be more expensive to construct and to test. An economic comparison of the two structures shows that fabrication of the c.g. structure will cost approximately 10% more per unit length than the c.i. structure.

(2) There has been relatively little operational experience with the constant-gradient structure compared with that of the uniform structure.

We have concluded that the advantages of the c.g. structure given above outweigh the relatively small cost differential which its use entails. The c.g. structure has thus been tentatively adopted for

TABLE 3
COMPARISON OF CONSTANT-GRADIENT AND CONSTANT-IMPEDANCE
ACCELERATOR STRUCTURES

Characteristic	Constant-Gradient	Constant-Impedance	Ratio $\frac{c.g.}{c.i.}$
$\frac{E_o \ell}{V_o} \left(\frac{\text{Peak elec. field}}{\text{Aver. elec. field}} \right)$	1.00	1.31	0.76
$\frac{dP}{dz} \Big _{z=0} / \frac{dP}{dz} \Big _{z=\ell}$	1.00	3.13	0.32
V_o (no-load energy)	11.17 Bev	11.02 Bev	1.01
- dV/di	35.53 $\frac{\text{Bev}}{\text{amp}}$	36.41 $\frac{\text{Bev}}{\text{amp}}$	0.98
V (at $i = 25$ mamps)	10.28 Bev	10.11 Bev	1.02
η_{\max} (max beam-conversion efficiency)	0.73	0.70	1.05
$i_{\eta_{\max}}$	157.1 ma	151.3 ma	1.04
v_g/c (normalized group velocity)	.0204 \rightarrow .0065	0.0121	1.68 \rightarrow 0.54
t_F (filling time)	0.83 μsec	0.83 μsec	1.00
U (stored energy)	593 joules	593 joules	1.00
$\Delta_{z=\ell}$ (phase shift for $\delta f = 0.1$ Mc/sec)	0.52 rad	0.52 rad	1.00
$\delta V_o/V_o$ (for $\delta f = 0.1$ Mc/sec)	0.033	0.039	0.85

Assumed parameters: $\tau = 0.57$

$P_{oT} = 1330$ Mw (90% of which enters accelerator)

$L = 10,000$ ft (94.8% effective)

Number of sections = 960

$f = 2856$ Mc/sec

$r = 0.53 \times 10^6$ ohms/cm

$Q = 13,000$

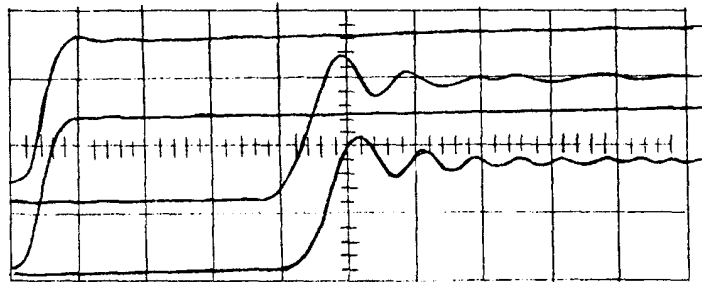


FIG.15--Shapes of input and output rf pulses in a constant gradient accelerator section (upper curves) and a constant impedance accelerator section (lower curves). Length of section = 10 ft, $\tau = 0.57$, and $2\pi/3$ mode in each case. Rise time of input pulse $\approx 0.1 \mu\text{sec}$; time scale = $0.2 \mu\text{sec/cm}$.

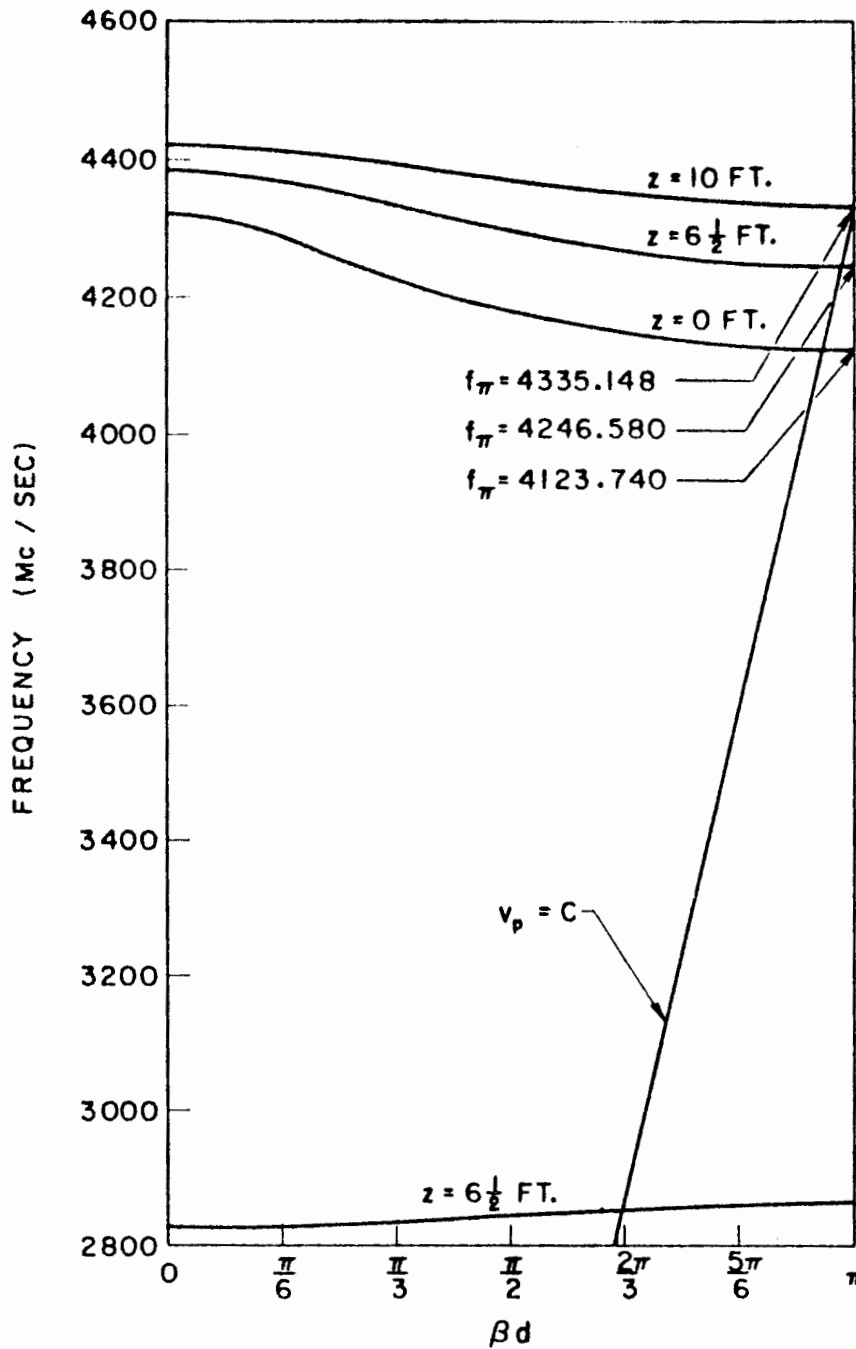


FIG.16- ω - β DIAGRAMS FOR THE FUNDAMENTAL TM_{01} MODE AT THE MIDPOINT OF A 10-FOOT CONSTANT GRADIENT SECTION AND FOR THE TM_{11} MODE AT THE INPUT, MIDPOINT AND OUTPUT. NOTE THAT THE $v_p = c$ LINE INTERSECTS EACH OF THE HIGHER MODE CURVES AT A DIFFERENT FREQUENCY.

the two-mile accelerator, and high-power tests under way since the spring of 1962 have confirmed theoretically predicted performance.

H. Choice of Attenuation Parameter

The attenuation parameter is defined as the net attenuation in nepers in an accelerator section caused solely by resistive wall losses. It is equal to the product of the voltage attenuation per unit length and the length of the accelerator section. We have designated this product by the symbol τ . As stated previously, $\tau = \omega t_F / 2Q$, where ω is 2π times the operating frequency, t_F is the filling time, and Q is the loss factor in the rf structure. As will be evident in the following discussion, the value of τ influences the performance in many ways, and therefore the proper choice of this parameter is quite important in the design of the two-mile accelerator.

The total energy gain V_T in a constant-gradient accelerator of total length L and shunt impedance r is given by³

$$V_T = \left(1 - e^{-2\tau}\right)^{\frac{1}{2}} \left(P_T L r_o\right)^{\frac{1}{2}} - \frac{i r_o L}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right) \quad (7)$$

where P_T is the total input rf power, i is peak beam current, and r_o is the shunt impedance per unit length.

The first term on the right in Eq. (7) is the no-load energy (i.e., the electron energy at negligible current), and the second term gives the reduction in energy caused by beam loading. The reduction of energy is linear with increase in beam current, as shown in Fig. 17. In plotting these curves it is assumed that the electrons are situated at the peak of the traveling wave.

In the discussion which follows we shall consider the effect of different values of τ upon the constant-gradient accelerator performance. The various accelerator characteristics are shown numerically in Table 4 for these values of τ .

1. Beam-loading characteristics

Beam-loading curves for the various values of τ under consideration are shown in Fig. 17. The terminal point on each curve is the beam current resulting in maximum transfer of rf power to the beam. We note that

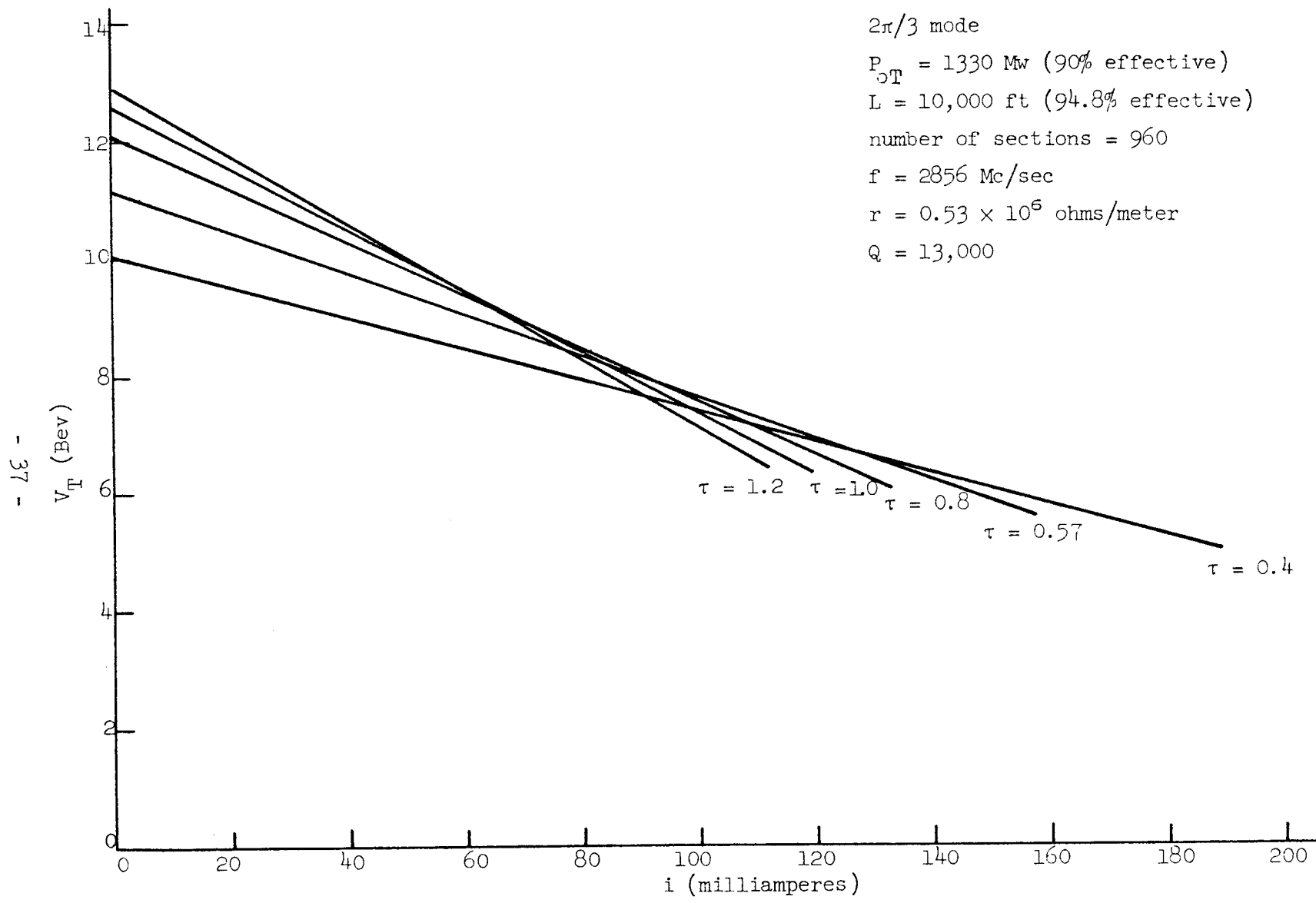


FIG. 17--Beam-loading curves for constant-gradient accelerator at various values of the attenuation parameter τ .

TABLE 4
CALCULATED PERFORMANCE OF CONSTANT-GRADIENT ACCELERATOR
AT VARIOUS VALUES OF ATTENUATION PARAMETER τ

	τ (nepers)				
	0.4	0.57	0.8	1.0	1.2
(V_{To}) unloaded energy (Bev)	10.05	11.17	12.10	12.59	12.91
$(-dV/di)$ beam loading derivative (Bev/amp)	26.59	35.53	45.58	52.61	58.24
(V_T) energy at 25 ma beam current (Bev)	9.38	10.28	10.96	11.28	11.46
$(\Delta V)_t$ transient energy spread (in Bev) between $i = 0$ and $i = 25$ ma	0.67	0.89	1.14	1.31	1.45
$(i_{\eta_{max}})$ beam current at max conversion efficiency (ma)	188.9	157.1	132.7	119.7	110.8
$(\Delta V)_e$ energy loss in idle 10-ft section at $i = 25$ ma. (Mev)	0.66	0.88	1.13	1.30	1.44
(v_g/c) normalized group velocity*	.0252 → .0113	.0204 → .0065	.0174 → .0035	.0160 → .0022	.0152 → .0014
(t_F) filling time (usec)	0.58	0.83	1.16	1.45	1.74
$(-\delta V/V)$ energy loss for $\delta f = 0.1$ Mc/sec	0.018	0.033	0.056	0.077	0.098

Assumptions: $2\pi/3$ mode, constant-gradient design
 $P_{CT} = 1330$ Mw (90% of which enters accelerator)
 $L = 10,000$ ft (94.8% effective)
 Number of sections = 960
 $f = 2856$ Mc/sec
 $r = 0.53 \times 10^6$ ohms/cm
 $Q = 13,000$

* The group velocity in each 10-ft accelerator section varies linearly between the limits given in each column.

the slope ($-dV/di$) of the beam-loading curves decreases in magnitude as τ decreases. Since electrons with energies from V_{T0} to V_{Ti} emerge from the accelerator during the transient period, lower values of τ are preferred to reduce the energy spread.

