TABLE OF CONTENTS

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ACKNOWLEDGMENT

Having been put in charge of the technical supervision of the construction of microwave equipment to be used for instructional purposes by 20 colleges selected to teach ESMWT Microwave Courses, so much of my time was put in this project it was decided by the Graduate Committee that this work should fulfill the partial requirements for the degree of Master of Science.

Since so many staff members, mechanics, and others in the Department of Electrical Engineering were interested in this project, it is difficult for me to give due credit. To each and all, however, I wish to express my sincere gratitude for their constructive help and support. In particular, I wish to express appreciation to Professor Arguimbau, the supervisor of this thesis.

R. C. Habich

M.I.T.
May, 1943

Chapter I

INTRODUCTION

In presenting this thesis in partial fulfillment of the requirements for the degree of Master of Science, it may be helpful to the reader to have a brief statement as to the background and conditions which made the departure from the usual form of such a thesis necessary.

Technical research and development in the field of microwaves has been greatly accelerated due to the importance of this subject in the war effort.

The Government, recognizing the need for qualified men in ultrahigh-frequency techniques, organized a program for the training of personnel for work in this field. A special ultrahigh-frequency lecture and laboratory course with emphasis on microwaves was set up as an Engineering Science Management War Training program of the U. S. Office of Education.

The Communications Division of the Department of Electrical Engineering at the Massachusetts Institute of Technology, being one of the leaders in this field of ultra-high-frequency techniques, was chosen as a logical meeting place for representatives of some forty colleges from all over the country. At this meeting (November 1941) the ground work was laid for the teaching of this subject during the academic year 1941-1942 by the colleges represented.

In the Fall of 1942 a second "Teachers' Conference" took place at the Institute. Representatives of the first "Teachers' Conference" were asked to give their views based on their past year's teaching experience. Twenty additional colleges were selected and asked to teach this same ultrahigh-frequency course so as to assure a greater number of men trained in this field.

It was decided by the ESMWT Committee for Equipment that since most of the microwave apparatus was not available commercially it would be best to have the equipment for the twenty new colleges constructed at one place. This would not only save mechanics' time and simplify procurement of material and priority procedure, but would also insure a uniform construction of the equipment.

The design and construction of this equipment was to be based on a set which was developed by the Communications Division here at the Institute during 1942. The ESMWT Committee asked that the Massachusetts Institute of Technology supervise this construction work which, due to wartime conditions, they assigned mainly to a newly organized machine shop to construct the so-called "microwave kit" and to a local instrument company to construct the "harmonic 10 centimeter oscillator".

Unfortunately, probably due to the pressure of getting this program under way, the construction contracts were entered into by the ESMWT Equipment Committee without adequate check as to the ability of the companies chosen to do the work. Delivery dates were far too optimistic. In addition, it turned out that the machine shop was unfit to do the work. Almost constant supervision was required and it was necessary to transfer a large amount of the microwave-kit work to the Electrical Engineering Shop of the Institute to complete this "kit" as soon as possible. Construction was started on October 15, 1942 and completed on May 15, 1943 - about twice as long as had been originally anticipated.

Handicapped with the unfortunate choice of an inexperienced machine shop the Institute did everything possible to speed up the construction of the necessary equipment since the schools were badly in need of it. Therefore, an unconscionable amount of time was put in by Institute personnel. I, myself, being in charge of the technical supervision, was asked by the Graduate Committee to interrupt my original thesis work on "Signal Generator for 10 Centimeters" which, naturally, I should like to have finished, and devote my entire time to conclude the construction program of the microwave kits.

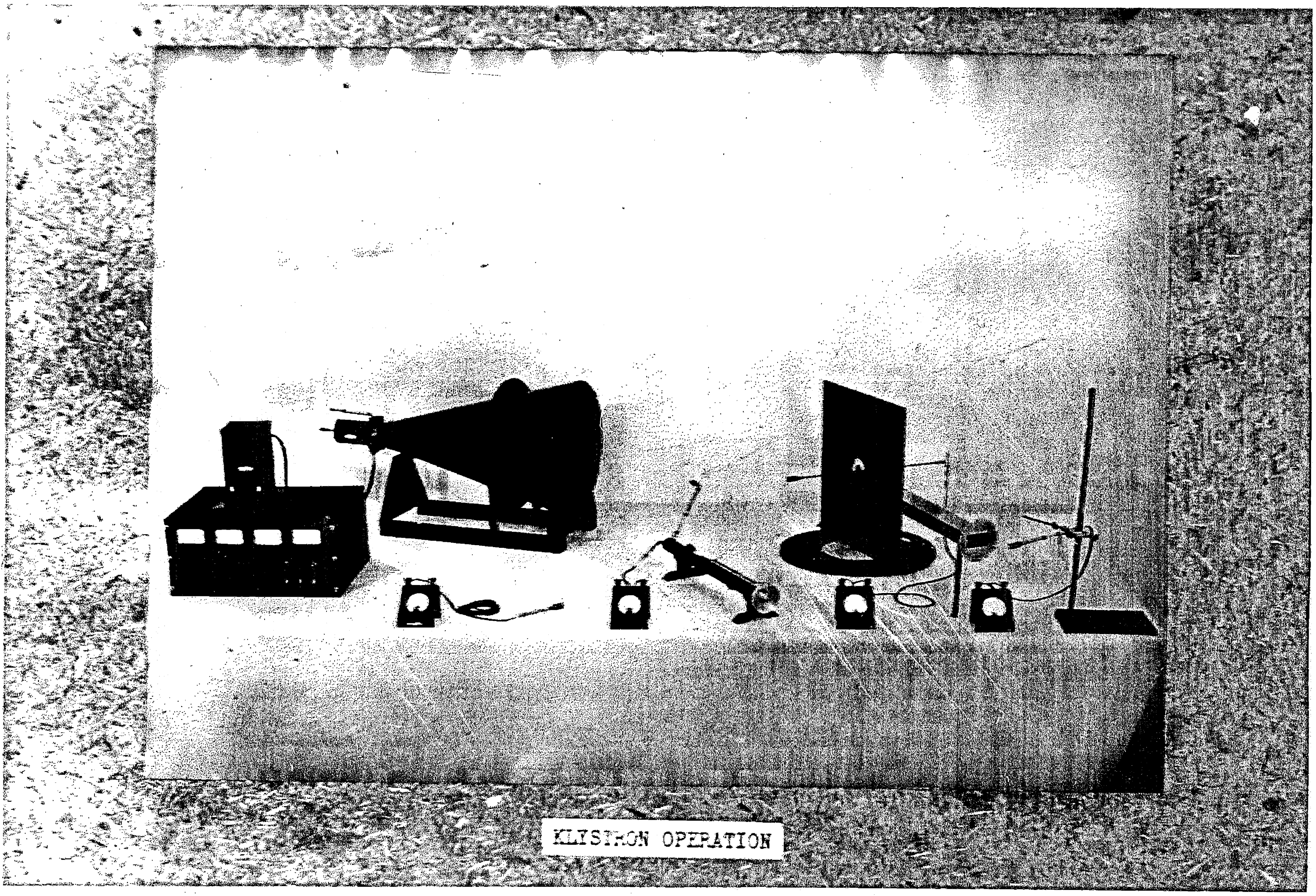
It is unfortunate that the schools did not receive the microwave equipment in time for their use as originally contemplated. However, I feel that the equipment will be of use in teaching future ultrahigh-frequency courses, and I do have the gratification of knowing that I have contributed my time, patience, and energy to bring this undertaking to a satisfactory completion - at least so far as the Institute is concerned.

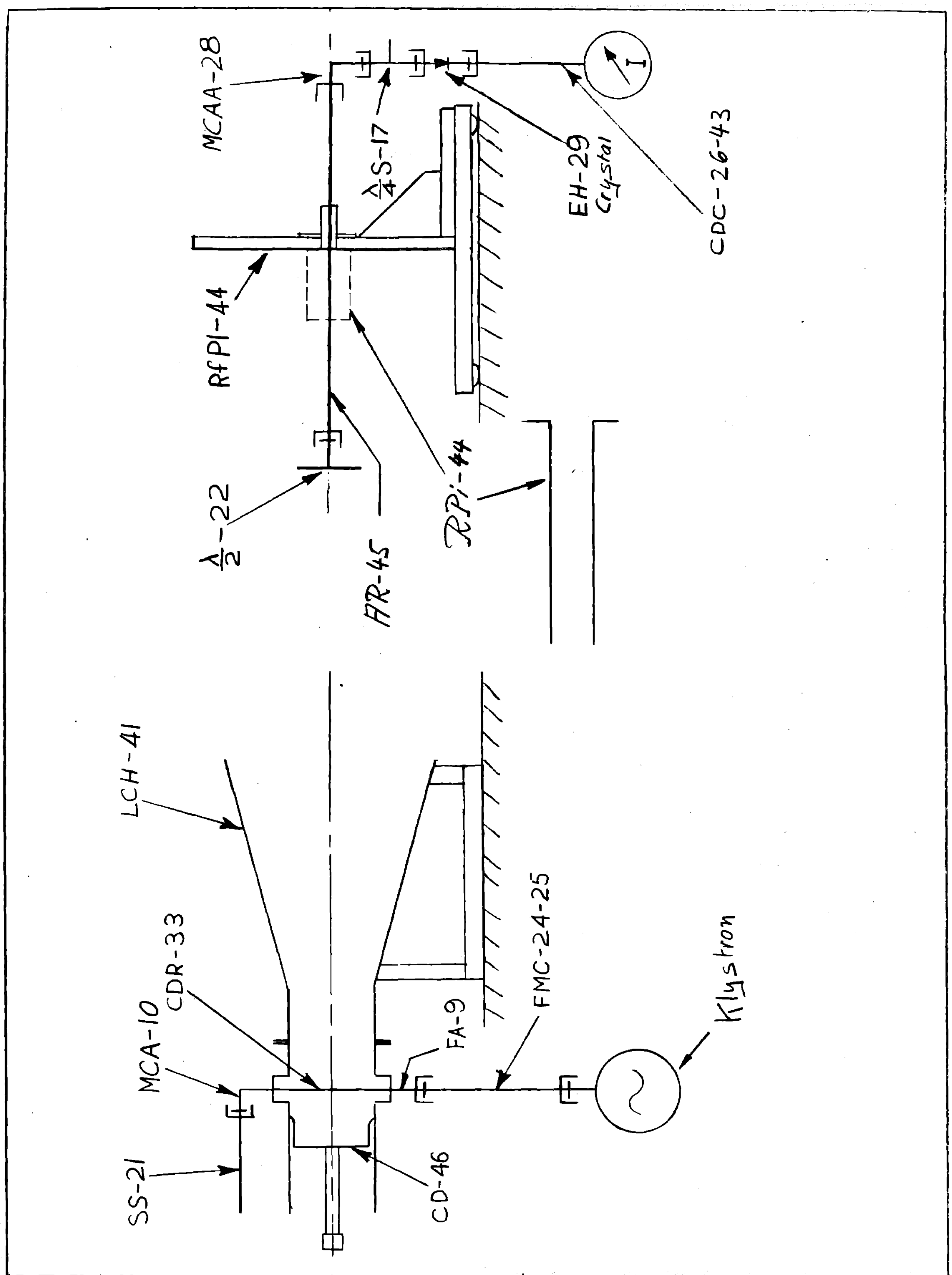
This thesis, therefore, describes the development of the microwave laboratory equipment in the Communications Division of the Department of Electrical Engineering at the Massachusetts Institute of Technology as well as the design and construction of selected microwave sets constructed for the 20 additional colleges chosen to teach the ESMWT ultra-high-frequency courses. The experiments which can be performed with this equipment are outlined; the characteristics and the functioning of the different units are explained, thus giving the reader the fundamentals of microwave measuring techniques.

* * * * *

Chapter II

10 CENTIMETER TRANSMISSION.


KLYSTRON OPERATION



Klystron Operation

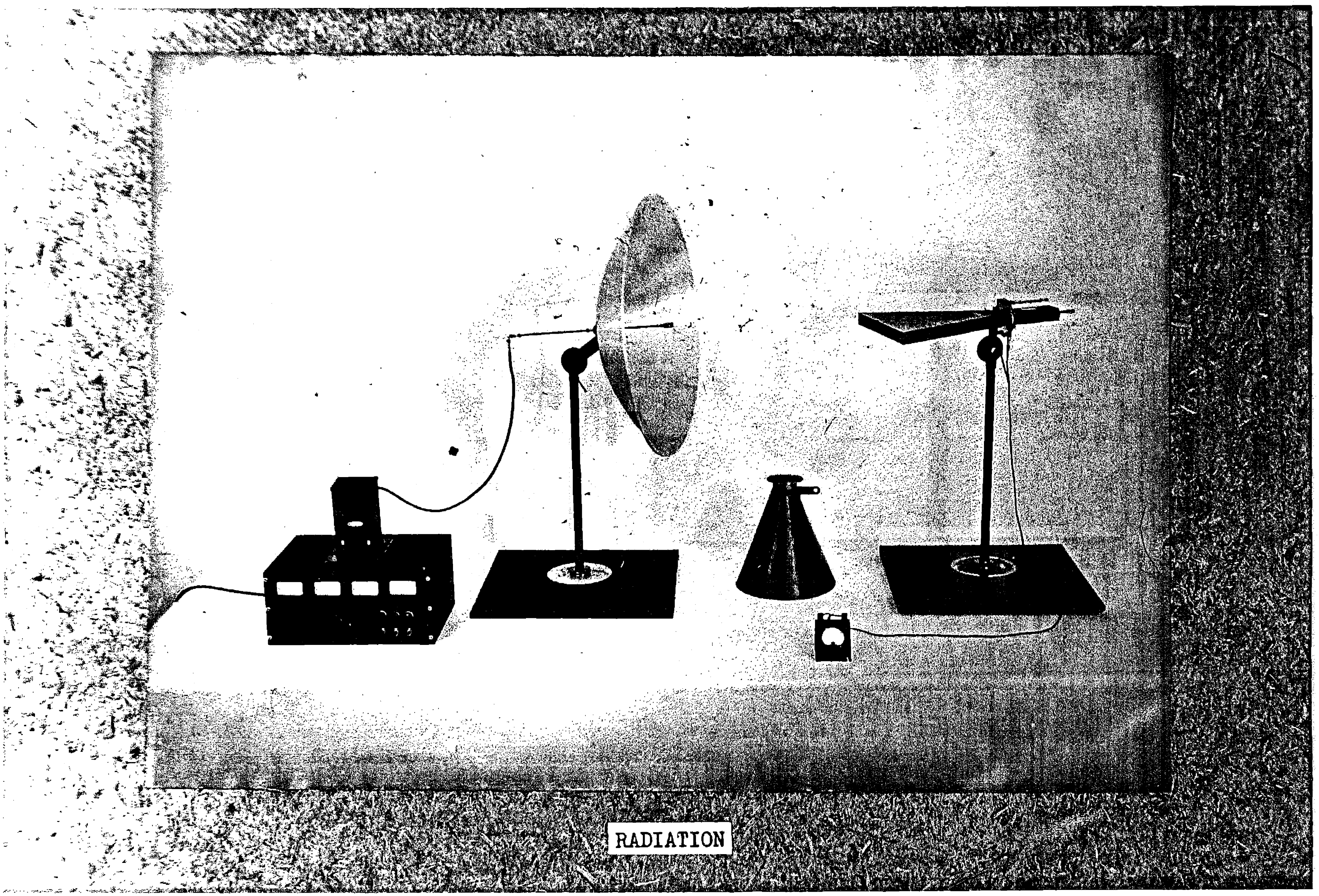
Assembly Dwg.

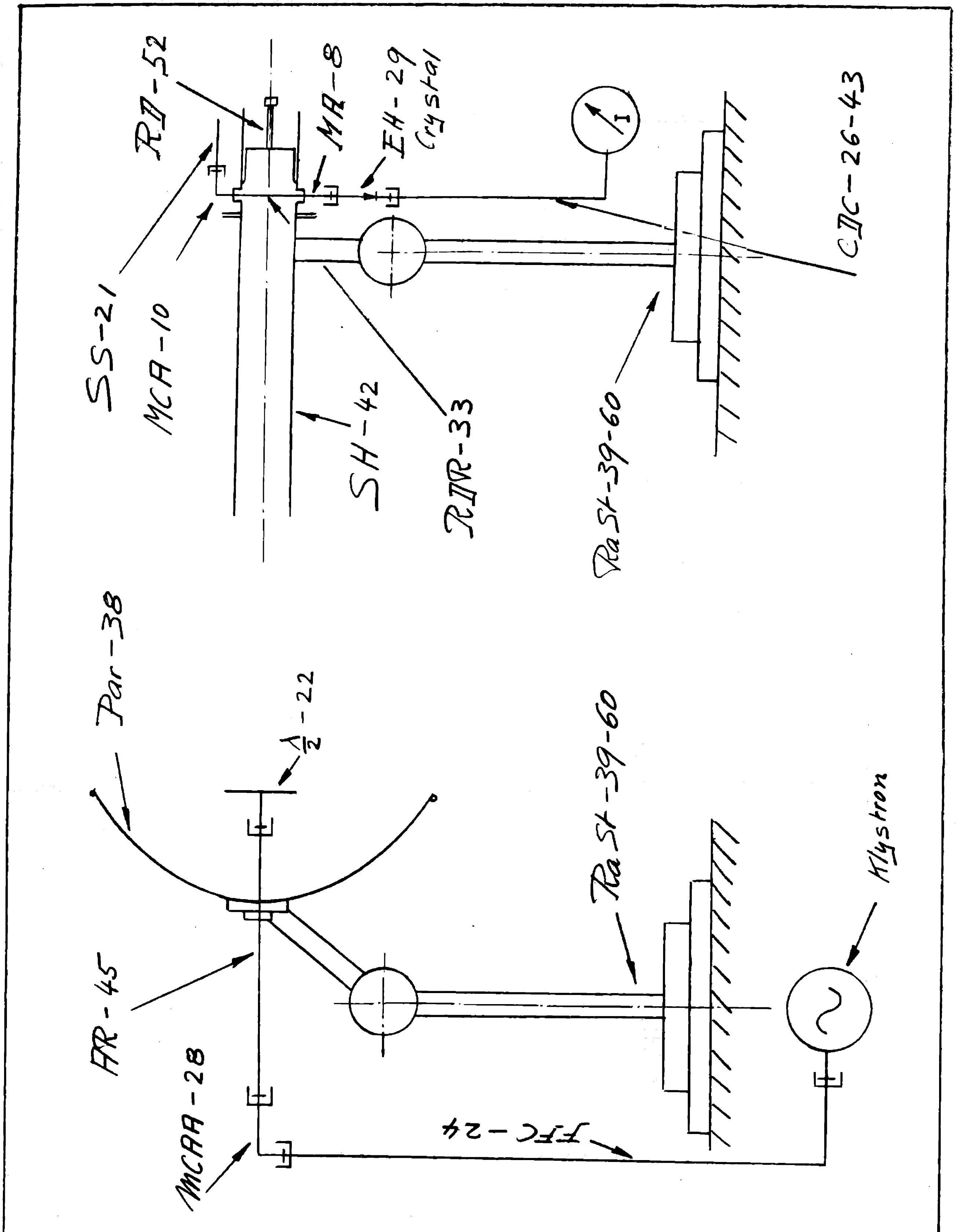
2-5-43

Dr: J.L. Ch:

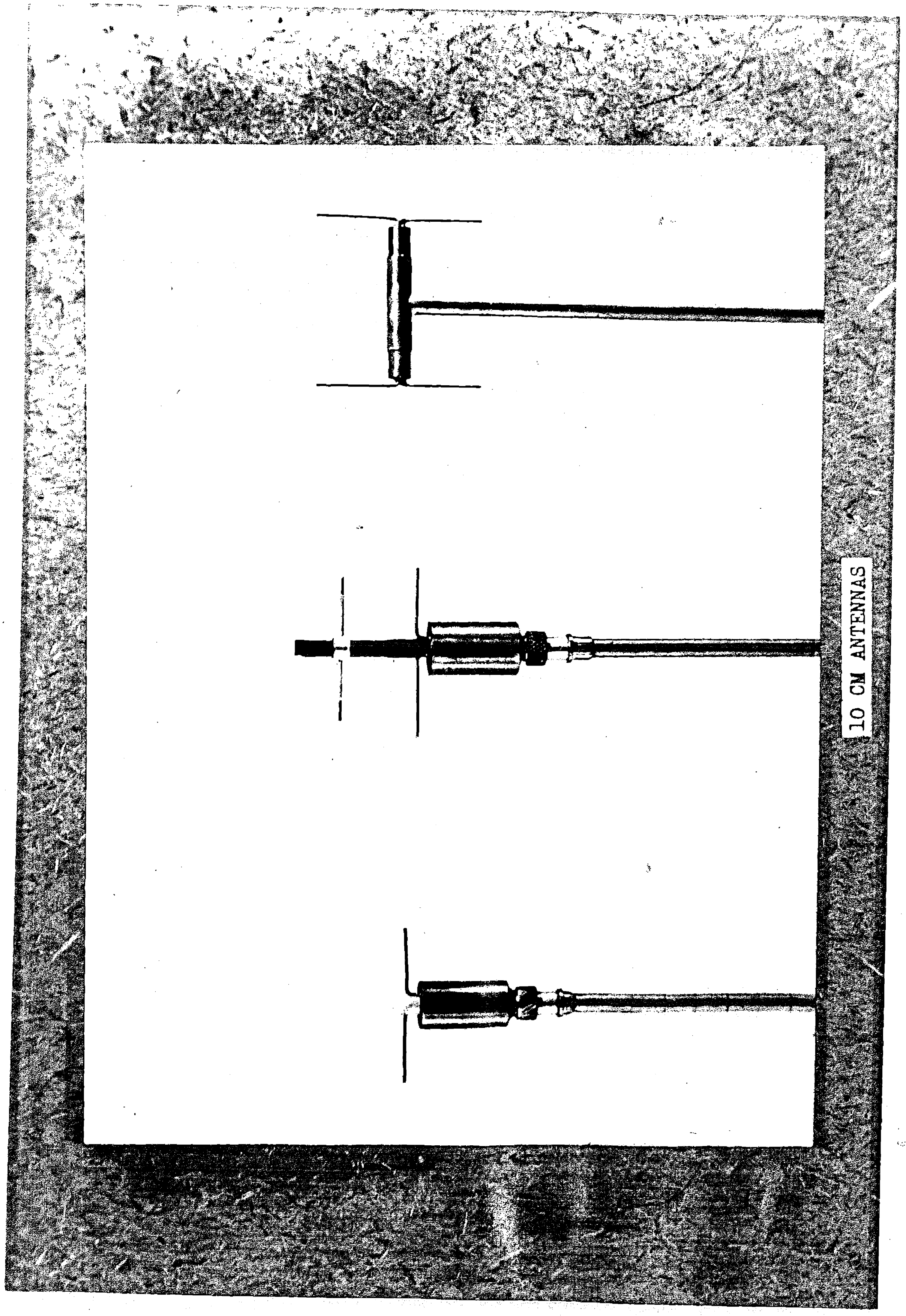
Kl. Op.

A-1


RADIATION



Radiation	Assembly Dwg	Rad
	2-9-43	
	Dr # Ch #	A-2



10 CM ANTENNAS

Chapter II

10 CENTIMETER TRANSMISSION

1. Fundamental Experiments*

Laboratory experiments were prepared by the staff members of the Communications Division to familiarize the student with the field of microwaves. The necessary laboratory equipment to enable the Communications Division to conduct these experiments was designed and built.

The experiments outlined in this chapter were set up to investigate the propagation properties of these quasi-optical waves. In some respects microwaves behave similarly to sound waves, since they have wavelengths of about the same magnitude.

One of the first units the student comes in contact with is a megaphone-like horn, - an excellent broad-band microwave radiator. This horn emits transverse electromagnetic waves (TEM waves) a few wavelengths away from the mouth of the horn. The electric lines E and the magnetic lines H are at right angles to each other and the TEM waves are in a plane normal to the direction of propagation. The direction of the electric lines can be determined with the help of a small E-line detector. The concept of polarization of electromagnetic waves is introduced and explained.

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*See Reference 13 in Ch. VII.

A half-wave antenna detector can be calibrated on a relative basis in a linearly polarized field, since the pickup voltage is proportional to the cosine of the angle between the antenna and the polarization direction.

The energy of electromagnetic waves is propagated through free space in the form of traveling waves. Such a traveling wave can be shown by moving the detector in the direction of propagation. When a wave travels a distance of several wavelengths no change in amplitude is observed. However, if the radiation is directed toward a reflecting object, then standing waves can be detected. A wooden plane covered with thin copper foil is an excellent reflector since the skin depth is extremely small at these frequencies. Here, for the first time, the experimenter comes in contact with boundary conditions along a good conducting metal surface. E tangential to the surface must be zero, as any potential difference along an ideal conductor would create an infinite surface current. This is physically impossible. The analogous condition for the H lines is that H normal must become zero, since the H lines must close and cannot end on a surface.

The wave reflected from an obstruction adjusts itself in phase and magnitude in such a way as to fulfill the boundary conditions along the reflecting surface. Incoming and reflected waves interfere in the space in front of the reflector. The concept of nodal surfaces is of value here; they are loci of points where the resultant E vector becomes zero. The loci are planes in the case of a plane reflector and are spaced $\lambda/2$ apart if the incident wave hits the reflecting surface at right angles to it. This enables one to measure the wavelength of an electromagnetic wave in front of a reflecting plane with the aid of a small E-field detector. The result can then be compared with a direct-reading coaxial wavemeter. This experimental setup is shown on pages II-2 and II-3. Furthermore, this same arrangement makes the study of oscillator operation possible. The oscillating conditions of a 10 centimeter klystron or a 368-A oscillator can be investigated. The microwave sources are adjusted and the operation data recorded. In addition, the effect of matching the source to the radiator can be studied.

2. Microwave Demonstration

The more advanced microwave transmission experiments explained in this section are best suited for microwave demonstration. These experiments can be carried through in an illustrative way by modulating the microwave source with an audio tone. The 10 centimeter energy is picked up by receiving antennas and fed to crystal detectors, where it is demodulated. The crystal output is then amplified and applied to a loud-speaker. The sound intensity of the speaker is thus a qualitative measure of the field intensity picked up by the receiving antenna.

For this reason, the power supplies of the microwave sources were built in such a way as to allow grid modulation. A word of precaution is necessary. To avoid destruction of the fine grid structure of a klystron, due to overcurrent, never allow a positive grid potential with respect to the cathode to take place when the beam voltage is turned off. Beam and grid fuses are mounted in the klystron chassis to protect the elements of the tube. Care must also be taken in supplying the modulation voltage. Well-insulated modulation transformers are necessary as the grid voltage is on high potential. The cavity is the element of a klystron oscillator which is connected to ground. With this in mind, and with some careful adjustments of the klystron operation voltages it was possible to set up a 10 centimeter communication system of good tone quality. Successful microwave retransmission was made with the broadcast signal of the FM station at Paxton.

This setup permits demonstration of the following group of experiments in a very illustrative, qualitative way.

(a) Radiation:* Investigating different microwave radiators such as paraboloids and horns, explaining field patterns, power gain, directivity and so on. (See pages II-4 and II-5).

(b) Propagation and detection of waves: Demonstrating polarization, reflection

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*See Reference 14 in Ch. VII.

from, and transmission through different materials and parallel wire grids. Investigation of different detectors, introducing the reciprocity theorem.

(c) Microwave circuit elements: Indicating their use and behavior, explaining resonant effects, tuning, matching, and so on.

To improve the demonstration equipment other special units were built. One of them is a coaxial selector switch, which made it possible to connect selectively an incoming coaxial line to any of eight different outgoing lines. (See page V-2). The unit is used to compare the characteristics of different radiators.

A demonstration experiment, which is worth while mentioning here, since it involves a great deal of microwave technique, is the setup of a simultaneous two-way communications system over one pair of paraboloids. The two modulated carriers were operating on 9.9 and 10 centimeters. Good selectivity was achieved on the receiving and transmitting end by using high Q resonant cavities tuned to their respective frequency, thus acting as band-pass filters.

The students are urged to repeat the experiments outlined in this section in a quantitative manner in which case the crystal detectors are connected to a direct-current instrument, calibrated in electric field intensity.

3. Antennas

The antenna most used in this equipment is a half-wave dipole with quarter-wave balancing sleeve. This dipole is used as: a) pickup for the simple hand-detector; b) detector in the reflecting-plane experiment; c) driver unit for paraboloids or d) coupling unit, used in pairs.

A twin half-wave antenna, or H antenna, is the simplest form of an array. The coaxial mounting makes turning of the antenna around the axis of the balancing sleeve possible.

The two half-wave radiators spaced half a wavelength apart can thus be fed in phase or out of phase. The respective figure 8 field patterns can be observed. Page II-6 shows such an H antenna as well as a half-wave antenna with parasitic elements adjustable in spacing and length. The latter was used as a driver in a paraboloid to reflect the forward radiation of the single dipole back into the reflector.

The other typical microwave radiator, the electromagnetic horn, is excited by a circular driver unit, explained in the next chapter.

The shortness of wavelength permits the study of antennas on reduced scale (model antennas) inside a laboratory.*

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*See Reference 16 in Ch. VII.

Chapter III

HOLLOW-PIPE WAVE GUIDES[*]

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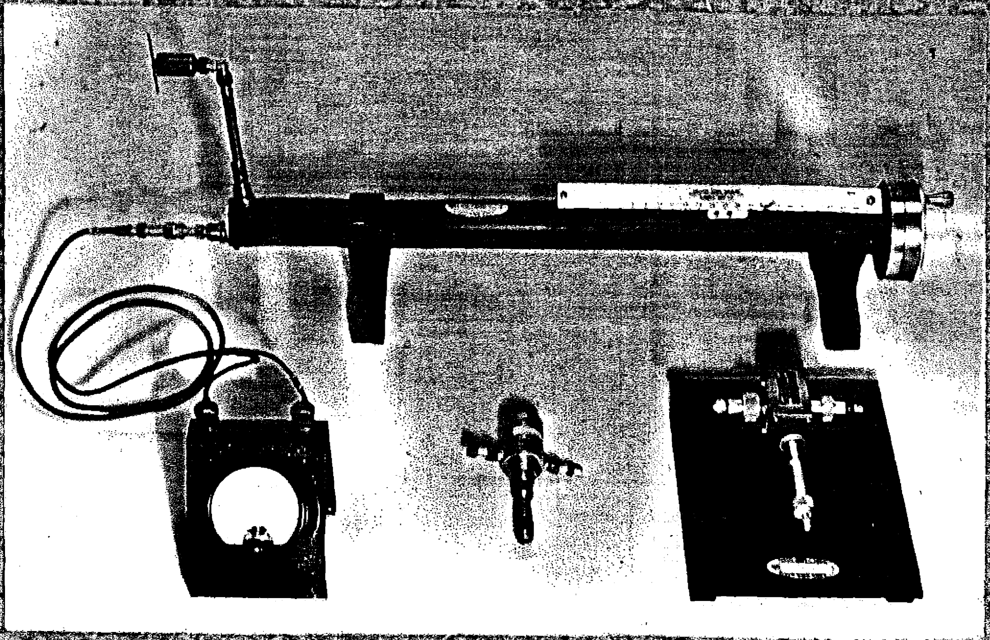
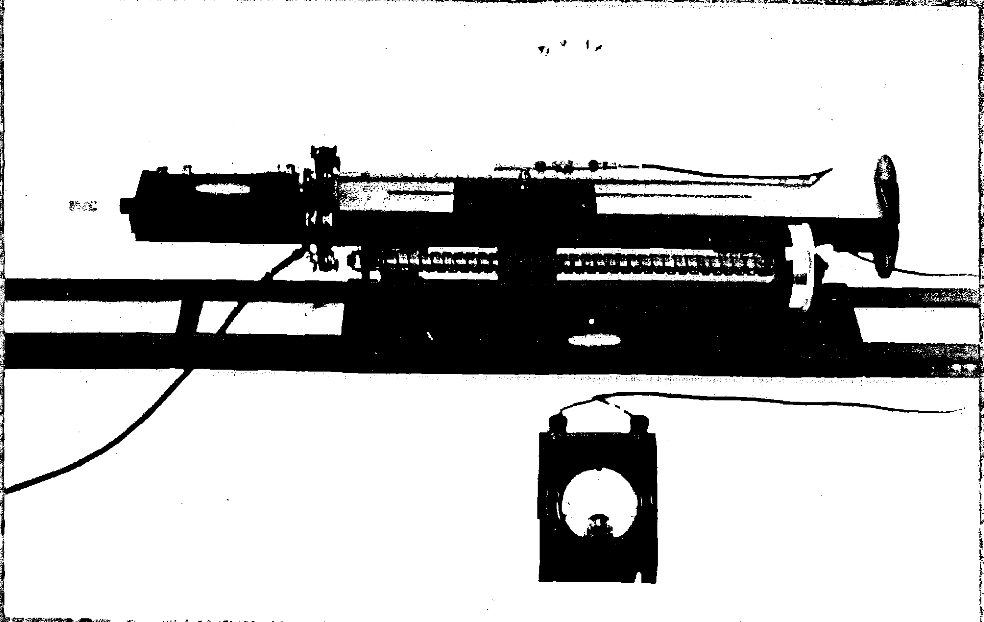
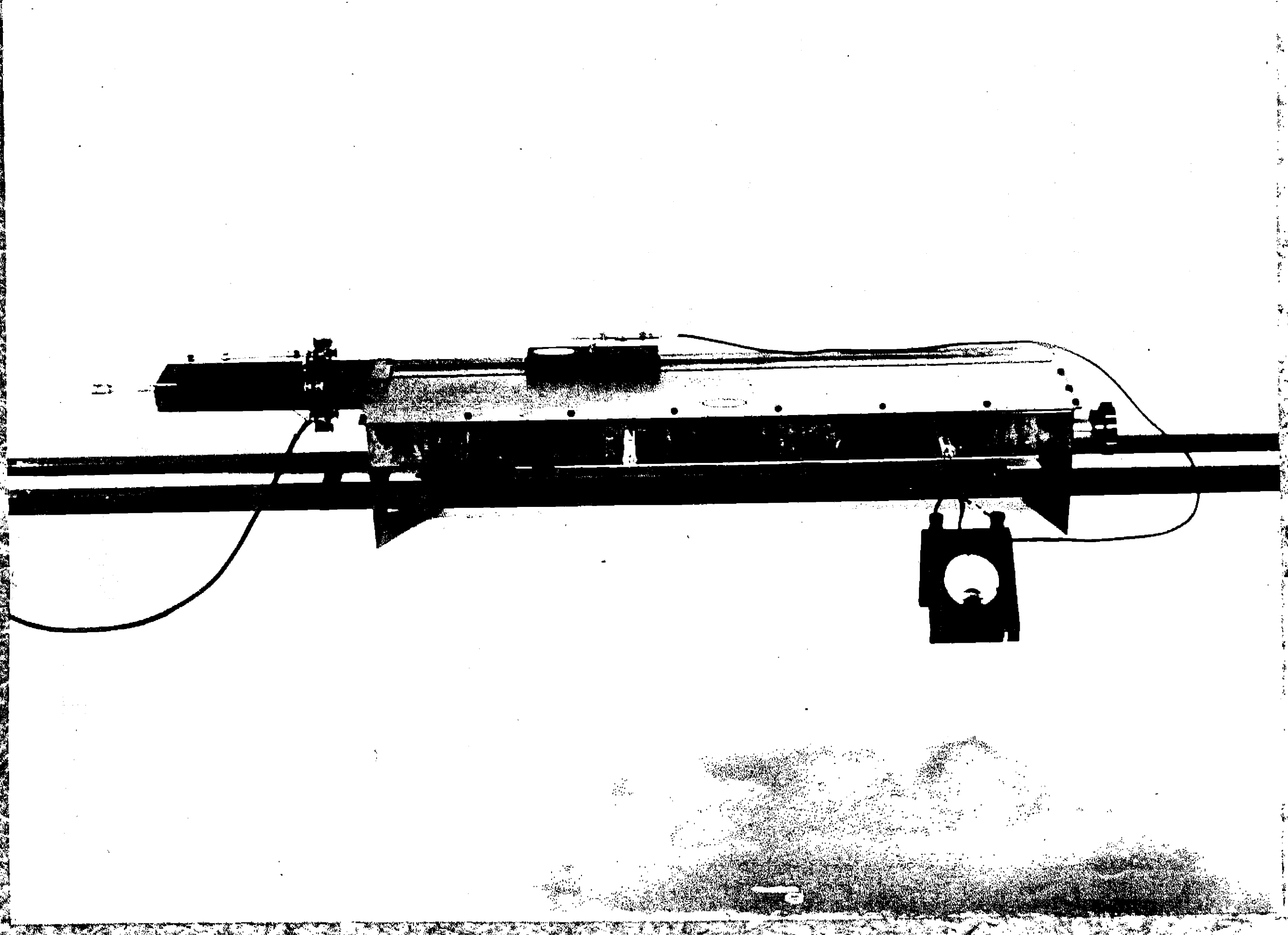
[*] See References 3, 11, 15



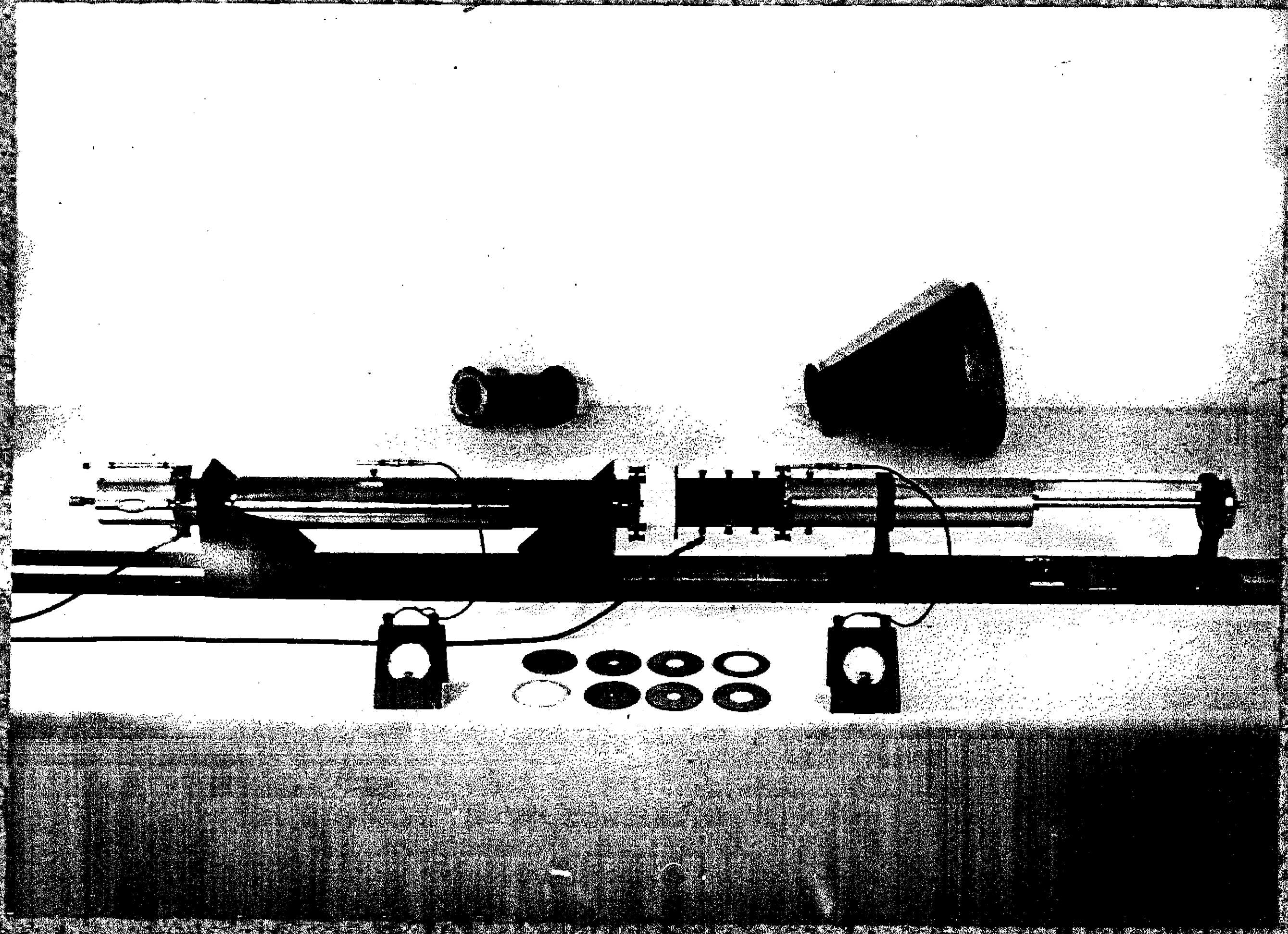
WAVEMETERS



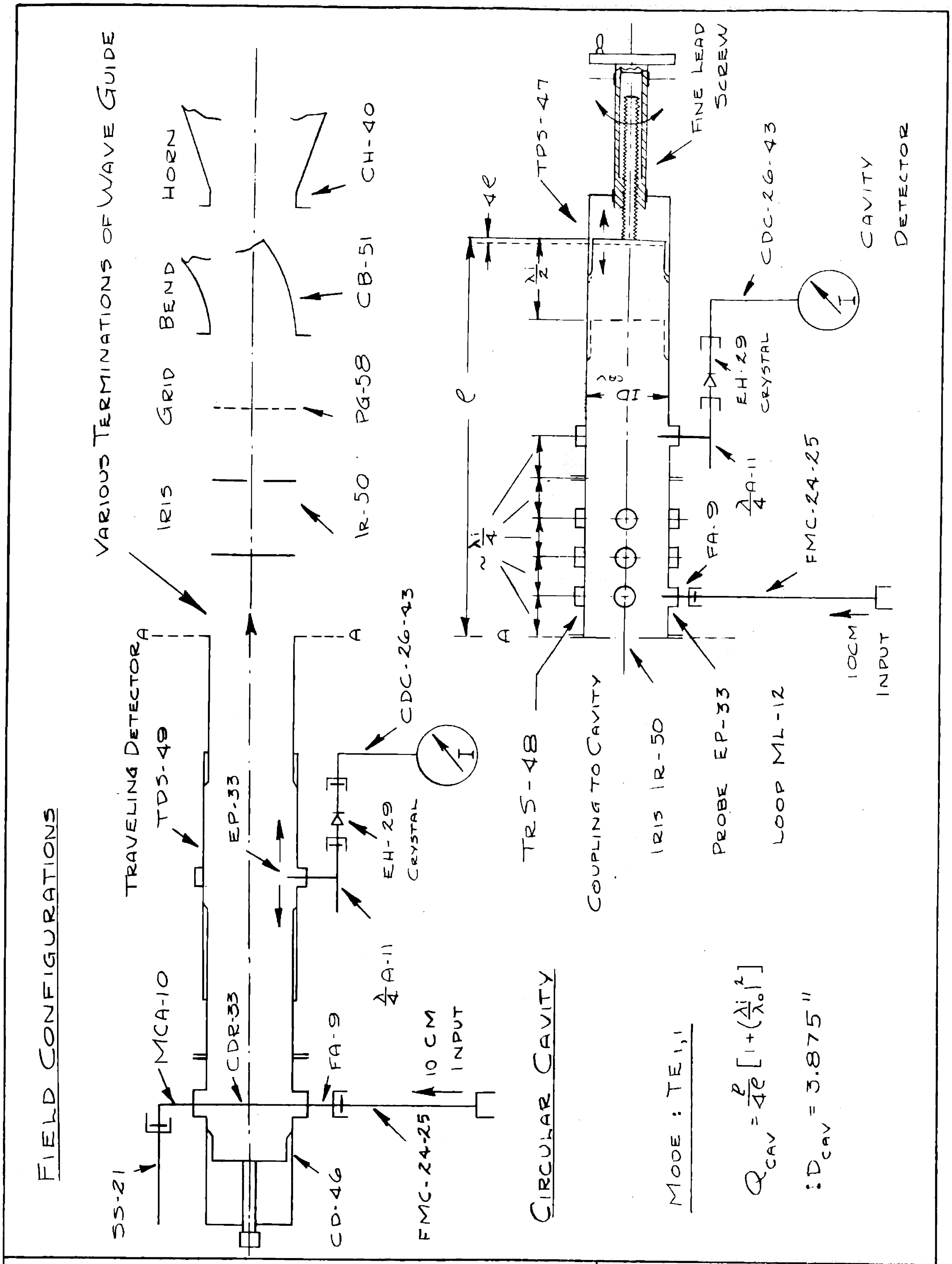
RECTANGULAR TRAVELING DETECTOR SECTION



RECTANGULAR VARIABLE WIDTH SECTION



CIRCULAR WAVE GUIDE



CIRCULAR WAVE GUIDE	ASSEMBLY DWG	CWG
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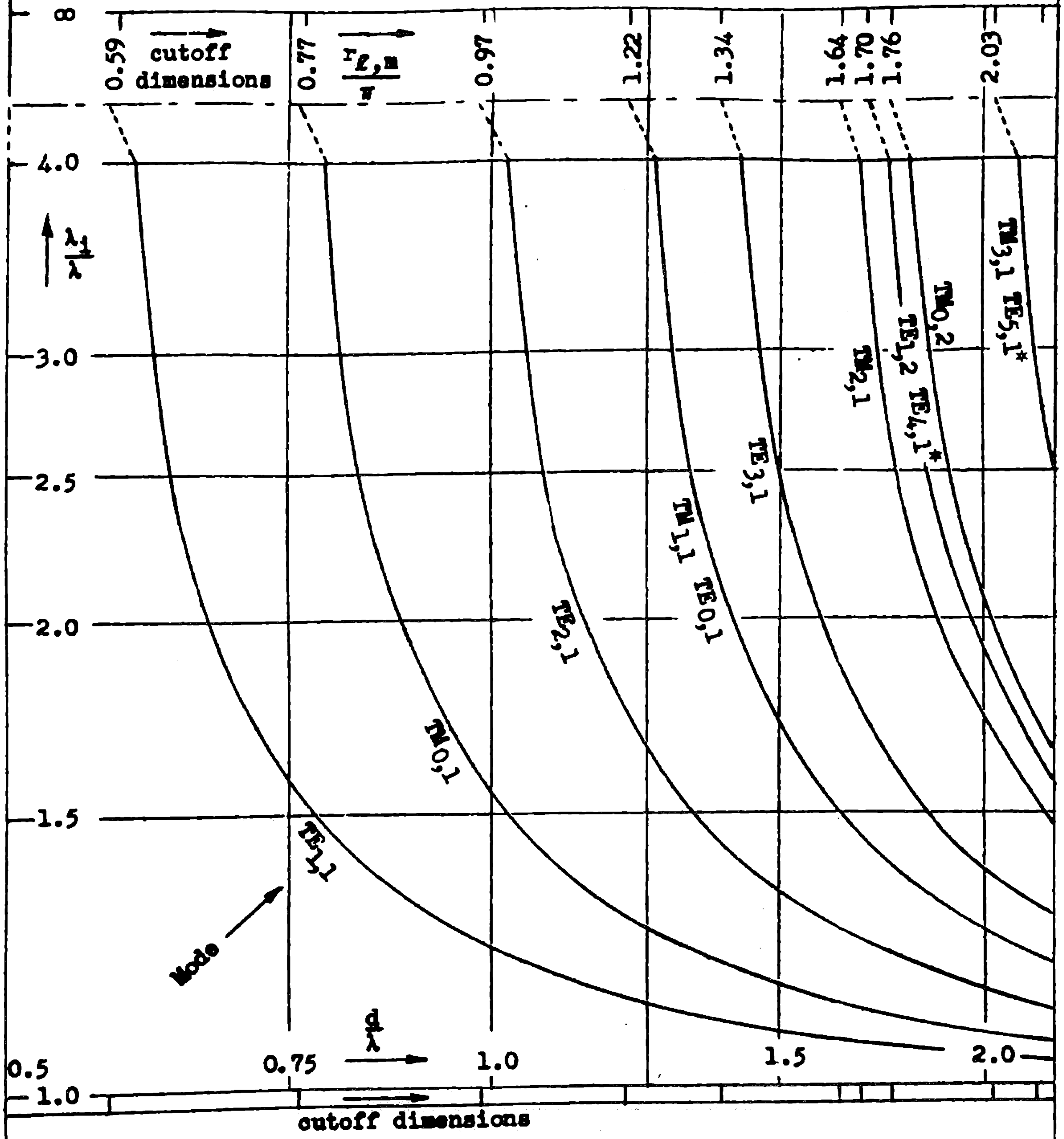
	CH. BY. #	A-4