2. Maximum conversion efficiency

The maximum conversion efficiency of rf power to beam power is given by³

$$\eta_{\max} = \frac{1}{2} \left[\frac{(1 - e^{-2\tau})^2}{(1 - e^{-2\tau}) - 2\tau e^{-2\tau}} \right] \quad (8)$$

Maximum conversion efficiency occurs when the beam current reaches the value³

$$i_{\eta_{\max}} = \left(\frac{P_T}{r_o L} \right)^{\frac{1}{2}} \left[\frac{(1 - e^{-2\tau})^{\frac{3}{2}}}{(1 - e^{-2\tau}) - 2\tau e^{-2\tau}} \right] \quad (9)$$

in which case the beam energy is equal to one-half of the no-load energy.

3. Energy loss when beam passes through sections not supplied with rf power

When one of the klystron rf power sources becomes defective, it is desirable to be able to continue operation of the accelerator while the klystron is being changed. The amount by which the electron beam energy is reduced by excitation of an idle accelerator section of length l is given by³

$$(\Delta V)_e = \frac{ir_o l}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}} \right) \quad (10)$$

The energy loss decreases as τ increases, as shown in Table 4. Since each rf source supplies four accelerator sections during Stage I operation, the total energy loss given by Eq. (10) must be multiplied by four. This loss is, of course, in addition to the loss of beam energy that would normally be contributed by the four sections (about 40 Mev when the total

energy is 10 Bev).

4. Group velocity

In the constant-gradient accelerator, the group velocity decreases linearly with distance along the accelerator section. It is given by³

$$v_g = \frac{\omega \ell}{Q} \left[\frac{1 - (z/\ell)(1 - e^{-2\tau})}{1 - e^{-2\tau}} \right] \quad (11)$$

5. Filling time

A small filling time is desirable to allow the maximum available portion of the rf pulse length for the acceleration of electrons. The filling time is given by³

$$t_F = \frac{2Q}{\omega} \tau \quad (12)$$

Values of filling time for the various cases are given in Table 4.

6. Frequency sensitivity

The fractional beam-energy loss from a fractional frequency shift $\delta f/f$ is given by

$$\frac{\delta V_o}{V_o} = \left(Q \frac{\delta f}{f} \right)^2 \left[\frac{2\tau e^{-2\tau} (\tau + 1)}{1 - e^{-2\tau}} - 1 \right] \quad (13)$$

Values of $\delta V_o/V_o$ are shown in Table 4 for $\delta f = 0.1$ Mc/sec.

7. Conclusions

From Table 4 it is clear that there are several advantages to using a reduced attenuation parameter τ . Except for the reduction in beam energy, the general statement can be made that the use of a low value of τ results in improvement of all of the factors measuring the performance of the accelerator. Moreover, the percentage improvement of each of these factors resulting from a given reduction in τ usually exceeds the percentage loss in beam energy. If it were not for the paramount importance of high beam energy in particle-physics research, the

adoption of a very low value of τ would clearly be indicated. It has not seemed reasonable to us to make the selection on a strict analytical basis. We have instead made the choice of τ on the basis of broad considerations, including reference to such tabulations as shown in Table 4, the prospective requirements of physics research, and previous accelerator experience. We have chosen the value⁹ of $\tau = 0.57$ for the sections of the two-mile accelerator.

III. EMPIRICAL DESIGN OF THE ACCELERATOR STRUCTURE

A. Choice of the Disk-Loaded Waveguide

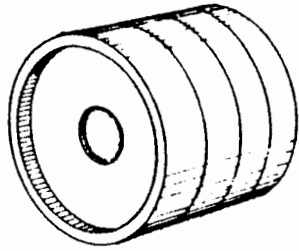
The previous sections of this paper have been concerned with the general determination of accelerator parameters. This section describes the procedures used to design empirically an accelerator structure that satisfies the above parameters.

The disk-loaded waveguide is not the only slow-wave structure capable of accelerating electrons. In fact, other structures (see Fig. 18) such as the grid-loaded waveguide yield shunt impedances about twice that of the disk-loaded guide. But in every case we have examined where a large improvement in shunt impedance (r) has been obtained, the bandwidth and resulting group velocity are at least ten times as high as desired. Efficient utilization of the available rf power under these conditions would have required its recirculation (feedback) or the use of extreme lengths between feeds. The former is undesirable, especially in a long multi-section accelerator, since it results in undue operational complications; the latter requires that each accelerator section transmit an excessive amount of power. Several variations of structures 2-8 shown in Fig. 18 were devised which succeeded in reducing the group velocity to the desired values (in the range of 0.01 c), but these measures also caused the shunt impedance to be reduced until no advantage remained; moreover, they resulted in increased cost of fabrication. For these reasons, the disk-loaded waveguide appears preferable for the two-mile accelerator to all other structures examined to date.

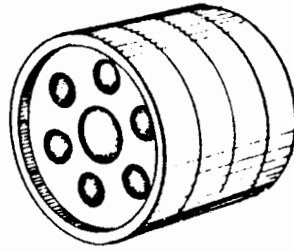
B. Definition and Discussion of Dimensions

The modular dimensions of the disk-loaded waveguide which can be adjusted to achieve the intended parameters are illustrated in Fig. 3. Figure 3(a) shows the cylindrical guide diameter $2b$, the disk-hole diameter $2a$, the disk-edge radius ρ , and the land in the disk aperture s . Figure 3(c) shows further variations of the disk-loaded waveguide using so-called "conical" or "anti-conical" disks. The conical disk was rejected because of its comparatively low r/Q . The anti-conical disk was also dismissed; although it has a five percent higher r/Q than the corresponding flat disk structure with $t = t_1 = 0.230$ in., this value is still five

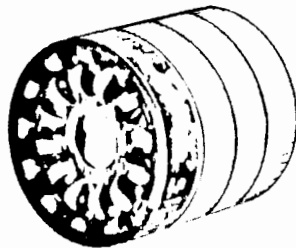
FORWARD-WAVE STRUCTURES



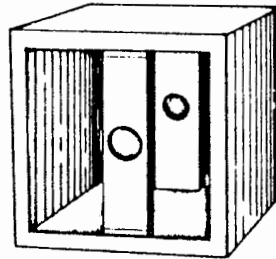
1. DISK-LOADED STRUCTURE



2. VENTILATED STRUCTURE

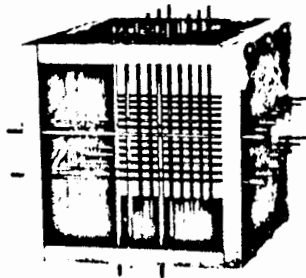


3. CENTIPEDE STRUCTURE

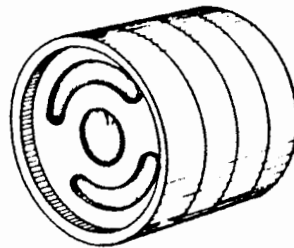


4. RECTANGULAR SLAB

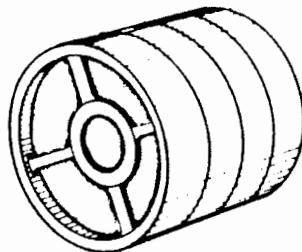
BACKWARD-WAVE STRUCTURES



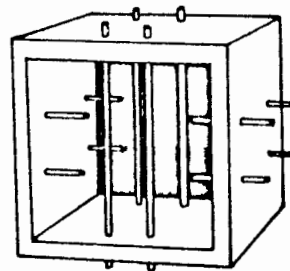
5. "JUNGLE GYM"



6. SLOTTED DISK STRUCTURE



7. RING & BAR STRUCTURE



8. LOADED EASITRON

FIG. 18--Slow-wave structures designed for linear accelerators.

percent below that of the thinner flat disk with $t = t_2 = 0.120$ in.

As indicated in Section II.F, a 10-percent improvement in shunt impedance can be gained by adopting the $2\pi/3$ mode rather than the $\pi/2$ mode. Figure 19 illustrates the respective traveling-wave field configurations at an instant in time over two wavelengths (the zero and π "standing-wave modes" are also illustrated for reference). These patterns are deformed as they slide down the guide but reappear in the same configuration, shifted by one cavity, at an instant $\delta t = \Phi/2\pi f$ later, where Φ is the phase shift per cavity at the frequency f . For standard accelerator sections, the objective is to obtain a phase velocity equal to the velocity of light. Thus specifying the operating mode and frequency (or free-space wavelength) fixes the distance between disk center lines at $d = \Phi c/\omega$.

After this choice, only four dimensions remain to be specified: $2b$, $2a$, ρ and t . The lower cut-off frequency of the disk-loaded waveguide or "zero-mode" frequency is strongly dependent on the guide diameter $2b$, whereas the bandwidth and thus the group velocity depend primarily on the ratio a/b at given values of ρ and t . This point is illustrated by the three ω - β (Brillouin) diagrams shown in Fig. 20. It is important to verify, through some technique such as that utilizing a steel ball illustrated in Fig. 3(b), that the disk aperture edge has been properly formed. Errors in the ball height h or the land s cause significant errors in the resonant frequency of test sections and hence in the resulting phase and group velocities. This fact is easily understandable since the electric field intensity is relatively strong at the disk edge. The choice of ρ can be quite arbitrary from the rf point of view as long as the tolerances are respected and electric breakdown does not result.

The choice of the disk thickness t , as discussed in Section II, involves a compromise between thin disks to increase the shunt impedance and thick disks to reduce the danger of electric breakdown and to improve heat-transfer characteristics.

C. Evolution of Stanford Designs

Prior to 1960, all Stanford accelerators were designed to operate in the $\pi/2$ mode. Starting in 1960, the first $2\pi/3$ mode structures were tested on the 20-foot Mark IV accelerator.¹⁰ Until 1962, all Stanford

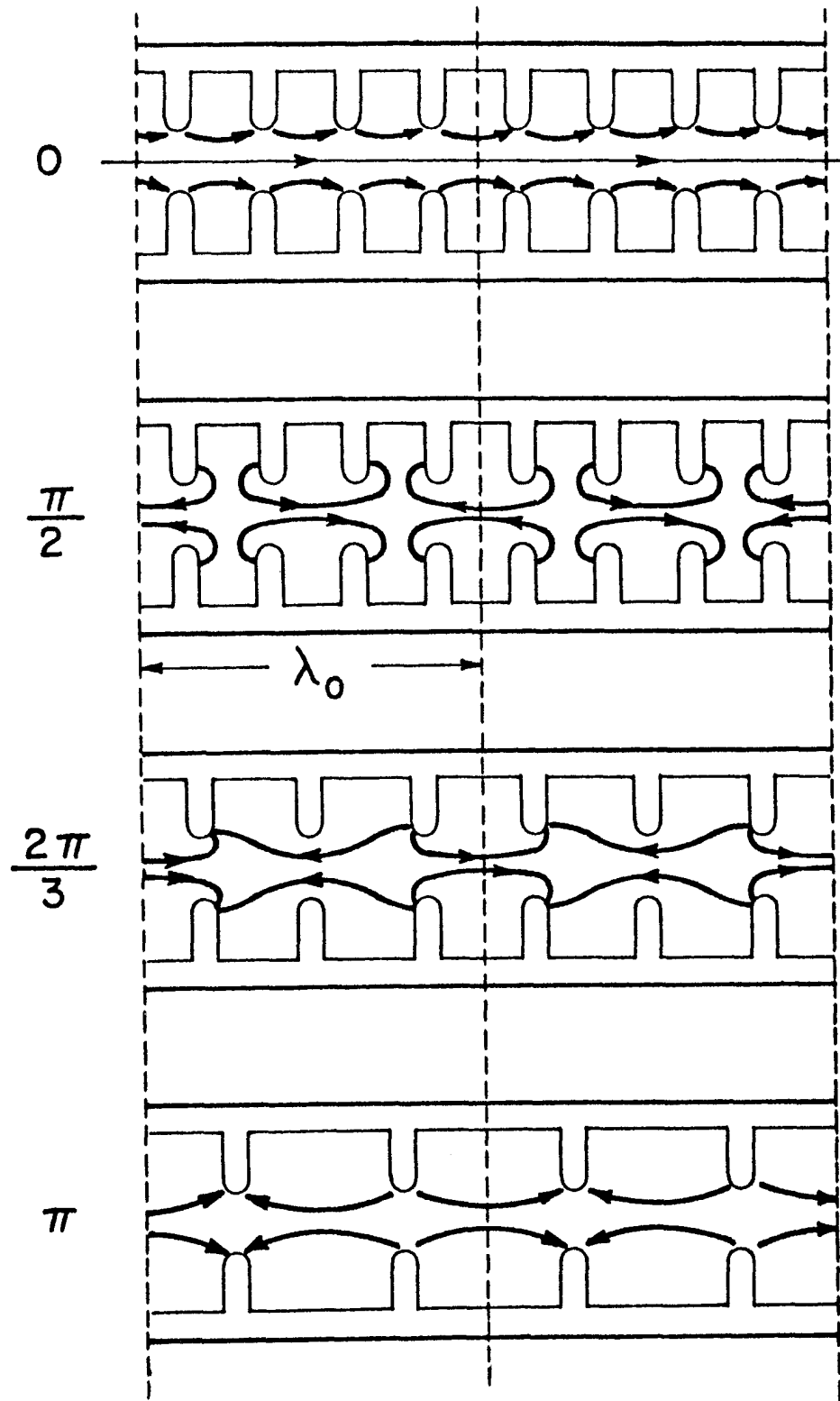


FIG. 19--Traveling-wave electric field configurations for 0, $\pi/2$, $2\pi/3$ and π phase shift per cavity.

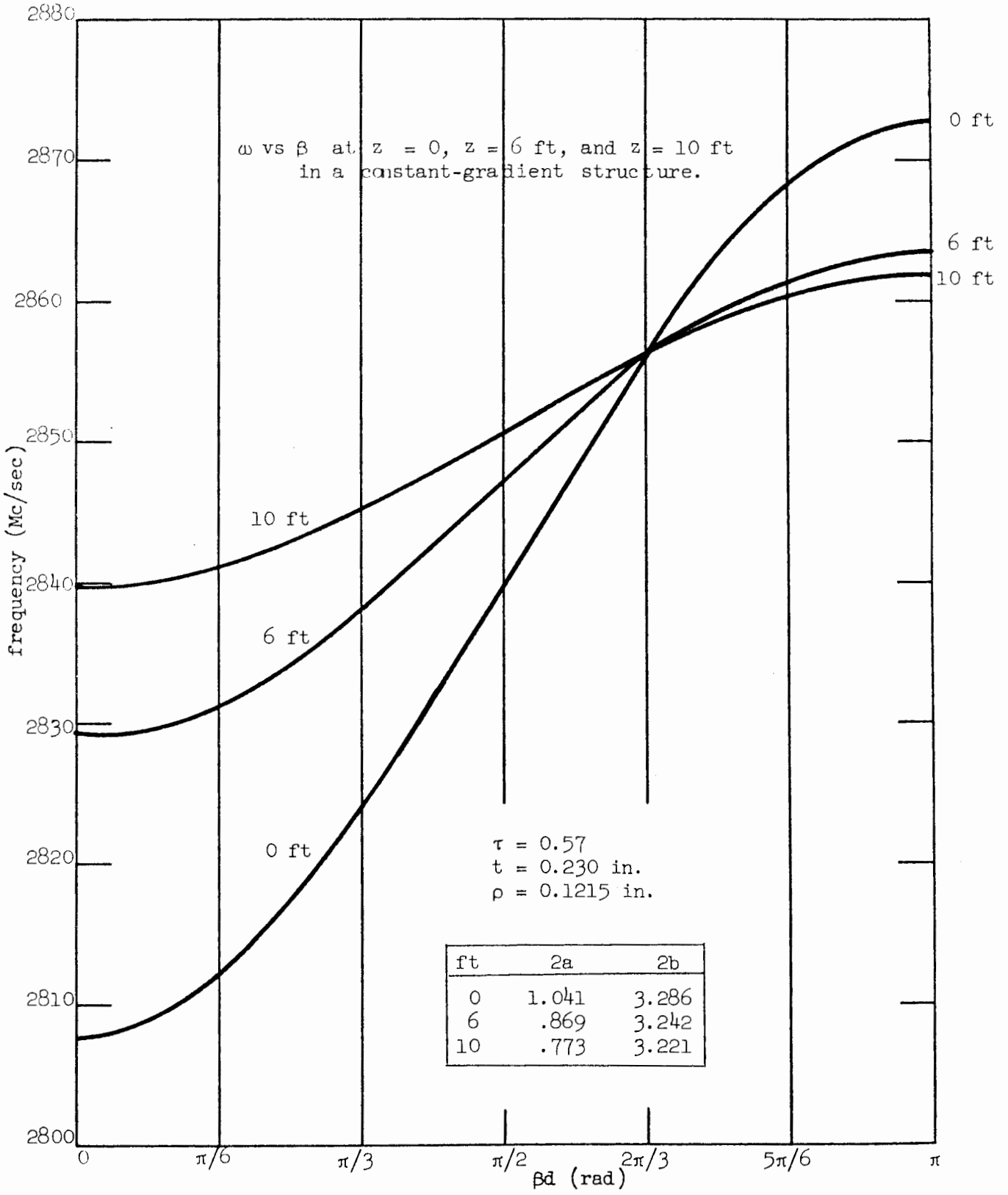


FIG. 20--Brillouin diagrams for three different points in a typical constant-gradient section.

accelerators had constant-impedance structures. In April, 1962, the first constant-gradient structure was installed on the Mark IV.

Table 5 shows the respective characteristics of constant-impedance structures operating in the $\pi/2$ mode on the Mark III accelerator and in the $2\pi/3$ mode on the Mark IV accelerator.

The more recent constant-gradient designs are discussed below.

D. Constant-Gradient Structure Dimensions

As discussed in Section II, the two-mile accelerator will be of the constant-gradient type, propagating in the $2\pi/3$ mode. The constant field will be obtained by tapering the cross-sectional dimensions of the waveguide so as to produce the required linear decrease in group velocity. The constant-field condition results only if the shunt impedance and the Q of the cavities remain constant over the length of the section in spite of the cross-sectional variation of the structure. In practice, for a group velocity variation such as that chosen for the Stanford design, the shunt impedance r_0 (corrected for the fundamental space harmonic) increases by a small percentage over a ten-foot section, thereby yielding a structure with a gradual input- to output-field increase of five percent. This result is actually desirable because the effect of beam loading will tend to depress the rising field characteristic by an amount depending on the beam current.

Two constant-gradient structures have been designed, one for thick disks ($t = 0.230$ in.), the other for thinner disks ($t = 0.120$ in.). Their performances are being compared and a final choice will be made shortly. Figures 21 and 22 show the respective variations of $2b$, $2a$, v_g/c , and r_0 as a function of cavity number along a 10-foot section. Cavities 0 and 85 are coupler cavities. It is seen that whereas $2b$ varies by less than 2 percent, $2a$ is reduced at the output by 30 percent from its input value to satisfy the group-velocity variation.

For reasons of economy, a constant-gradient design can be approximated by adjusting the dimensions in steps, each step consisting of several identical cavities. However, for the two-mile Stanford accelerator, the cost of the slow-wave structure represents only a small percentage of the total cost; and the small increase incurred by varying the dimensions,

cavity by cavity, is well justified to achieve a very smooth field gradient with virtually no reflections.

TABLE 5

Characteristics of Stanford Constant-Impedance Structures

Parameters	Mark III Accelerator (1952)	Mark IV Accelerator (1960)
Operating mode	$\pi/2$	$2\pi/3$
Length (feet)	10	10
Guide inside diameter 2b (inches)	3.247	3.247
Disk hole diameter 2a (inches)	0.8225	0.890
Disk thickness t (inches)	0.230	0.230
Periodic length d (inches)	1.0335	1.378
Disk radius edge ρ (inches)	0.1215	0.1215
Matching iris aperture (inches)	1.042	1.014
Frequency (Mc/sec)	2856	2856
Group velocity v_g/c	0.0100	0.0122
Shunt impedance r (ohms/meter) corrected for fundamental space-harmonic amplitude	47×10^6	53×10^6
Q	10,000	13,200
Attenuation τ (nepers)	0.90	0.57

E. Cold Tests and Corrections to Achieve the Empirical Design

1. Objectives and validity of cold tests

A theoretical treatment sufficiently accurate to permit calculation of the dimensions of the constant-gradient designs shown in Figs. 21 and 22 does not exist. Consequently these dimensions had to be determined experimentally from cold tests. To achieve an accurate design, a fair number of pairs of 2b and 2a values must be determined, each set of values being obtained from a different test cell. About ten different test cells were used for each of the constant-gradient designs. For each test cell, the following quantities were measured: the phase velocity v_p ,

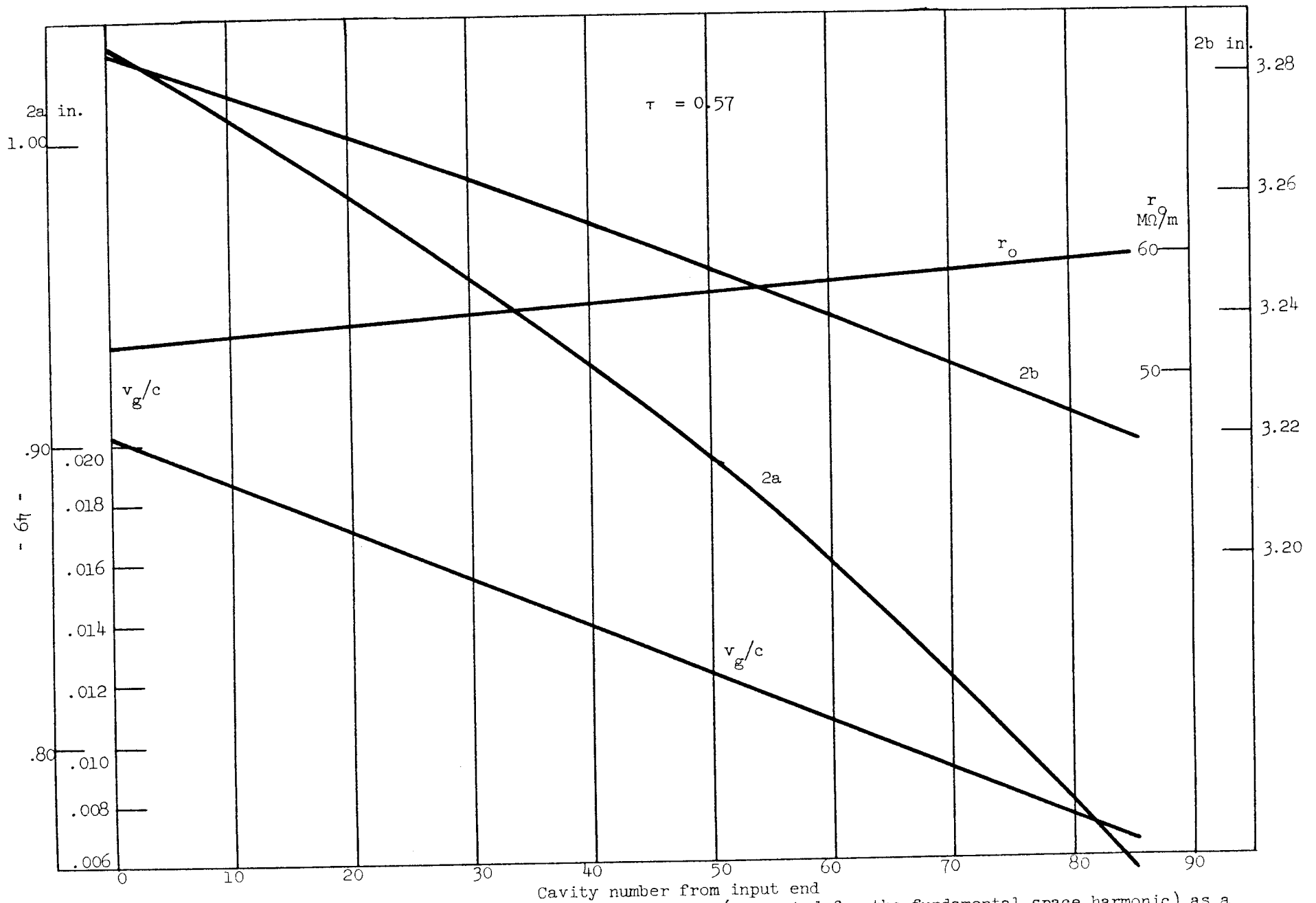


FIG. 21--Variation of $2b$, $2a$, v_g/c , and the shunt impedance r_o (corrected for the fundamental space harmonic) as a function of cavity number along a 10-foot constant-gradient section for $t = 0.230$ in.

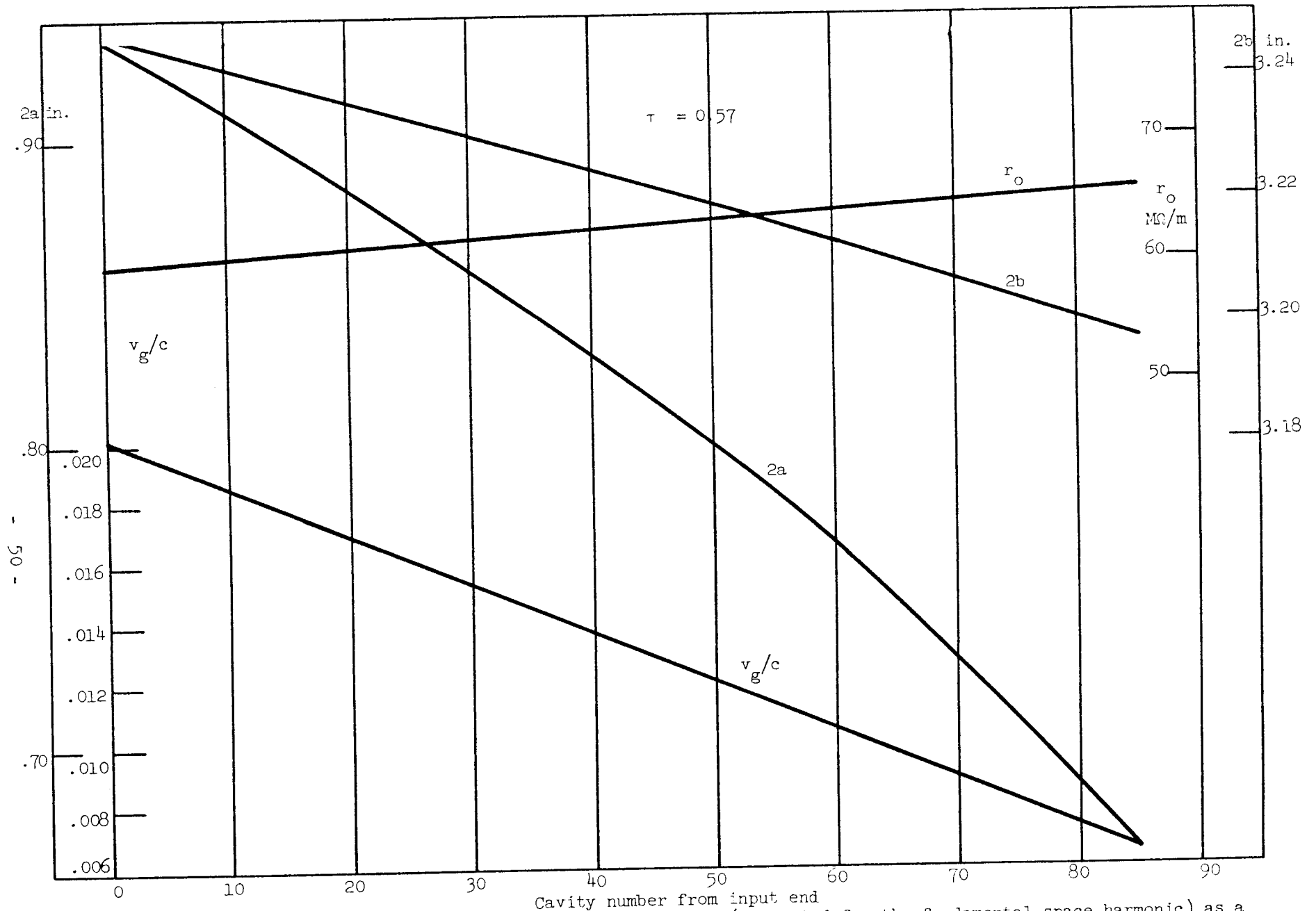


FIG. 22--Variation of $2b$, $2a$, v_g/c , and the shunt impedance r_o (corrected for the fundamental space harmonic) as a function of cavity number along a 10-foot constant-gradient section for $t = 0.120$ in.

the group velocity v_g , r/Q , Q , and the fundamental space harmonic amplitude $a_0^2/\Sigma a_n^2$. It is not the objective of this paper to describe in great detail each of these microwave measurements. A comprehensive treatment of this subject can, for example, be found in references 2, 11 and 12. However, a brief comment will be made on each of these measurements to outline the techniques used and to point out some of the necessary precautions. A discussion of the corrections applied to the experimental results will then be given.

Results of cold tests on short test cells are valid if the reflection symmetries of the structure are carefully taken into account. Shorting plates must be located only in planes to which the electric-field vector is normal and in such a way that the standing wave "trapped" between them is an exact representation of the traveling wave one wishes to study. The dotted lines shown in Fig. 19 show such planes. For observation of the $2\pi/3$ mode, sets of three or six identical cavities are used, covering one or two full wavelengths. These cavities are made of carefully machined copper or brass cups and rings, half rings being used at the ends to meet the correct boundary conditions.

When measurements are being made, it is essential that the cavities be stacked and aligned very carefully, preferably by means of a concentric jacket, and that good electrical contact be obtained through a uniformly applied pressure.

2. Measurement of phase velocity v_p

Figure 23 shows a typical Brillouin diagram with the phase velocity $v_p = c$ for a $2\pi/3$ phase shift per cavity at $f = 2856$ Mc/sec. The disk spacing is fixed at $\lambda/3 = (c \times 10^{-6})/(3 \times 2856)$ cm. With 3 or 6 cavities of the type shown, 4 or 7 resonant frequencies respectively representing $n\pi/3$ ($0 \leq n \leq 3$) or $n\pi/6$ ($0 \leq n \leq 6$) phase shift per cavity can occur; these points can be recorded to draw the ω - β diagram. With a moderate amount of experience, three rounds of machining correction of the diameter $2b$ are sufficient to approach the operating frequency (2856 Mc/sec) within less than 1 Mc/sec at the $2\pi/3$ resonance. The remaining correction is done by mathematical extrapolation. In this manner one insures that the resonant frequency for the $2\pi/3$ mode will be 2856 Mc/sec and the operation at this frequency will result in propagation of a traveling wave in a structure of the same modular dimensions at $v_p = c$.