TE AND TM MODES IN CIRCULAR WAVE GUIDES



d = i.d. of wave guide

λ = λ free space

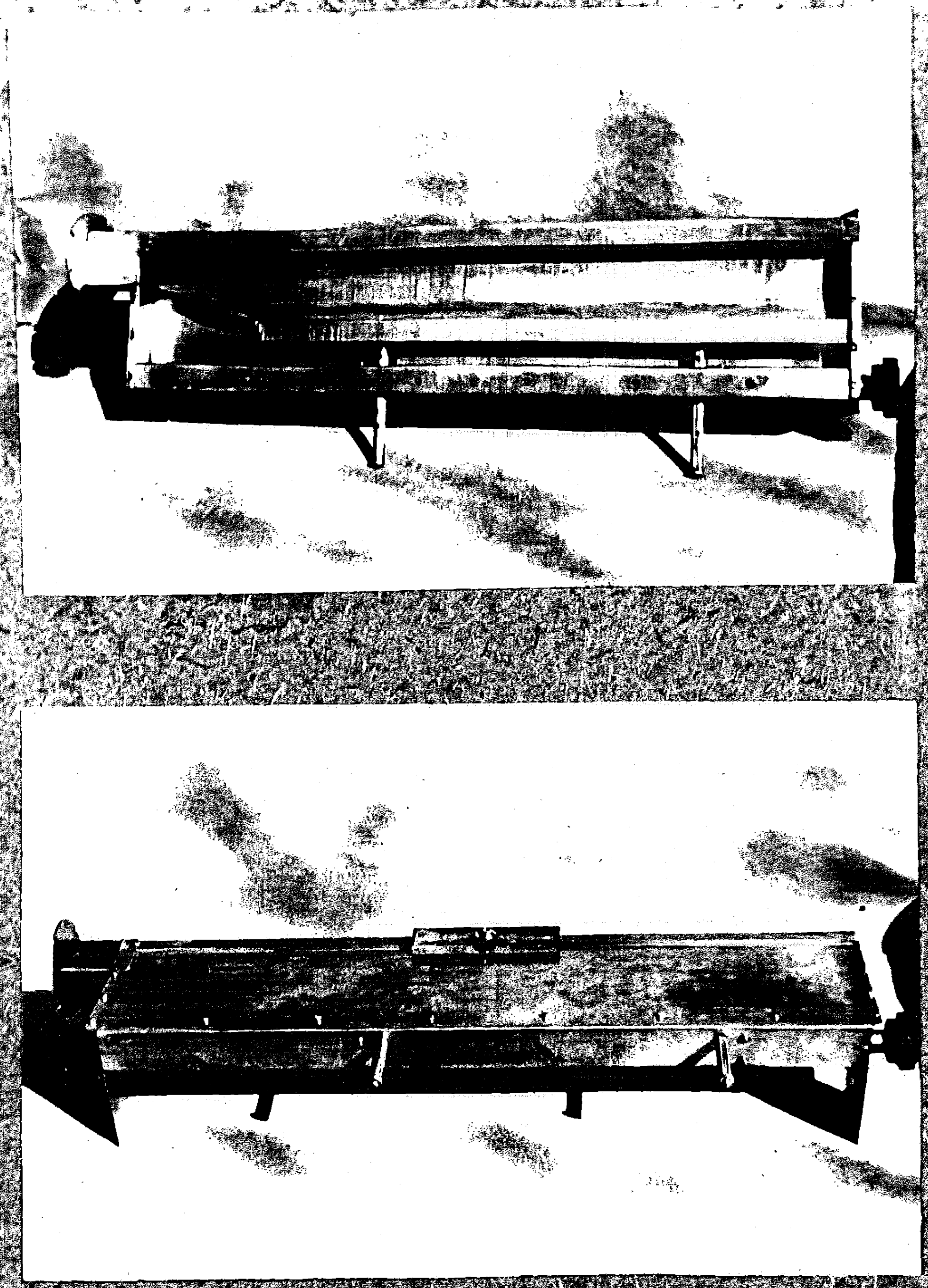
λ_i = λ wave guide

λ_o = λ cutoff = $\frac{\pi}{r_{\ell,m}} \cdot d$

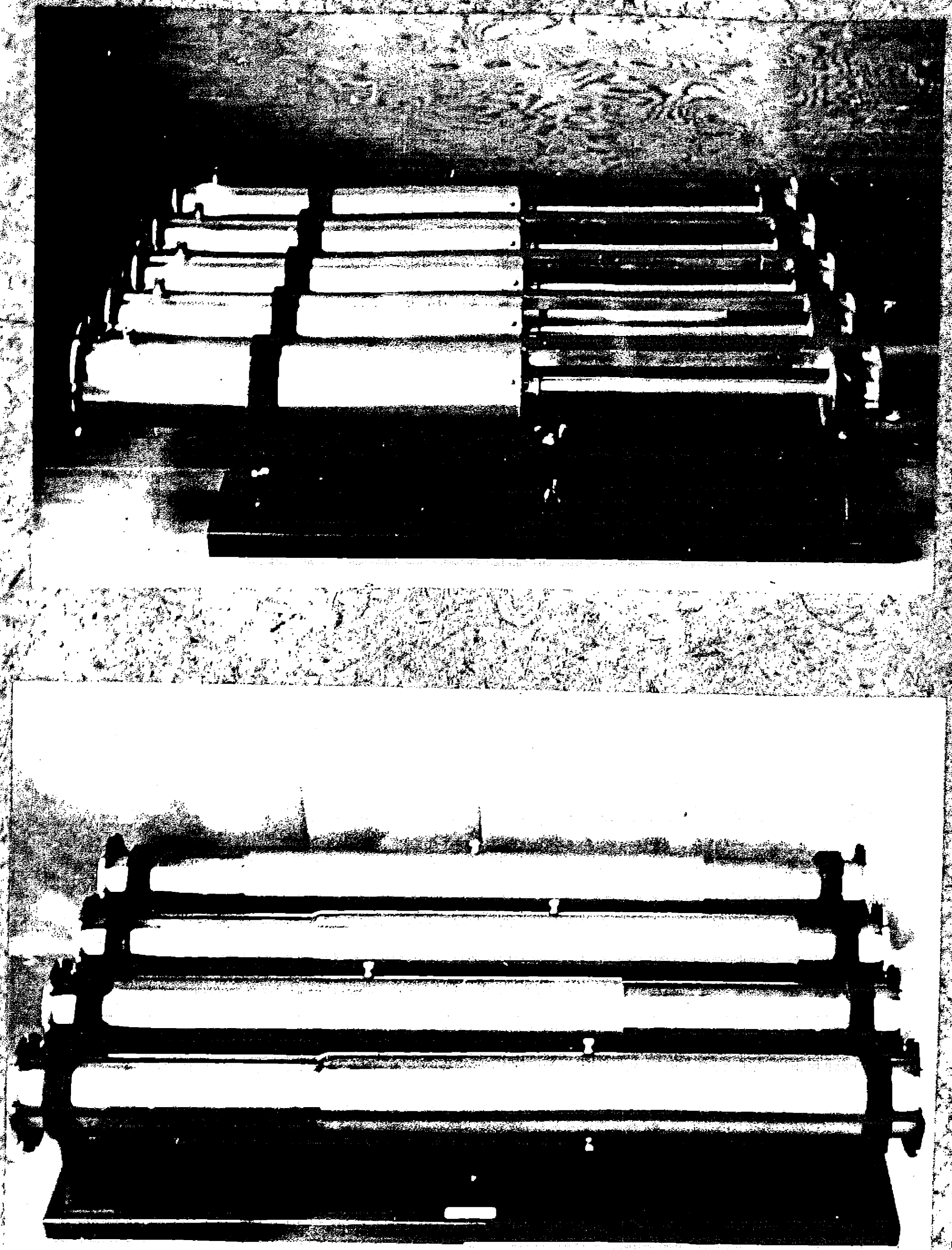
Mode	$r_{\ell,m}$ = m^th root of
TE	$J'_{\ell}(x)$
TM	$J_{\ell}(x)$