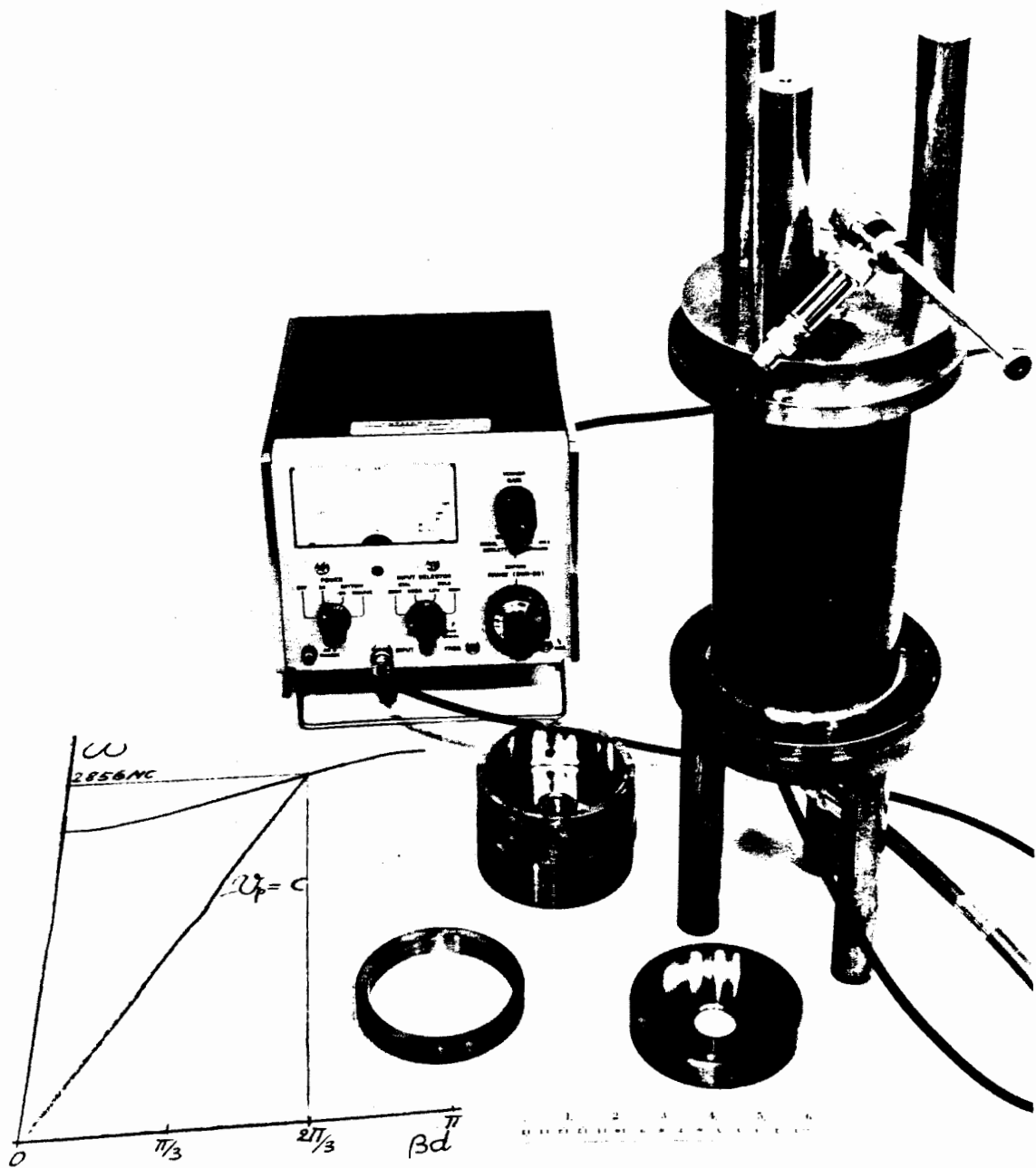


FIG.23--Typical experimental setup showing cavity stack used to obtain Brillouin diagram by successive resonances.

3. Measurement of group velocity v_g

The condition $v_p = c$ can be obtained for various pairs of $2b$ and $2a$ values. Each pair yields a different ω - β diagram and hence a different group velocity. This fact was illustrated in Fig. 20. Figure 24 shows the two cavity stacks for the extreme cases, the first and the last cavities of the constant-gradient section. The differences in $2a$ for $v_g/c = 0.0204$ and $v_g/c = 0.0065$ should be noted. To obtain the group velocity, one can graphically take the slope of the ω - β diagram or, for better accuracy, use the measured resonance frequencies in connection with a Stirling or Fourier approximation formula.¹³

4. Measurement of r/Q

The ratio of shunt impedance per unit length to Q is best measured by axially perturbing the test cell with a thin dielectric rod, and by measuring the resonant frequency perturbation Δf . Using Slater's perturbation formula^{12,14} the value of $(r/Q)_T$, where the index T denotes the sum of all space-harmonic components, is given by

$$\left(\frac{r}{Q}\right)_T = \frac{240c}{(\epsilon - 1)A} \frac{\Delta f}{f^2} \quad (14)$$

where ϵ is the dielectric constant of the rod (for sapphire $\epsilon \approx 10$), and A is its cross-section. It is desirable to calibrate the dielectric rod in a simple TM_{010} cavity, for which r/Q can be calculated.

5. Measurement of the space-harmonic amplitude

With the design procedure indicated in III.E.2 above, only the fundamental space-harmonic propagates at $v_p = c$, and consequently it alone gives a net energy gain to the electrons. Thus, to obtain the effective $(r/Q)_o$, it is necessary to obtain the amplitude of the fundamental. The figure of merit by which to multiply $(r/Q)_T$ to obtain $(r/Q)_o$ is $a_o^2/\Sigma a_n^2$, the ratio of the square of the fundamental harmonic amplitude divided by the sum of the squares of all harmonic amplitudes. This ratio can be obtained by noting the frequency perturbation caused by a short electric bead drawn along the axis of the test cell. The field E_c at a given axial position is related to the frequency perturbation Δf caused by a bead located

TYPICAL COLD-TEST SET-UP

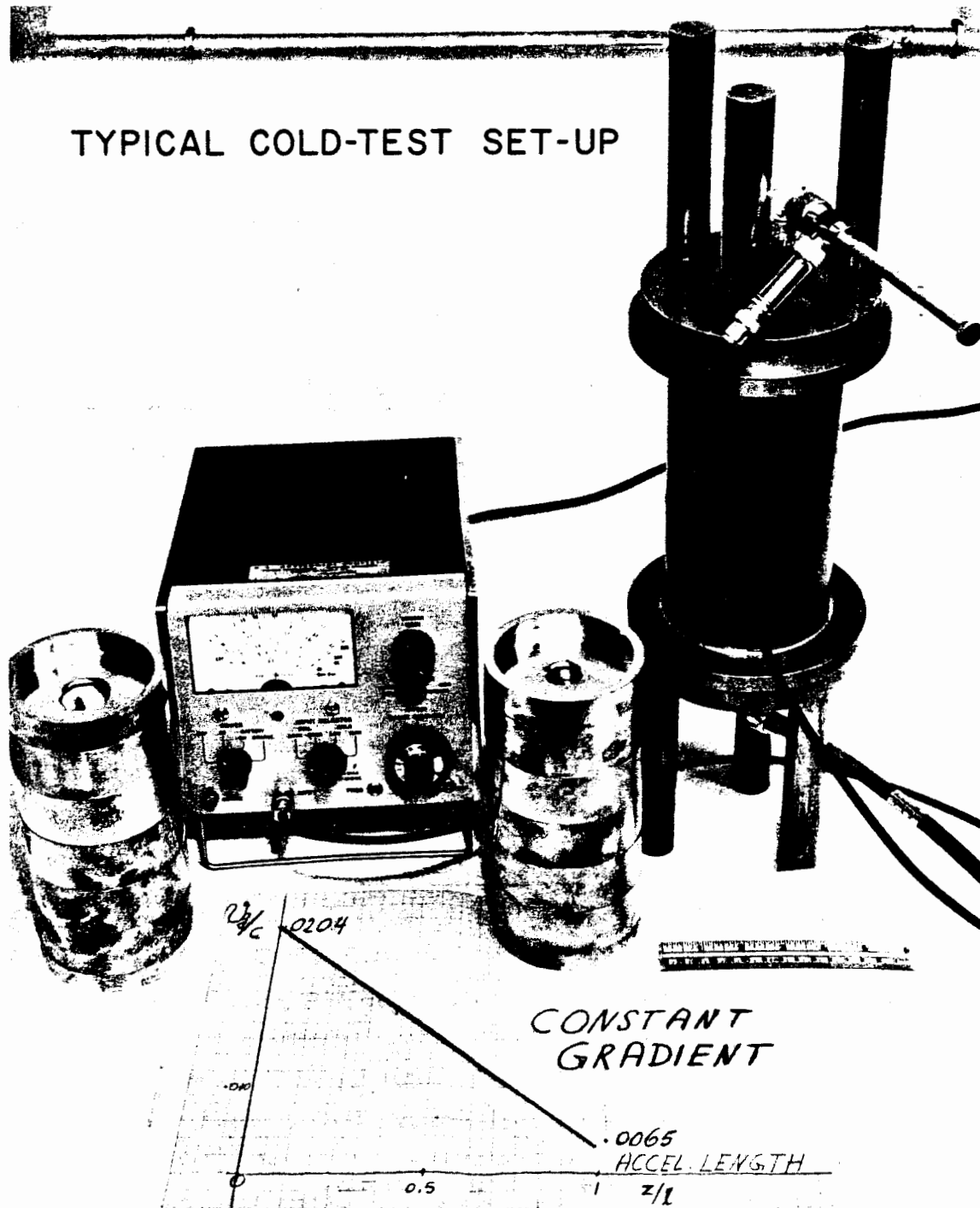


FIG. 24--Typical cold-test setup showing cavity stacks and group-velocity variation as a function of length along a constant-gradient section.

at that position by

$$E_c^2 = k\Delta f \quad (15)$$

where k is a constant depending on the characteristics of the bead.

For best accuracy, the following precautions should be taken:

- (a) The bead should be no longer than 2 to 3 mm to give good resolution.
- (b) Six rather than three cavities should be used so that an entire half-wavelength can be probed without letting the bead approach the end plates, where its image increases the actual perturbation.
- (c) It is preferable to measure the perturbed frequency by adjusting frequency to locate the new peak of the response curve rather than by observing power response as a function of bead position at constant frequency. This technique avoids the difficulties mentioned in references 15, 16, 17 which arise from simultaneous changes in the resonant-frequency and the coupling coefficients of the cavity.
- (d) Before plotting the whole field pattern, one should insure, by using the method recommended in (c) above for a few points symmetrical with respect to points of reflection symmetry, that the field is symmetrical. If it is not, the adjustment of small tuning plungers at the top of the test cell will enable symmetry to be established. These plungers compensate for the asymmetry created by slight differences in insertion of the input and output coupling loops.

After the field pattern has been obtained, one can divide it into N (typically $N = 21$) and carry out a Fourier analysis to obtain the figure of merit, which is given by

$$\frac{a_o^2}{\sum a_n^2} = \left(\frac{2}{N} \right) \frac{\left[\sum_{m=0}^{m=N} E_{cN} \cos \frac{m\pi}{N} \right]^2}{\sum_{m=0}^{m=N} E_{cN}^2} \quad (16)$$

The denominator is simply the area under the Δf curve. The numerator is obtained by extracting the square root of the Δf curve and using physical reasoning to determine the sign of the electric field at each point.

6. Measurement of Q

To obtain the value of Q is the most delicate of these measurements because it depends on the state of the metal surface and on good contact between cavities, conditions which are hard to achieve and to maintain. It is preferable to take the measurements immediately after electro-polishing the cavities. Using very weak coupling, one successively obtains the Q's of three-cavity (Q_3) and six-cavity (Q_6) sets by the half-power point technique:

$$Q = \frac{f}{\Delta f} \quad (17)$$

where f is the resonant frequency, and Δf is the frequency variation between half-power points. Although these Q's contain the losses caused by the end plates, it is simple to show¹² that end-plate effects can be eliminated through use of the following expression:

$$Q = \frac{Q_3 Q_6}{2Q_3 - Q_6} \quad (18)$$

The Q measurement requires the following precautions:

- (a) The signal generator should not exhibit spurious outputs.
- (b) The input power must be carefully monitored.
- (c) To eliminate errors due to uncertainties in crystal law behavior at varying power levels or indicator calibrations, it is preferable to work at a constant crystal power level. This can be achieved by using a precision attenuator which is adjusted from 3 db to 0 db as the resonant frequency and the half-power frequencies are sought.

A check of the Q measurement can be obtained by measuring the attenuation of an accelerator section after final assembly.

7. Corrections and use of computers

In order to build a constant-gradient section with fixed t , d and ρ dimensions, only $2b$ and $2a$ must be determined. These depend only on v_p and v_g , and their relationship with these parameters must be determined accurately. The quantities $(r/Q)_0$ and Q need not be known as precisely, since to a first approximation they do not enter into the design.

Measurements should be carried out in an environment having accurately controlled temperature and humidity. Further, machining test cavities to attain the exact design frequency is not practical, and $2b$ must be corrected for the residual Δf . It is usually sufficient to base the correction on the simple relation

$$\frac{\Delta 2b}{\Delta f} \approx - \frac{2b}{f} = - .0011 \text{ in./Mc (at 2856 Mc/sec)}$$

Another correction is required to arrive at a certain operating frequency for a given copper temperature which differs from the room temperature at which the tests are being performed. In addition, most cold tests are done in air, and a correction must be applied to obtain the dielectric of air which is a function of the ambient humidity and temperature (see Adam's Nomograph in any engineering handbook). These problems are not very critical for short test-cell measurements, but they become important during matching and tuning operations (section III.F). For copper, the following rules of thumb can be applied at 2856 Mc/sec:

$$\frac{\Delta f}{\Delta T} = - 0.100 \text{ Mc/2}^\circ\text{C}$$

For a passage from air at 80°F and 40 percent humidity to vacuum, the frequency increase is about 300 parts in one million.

Having applied these corrections, the data can be smoothed by plotting the points, or alternately, by computer techniques. Using a fourth- or sixth-order polynomial, a method minimizing least-square deviations from the experimental points can be used to yield the required combinations of v_g and $(2b, 2a)$ to produce the constant-gradient design.

F. Matching and Tuning an Accelerator Section

If the process of machining parts and fabricating an accelerator structure could be carried out with perfect accuracy, a section such as the one shown in Fig. 25 should be ready for installation and use immediately after fabrication.

In practice, however, it is difficult to control the process of manufacturing to this extent; moreover, it does not appear economically desirable to try to do so. By relaxing the tolerances on either of the techniques described later in Section IV, it is possible to reduce the cost of the accelerator considerably. The imperfections can be corrected through the process of tuning and matching as described below for a relatively small incremental cost.