* approximate value only

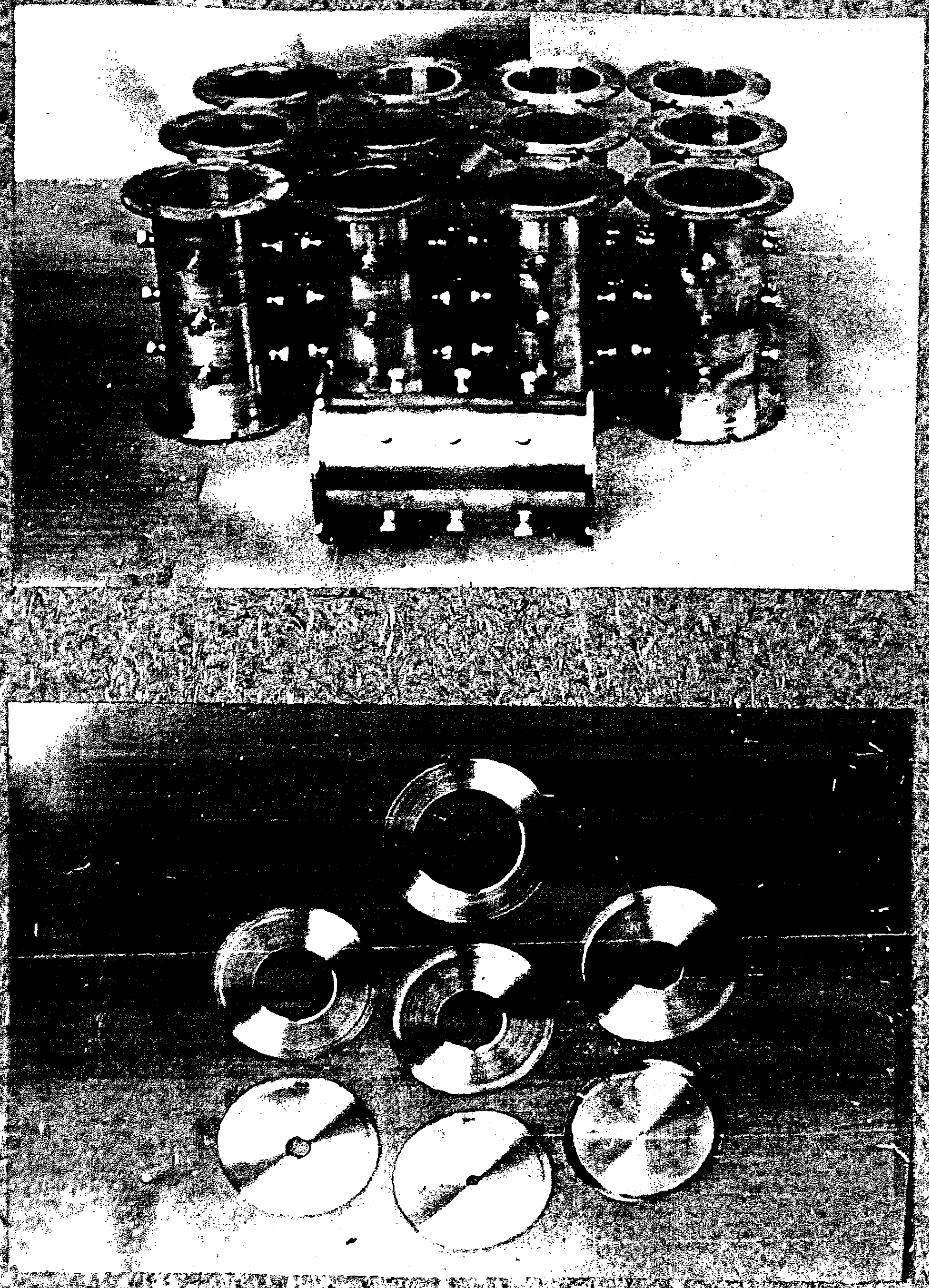
RCH 5/13/43



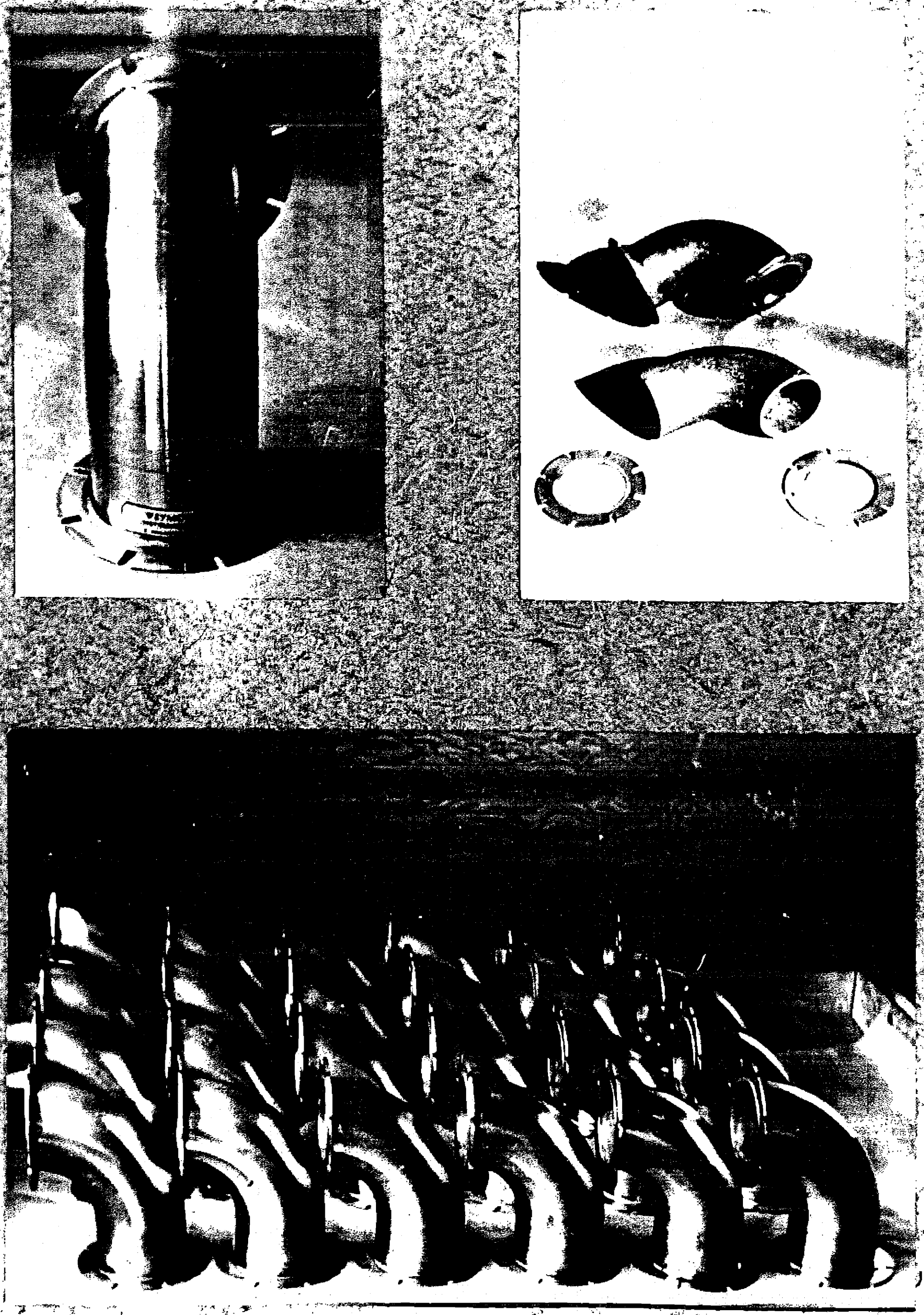
CONSTRUCTION OF RECTANGULAR
VARIABLE WIDTH SECTION



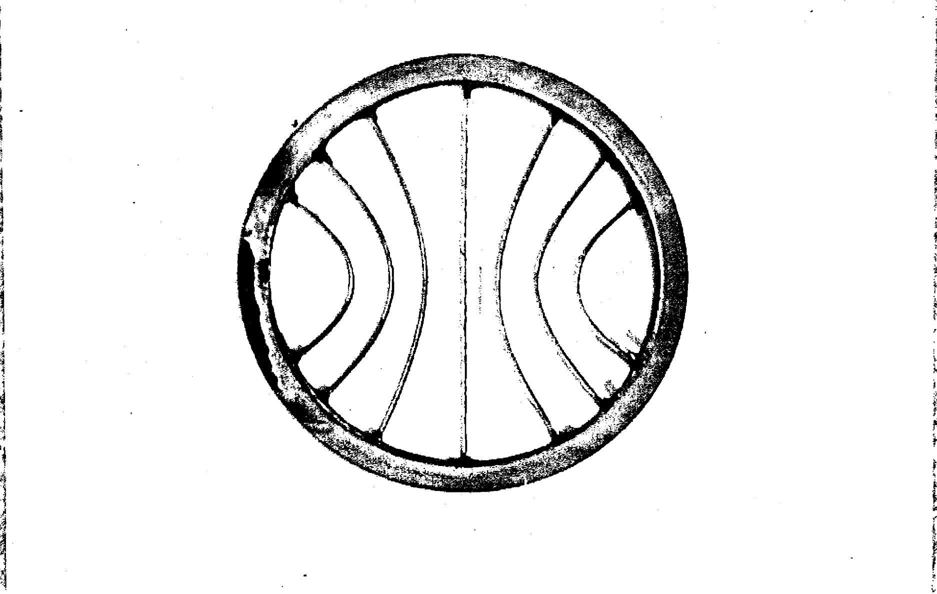
CIRCULAR TRAVELING DETECTOR SECTION
AND TERMINATING PLUNGER SECTION



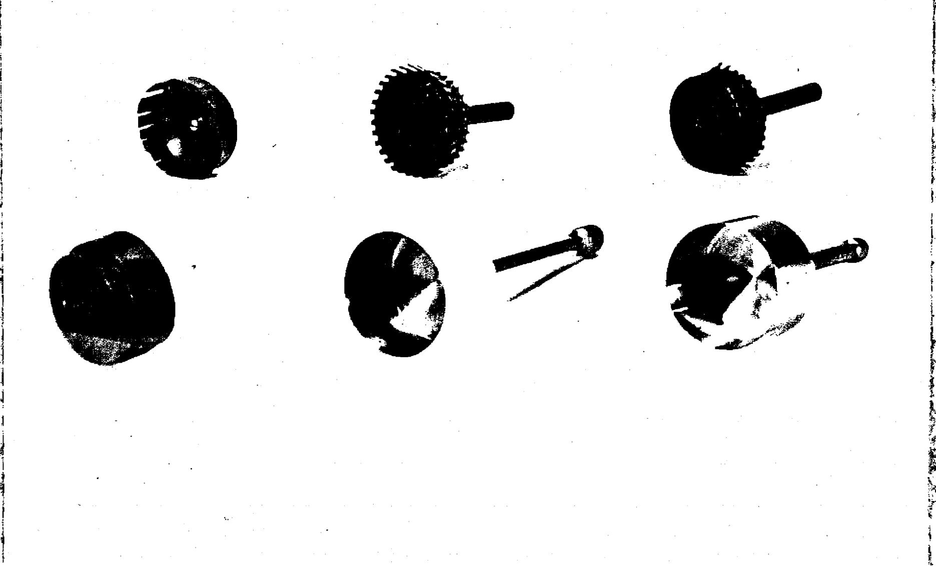
COUPLING TO CIRCULAR WAVE GUIDE.
IRISES AND TRANSFER SECTION



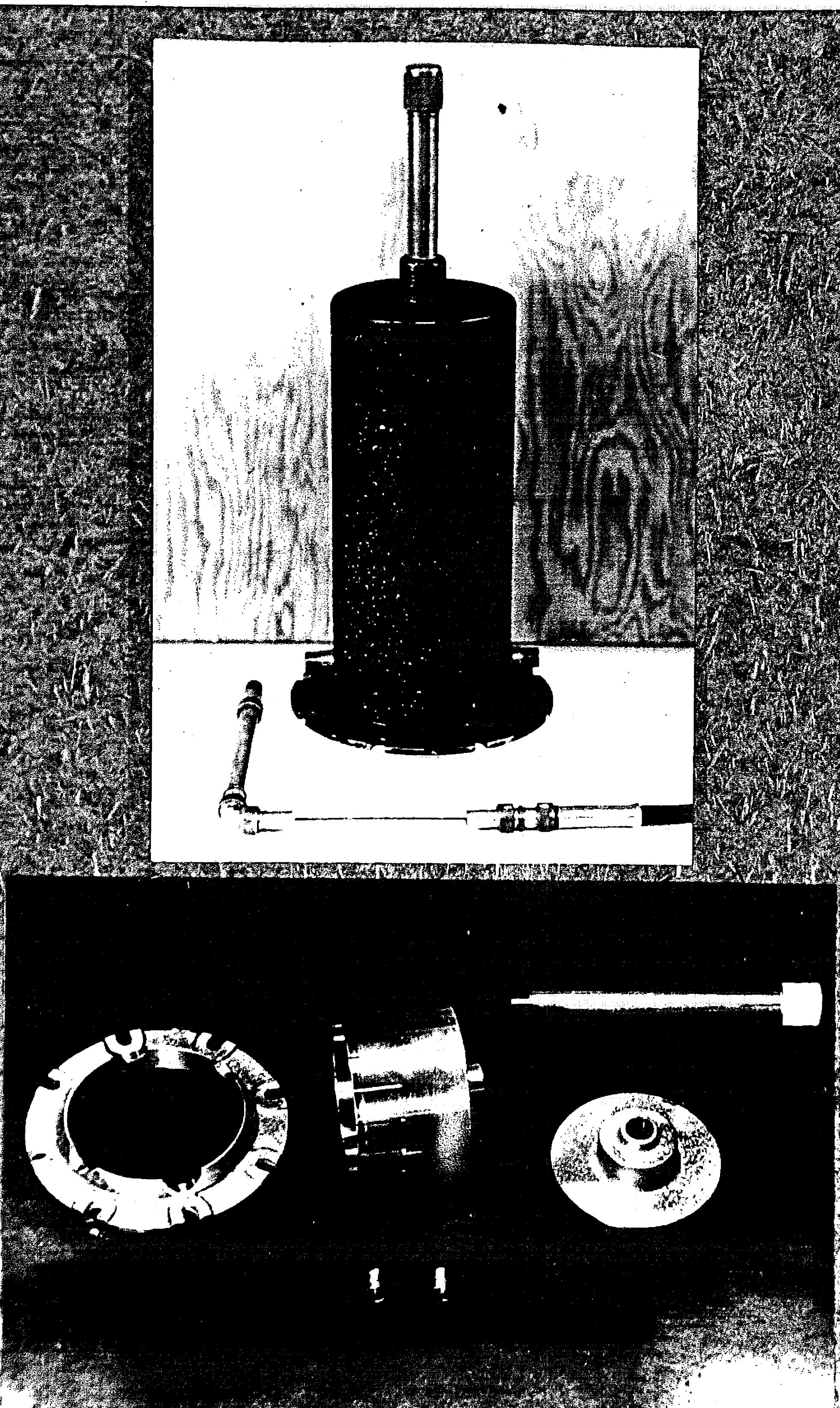
CONSTRUCTION OF CIRCULAR BEND



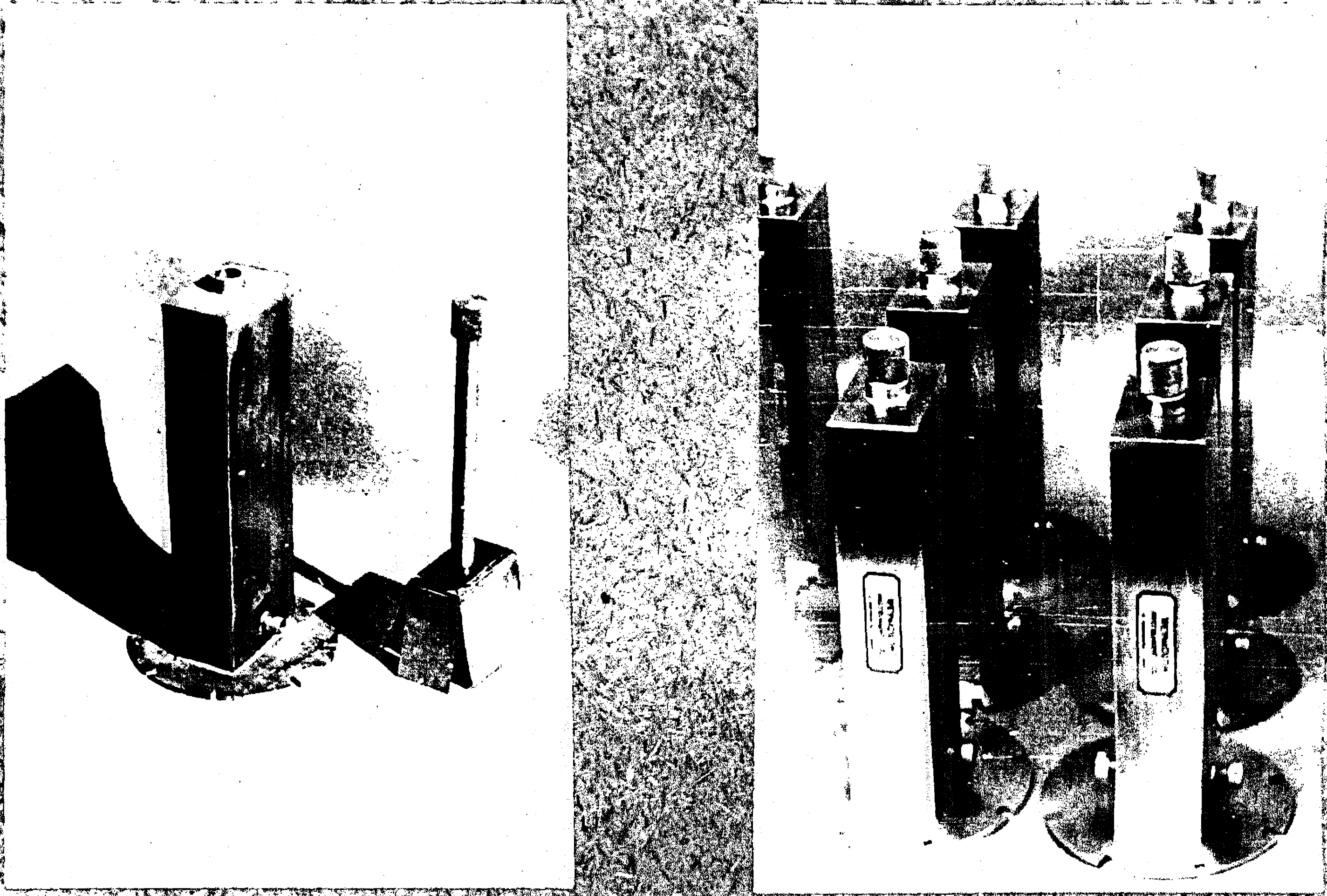
POLARIZATION GRID



DEVELOPMENT AND CONSTRUCTION
OF CIRCULAR PLUNGERS



CONSTRUCTION OF CIRCULAR DRIVER UNIT



CONSTRUCTION OF RECTANGULAR DRIVER UNIT

Chapter III

HOLLOW-PIPE WAVE GUIDES

1. Propagation Through Hollow Pipes

The conventional parallel-wire and coaxial transmission lines in the microwave region are generally replaced by hollow-pipe wave guides. The equipment was built and experiments were prepared to demonstrate and study the propagation of electromagnetic waves through hollow pipes of different cross sections. TEM waves are reflected on a metal plane into a rectangular wave guide; the transmission of wave energy through hollow pipes is demonstrated with the help of a small detector at the output end of the pipe. The guide is in this case excited by standing waves in front of the reflector surface. The nodal planes of the standing waves must coincide with the narrow sides of the rectangular pipe to fulfill the boundary conditions for wave-guide transmission. These planes are adjusted by varying the angle in which the TEM waves are directed toward the reflecting plane. It can be shown mathematically that the lowest mode in a rectangular pipe, that is the $TE_{0,1}$ mode, can be made up of two TEM waves which travel down the pipe at an angle to the axis of the pipe. This results in multiple reflections at the smaller end of the rectangular pipe. (Criss-cross waves.)

Another way to excite wave-guide transmission is by means of radiating elements. Doublets, single wire antennas, or loops are placed in the guide in such a way as to excite the electric or magnetic field of the desired mode. Reflecting surfaces or plungers, are often placed on one end of the guide to intensify the transmission in the desired direction. They are located at such a distance from the radiating element that the reflected wave aids the one directly radiated. Such a combined unit (that is a tunable electrostatic exciting rod and reflecting plunger) is called a driver, samples of which are shown on pages III-13 and III-14.

The cutoff wavelength of a guide is of importance. This is a function of the geometric form and size of the cross section. The computation of the cutoff wavelength of a desired mode is a boundary condition problem and is solved by satisfying Maxwell's equations for the geometry of the pipe cross section. A certain mode can thus be transmitted through a hollow pipe wave guide when the wavelength λ is smaller than the cutoff wavelength λ_o. (Transmission region.) The attenuation region on the other hand, is characterized by the condition that $\lambda > \lambda_o$. The wavelength inside the pipe, λ_i, becomes imaginary in this case and the mode is exponentially attenuated. Thus a hollow pipe wave guide acts much like a high-pass filter. A special unit, the rectangular variable width section, was constructed to demonstrate the cutoff wavelength of a rectangular pipe in relation to the width of the pipe. (See pages III-4 and III-8.)

2. Field Configurations in Hollow Pipes - Traveling Detector

Field configurations in hollow-pipe wave guides can be studied with the help of traveling detector sections.[*] The phase relations of a certain transmission mode within a pipe are given, provided the wavelength inside the pipe is known. This wavelength can be measured with a traveling detector by setting up standing waves in the pipe. The measured value can then be compared with the calculated value, computed from the free space, and the cutoff wavelength of the mode propagated through the pipe.

Matching conditions in a wave guide can also be investigated with the help of a traveling detector. The ratio of the standing waves can be found for different terminations of the guide. (Horns, bends, irises, resistive disks, etc.).[**] Furthermore one can study the influence of obstruction or irregularities in the hollow pipe upon the propagation along the guide. The effect of a change of cross section or dielectric of longitudinal or transverse slots, traps, flanges or irises and of mode filters, such as the polarization grid shown on page III-12, can be investigated.

The traveling-detector section for the circular wave guide was built of telescoping tubing; it is rotatable around its axis.[***] Thus this rotary detector permits, in addition

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[*] See page III-2
[**] See pages III-5 and III-6
[***] See page III-9

to measuring standing waves in a circular pipe, the determination of the field distributions along the circumference of a pipe. The $TE_{1,1}$ mode can therefore be investigated more thoroughly; the polarization direction can be found, and the mode can thus be distinguished from the symmetrical $TM_{0,1}$ mode. The rotary detector is used in this case as a mode detector.

For all these studies it is of great importance to visualize the field distributions of E and H lines for the different modes, as well as of the surface currents in the walls of the hollow pipe. The graph "TE and TM Modes in Circular Wave Guides" on page III-7 illustrates the properties of different transmission modes in a circular hollow pipe. Wave guide and cutoff wavelength of a desired mode can be read directly as a function of the free space wavelength and of the inside diameter of the pipe.

3. Wave Guide Sections as Cavity Resonators.

The wave guide equipment not only allows the study of reflections in wave guides but also that of cavity resonators as outlined below. In a wave guide with closed termination, strong standing waves can be observed. Nodal planes for the electric vector parallel to the guide cross section are located $n \cdot \frac{\lambda_1}{2}$ from the end. A transverse conducting sheet can be placed at the nodal plane, without violating the boundary conditions. Thus a section of the wave guide is cut off and completely enclosed forming a hollow pipe resonator. The field inside the cavity is excited by means of probes, loops or irises. The detector, that is, the resonator output, is coupled to the cavity in an analogous way. A resonant cavity can be tuned to different frequencies by changing its resonant length. Such a variable length resonant chamber for a circular $TE_{1,1}$ mode is shown on page III-6. It comprises a circular hollow pipe (transfer section*), a fine adjustable plunger (terminating plunger section) and a coupling unit (iris*). The transfer section with its bushings spaced $\frac{\lambda_1}{4}$ permits the study of electric or magnetic coupling to cavities. Rods of dielectric materials can be placed in the transfer section at a maxima or minima of the standing waves; parallel or at right angles to the direction of polarization. The influence of these dielectric rods upon the Q of the cavity can thus be observed. An important unit of the variable length cavity is the terminating plunger section, making up the fine adjustable end of the cavity. Much effort was spent in the design of this unit in order to achieve as perfect a reflecting plunger as possible. The reflection properties of a plunger must be constant and are thus not allowed to vary with the position of the plunger along the cavity. This was accomplished by developing the

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*See page III-10

quarter-wave plunger. The open end of the plunger is placed at a level of infinite impedance. The effect of the change from wave guide to plunger can thus be neglected. Insulated plungers, as well as plungers with contact fingers were built. The figure on page III-12 gives a rough idea of the development of the plunger construction. It was possible to improve the Q value of a variable length cavity by a factor of two using a quarter-wave plunger, instead of an old short finger-type plunger. The Q value, a measure of the resonant sharpness of a variable length cavity can be computed by using the following formula:

$$Q_{cav} = \frac{\ell}{\Delta\ell}\left[1 + \left(\frac{\lambda_1}{\lambda_0}\right)^2\right]$$

where $\Delta\ell$ is the change in cavity length required to move from one half-power point of the resonance curve to the other.

The construction of high Q cavity resonators of fixed resonant length, so-called wave standards, is explained in detail in Chapter IV.

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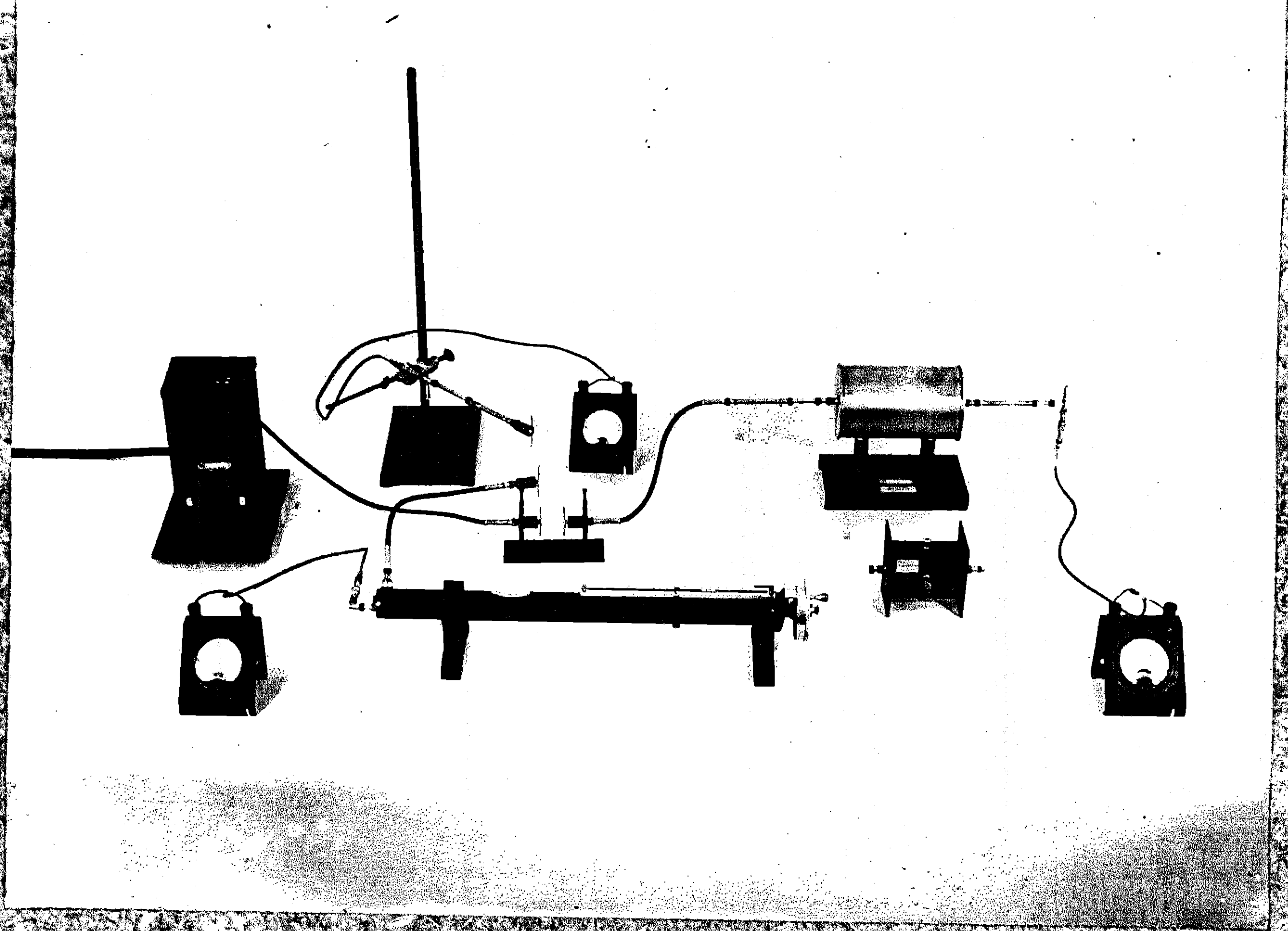
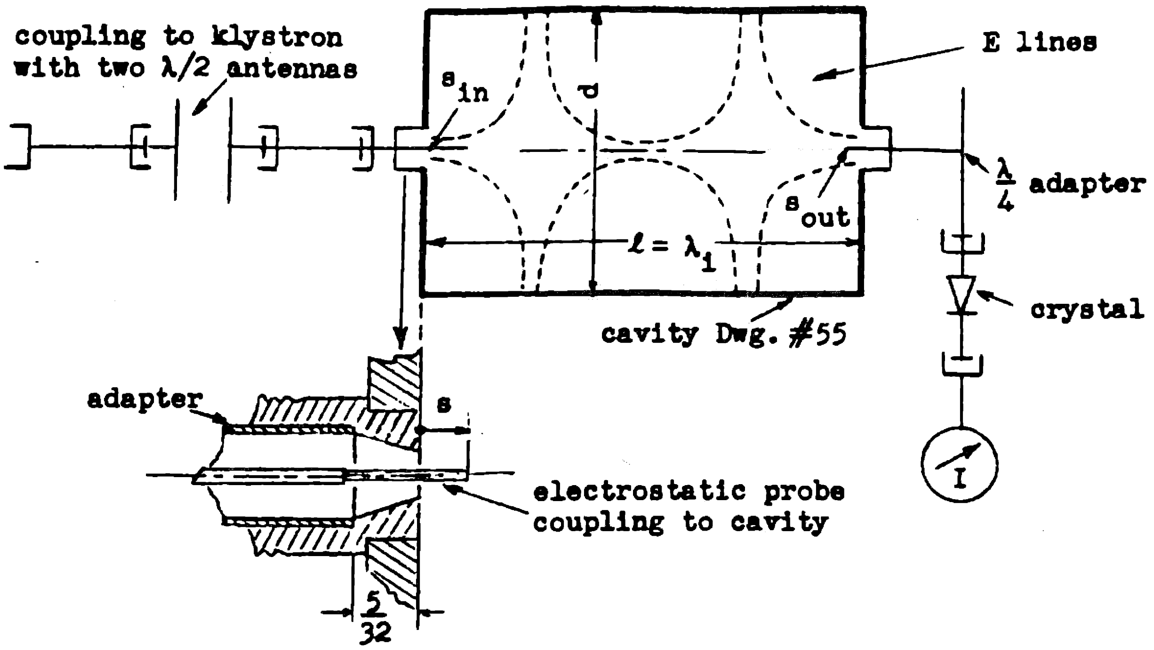
Chapter IV

HIGH-Q CAVITY - WAVE STANDARD



CALIBRATION AND Q MEASUREMENT OF CIRCULAR CAVITY RESONATOR

CAVITY RESONATOR $TM_{0,1,2}$ MODE	Cavity No. 13



NOTE: The Q of the cavity is a function of the coupling.

The coupling to the cavity may be adjusted by varying the length (s) of the electrostatic probes and may be increased by matching the probes with variable-length sections.

CAVITY DATA: **Wall:** Brass, silver-plated, polished.

$$\lambda_{res} \text{ calc} = \lambda_1 \left[1 + \left(\frac{\lambda_1}{\lambda_o}\right)^2 \right]^{-1/2}$$

$\ell = \lambda_1 = 16.580$ cm

$d = 9.599$ cm

$$\lambda_{o\,TM_{0,1}} = \frac{\pi d}{r_{0,1}} ; \quad r_{0,1} = 2.4048$$

$\lambda_{res} = 10.002$ cm (calc)

$Q_{calc} = 26{,}300$

TEST RESULTS:

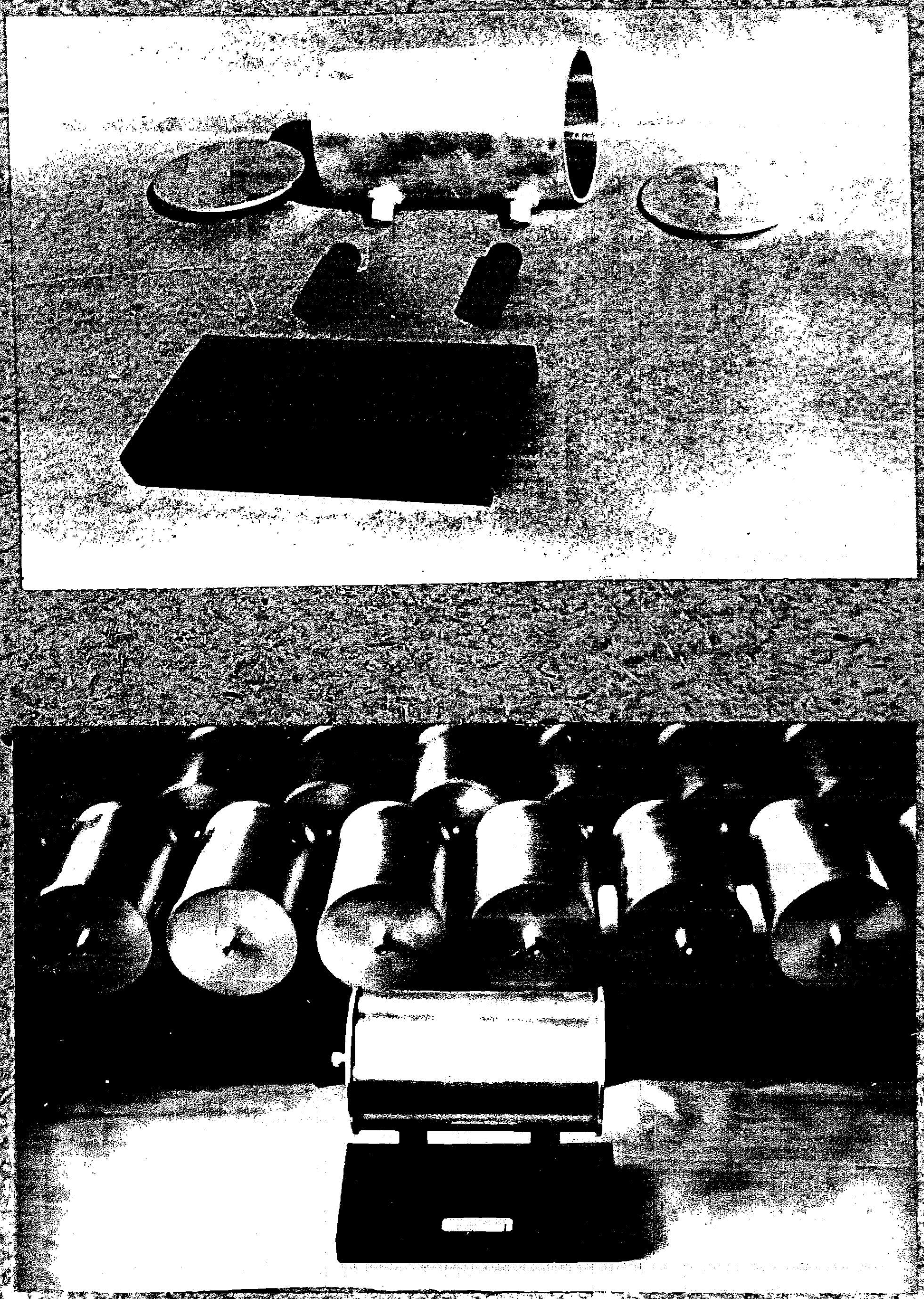
$Q_{cav} = \left(\frac{f}{\Delta f}\right) \cong 25{,}000$
half-power point

$\lambda_{res} = 10.000$ cm (meas)

For:
el. probe: $s_{in} = 0$ inches $s_{out} = -\frac{2}{32}$ inches
matching : ☒ input ☒ output

TEST		MECHANICAL		ELECTRICAL	
Date	Operator	5/11/43	S	5/11/43	W

RCH 4/30/43



CONSTRUCTION OF CIRCULAR CAVITY RESONATOR

Chapter IV

HIGH-Q CAVITY - WAVE STANDARD

1. Microwave Resonators

Circuit elements have different forms in the different frequency bands. Let us consider as an example a parallel resonant circuit. A tank circuit consisting of a coil and a condenser at radio frequencies finds its equivalent resonant circuit in the microwave region in the cavity resonator. Such a cavity, with walls of high conductivity, is a completely shielded resonator of great selectivity. High Q values up to 50,000 may be obtained. The cavities can be built in different shapes. Short sections of hollow pipe wave guides of rectangular and circular cross sections closed with two plane end plates are treated here. These were previously outlined in Chapter III. The resonant wavelength and the Q value of these geometrically simple resonators can be calculated.

The Resonant Wavelength.

The resonant wavelength can be computed, using the following equation:

$$\frac{1}{\lambda_{res}^2} = \frac{1}{\lambda_i^2} + \frac{1}{\lambda_o^2}$$

where:

$$\lambda_1 = \frac{2\ell}{p}\,; \quad p = 1, 2, 3 \cdots\cdots$$

ℓ = length of cavity

and

λ_o = cutoff wavelength of cavity.

The merit factor Q of a cavity.

In lumped circuit theory we have:

$$Q = \frac{\omega L}{R} + \frac{G}{\omega C}\,; \quad Q = \frac{\omega L}{R} \quad \text{(assume } G = 0\text{)}$$

$$Q = \frac{\frac{1}{2}\,\omega L\, I^2}{\frac{1}{2}\,R\, I^2} = \omega\,\frac{\frac{1}{2}\,L\,I^2}{\frac{1}{2}\,R I^2} = \frac{2\pi}{T}\,\frac{\text{energy stored}}{\text{average power dissipated}}$$

assume I = peak value of current in tank circuit.

Q values of cavities are computed using the last definition. The power lost in such a resonator is dissipated in the cavity walls. ($\sigma_2 \neq \infty$ but $\sigma_1 = 0$)

1: dielectric of cavity

2: cavity wall

$$Q \text{ in cavities} = 2\pi\,\frac{\text{peak value of magnetic energy stored}}{\text{energy dissipated per cycle}}$$

$$Q = \frac{2\pi\frac{1}{2}\int_v \mu_1\, H_1^2 \cdot dv}{T\,\frac{1}{2}\Re\int_a E_{2T} \times H_{2T} \cdot da} = 2\pi f\,\frac{\mu_1\int_v H_1^2\, dv}{\text{Real}\ \eta_{o2}\int_a H_2^2\, da}$$

$$\eta_{o2} = \sqrt{\frac{j\omega\mu_2}{\sigma_2}} = \sqrt{\frac{\pi f\mu_2}{\sigma_2}} + j\sqrt{\frac{\pi f\mu_2}{\sigma_2}}$$

for good conductor where $\omega \varepsilon_2 \gg \sigma_2$

$$Q = 2\mu_1 \sqrt{\frac{\pi f \sigma_2}{\mu_2}} \cdot \frac{\int_v H_1^2 \, dv}{\int_a H_2^2 \, da}$$

figure of merit of cavity

For cavities made of nonmagnetic material we have: $\mu_1 = \mu_2$

$$Q = 2 \sqrt{\pi f \mu_2 \sigma_2} \, \lambda \cdot \left[\frac{\int_v H_1^2 \, dv}{\lambda \int_a H_2^2 \, da} \right] \qquad \text{for } \mu_1 = \mu_2$$

v : volume of cavity

a : inside surface of cavity includes pipe as well as end plates.

$$\boxed{Q = 2\frac{\lambda}{\delta} \cdot S} \qquad \text{for } \mu_1 = \mu_2$$

where:

$$\delta = \frac{1}{\sqrt{\pi f \mu_2 \sigma_2}} = \text{skin depth of cavity wall}$$

λ = resonant wavelength

$$S = \frac{\int_v H_1^2 \, dv}{\lambda \cdot \int_a H_2^2 \, da} = \text{shape factor (dimensionless)}$$

For 10 cm band:

$$\delta = 1.16 \cdot 10^{-6} \cdot \sqrt{\frac{\lambda}{\lambda_{10}}} \cdot \sqrt{\frac{\sigma_{Ag}}{\sigma}} \text{ meter}$$

or

$$\delta = 4.57 \cdot 10^{-2} \cdot \sqrt{\frac{\lambda}{\lambda_{10}}} \cdot \sqrt{\frac{\sigma_{Ag}}{\sigma}} \text{ mils}$$

with:

$$(\lambda_{10} = 10 \text{ cm}; \ \sigma_{Ag} = \sigma_{silver} = 6.3 \cdot 10^{7} \frac{\text{mhos}}{\text{m}}).$$

To obtain a high Q-value for these resonators the ratio of volume to surface of the cavity must be as large as possible.

The microwave resonators are good units for use in laboratory demonstrations since the theoretical results can be closely checked with the experimental ones. They also aid in helping the student to visualize field configurations in cavities.

The first cavity resonator built, was made up of rectangular tubing. The mode in this resonator is called a $TE_{0,1,1}$ mode;* the length of the cavity ℓ is thus equal to $\lambda_1/2$. Calculations were made so that the cavity resonates at 10 cm. The dimensions of the parallelepiped are:

width = 5.938 cm
height = 3.399 cm
length = 9.267 cm.

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*See Reference 11

Q value for a cavity with brass walls:

Q calculated = 6,350
Q measured = 5,300.

A circular cavity, made up from a section of circular hollow pipe, with a $TM_{0,1,2}$ field configuration, as shown in IV-2 and IV-4 was selected for construction as part of the microwave kit. With this unit the experimenter can study a TM mode. The Q calculation of this resonator is given below:

The magnetic field intensity in the cavity can be written:

$$H_1 = H_\theta = AJ_1\left(2\pi\frac{\rho}{\lambda_o}\right)\cos\left(\frac{2\pi}{\lambda_i}x\right)$$

$$H_2 = H_\theta \text{ putting } \rho = b$$

where:

$$\frac{2\pi}{\lambda_o} = \beta_o \text{ and } \frac{2\pi}{\lambda_i} = \frac{p\pi}{\ell} \text{ as } \ell = \frac{\lambda_i}{2}p$$

ℓ = resonant length of cavity.

Thus:

$$H_\theta = AJ_1(\beta_o\rho)\cos\left(\frac{p\pi}{\ell}x\right).$$

The shape factor $S = \dfrac{\int_v H_1^2\,dv}{\lambda\int_a H_2^2\,da}$ can now be written:

$$S = \frac{1/\lambda\int_0^b A^2\ J_1^2\ (\beta_o\rho)\ 2\pi\rho d\rho\int_0^\ell \cos^2\ (p^\pi/_\ell\ x)\ dx}{\int_0^b 2\ A^2\ J_1^2\ (\beta_o\rho)\ 2\pi\rho d\rho + A^2\ J_1^2\ (\beta_o b)2\pi b\int_0^\ell \cos^2\ (\frac{p\pi}{\ell}\ x)dx} =$$

$$= \frac{1}{\lambda} \frac{\int_0^b J_1^2\ (\beta_o\rho)\rho d\rho}{\frac{8}{p\lambda_i} \int_0^b J_1^2\ (\beta_o\rho)\rho d\rho + b\ J_1^2\ (\beta_o b)}$$

$$\int_0^b J_1^2\ (\beta_o\rho)\rho d\rho = \left\{ \frac{\rho^2}{2} \left[J_1^2\ (\beta_o\rho) - J_o(\beta_o\rho) J_2(\beta_o\rho) \right] \right\}_o^b = {}^{*}$$

$$= \frac{b^2}{2} \cdot J_1^2\ (\beta_o b)$$

$J_o = 0$ ($E_\theta = 0$ at the boundary $\rho = b$)

introduce in S result in:

$$S = \frac{1}{\lambda} \frac{\frac{b^2}{2}\ J_1^2\ (\beta_o b)}{\frac{8}{p\lambda_i} \frac{b^2}{2} J_1^2\ (\beta_o b) + b\ J_1^2\ (\beta_o b)}$$

$$S = \frac{b}{2\lambda} \frac{1}{(1 + \frac{4b}{p\lambda_i})}$$ <u>Shape factor</u> of circular $TM_{0,1,p}$ cavity.

<u>Numerical values:</u>

$\lambda = 10$ cm; $b = 4.8$ cm; $\lambda_i = 16.6$ cm

$$S = \frac{0.24}{(1 + \frac{1.15}{p})}$$

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[*] See Reference 6 p 146

$$Q = 172 \cdot 10^3 \sqrt{\frac{\sigma}{\sigma_{Ag}}} \cdot s$$

$$Q = \frac{41,300}{(1 + \frac{1.15}{p})}$$

Q value of a circular $TM_{0,1,p}$ cavity with silver walls and a resonant length $\ell = p \frac{\lambda_i}{2}$.

This can also be written:

$$\frac{1}{Q} = \frac{1}{Q\ \text{pipe}} + \frac{1}{Q\ \text{end plates}} =$$

$$= \frac{1}{41,300} + \frac{1/p}{35,900} .$$

The following table demonstrates the effect of the end plates on the figure of merit Q for different cavity lengths:

p	∞	10	6	4	<u>2</u>	1
Q	41,300	37,100	34,700	32,100	<u>26,300</u>	19,200

The Q value of a circular cavity of given pipe diameter and resonating on a fixed frequency, can be raised by increasing the cavity length in steps of $\lambda_i/2$, thus reducing the effect of the end plates. The cavity constructed for the microwave kit has a length $\ell = \lambda_i$ (p = 2). The brass walls of the resonator were silver-plated and then polished. The Q value of a silver-plated cavity is about twice as great as one with brass walls.

The thickness of the silver deposit was kept above 1/4 mil; since the skin depth at 10 cm for silver is about 5/100 of a mil. For comparison of calculated and measured cavity data see test sheet IV-3.

2. Q Measurements of Cavities*

The figure of merit Q of cavity resonators of fixed length is measured by using the frequency change method. That is, $Q = \frac{f}{\Delta f} = \frac{\lambda}{\Delta \lambda}$, where λ is the resonant wavelength and $\Delta\lambda$ the wavelength change between the two half-power points. It is essential that the oscillator output is constant over the frequency band used. If the Q value to be measured is lower than 10,000, then the measurements in the 10 cm band can be successfully carried through by changing the frequency with the mechanical klystron tuner. The micrometer head of the tuner can be calibrated in frequency change by means of a coaxial wavemeter. The calibration value for a single Sperry tuner used with the 10 cm klystron MIT-C3124X is: 1 turn of micrometer head $\doteq$ 0.008 cm wavelength change. The output of the klystron is constant over the tuner range used.

Difficulties arise, in using the mechanical tuning method to vary the frequency, when the Q values are above 10,000. The necessary frequency changes are so small that tuner adjustments are not accurate enough. Q values between

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*See Reference 20

10,000 and 30,000 were satisfactorily measured (accuracy about ± 10%) in varying the frequency by means of changing the beam voltage of the klystron. This can best be accomplished by varying the grid bias of the voltage regulating tube in the power supply, by means of an adjustable resistance (decade resistance box). The resistance value thus determines the beam voltage and hence the frequency. Hence wavelength change is calibrated in resistance change:

$$\Delta\lambda = K\Delta R \ .$$

The mean frequency is adjusted with the help of the mechanical tuner and the mean beam voltage is then set to obtain maximum klystron output. At this operating point the output is constant over the narrow frequency band required. It was found that the relation of $\Delta\lambda$ with respect to ΔR is furthermore linear in this region.

This method, however, is not too good for measurements of low Q values, as one must change the beam voltage by a considerable amount to get the necessary frequency change. The output of the klystron does not stay constant over the whole range, thus requiring additional output corrections. The Q calculations of the cavity on page IV-5 only take into account the losses of the cavity walls. These calculated values therefore can only be brought into agreement with the measured ones if in the actual case all other energy losses can be neglected, compared with the losses of the walls. The tests undertaken with the circular wave guide cavities proved the above statement to be true. The coupling of the detector of the cavity was decreased, and thus the energy absorbed by the crystal unit was reduced, with the effect that the Q value was increased very close to the calculated value. At this point the energy absorbed by the crystal detector was negligible compared to the energy dissipated in the cavity walls. A further decrease in crystal coupling had no effect on the Q value; it remained at its maximum. The fine adjustable coupling to the cavity was accomplished by using a small electrostatic probe of variable length connected to the coaxial feeding line by means of a tapered section.

3. Construction of a 10 cm Wave Standard

The circular $TM_{0,1,2}$ cavities were constructed to oscillate very close to 10 cm. Besides measuring the Q value of all the cavities, the resonant wavelength was calibrated. Thus the unit can be used as a 10 cm wave standard.

The inside diameter of the circular tubing was measured carefully with a micrometer. From this data the necessary cavity length was computed, so that the resonant wavelength was close to 10.015 cm. An actual measurement of the resonant wavelength was then made and from this a second length was computed so that the cavity resonated at approximately 10.000 cm. The end plates were then soft-soldered to the pipe and a final measurement of the resonant wavelength and of the Q value was taken. The solder joint is of importance, as the surface currents are at a maximum at the junction and at right angles to it. Measurements showed that the Q value increased by a factor of about five when the end plates were soldered on instead of pressed on.

The mechanical dimensions of the cavity were computed using the following general relations.

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_i^2} + \frac{1}{\lambda_o^2} \qquad \ell = p\,\frac{\lambda_i}{2}$$

$$\lambda = \left(\frac{\lambda}{\lambda_i}\right)^3 \Delta\lambda_i + \left(\frac{\lambda}{\lambda_o}\right)^3 \Delta\lambda_o; \qquad d = \frac{r_{\ell,m}}{\pi}\,\lambda_o.$$

The equation $\Delta\ell = p\,\frac{\Delta\lambda_i}{2}$, for instance, was used to determine the necessary reduction of the cavity length (mechanical cutting operation) in order to decrease the resonant wavelength by $\Delta\lambda$, for a cavity of constant diameter ($\Delta\lambda_o = 0$).

A sample test sheet indicating the operation data of an average wave standard is given on page IV-3.

* * * * *

Chapter V

DESIGN, CONSTRUCTION AND MEASUREMENTS[*]

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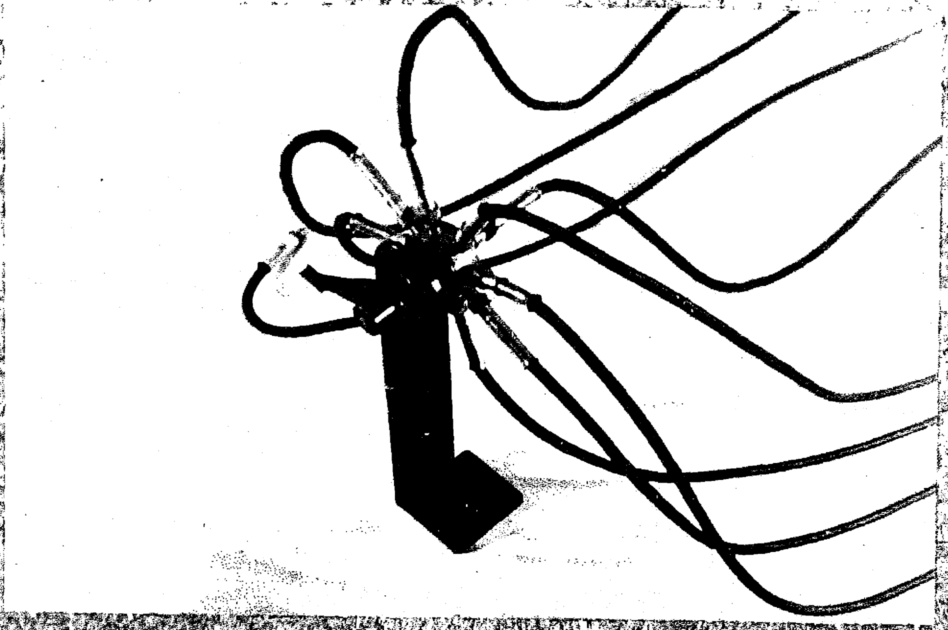
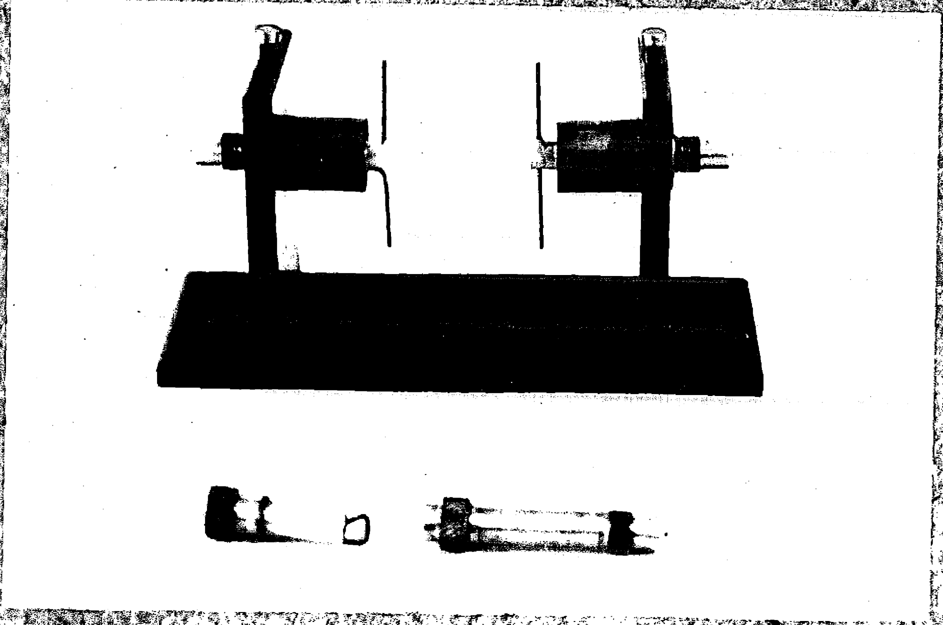
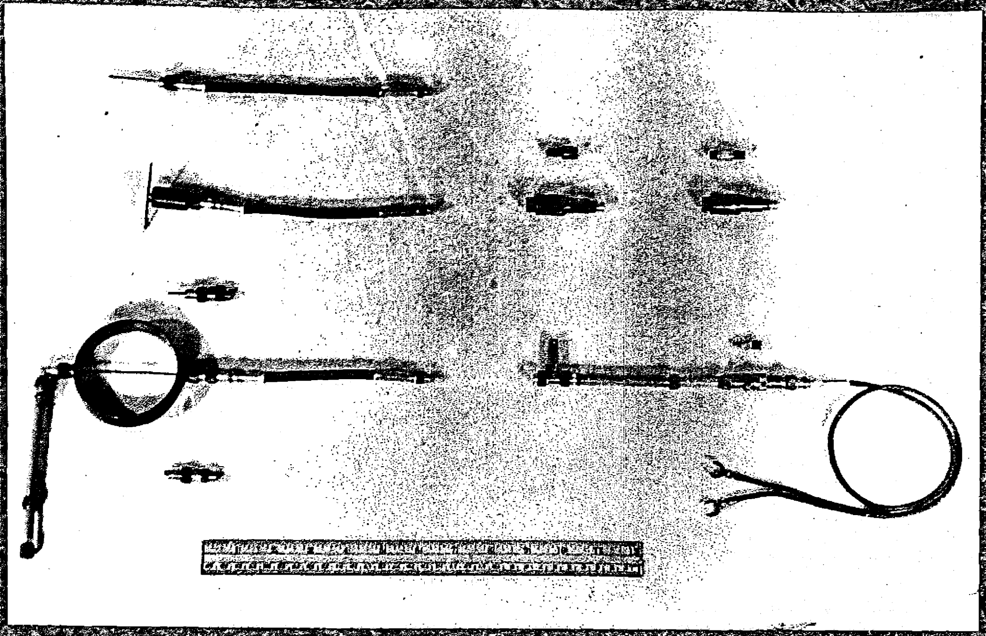
[*] See References 2, 19



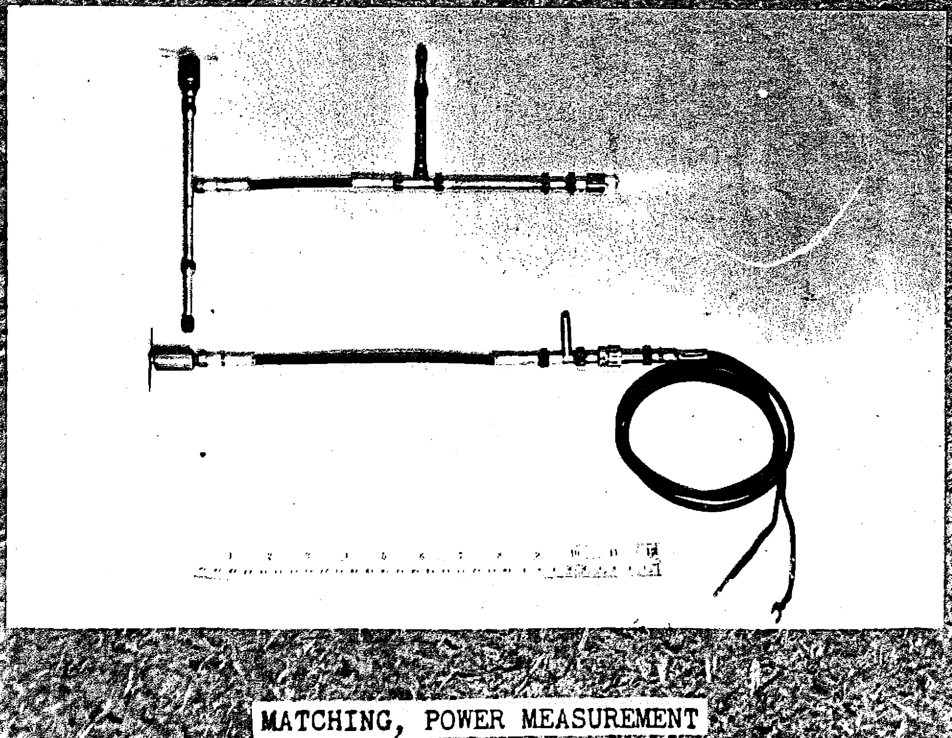
COAXIAL SWITCH



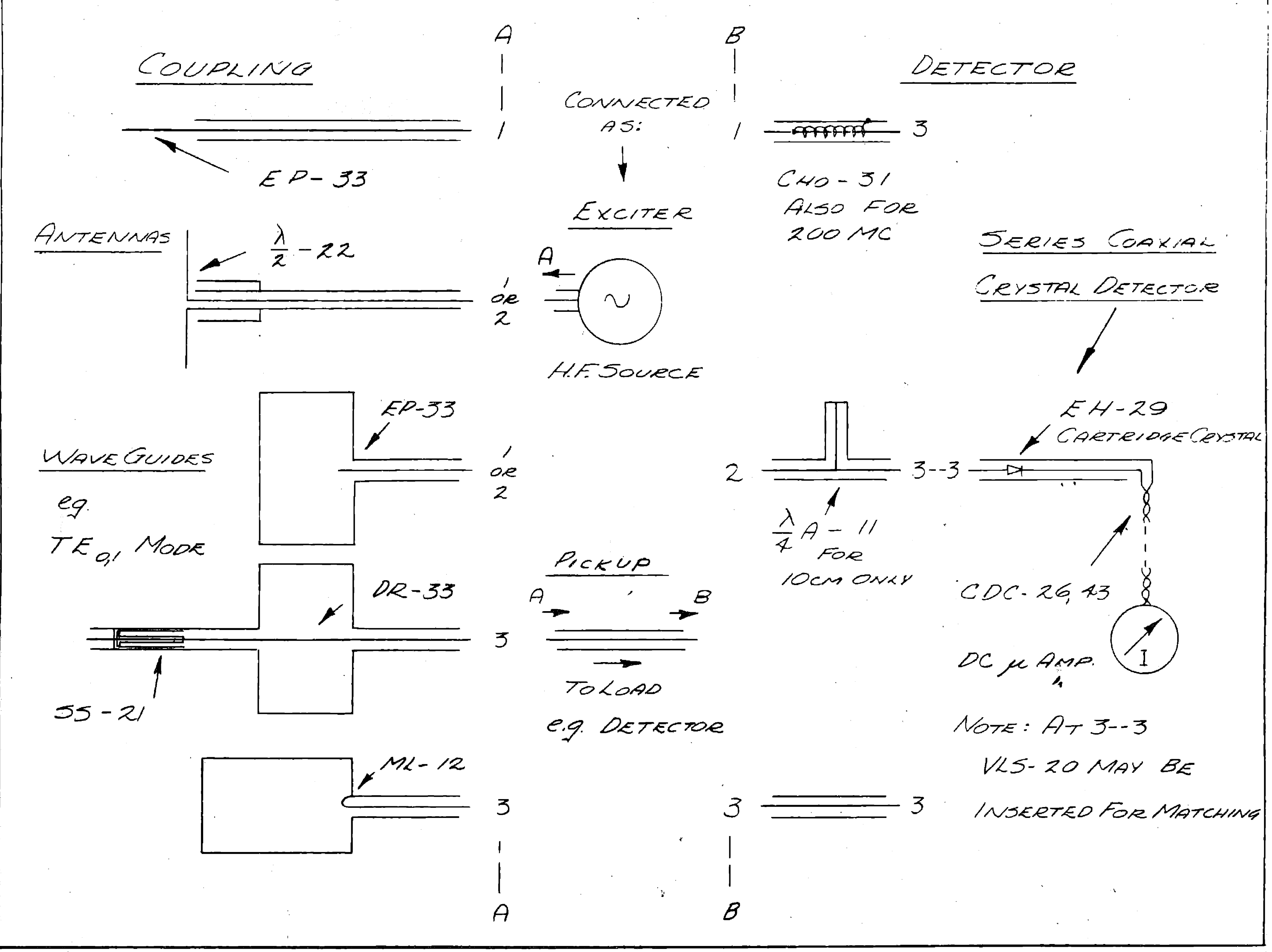
COUPLING UNITS



COUPLING, CRYSTAL DETECTOR



MATCHING, POWER MEASUREMENT



COUPLING, CRYSTAL DETECTOR

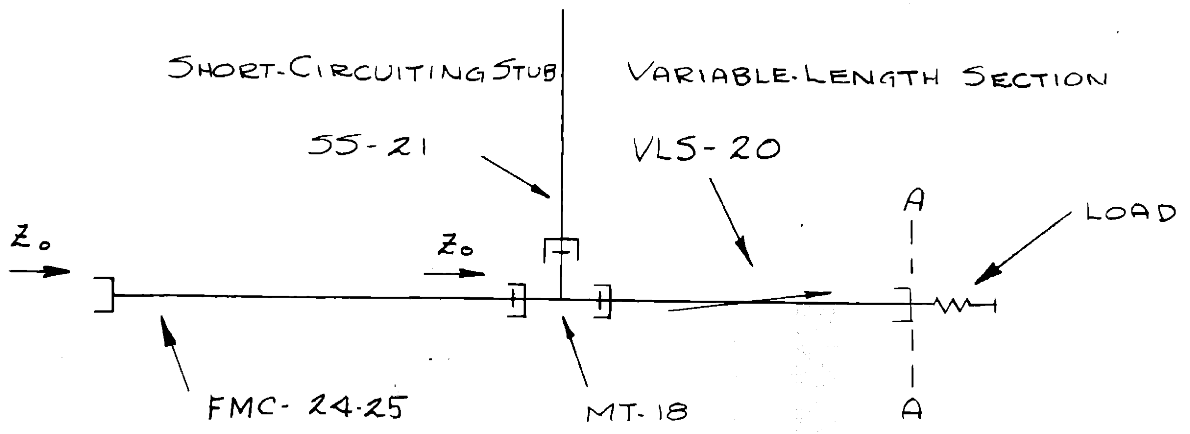
ASSEMBLY DWG.
2-7-43
5-3-43

CH. BY:

CPL, CR DET

A-5

MATCHING LOAD TO COAXIAL LINE

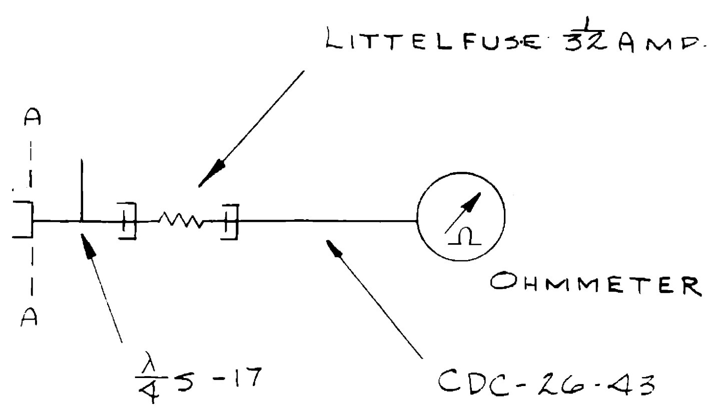


POWER MEASUREMENTS

$$R_{\substack{\text{DC OF FUSE}\\ \text{OHM}}} = f\left(P_{\substack{\text{10 CM}\\ \text{MILLIWATTS}}}\right)$$

$$\underbrace{P_{\substack{\text{10CM}\\ \text{MILLIWATTS}}} \cong K \cdot \Delta R_{\substack{\text{FUSE}\\ \text{OHMS}}}}$$ FOR $10 < P < 80$ MW.