The process of tuning an accelerator section consists of applying an external mechanical pressure which imparts a permanent deformation to the inside wall of any cavity whose phase shift differs from the design value. A maximum phase excursion of $\pm 2.5^\circ$ has been imposed on the 10-foot sections of the two-mile machine.

The process of matching the couplers of an accelerator section consists of adjusting the dimensions of the input and output coupling irises (see Fig. 25) so as to insure a low standing-wave ratio at the input and output of the structure. An upper VSWR limit of 1.05 has been set as the matching requirement for all couplers. The main technical difficulty stems from the fact that the processes of tuning and matching are inter-related; the shape of the coupling iris determines both the coupling to and the phase shift of the first cavity.

A complete description of the theory and operations involved in tuning and matching an accelerator section is beyond the scope of this paper.^{2, 11, 12, 18, 19, 20}. Only a few of the general principles and relevant precautions are given below.

Although the simplest mode to tune and match is the $\pi/2$, any sub-multiple of 2π , such as the $2\pi/3$, can be dealt with without undue difficulty.

Figure 26 illustrates the principle of the nodal-shift technique utilized in tuning. A copper plunger, progressively pulled through the structure (shown in cutaway section in the figure), detunes successive cavities and thereby causes the standing-wave pattern to shift. If the coupler is perfectly matched and all cavities have 120° of phase shift ($2\pi/3$ mode),

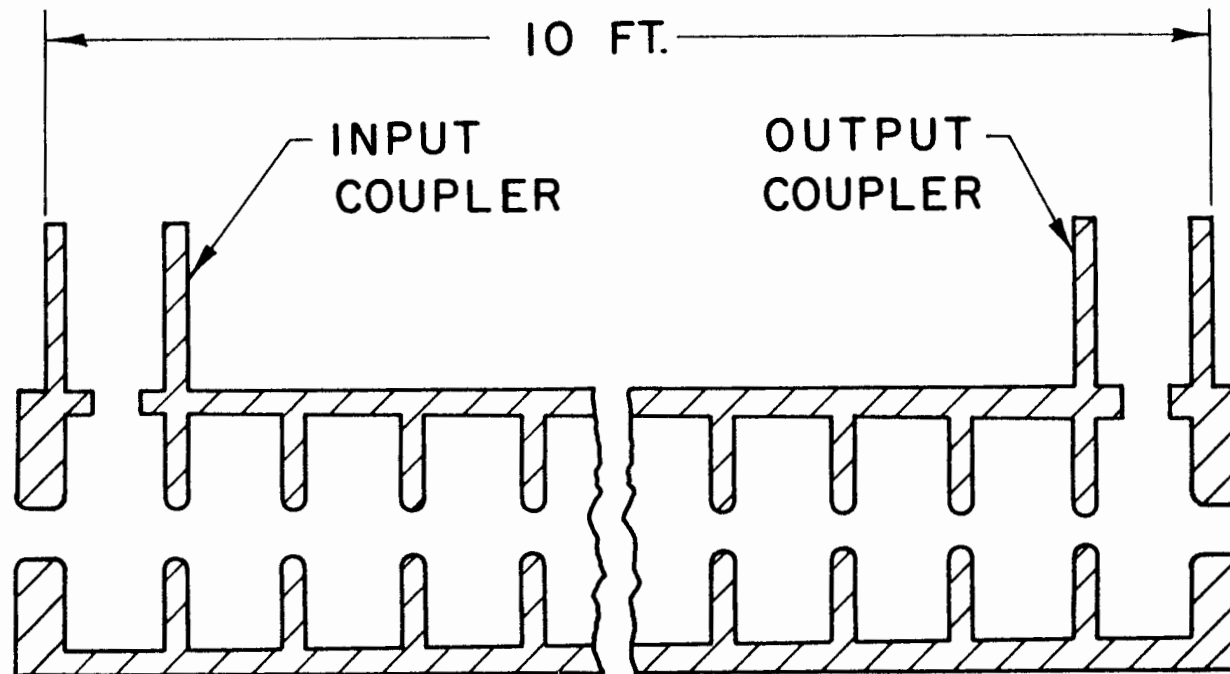


FIG. 25--Sketch of a ten-foot-long constant-gradient accelerator structure with input and output couplers. Notice slight taper in modular dimensions (diameter of inner wall).

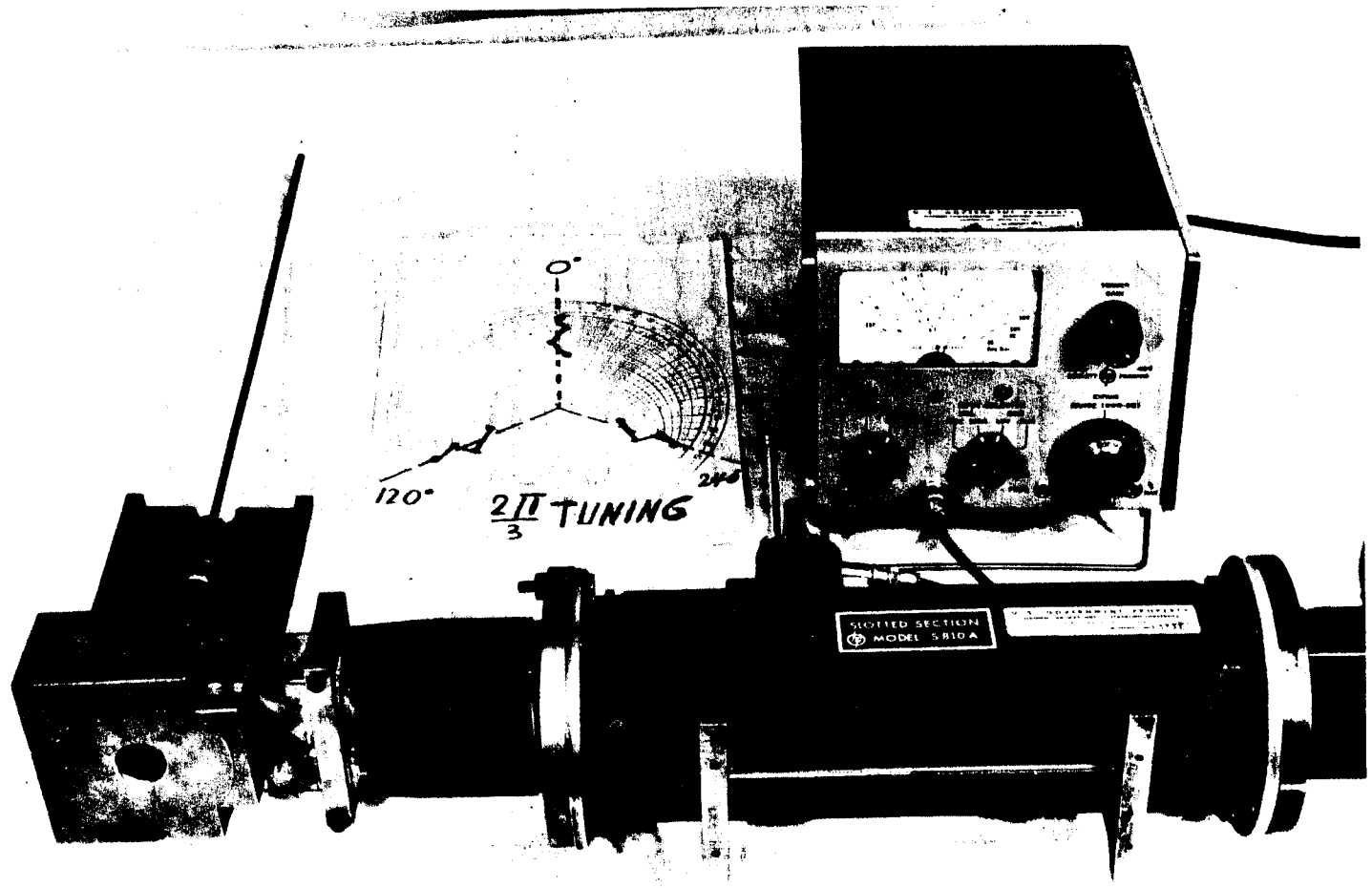


FIG. 26--Principle of the nodal shifting technique. Shown are cutaway section, copper plunger, and typical Smith chart plot.

pulling the plunger away from the coupler causes the plotted null points to rotate clockwise by 240° on the Smith chart for each cavity length through which the plunger is moved. Starting from the reference point of 0° , obtained by detuning the coupler cavity (and hence representing the plane of the iris), the points move clockwise as shown in Fig. 26 from the 0° to 120° , from the 120° to 240° , from 240° to 0° , and so on. For the first cavities, the VSWR is infinite and the points are on the rim of the chart. Further down the section, the VSWR decreases because of the increasing net attenuation between the input of the section and the short. Thus, the plotted points move towards the center of the chart along the three radii, shown as dashed lines in Fig. 26. With the coupler perfectly matched but the cavities not exactly tuned, the points move erratically toward the center, as shown by the heavy lines. However, the center of the circle passing through three consecutive points still coincides with the center of the chart. When a systematic phase-shift error exists, because of an inaccurate choice of frequency, the points spiral in towards the center, clockwise if the phase-shift is too large (frequency too high), or counterclockwise if it is too small (frequency too low). If the coupler is mismatched (see Fig. 27), the circle passing through the three points is no longer concentric with the rim of the chart. It now has two "centers," a geometrical center and a "Smith center." Neither coincides with the center of the chart. The Smith center is the point that would be obtained if the perfectly reflecting plunger were replaced by a perfectly matched load. It can be determined mathematically^{11, 12} from geometric considerations. The matchpoint (C) will lie on the extension of the straight line from the center of the Smith chart (O) to the geometric center of the circle (M). Its VSWR (σ at the matchpoint) is determined by $\sqrt{\sigma_{\max}/\sigma_{\min}}$ if the circle encompasses the center of the chart, and by $\sqrt{\sigma_{\max}\sigma_{\min}}$ if it does not. Matching the coupler consists of bringing point C as close as possible to point O. This is achieved by adjusting the coupling iris. Filing or squeezing affect the coupling, but they also affect the phase shift of the coupling cavity. Bending the iris in or out can compensate for this change. For the location of point C shown in Fig. 27, the actions indicated must be taken (bending the iris inward and filing to increase the iris opening). In general, the combination of bending and filing is required to achieve a good match.

MATCHPOINT (C)

$$\sigma_{sc} = \frac{6.4}{1.9} = \underline{1.84}$$

$$\left(\frac{N-N_0}{\lambda_g}\right)_{sc} = \underline{.444}$$

MATCHPOINT (C) FROM
THREE SUCCESSIVE
SHORTING PLUNGER DATA.

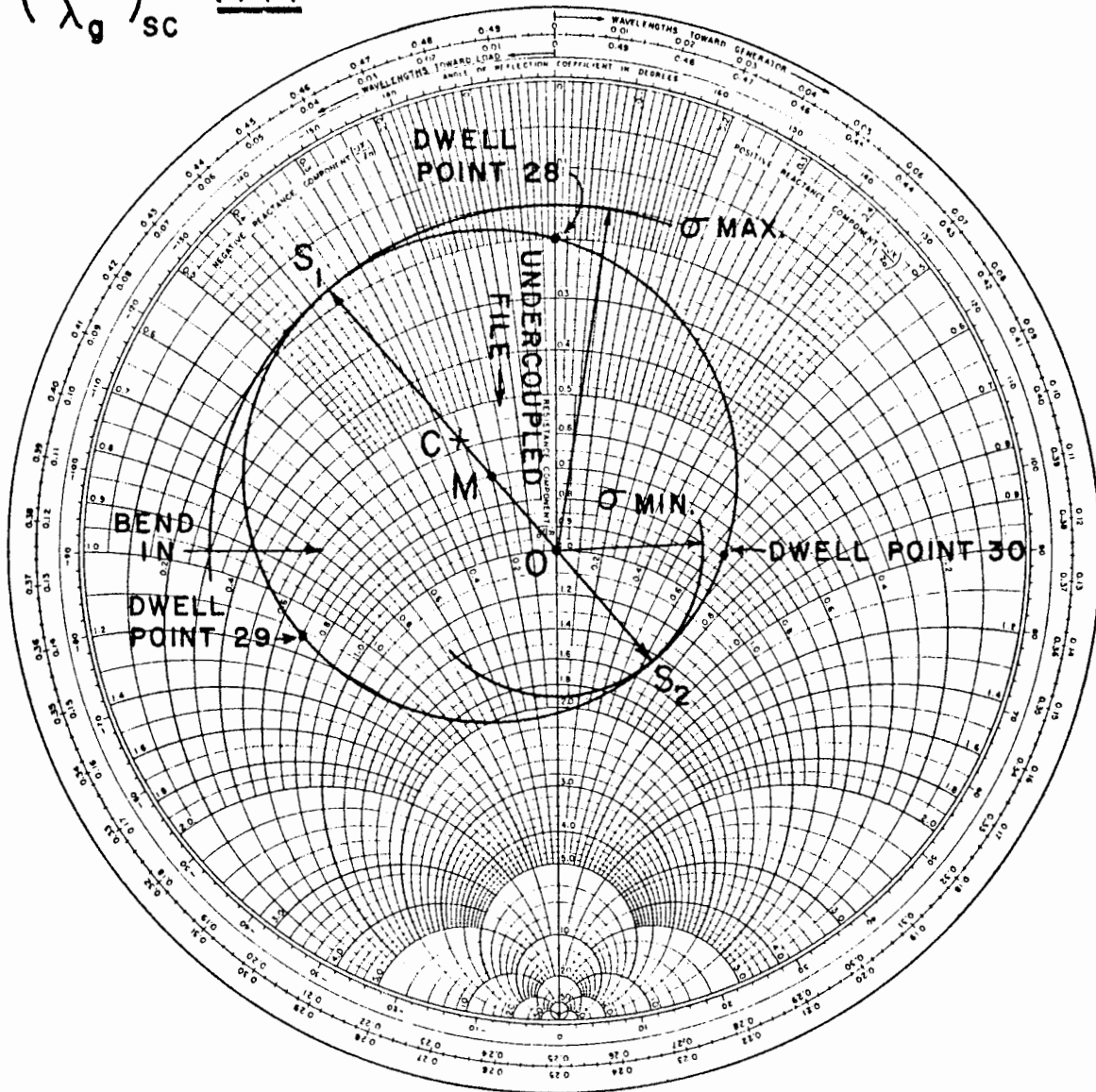


FIG. 27--Smith chart plot obtained in the coupler-matching technique.

The process of tuning is illustrated in Fig. 28 for a short experimental section of accelerator pipe. The tuning tool here is applied to the third cavity. It consists of a demountable collar with two or three radially adjustable screws having rounded ends. By driving the screws into the wall of the accelerator, a gentle protrusion on the inside wall of the cavity can be created. To preserve cylindrical symmetry, it is best to obtain the desired phase shift with two or three dimples uniformly distributed around the circumference. Errors $\Delta(2b)$ in the dimension $2b$ create phase shifts $\Delta\phi$ given by

$$|\Delta\phi| = \frac{2\pi}{3} \frac{c}{v_g} k \frac{\Delta(2b)}{f} \quad (19)$$

where $k \approx 1.1 \text{ Mc}/.001 \text{ in.}$ For example, an error of 1° corresponding to a $\Delta(2b)$ of 0.0002 in. can easily be eliminated. In fact, it is advisable with a multi-section accelerator to make all cavities slightly oversize to begin with, since the lowest frequency which can be tuned to with this technique is determined by the smallest cavity in the assembly, and all cavities must be tuned to the same frequency.