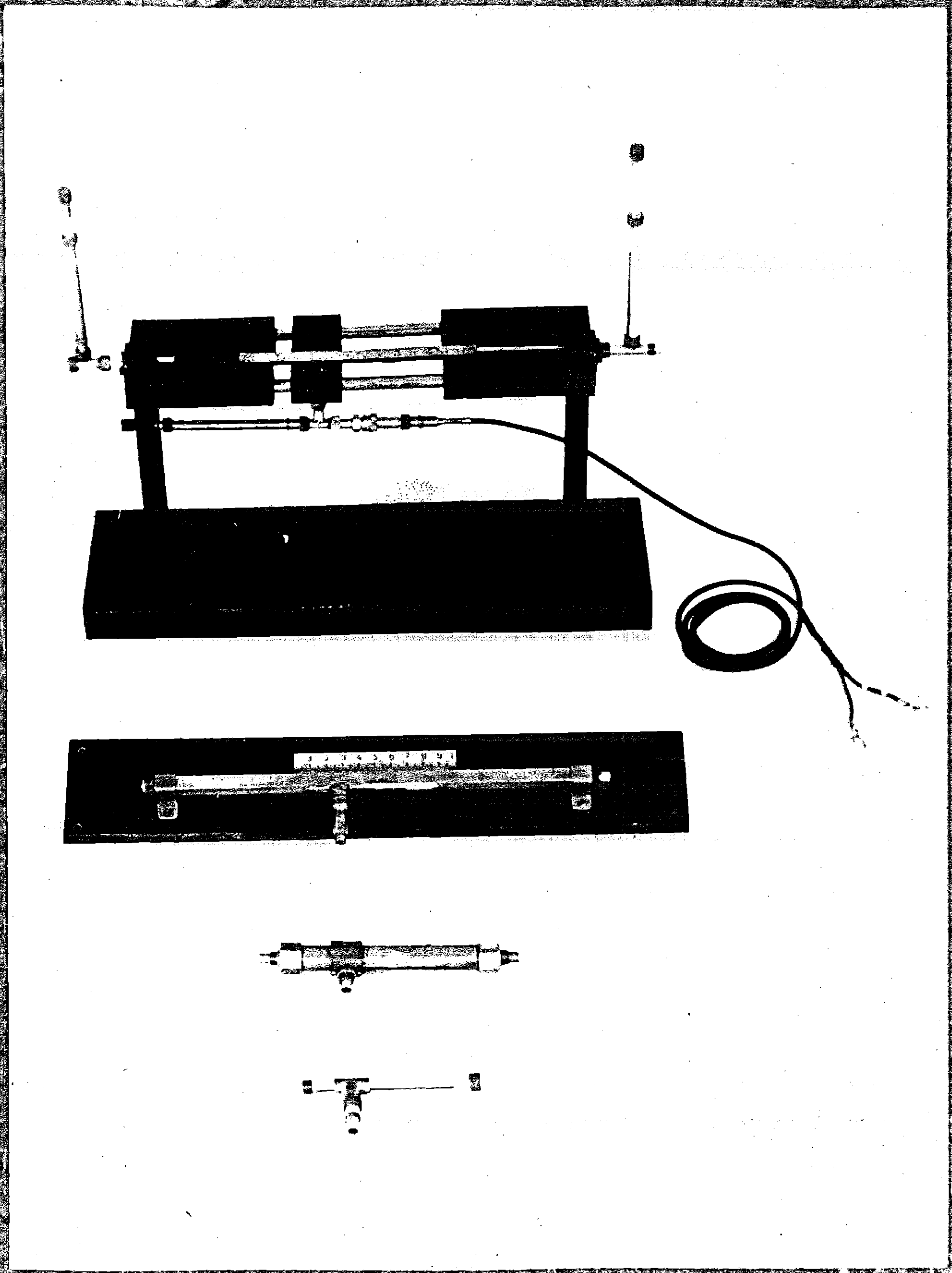
$$K = 2 \text{ TO } 3 \ \frac{\text{MILLIWATTS}}{\text{OHM}}$$



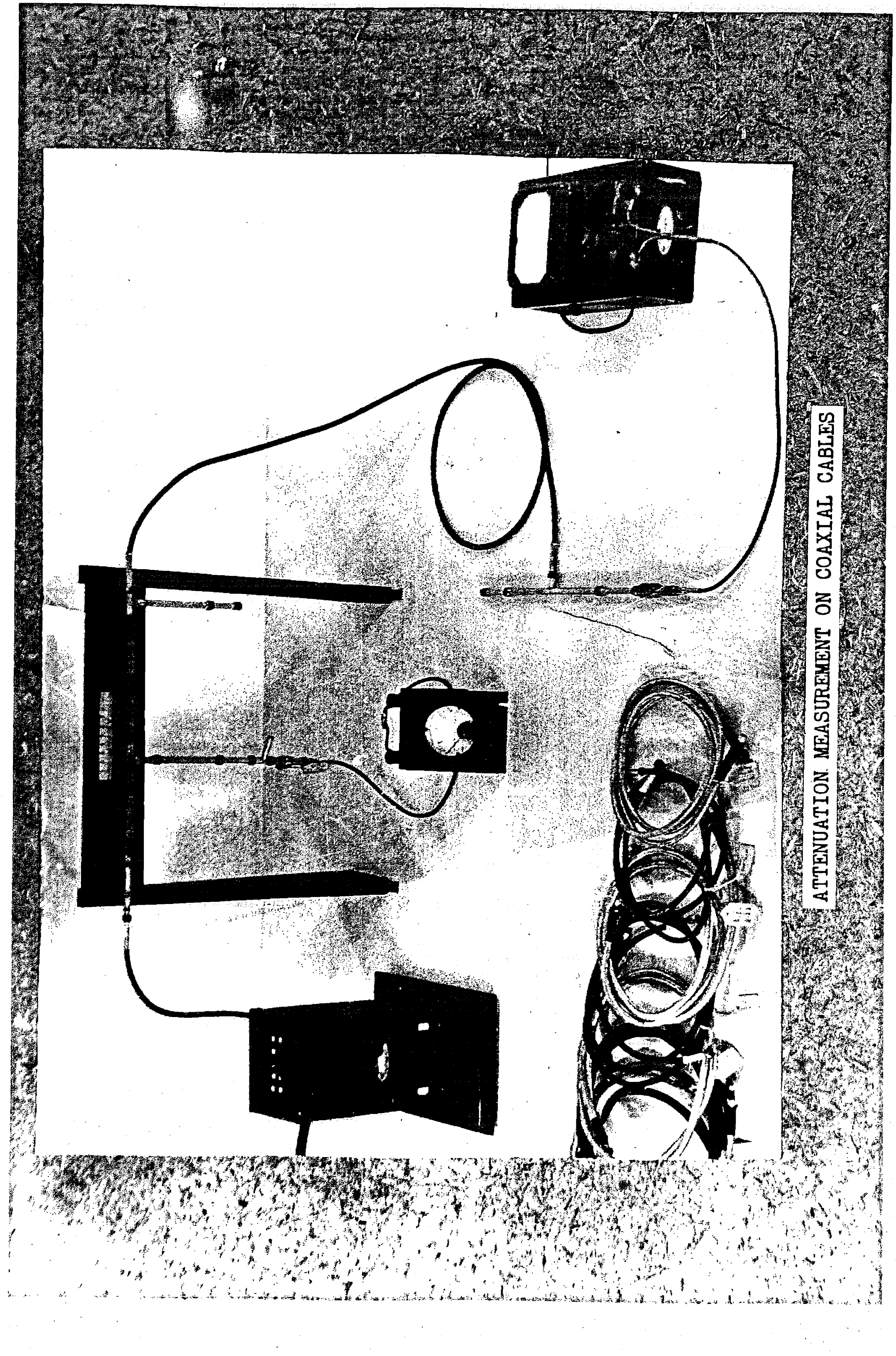
MATCHING, POWER MEASUREMENT

ASSEMBLY DWG.
10-13-42
4-29-43
CH. BY.

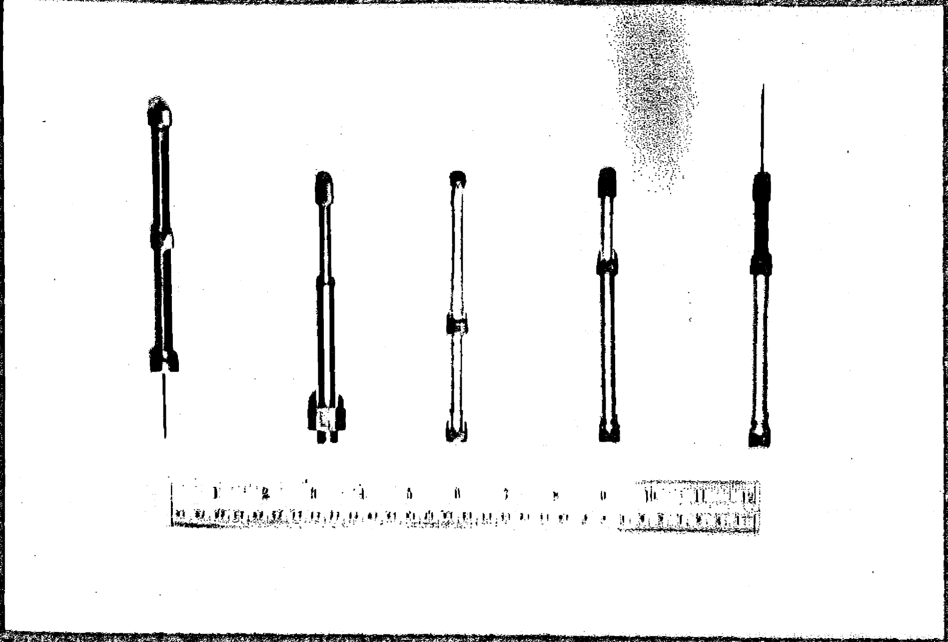
MA, P MEAS
A-6



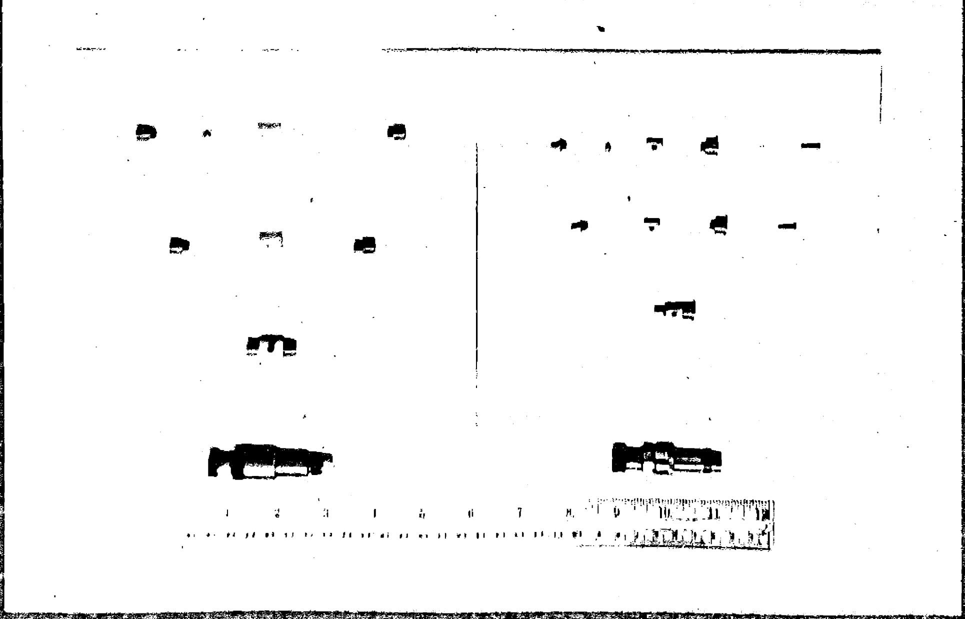
DEVELOPMENT AND CONSTRUCTION OF A TRAVELING DETECTOR



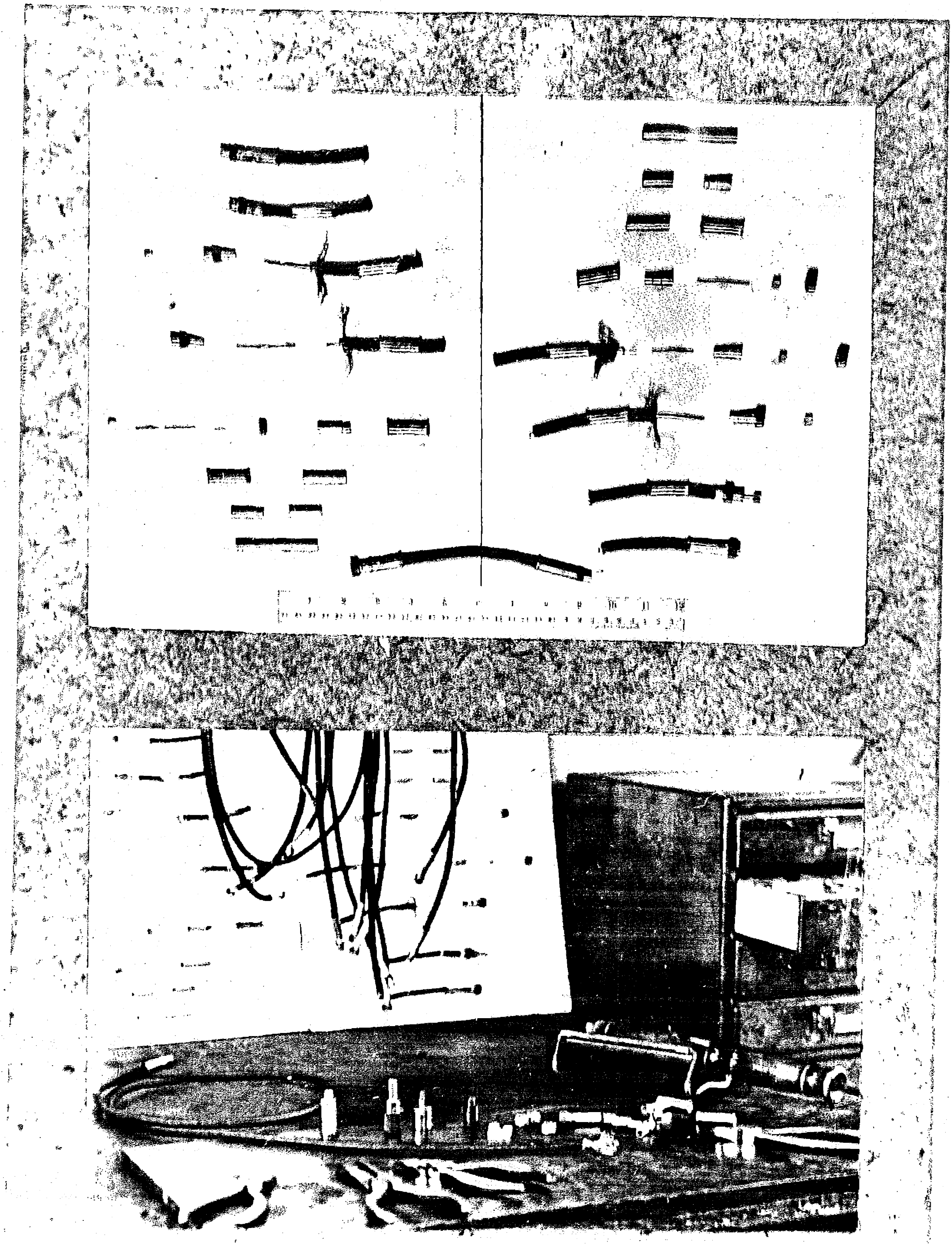
ATTENUATION MEASUREMENT ON COAXIAL CABLES



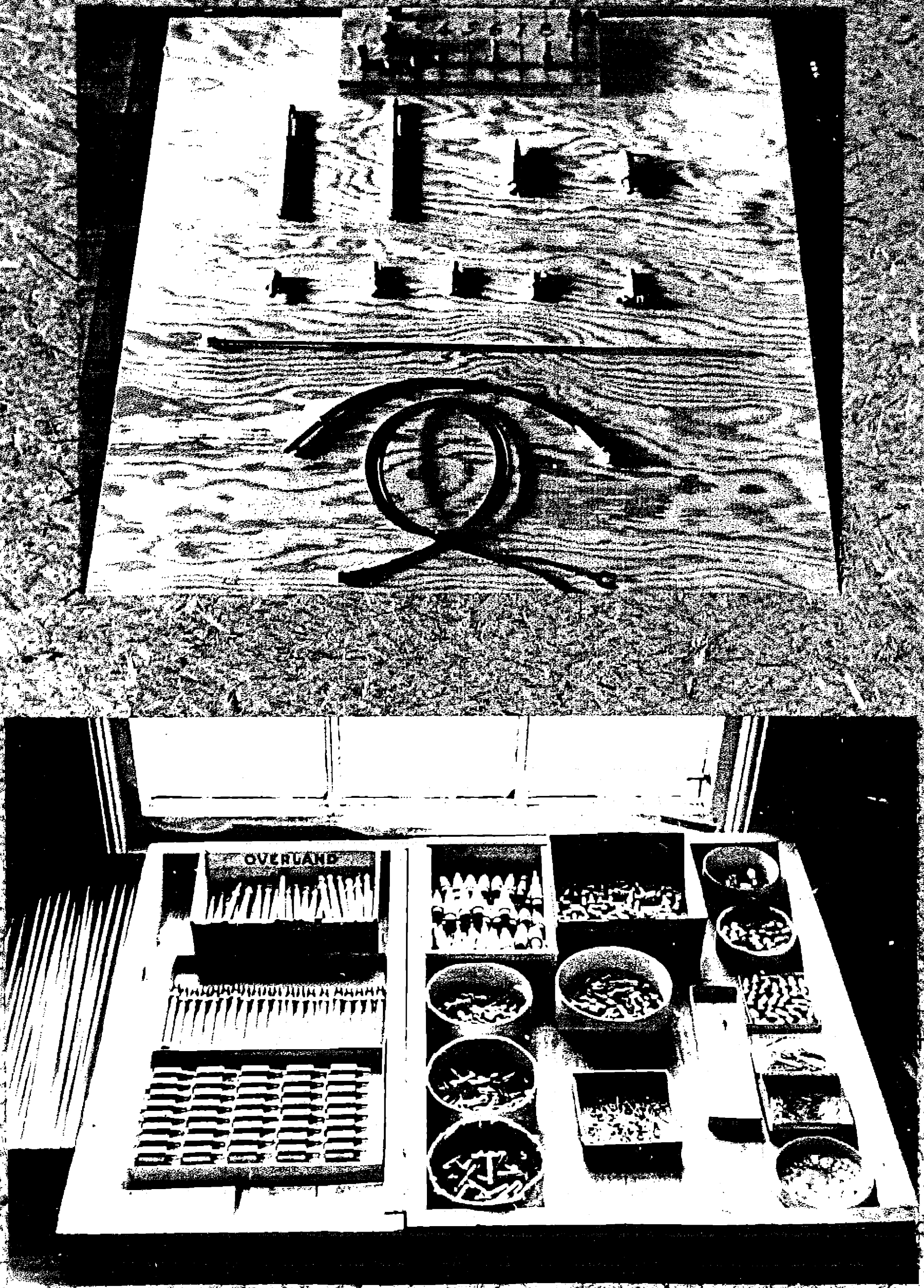
DEVELOPMENT AND CONSTRUCTION OF COAXIAL PLUNGERS



CONSTRUCTION OF CRYSTAL DETECTORS



CONSTRUCTION OF COAXIAL CABLES



CONSTRUCTION OF COAXIAL PARTS MADE OF SILVER
TEST GAUGES, STANDARDS

Chapter V

DESIGN, CONSTRUCTION AND MEASUREMENTS

1. Coaxial Elements and Cables

The microwave kit was designed in such a way that it is possible to set up several different experiments. Many connectors, adapters and cables are necessary to connect the various units. The study of the action of a matching unit, for instance, is most useful when this unit is designed so that it can be inserted at different points in the system. Furthermore, the various units must be interchangeable. Delicate small parts must be replaceable when defective, without holding up the entire setup. Equipment to be used for student experiments and laboratory demonstration must be constructed somewhat differently from a more permanent setup. For this reason, detailed attention was given to the design of these small parts. Standard endings and fittings were designed and rigorous specifications set up. The use of these parts is illustrated in the various assembly drawings.

In the following some detailed information concerning the construction of the different connectors, adapters, etc. (see page V-10) may be found; conductors of the following sizes are convenient for the construction of coaxial fittings:

		OD	ID		Material
Outer Conductor	I	5/16	9/32	tubing	coin silver
	II	9/32	1/4	tubing	coin silver
Inner Conductor	I	0.060	0.050	tubing	coin silver
	II	0.049	No.18 stub gauge wire		brass

Short-circuiting stubs and variable-length sections can easily be made up using these two sizes of telescoping tubing. Coaxial cable fittings made up of these tubings are shown on page V-9. Fine thread 3/8 - 32 is used for ferrule and nut. The use of coin-silver tubing is recommended, first, because silver is a good conductor and, secondly, because such tubing can easily be spun or pressed to any desired form, thus simplifying the manufacturing process of the parts. The assembly of beaded coaxial cable with male and female fittings is a delicate job. Much effort was spent until a satisfactory solution was found. It is essential that the beads are tightly strung onto the inner conductor, thus preventing the short circuiting of the outer braid to the inner conductor, when the cable is bent.