Because field lines can extend over three disks in the $2\pi/3$ mode configuration, the tuning of the first cavities and the matching strongly interact. It has been pointed out²¹ that this property can cause serious difficulties. If the coupler is not well matched, then tuning the first cavities by bringing the points to the proper positions on the Smith chart can actually cause the following effect: successive cavities will have built-in cyclic phase errors $\Delta\phi_1, \Delta\phi_2, \Delta\phi_3$ which compensate for the reflection caused by the coupler. Since the VSWR for the nodal shift in the first cavities is infinite, the matchpoint C is indistinguishable from the center O of the Smith chart, and the structure appears to be tuned and matched. In reality, a double or triple periodicity can be built into the section which causes pass-band splitting. It has been predicted²¹ that the split would occur at approximately the $\pi/2$ frequency for a $2\pi/3$ section.

Precautions can be taken to avoid this possible ambiguity. One remedy consists of using a resistive plunger which even in the first cavities allows the position of the matchpoint C to be identified. Another remedy consists of achieving the match by successive approximations, e.g., tuning and matching very carefully with the reactive plunger alternately in the first three cavities and, say, cavities 9, 10 and 11. At the latter points, there is enough

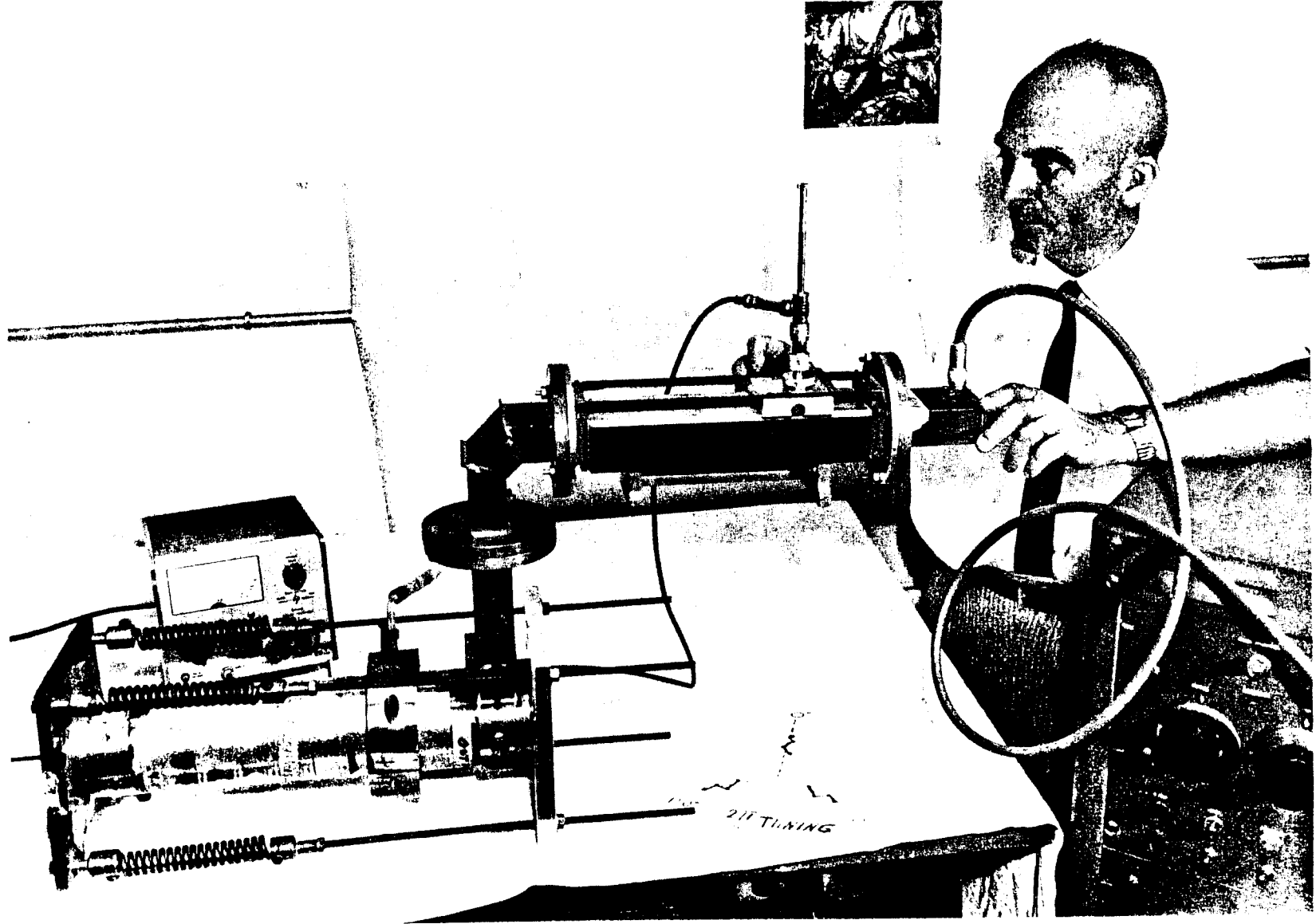


FIG. 28--Experimental arrangement for tuning a short accelerator section, with illustration of tuning tool.

loss to permit determination of the VSWR of the matchpoint C with good accuracy. This result can also be achieved²² by separately pre-matching the couplers with a perfect three-cavity assembly before final brazing of the section.

A few more remarks may be pertinent:

(a) The matching and tuning operation must be performed in a carefully temperature-controlled, dry room. Sections should be allowed to stabilize thermally for several hours. Ideally, the tuning operation should be done with the section filled with a dry atmosphere.

(b) The detuning plunger should be light and clean in order to prevent damage or contamination of the disk edges. Notches should be provided so that the plunger always rests in the same relative position, or dwell point, around which small motions do not disturb the null. When tuning a constant-gradient section, where the $2a$ dimension changes as a function of length, the largest possible plunger compatible with the smallest $2a$ dimension should be used. It has been verified that, in this manner, the dwell condition can be achieved in all cavities.

(c) In the $2\pi/3$ mode it has been found that moving the plunger slowly (less than a full cavity) away from the coupler causes the null on the slotted line to move towards the generator by half the phase shift introduced. This surprising effect is attributable to the manner in which the plunger detunes the cavity and not to any actual phase reversal. When the plunger finally moves into the dwell point in the next cavity, the null appears in the correct place.

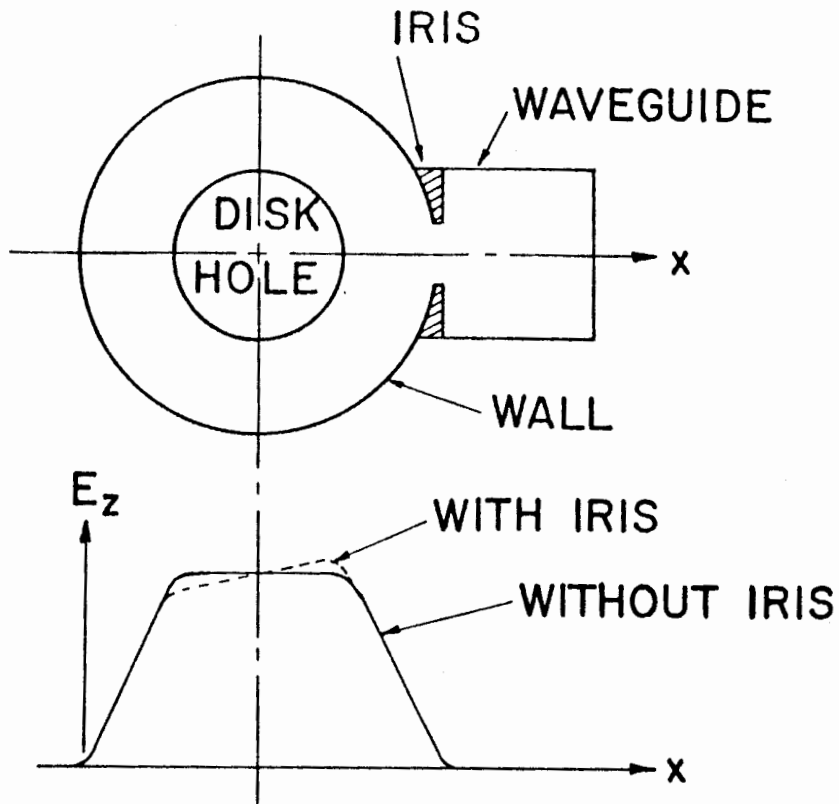
(d) The two-mile accelerator sections will be provided with output couplers and loads to prevent a reflected wave from appearing at the klystron amplifiers. These couplers must be tuned in the manner described in conjunction with the input couplers, preferably by switching over the whole experimental set-up to the output coupler.

(e) When a section has been matched and tuned, three final rf checks are advisable: (1) The global match can be checked with a continuously movable short in the rectangular waveguide beyond the output coupler.¹² This measurement involves observing the image of two intersecting diameters on the Smith chart, transformed through the complete section including the two couplers. This image of the "iconocenter" must fall at the center of the chart.

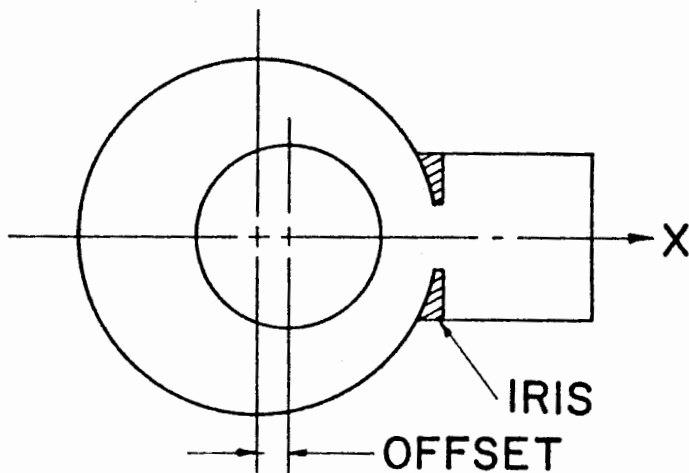
(2) The global match can be checked with a matched load at the output or input ends. (3) The attenuation can be measured globally for the entire section by direct substitution techniques, or for a part of the section by measuring the change in reflection coefficient as a function of plunger position.

G. The Coupler Asymmetry Problem

A problem arising in a multi-coupler accelerator is that the slight field asymmetry existing in the coupler cavity because of the iris opening will cause the electron beam to be subjected to a transverse deflecting force of approximate magnitude $(\lambda_0/E_z) (\delta E_z/\delta x)$, where x is measured in a direction perpendicular to the plane of the iris. In an uncorrected coupler, as shown in Fig. 29(a), the transverse variation in axial electric field is about 12 percent. Although the net electron deflection caused by this asymmetry force could be cancelled by magnetic steering, the phase spread of the electron bunches is coupled into the transverse momenta, leading to an increase in final angular divergence. Calculation shows that a final angular divergence of about 10^{-5} radians in the two-mile accelerator requires that the transverse field variation in the coupler cavity must not exceed 0.5 percent in the region of the cavity traversed by the beam. Several techniques have been proposed to reduce the field variation. One of the most practical methods is illustrated in Fig. 29(b). The axis of the coupler cavity is offset in the direction opposite to the iris, while the disk hole center remains on axis. It appears that nearly perfect symmetry can be achieved with this method. A further reduction in the effective asymmetry may be obtained by alternating the orientation of the couplers. Hence, the input and output couplers will point alternately right and left or up and down.



a) COUPLER CROSS-SECTION AND CORRESPONDING LONGITUDINAL ELECTRIC FIELD INTENSITY.



b) COUPLER OFFSET TO CORRECT FIELD ASYMMETRY.

FIG.29 - COUPLER ASYMMETRY STUDIES

IV. FABRICATION TECHNIQUES

A number of techniques of fabricating disk-loaded waveguide meeting the close tolerances necessary to establish the correct phase and group velocities have been explored at Stanford. Of the many methods considered only three have been used to construct accelerator sections, namely, shrinking, electroforming, and brazing. While the shrinking method² was used at Stanford to construct the 300-foot 1 Bev accelerator, it is now considered unsatisfactory when compared to recent developments.

Extensive work with electroforming and brazing has demonstrated that satisfactory disk-loaded waveguide sections can be made by either of these techniques. The specification for maximum phase shift excursions at any point along the axis of a 10-foot accelerator section is $\pm 2.5^\circ$. This corresponds to a mechanical tolerance of $\pm .00005$ inch for 2b; $\pm .00002$ for 2a; $\pm .001$ for d; $\pm .0002$ for t; and $\pm .0005$ for ρ (see Fig. 3). It is evident from these tolerances that special techniques must be utilized if they are to be achieved economically.

The most exacting of the tolerances is the $\pm .00005$ inch required for the 2b dimension. This is achieved by machining the parts that go into the assembly to a tolerance of $\pm .00002$ in. It is not sufficient simply to air-condition the room in which these parts are made; it is also essential that a temperature-controlled cutting solution be flowed over the part during the time it is being machined. Hence, these parts are machined in an air-conditioned room and with a coolant oil which is controlled within a quarter of a degree Centigrade. After the assembly is completed, the equivalent of the .00005 inch tolerance is achieved by making slight deformations in the wall of each cavity. The deformations are made simply by squeezing 1/4-in. diameter dimples into the 3/8-in. wall. This procedure is used with both the brazing and the electroforming methods of fabrication.