Similar difficulties were encountered in the construction of other coaxial elements. It is important to keep the polystyrene beads on the inner conductor from moving. Solvents such as Toluol are not always sufficient to make the polystyrene stick to the silver tubing. Crimps on the inner conductor over which the bead was forced and recesses in the outer conductor into which the polystyrene was pressed, were successfully applied to keep the beads in place. The design and assembly of the different elements can best be understood by studying the construction drawings of Chapter VIII.

The general theory of the quarter-wave plunger outlined in section 3 of Chapter III on the design of wave guide plungers, was also applied to the construction of coaxial parts. Adjustable, coaxial short-circuiting stubs were built so that the contact points (inner and outer conductor), regardless of position, were a quarter wavelength away from the short-circuiting end. In this way they were on an infinite impedance level. Negligible influence of contact resistance was thus achieved, allowing electrically smooth tuning of the plunger.

The $\lambda/4$ idea was also used in the design of coaxial filters.

Another interesting design problem is that of a coaxial line with cylindrical supporting beads. The reflection properties of such a line can clearly be investigated with the help of transmission-line charts. (See V-12.) The coaxial antenna rods of the microwave kit were designed to give no reflections at 10 cm. Bead length and spacing of beads were adjusted accordingly.

2. Coupling Units

These units were developed to couple one part of a circuit to another. The coupling units are adjustable so that the mutual impedance between the two circuit parts can be varied. For illustration take the coupling of one cavity resonator to another. The theory of coupled circuits can also be demonstrated at these frequencies. Multiple resonance occurs for close coupling.

One type of coupling units used with this equipment is shown on page V-2; it is made up of two $\lambda/2$ antennas facing each other. The unit can be adjusted to the desired degree of coupling by varying the distance between the two antennas, and by rotating the antennas with respect to each other thus changing their polarization directions.

The figure on page IV-2 shows the coupling units which are used in the setup for measuring values of a cavity resonator. Cavity, monitor unit, and wave meter must be loosely coupled to the klystron oscillator. These units are very easy to adjust. They are, however, influenced somewhat by reflections from nearby objects. A completely shielded, adjustable, coupling unit was developed which uses a small hollow pipe, operating in the attenuation range. The waves in this tube are excited and picked up by means of loops connected to a coaxial input and output line respectively. The attenuation is determined by the distance between the two loops and by the orientation of the loops with respect to each other. Such a unit is shown on page V-2.

3. Excitation and Detection

The coupling and detector arrangements on pages V-3 and V-4 illustrate in detail the various means of excitation and detection encountered in previous chapters. Antennas using straight electrostatic probes of $\lambda/2$ radiators with quarter-wave balancing sleeve as well as the coupling to wave guides are shown. In practice one distinguishes between coupling to the electric field with probes or driver rods and coupling to the magnetic field by means of loops. The diagrams on page V-4 indicate the connection of loops and probes to source or crystal detector.

In crystal-detector units one distinguishes between a shunt crystal and a series crystal arrangement. The detectors of the microwave kit use a coaxial series crystal as rectifying element. The indicator instrument is a sensitive d-c microammeter. To provide a return path for the high-frequency currents, a coaxial condenser is placed in the detector unit in parallel with the meter leads. Thus stray pickup in the leads does not influence the rectifying action of the crystal.

In case the high-frequency energy is picked up by means of electrostatic probes, a d-c return section must be inserted in front of the crystal to close the d-c path of the series detector. Loop pickups provide their own d-c return path. A very convenient d-c return section for 10-cm work is a quarter-wave stub which has, due to its high input impedance, a negligible influence on the high-frequency line. Such a $\lambda/4$ section acts exactly like a high-frequency choke; however, it is limited for use on a definite frequency only. For work around 200 mc, a coaxial choke was designed, since a $\lambda/4$ stub is inconveniently long at these frequencies.

It is of interest here, to explain the assembly of one of the coaxial 10 cm $\lambda/4$ stubs. One of the problems encountered was where the short circuiting stub was to be placed. This was solved with the help of a traveling detector. The stub of the test section was moved to such a position that the input impedance of this test section connected to a certain load was the same as the input impedance when the test section was replaced by an ideal section of equal length, but without a d-c return path. In other words the d-c return path was adjusted in such a way that its influence on the 10 cm line could no longer be detected.

A good measuring device, such as a detector, must have a negligible influence on the circuit to be measured. Thus a detector must consume as little power as possible. For detectors in lines and pipes an additional error arises, because of the physical size of the probes. These probes which pick up microwave energy disturb the field configurations to a certain extent and must therefore be made small. A resulting decrease in crystal power can be recompensated by improving the match of the crystal to the pickup; for instance by inserting variable-length sections. However, the detector then becomes much more frequency sensitive; and calibration curves are thus valuable only for the calibration frequency. To summarize: a good crystal detector causing the least disturbances is operated on low-power level and matched, to allow the smallest pickup probe possible. The construction of crystal detectors is explained in the next section.

4. Construction of Crystal Detectors*

Crystal detectors which were used in the first radio receivers are now being used in the field of microwaves. They are an essential part of the microwave laboratory equipment. For laboratory use, they must be sensitive, stable and mechanically rigid. The crystals used in the Communications Laboratories were built to a great extent in our own shop, as it was difficult to obtain commercial crystals. The most difficult problem was to get a good crystal and yet not a too delicate one. Much effort was spent in trying out different crystal-cat whiskers combinations, applying various assembly and testing methods. The best result was achieved by using silicon crystals with cat whiskers made of fine steel wire. Such a unit was not too difficult to adjust. The adjustment of this combination was investigated by observing forward and backward resistance with a low-current ohmmeter or by observing its behavior on the screen of a cathode-ray oscillograph. The cat whiskers

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*See page V-8 and Reference 21

were fixed in position by imbedding them in beeswax. The adjusted crystals were then given a final test at 10 cm to check their microwave rectification action.

The relation between the d-c current in the indicating microammeter, fed by the crystal detector, and the 10 cm input voltage is given by the equation:

$$I_{dc} = K \cdot E_{10cm}^{n} \quad .$$

As a first approximation one can say the crystal acts like a square-law detector (n=2). For accurate calibration it is useful to plot I_{dc} versus E_{10cm} on log-log paper. The value of n can then be determined directly from the slope of this plot. Measurements for different crystals showed that n varied between 1.7 and 2. For most crystals n is near 1.8 and is rather constant for a 10 cm input voltage change by a factor of 10.

Measurements were made on the efficiency of the rectification action. In the test setup the microwave power, absorbed by the crystal, was measured by means of a calibrated traveling-detector section and the available d-c power was computed from measured direct current and known d-c load. The efficiency of power transfer is a function of the microwave power level, on which the detector operates, as well as of the proper matching of the d-c load to the crystal. The results of a power transfer test for an average crystal are given below:

10 cm power input to crystal = 100 microwatts

maximum rectified d-c voltage for approximately infinite load resistance = 0.55 volt

d-c load resistance for maximum d-c power = 50 ohms

maximum d-c power adsorbed by load resistance of 50 ohms = 1.4 microwatts

efficiency of power transfer = 1.4 %

The low efficiency shows that much work must still be done in the development of good microwave crystal detectors.

Unfortunately time did not permit the research work to be carried further. Interesting questions on the behavior of crystals are still open. For instance, does the rectification action change after subjecting the crystal to a direct current in forward or backward direction? Can thus the backward resistance of a crystal detector be increased in the same way as that of a selenium rectifier?

Another interesting investigation would be to determine how the rectification action of a crystal changes as a function of temperature.

5. Matching with Coaxial Stub and Variable Length Section[*]

An arbitrary load can be matched to a transmission

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[*] See Reference 12

line by means of a short-circuiting stub and a variable-length section, as shown on pages V-3 and V-5. The stub is placed at the point, where the real part of the terminating impedance is equal to the characteristic impedance of the line. In this way the length of the variable-length section is determined. The short-circuiting stub itself is adjusted so that its reactive component cancels the reactive component of the terminating impedance. The input impedance of the whole unit is then real and equal to the characteristic impedance of the line. The load thus is matched to the line.

The matching units at 200 mc are usually made up of parallel lines, where at 10 cm, it is very convenient to use coaxial parts. Page V-3 shows a matching unit made up of standard parts, a variable-length section and a short-circuiting stub, as well as one complete matching unit. The two sliding sections of this single unit are aligned on one axis to simplify the mechanical construction.

6. Power Measurements*

The original work on this subject was done by Mr. S. P. Ghosh in the Communications Laboratory. A wattmeter which is capable of measuring power at 10 cm can now be made up with standard parts from the microwave kit. The setup is shown on

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*See Reference 18, 17

pages V-3 and V-5. The essential part of this wattmeter is the Littelfuse fuse which acts as a 10 cm load. The d-c resistance of the fuse-wire changes with the 10 cm power absorbed by the fuse. The equation

$$P_{10cm} \text{ in mw} \cong K \cdot \Delta R_{fuse} \text{ in ohms}$$

permits the computation of the approximate 10 cm power. The indicating ohmmeter can be calibrated in milliwatts 10 cm power. The factor K is obtained by calibrating the unit. The d-c resistance change of the fuse wire is first determined as a function of absorbed d-c power.

$$R_{fuse} \text{ in ohms} = f\ (P_{dc} \text{ in mw}).$$

To effect the same d-c resistance change, more RF power than d-c power is needed since the beads and the sleeve of the fuse have some additional RF losses, which must be accounted for. The relation between the necessary RF and d-c power in order to achieve the same resistance change was measured by Mr. Ghosh. He compared the results obtained from a Littelfuse detector with those obtained from a more lossless Thermistor detector. For a Littelfuse, 1/32 Amp, P_{10cm} was approximately equal to 1.4 P_{dc}. This relation, as well as the d-c calibration, differ for each fuse. For accurate measurements, careful individual calibrations must be made, taking into account temperature and humidity.

The ohmmeter used to measure the d-c resistance should be of the low-current type, such as a Weston Model 763, so that the d-c power, absorbed by the fuse due to the measuring current, can be neglected, when its value is small, compared with that of the RF power to be measured.

7. Coaxial Traveling Detector

This is a detector arrangement to measure standing waves along coaxial lines. When properly calibrated the unit can be used as an impedance-measuring device or as a wattmeter.

The new coaxial traveling detectors developed in the Communications Laboratory are of the telescoping-tube-type as shown on page V-6. The slot-type traveling-detector section was found to be a very delicate unit, mechanically. For good operation, it requires very accurate guidance of the probe along the slot and a satisfactory shielding of the slot. Much mechanical skill and time is required to construct such a unit. The detector of the telescoping-tube-type, on the other hand, is simple and overcomes most of the difficulties of a slot arrangement. The inner conductor is supported by polystyrene beads $\lambda/2$ long to avoid unwanted reflections. The characteristic impedance of the traveling detector can be calculated from its dimensions:

Inside diameter outer conductor $= 2b = 9/32$ inch
Outside diameter inner conductor $= 2a = 0.065$ inch
$Z_o = 138 \log_{10} (b/a) = 88$ ohms.

The coupling of the detector to the coaxial line was made as small as possible by means of a tapered coupling line penetrating the wall of the coaxial line in a small 1/8 inch hole. The inner conductor of the coupling line terminates in an adjustable, small, electrostatic probe. This final design reduced to a negligible amount the influence of the detector position upon the transmission through the traveling-detector section. The detector must be calibrated at the operating frequency as the crystal is matched to the pickup. A relative voltage calibration is obtained by moving the probe along a known sinusoidal field distribution. This is achieved by setting up pure standing waves by terminating the traveling detector with a short-circuiting stub. The unit can then be calibrated in actual volts, between inner and outer conductor, by connecting a power-measuring device, such as is described in section 6 of this chapter, to the output end of the traveling detector. The following formula indicates the procedure:

The power flowing through the detector is given by:

$$P = \frac{1}{2}\,\frac{Vi^2 - Vr^2}{Z_o} = \frac{1}{2}\,\frac{(Vi - Vr)^2}{Z_o}\;\frac{(Vi + Vr)}{(Vi - Vr)}$$

where: Vi = peak voltage of incident wave

Vr = peak voltage of reflected wave

and with r denoting, furthermore, the standing-wave ratio:

$$r = \frac{Vi + Vr}{Vi - Vr} = \frac{V\,max}{V\,min}$$

thus

$$P = \frac{1}{2}\,\frac{(Vi - Vr)^2}{Z_o}\,r = \frac{r}{2}\,\frac{V\,min^2}{Z_o}\;.$$

Z_o of the coaxial detector is known; P is measured by the 10 cm wattmeter, and r is computed by using the relative crystal calibration. Thus the value for V min can be evaluated, determining the level of the relative calibration curve. A check of this calibration is recommended, by repeating the above measurements on different power levels with various standing-wave ratios, r. Satisfactory results can be obtained.

8. Attenuation Measurements on Coaxial Cables

This section describes a practical application of some of the units previously described. Beaded coaxial cables were electrically tested as a part of the construction program (see page V-7). The test object (in this case a cable) is connected between a calibrated traveling-detector section which measures the input power and a 10 cm wattmeter which measures the output power. These two measurements permit the computation of the attenuation of the test cable in decibels per foot at a frequency of 3000 mc.

$$\alpha \text{ in db/ft} = \frac{10}{\ell \text{ in ft}} \cdot \log_{10} \left(\frac{P \text{ in}}{P \text{ out}}\right).$$

This test method, combined with a megohmmeter check, proved to be very useful in discovering faulty cables. The attenuation of a cable depends on its make. The dielectric used in a cable greatly influences the attenuation. Cables must also be protected from humidity. In addition, it was found that at 10 cm the radiation losses through the outer braid of the coaxial cable must be taken into consideration. The losses thus vary depending on the bends of the cable and can be reduced considerably by the use of double shielded cables. The attenuation is also a function of the standing waves on the line and thus of the matching conditions.

Average attenuation values of test cables are given below.

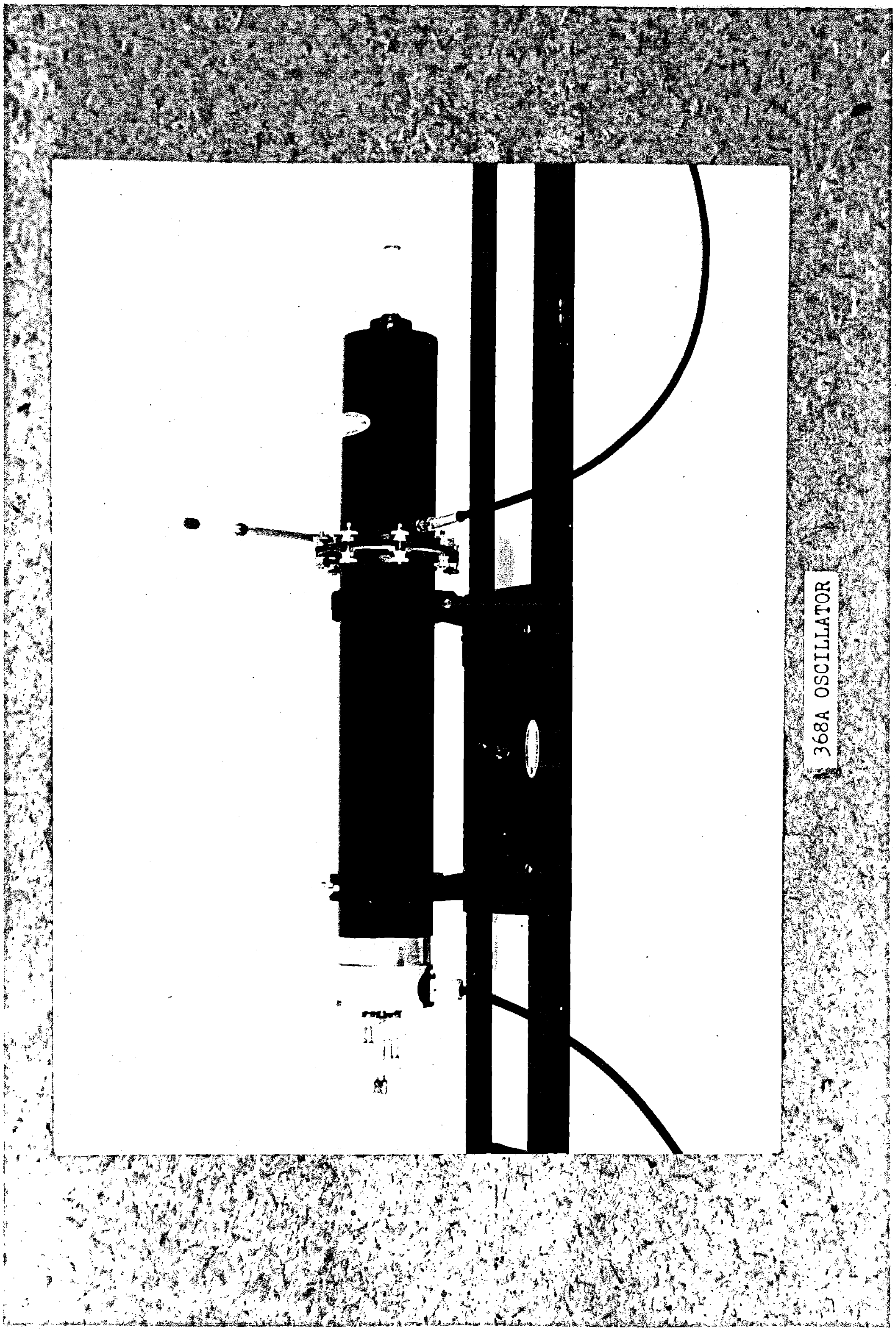
Description		Attenuation
dielectric	outer conductor	in db/ft
polystyrene beads	1 braid (new)	0.3
polystyrene beads	1 braid (in use 2 yrs)	1
polystyrene beads	2 braids (new)	0.15
rubber	2 braids (new)	1

With the measuring apparatus now available it is suggested that further investigations be made of attenuation and reflection phenomena in coaxial lines, junctions etc., and that further study be made of dielectric properties of new materials. New, solid, dielectric, copolene cables are available, and it would be interesting to compare them with the beaded coaxial cables. Solid, dielectric cables are definitely of advantage, as the construction of a good beaded coaxial cable with fittings is still rather complicated.

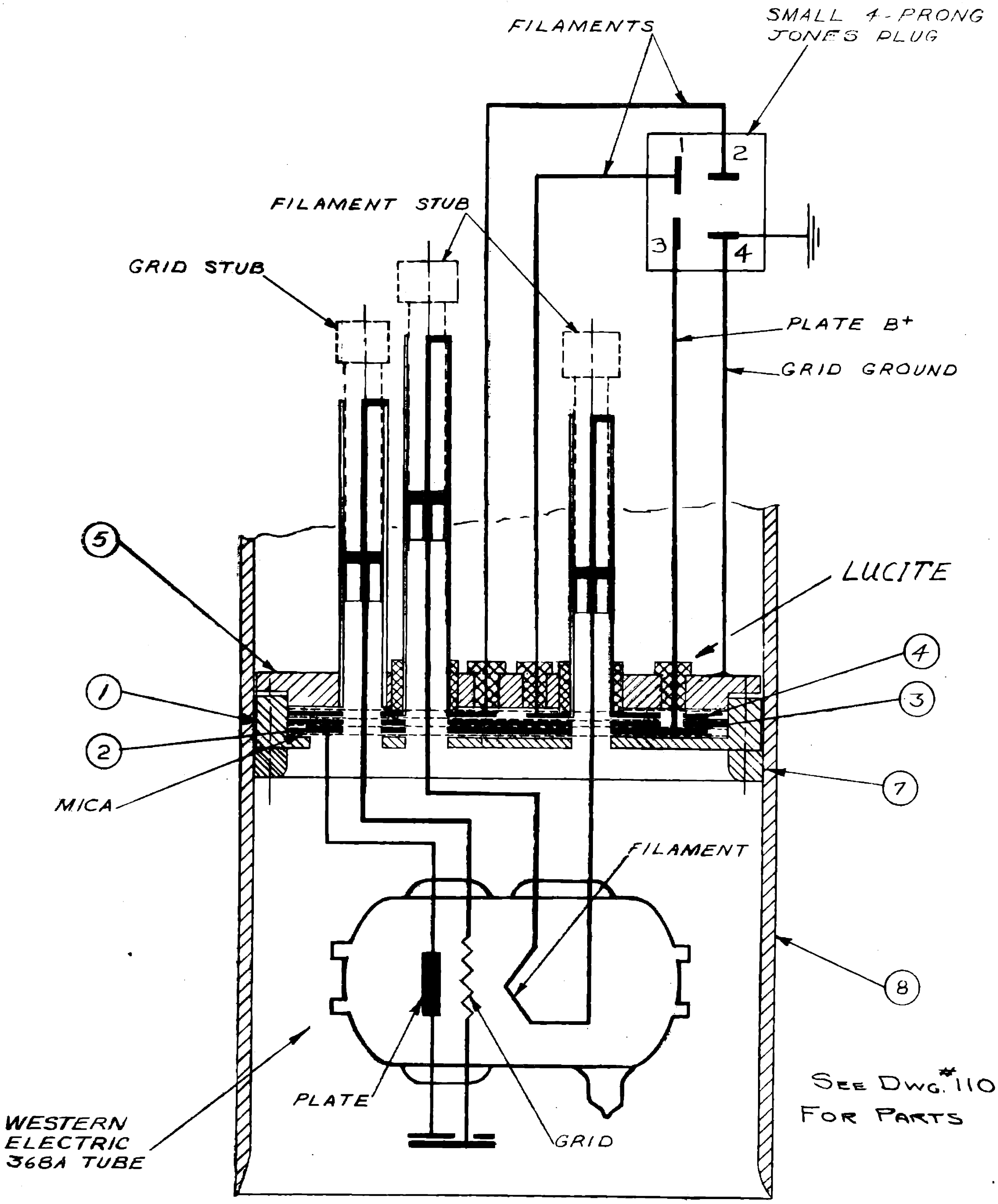
* * * * *

Chapter VI

HARMONIC 10 CENTIMETER OSCILLATOR



368A OSCILLATOR



SEE DWG. #110 FOR PARTS

368A OSCILLATOR PRINCIPLE

ASSEMBLY DWG
11-20-42
4-10-43
CHECKED BY H

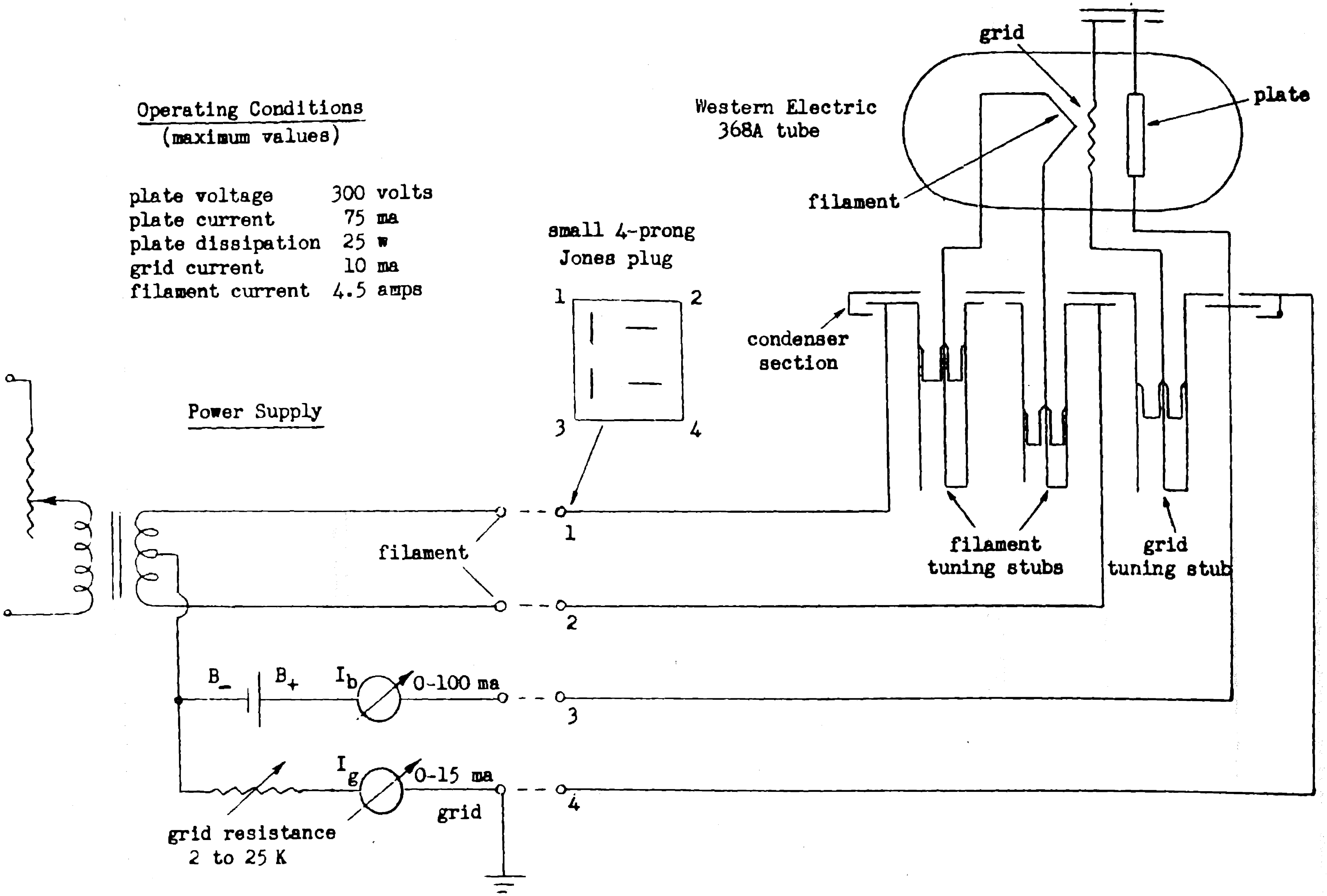
368A PRINC

A-7

368A 10 CM OSCILLATOR (WIRING DIAGRAM)