Figure 30 shows an exploded view of the parts used for electroforming, together with a completed piece of disk-loaded waveguide made by this process. The first step in the electroforming method of fabrication is the assembly of a 10-foot array consisting of the copper disks and aluminum spacers shown in the figure. After the parts are assembled in a V-block, a mandrel is inserted through the holes and is used to hold the

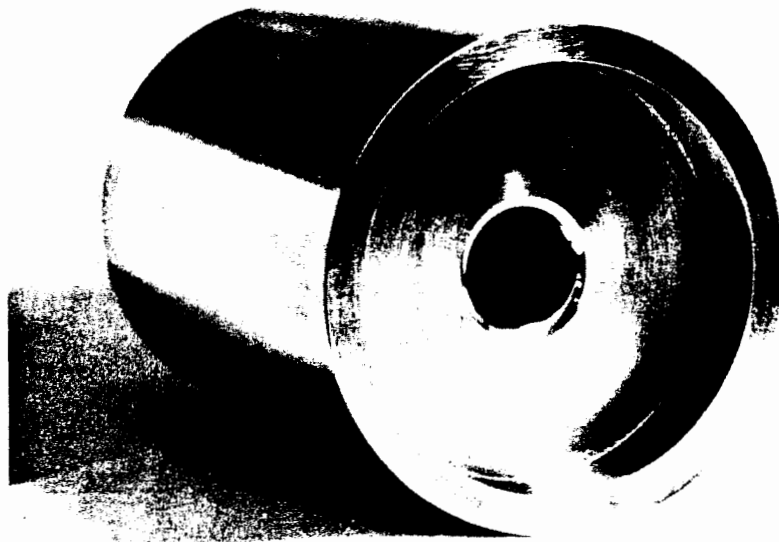
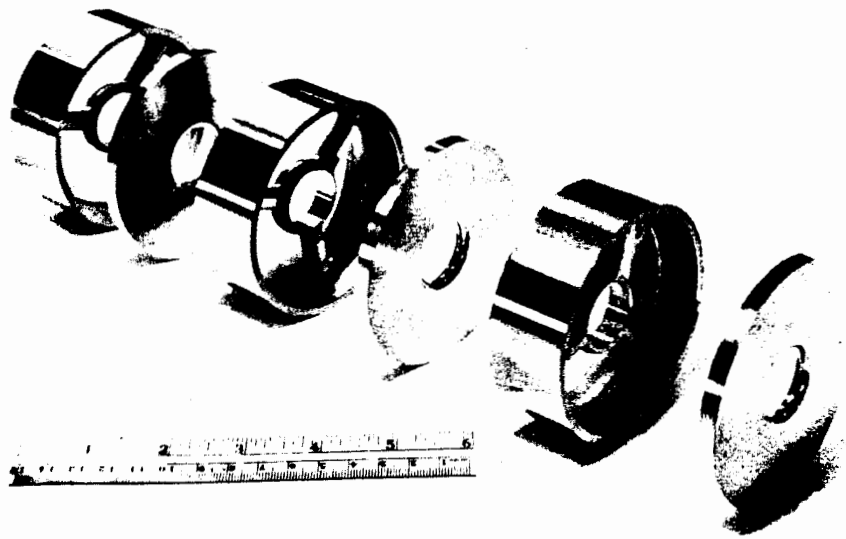


FIG. 30--Exploded view of parts assembled for the electroforming technique.

assembly together. The assembly work is carried out under water to assure that the hydrostatic pressure is equalized, hence reducing the probability of solution leakage. After assembly, the array is chemically cleaned and processed, and a thickness of $3/8$ in. of copper is electroformed over it. Figure 31 shows the completed assembly in a copper sulfate electroforming bath. During this procedure, the mandrel is held horizontally with the assembly half-submerged in the solution. During the plating, the assembly is rotated at approximately 30 rpm. An agate burnisher rides back and forth, continuously smoothing the surface of the plated copper. After the outer wall has been electroformed, the aluminum spacers are removed by etching in a sodium hydroxide solution. This procedure yields an all-copper disk-loaded waveguide fabricated to very close dimensions. A comparison of the crystalline structure of copper electroformed by this technique with that of OFHC copper produced by the usual mill fabricating procedure shows that the metallurgical properties are very similar. Electroformed copper as it comes from the bath has a surface finish of six micro-inches. Nine days are required to deposit the $3/8$ -in. wall thickness. Electroforming has been used to produce a number of 10-foot disk-loaded waveguide sections which have exhibited excellent characteristics.

In spite of these results, extensive studies of this method in comparison with brazing techniques have indicated that brazing is the preferable way of fabricating the 10,000 feet of disk-loaded waveguide. The preference for brazing arises primarily from the higher degree of flexibility that is available; this is a consequence of the fact that it requires only a few hours to complete a brazed assembly, whereas it takes nine days to complete an electroformed assembly. It is significant to note that the cost of the electroforming technique is the same as the cost of the brazing technique within the accuracy of the cost estimates.

The study of various brazing possibilities has led to the development of a new type of furnace. The essential features of this furnace are a moving ring burner which is fired by an oxygen-hydrogen flame, and a water-cooled chamber containing a reducing atmosphere in which the section can cool.

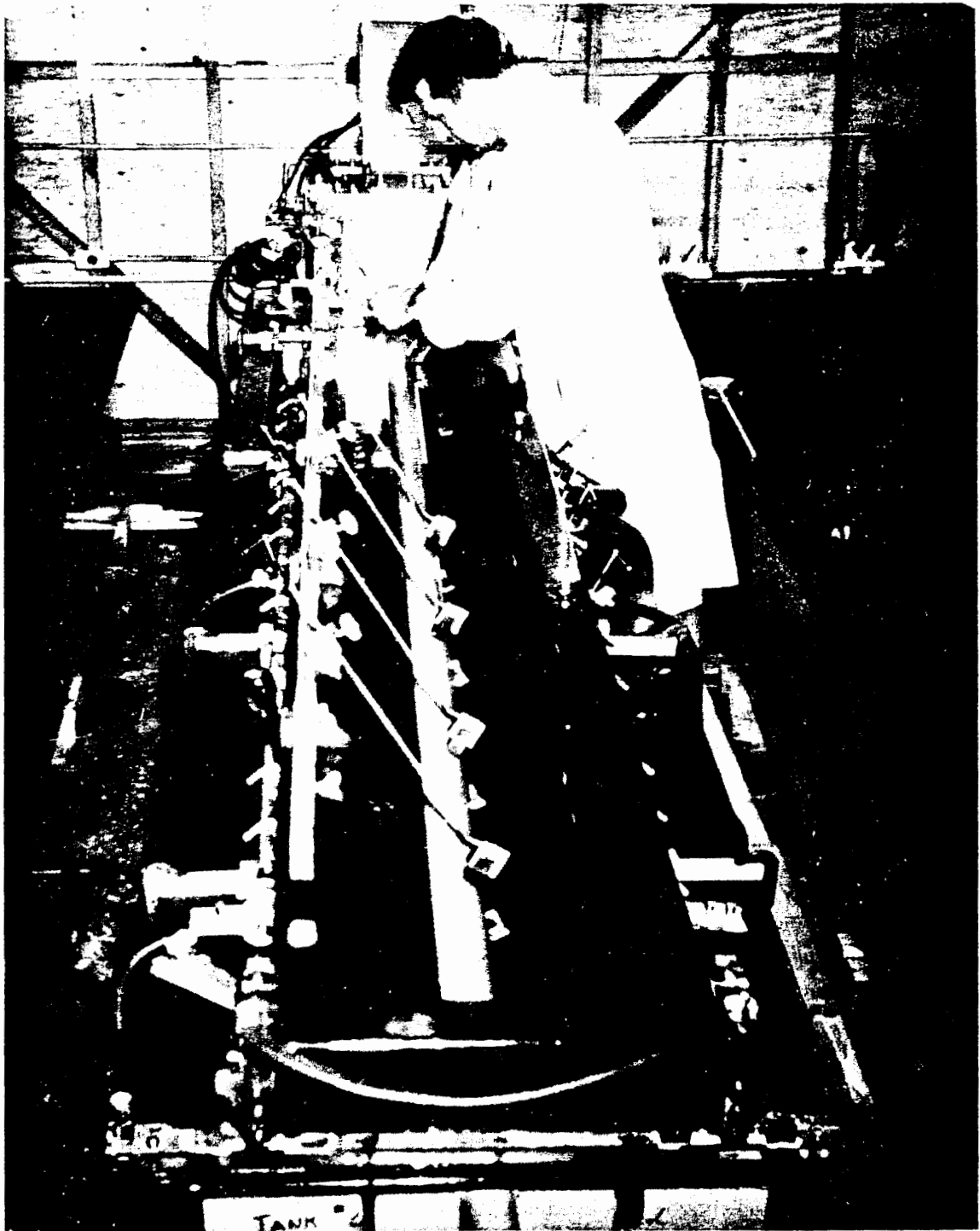


FIG. 31--Assembly being electroformed.

The essential features of the flame furnace are illustrated in Fig. 33. This illustration shows a 10-foot section nearing the completion of the brazing cycle. The procedure is carried out by first stacking the parts in the V block which is shown at the right. The brazing alloy, which is a silver-copper eutectic melting at 783° C, is inserted at each joint in the form of thin washers. The stacking of the unit parts shown in Fig. 32 is carried out while the V-block is at a 45° angle to the vertical. After the stacking is completed, the mandrel is inserted through the assembly and the end clamped by a spring-loaded mechanism. After the assembly is clamped, the V-block is tilted to the vertical position and the assembly is then transferred into the furnace by means of a jib crane. At the time the assembly is transferred to the furnace, the water-cooled cylinder D is in the fully raised position, and the assembly is attached to the metal tube E which serves to support the 10-foot section. The disk-loaded section then hangs as a free "plumb bob." Any swinging motion is damped by means of the water baffle assembly F. After the section is suspended, the split ring burner G is closed around the disk-loaded waveguide A. The burner is then raised to the uppermost end of the disk-loaded waveguide and the oxygen-hydrogen burner is ignited. When the melting point of the brazing alloy is reached, the ring burner together with the cylinder D is caused to move down the 10-foot section by means of lead screw sets H and J, Lead screw set J drives the cylinder, and lead screw set H drives the ring burner. Oxidation of the interior of the disk-loaded waveguide section is prevented by flowing a reducing gas through tube E. Reducing gas also flows into the cylinder D, providing a reducing atmosphere for the exterior of the section. A period of 25 to 30 minutes is required from the initiation of the heating cycle to its completion. The section is ready for removal from the furnace two and one-half hours after the heating cycle is finished.

Figure 34 shows the connection of the 10-foot assembly to its supporting tube and the "nose" plate which serves as a closure for the cylinder containing the reducing atmosphere in which the assembly is cooled. Figure 35 shows the furnace in operation with the flame on.

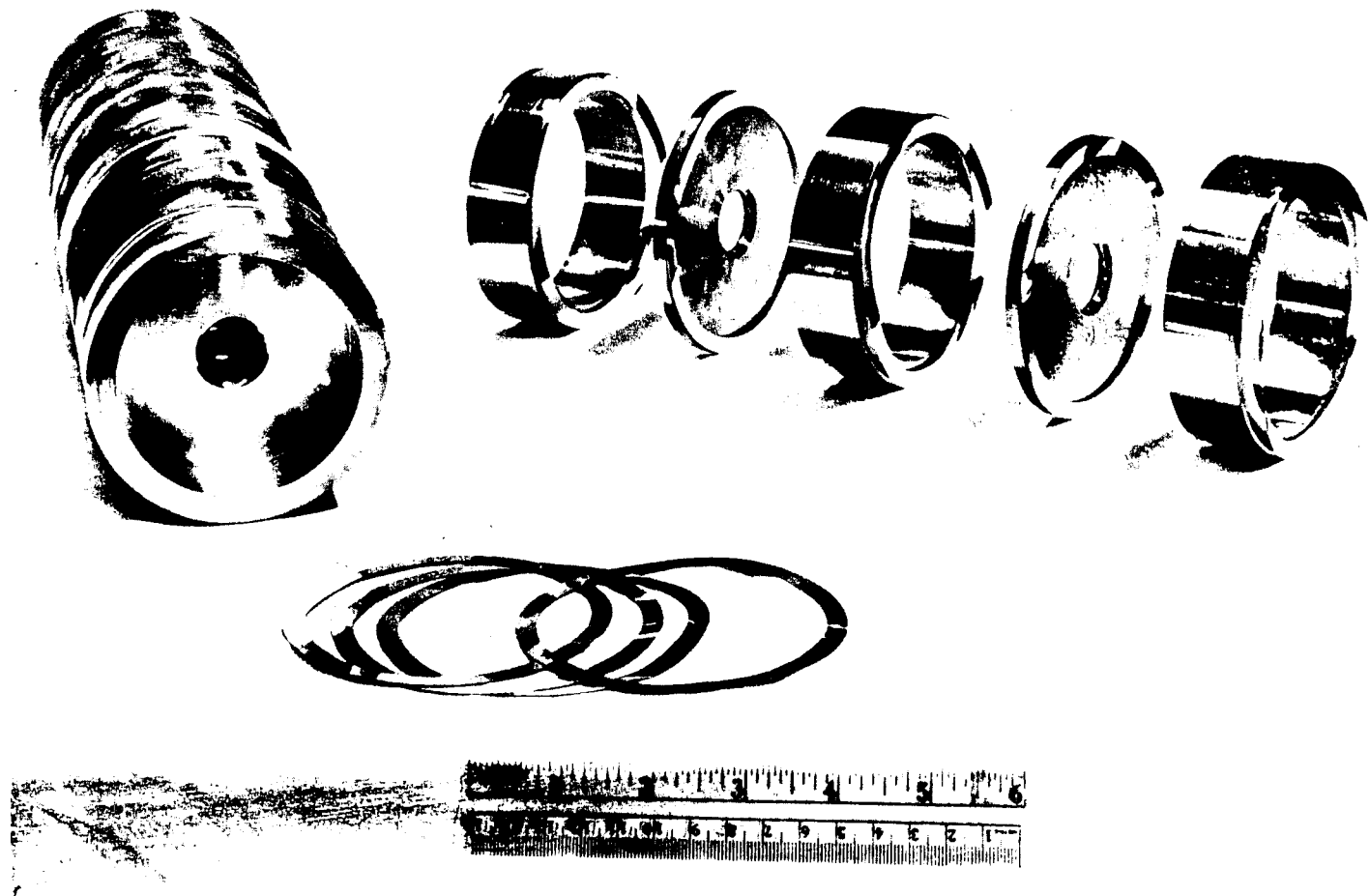
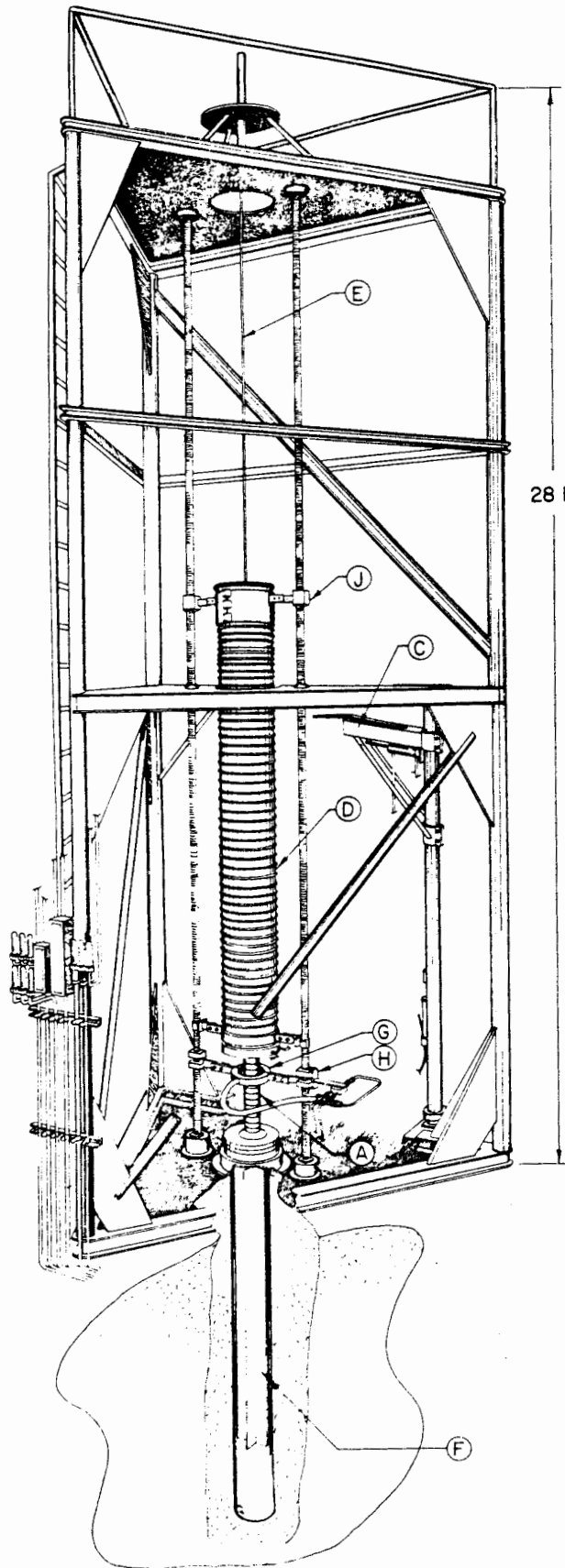
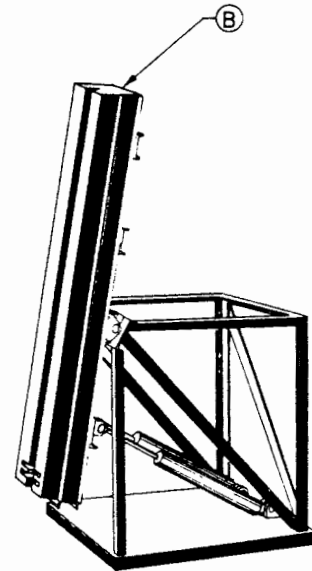


FIG. 32--Exploded view of parts stacked for the brazing technique.



28 FT.

- (A) ACCELERATOR TUBE SECTION
- (B) V-BLOCK
- (C) JIB CRANE
- (D) WATER-COOLED CYLINDER
- (E) METAL TUBE
- (F) WATER BAFFLE ASSEMBLY
- (G) SPLIT-RING BURNER
- (H) LEAD SCREW SET (BURNER)
- (J) LEAD SCREW SET (CYLINDER)



SCHEMATIC VIEW OF FLAME FURNACE

FIG. 33--Schematic view of flame furnace.

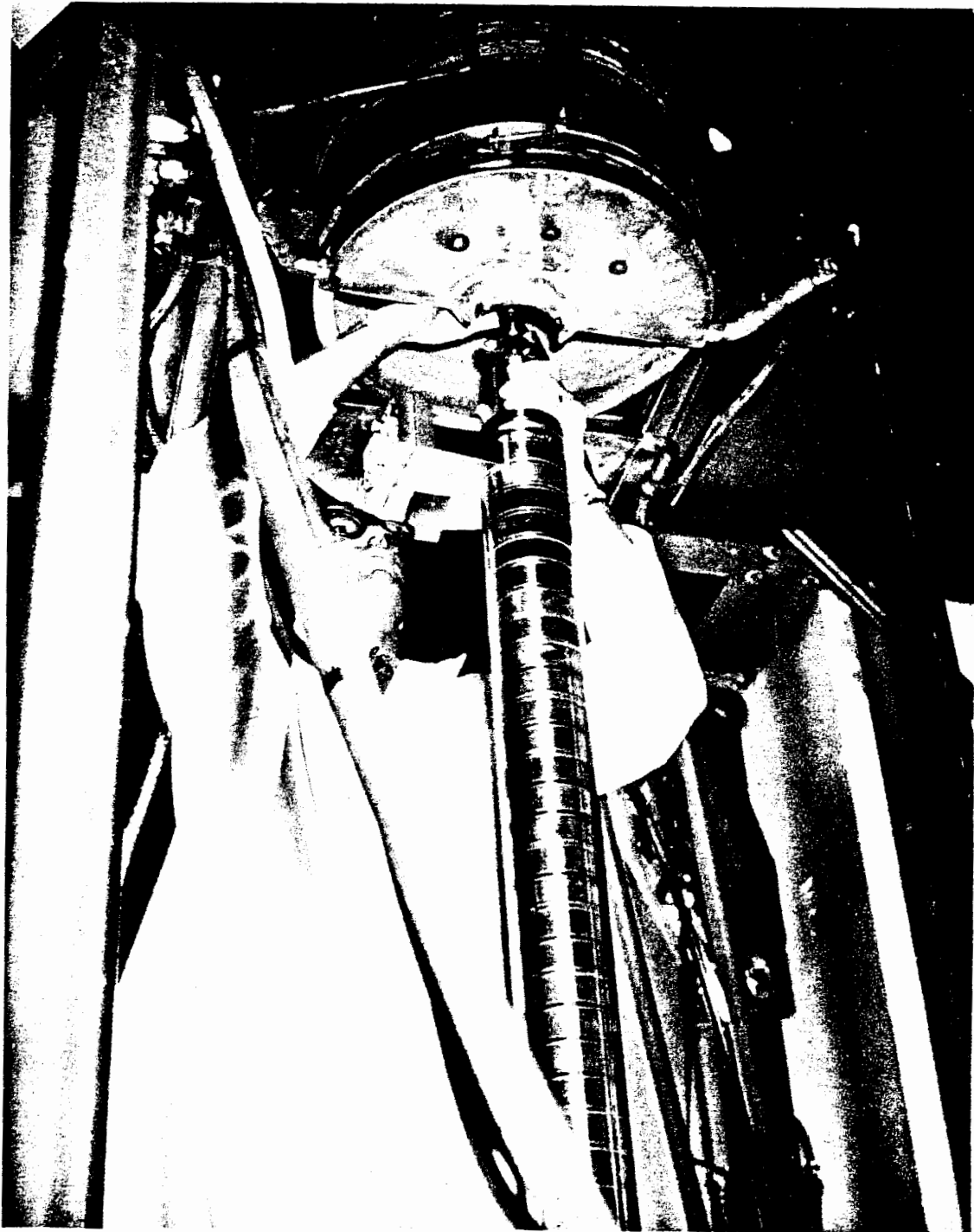


FIG. 34--Connection of 10-foot assembly to support tube.



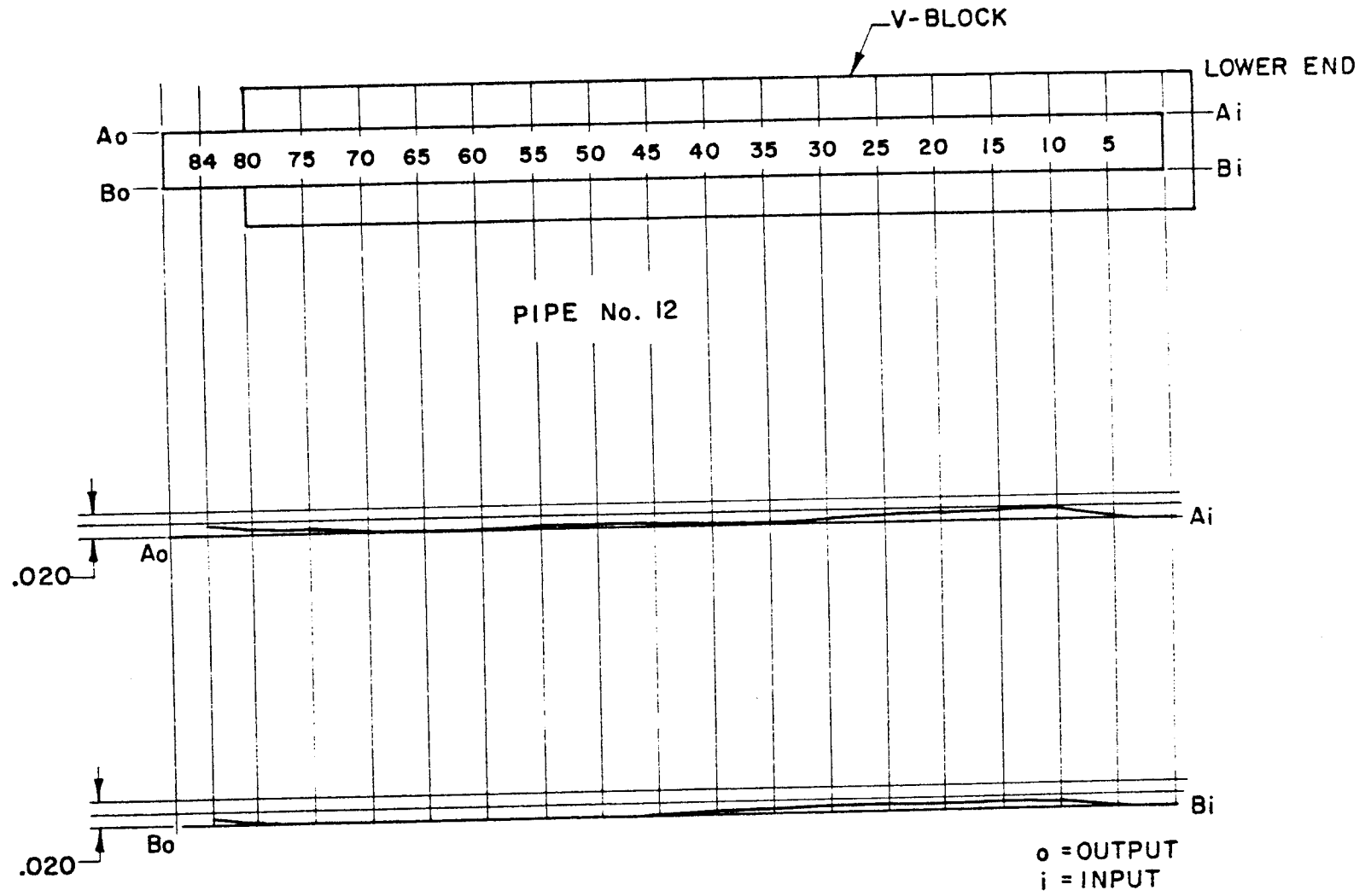
FIG. 35--Furnace showing ring burner in operation.

Input and output waveguides are made up as subassemblies. Each subassembly consists of the input or output waveguide, the end flange and approximately eight inches of disk-loaded waveguide. These units are used in the stacking of a complete 10-foot section.

Figure 36 shows a typical plot of the deviation from straightness of the section after brazing. The maximum phase excursion measured in brazed assemblies after brazing is approximately 30° . The required $\pm 2\frac{1}{2}^\circ$ phase shift can be readily achieved by tuning. Figure 37 shows a view of a finished accelerator section, together with the water-cooling tubes. During operation of the accelerator, the disk-loaded waveguide will be held within $\pm 0.4^\circ\text{C}$.

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**FIG. 36-DEVIATION FROM STRAIGHTNESS
OF ACCELERATOR SECTION (BRAZED)**

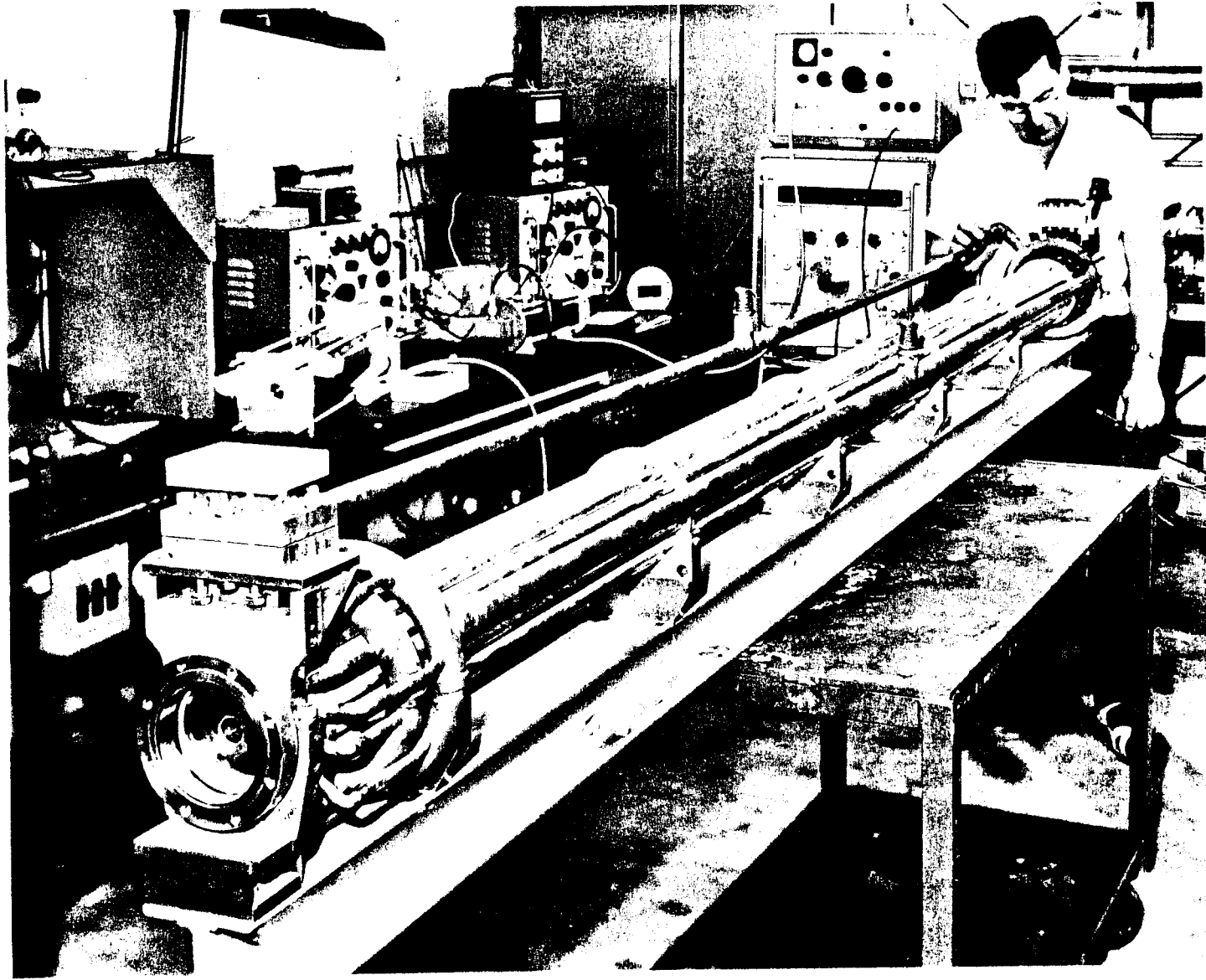


FIG. 37--View of finished accelerator section.

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4. The parameter τ has been called $I\ell$ in several previous reports, where I is the rf attenuation in nepers per unit length, and ℓ is the length of the accelerator section. The dependence of τ upon filling time t_F emphasizes the importance of comparing the c.g. and c.i. structures at the same value of τ for each. For equal τ , the two structures will have the same filling time, the same stored energies, and the same ratios of input to output rf powers (reference 3).
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9. The original basis for $\tau = 0.57$ was that this particular value resulted in a no-load energy in the constant-impedance accelerator which is 10% less than the maximum no-load energy which can be obtained (occurring at $\tau = 1.26$). This was judged to be the maximum penalty in energy which one could afford to pay to obtain the advantages of low τ discussed in the text. The same qualitative reasoning holds for the constant-gradient accelerator structure, and thus we have not seen fit to change the value of τ selected earlier.
10. The Mark IV accelerator is a two-section machine powered by two klystron amplifiers. It has been used since 1955, primarily as a

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(Continued)

vehicle for development and testing of accelerator components. The Mark III accelerator is a 30-section machine producing 1 Bev electrons for physics research.

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