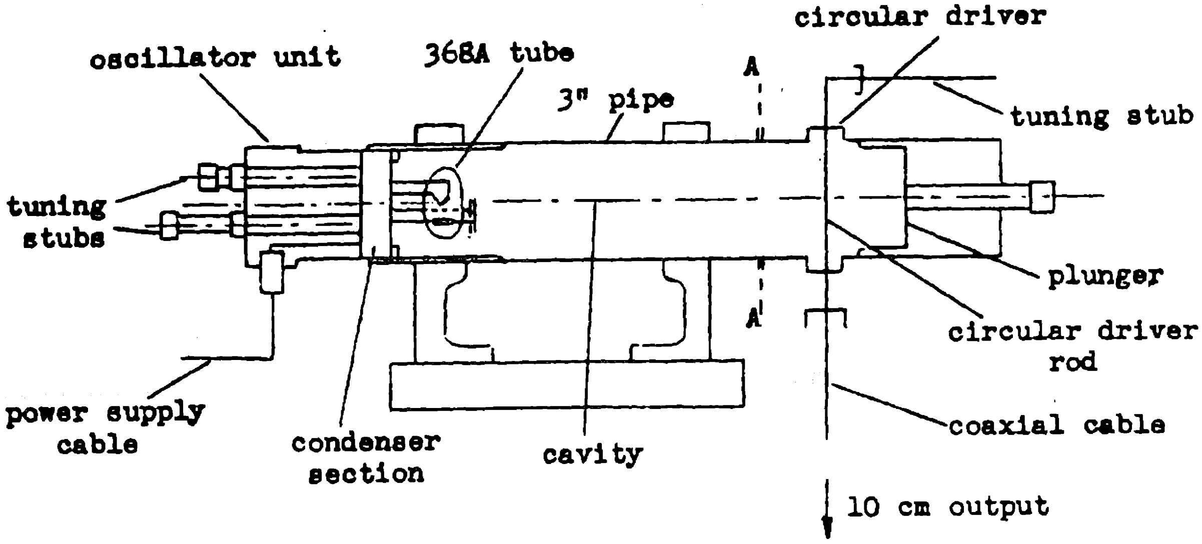
Operating Conditions
(maximum values)

plate voltage	300 volts
plate current	75 ma
plate dissipation	25 w
grid current	10 ma
filament current	4.5 amps

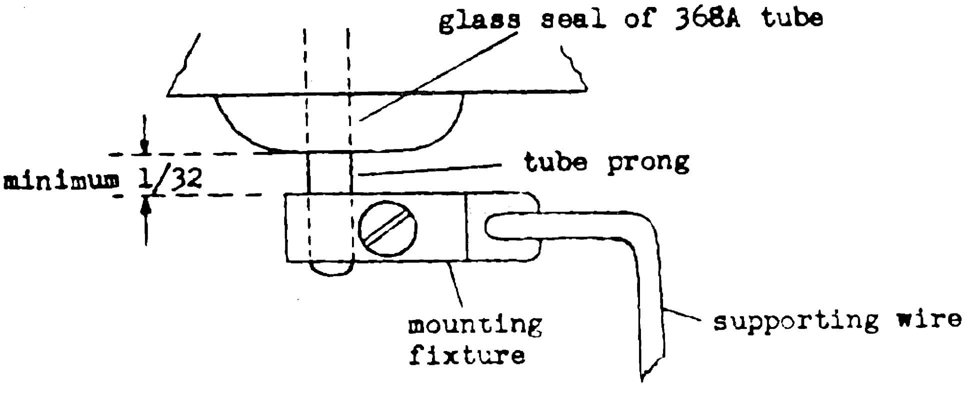


NOTE: The connections of the Jones plug correspond to the ones of the GR UHF generator, Type 757-A, except that on the GR oscillator B+ is grounded whereas in the 368A oscillator the grid is connected to ground.

M.I.T. Comm. Lab. 3/31/43.



Schematic Assembly of 368A 10 Cm Oscillator.



Mounting of Tube.

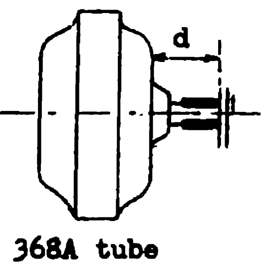
368A 10 CM OSCILLATOR TEST SHEET	Oscillator No. J

NOTE: The data on this sheet do not necessarily represent the maximum operating conditions, but they may be helpful in tuning up the oscillator.

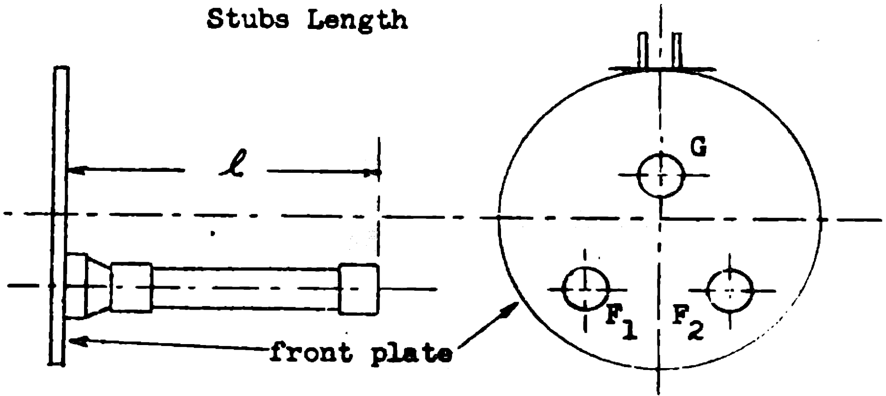
Operating Data	Symbol	Test 1	Test 2	Max.	Dimen.
ELECTRICAL					
Plate Voltage	E_b	300	300	300	volts
Plate Current	I_b	52	64	75	ma
Grid Current	I_g	9.2	9.3	10	ma
Filament Current	I_F	4.5	4.5	4.5	amps
Wavelength	λ	9.95	10.80	-	cm
Power Output	P	25	25	-	mw
TUNING OF OSCILLATOR					
Plate Grid Condenser	d	7/8	7/8	-	in
Grid Stub	ℓ_G	2-5/16	3-7/16	-	in
Filament Stub 1	ℓ_{F1}	3	4-1/16	-	in
Filament Stub 2	ℓ_{F2}	1-3/4	2-3/8	-	in

SYMBOLS

Condenser Mounting

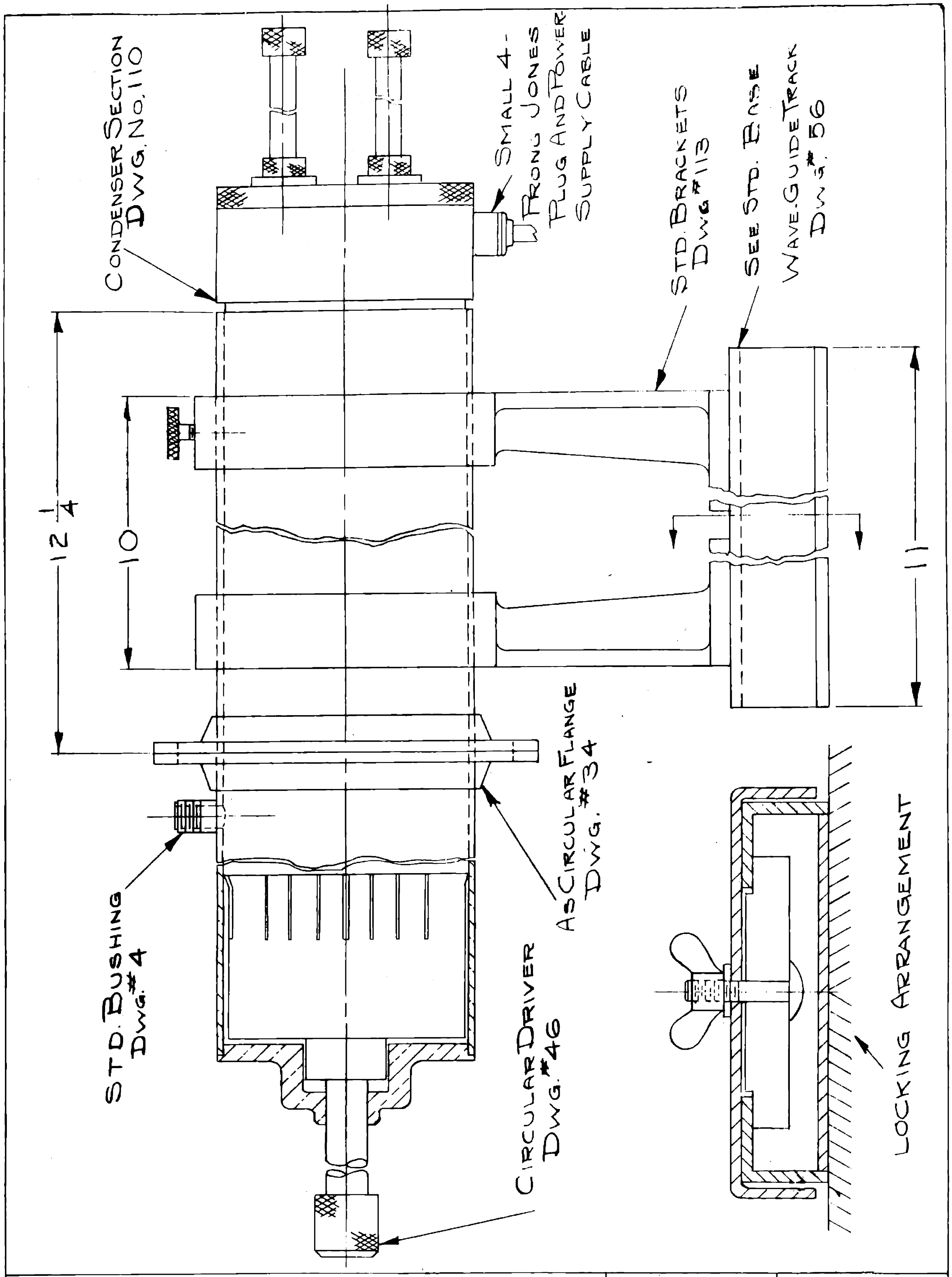


Stubs Length



TEST		MECHANICAL		ELECTRICAL	
Date	Operator	4/11/43	RBA	4/11/43	RBA

3/30/43
RCH



368A OSCILLATOR

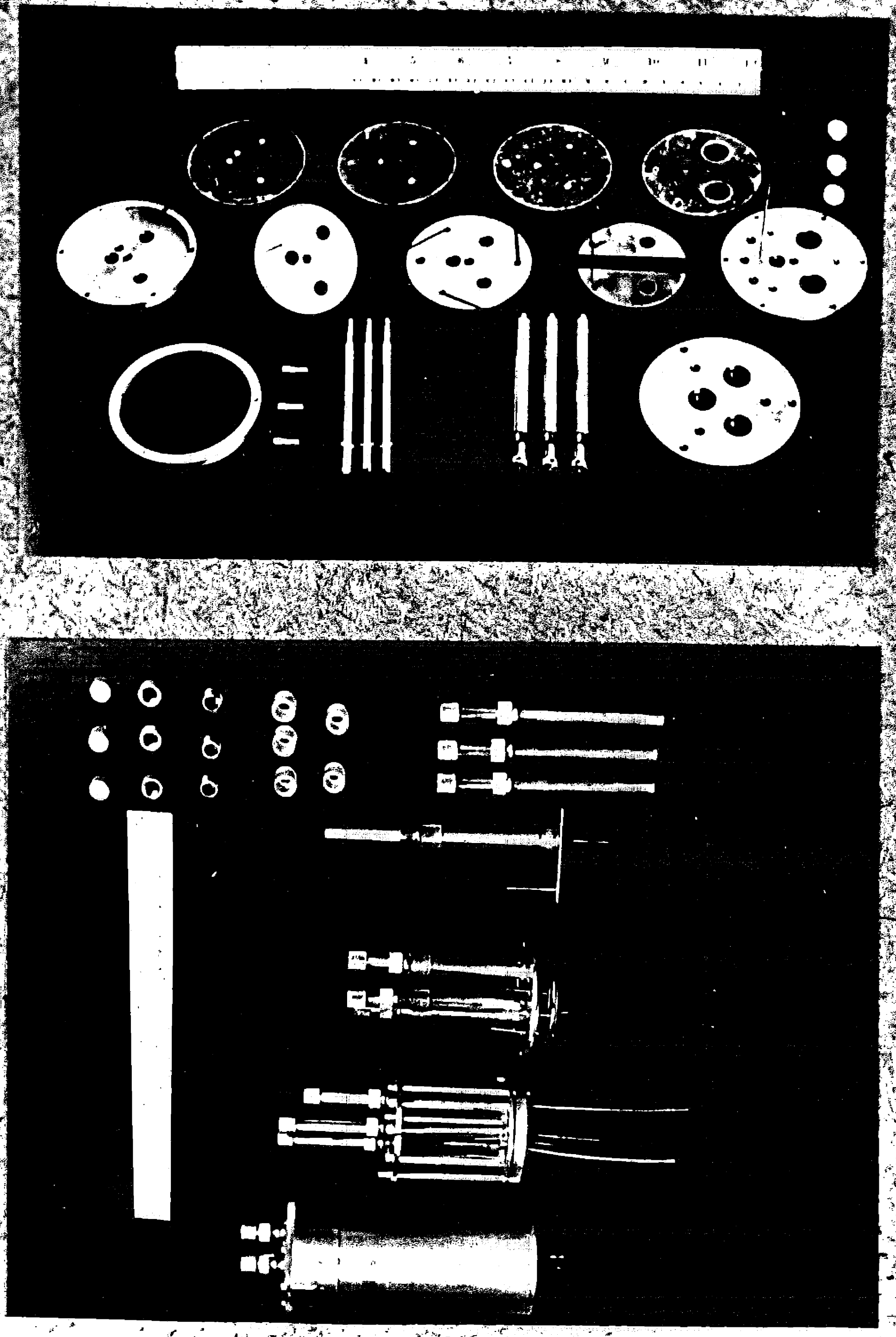
ASSEMBLY DWG

12-2-42
3-18-42

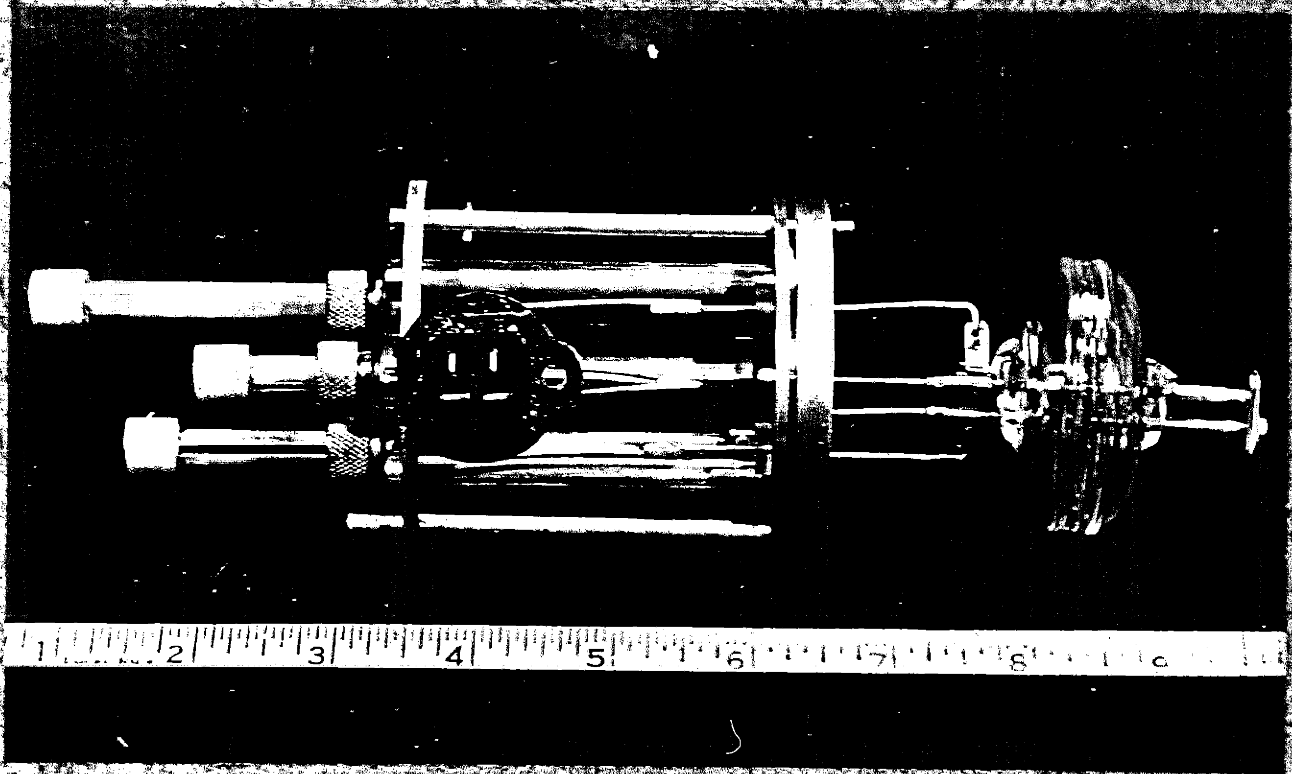
CHECKED BY #

368A
ASSEM

A-8



CONSTRUCTION OF OSCILLATOR UNIT



OSCILLATOR UNIT

Chapter VI

HARMONIC 10 CENTIMETER OSCILLATOR

1. Description of Oscillator*

This oscillator, using a Western Electric 368A tube, was manufactured primarily for laboratory instruction. It is to be used in connection with the microwave kit. As a 10-cm source the oscillator can serve as a substitute for a klystron. It is, however, more delicate and not as powerful. The electrical principles of the oscillator are explained in the assembly drawing on page VI-3. This 10-cm generator is a negative-grid harmonic oscillator which is tuned so as to emit strong harmonics in addition to its fundamental frequency. The fundamental frequency in the 20-cm band is eliminated in transmitting the radio-frequency energy through a hollow pipe which acts as a high-pass filter. Thus one obtains a source of microwave energy in the 10-cm band.

2. Tube Mounting

(a) To mount the doorknob tube it is necessary to slide the entire condenser section out of its mounting pipe, after unscrewing the three fillister-head screws on the top plate (not the capstan screws) as well as the Jones plug screw

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*See References 3, 5 and page VI-2

on the side of the pipe. Mount the tube carefully on the supporting wires of the condenser section. Page VI-5 shows a tube prong with mounting fixture. It is desirable to leave at least 1/32 inch clearance between fixture and glass to avoid any strain on the glass seal especially during the heating-up process.

(b) Adjust the sleeves of the grid-plate coupling condenser to the proper distance of the grid and plate prongs, and then mount the condenser on the tube taking the same precautions mentioned above.

(c) Test electrically and make sure that the grid of the tube is insulated from the plate before putting the oscillator in operation (no short circuit in adjustable plate-grid condenser). The condenser section with its tube is then brought back into the protecting mounting pipe thus making up the oscillator unit.

3. Operation of Oscillator*

Slide the complete oscillator unit into the three-inch pipe and adjust the coaxial tuning stubs to the values given on the test sheet. Before putting the oscillator into operation ground the case of the oscillator (grid) and set plate voltage

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*See Reference 4 and page VI-4

and filament controls of power supply to a minimum. The grid bias resistance is set to a maximum. Switch on filament current and increase slowly up to 4.5 amps. The filament current strongly influences the power output. Turn on the plate voltage and increase up to 300 volts. A flow of grid current indicates oscillation; this oscillation can be regulated by adjusting the grid resistance. If no grid current flows, change setting of tuning stubs until the tube is brought to oscillation.

4. Tuning of Oscillator for Maximum 10 cm Output

In order to receive maximum 10-cm output the oscillator must be tuned to produce strong harmonics. This is achieved by carefully adjusting the three coaxial tuning stubs. As shown on page VI-5, 10-cm output can be obtained either from the coaxial cable connected to the circular driver unit or directly from the circular pipe (cross-section AA). A sensitive crystal detector is used as an indicator for maximum power output. The oscillator unit, the three-inch pipe, and the circular driver unit comprise a cavity which has to be tuned to the $TE_{1,1}$ mode of the desired harmonic. Turning the oscillator unit in the cavity has an effect on the polarization. The longitudinal movement of the oscillator unit, together with a readjustment of the plunger in the circular driver unit, in effect changes the position of the circular driver rod in the cavity field. This gives an additional adjustment to match the cavity to the coaxial output line.

NOTE: The 10-cm output of these laboratory oscillators is small compared to the output of klystrons. Thus it is important that especial care be taken in the delicate tuning-up process.

5. Design and Construction Tests

The high-frequency oscillator described in this chapter is a modification of one which has been recommended for use with Western Electric 368A tubes. It was adapted for use with the microwave kit. Extensive tests were made on a model which was constructed at the Communications Laboratory. The proper tube mounting and tuning conditions were carefully investigated, to assure stable oscillation and to obtain as much 10-cm power output as possible.

Several plate-grid coupling-condenser designs have been tested in this way. The position of the condenser with respect to the tube determines the oscillator frequency. An increase of the distance between condenser and tube end raises the oscillating wavelength slightly, and generally increases the power output.

The mounting of the tube itself in the cavity has an influence on the excitation of the desired $TE_{1,1}$ mode. The position of the tube with respect to the end plate of the cavity had some effect on the coupling to the cavity and thus on the power output. Also the mounting of the connecting filament, plate and grid leads seem to have some influence on the excitation.

Chapter VII

REFERENCES

Chapter VII

REFERENCES

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14. Communications Laboratory Experiment: "Radiation Patterns of Paraboloid and Horns".

15. Communications Laboratory Experiment: "Wave Guides and Cavities",
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Part II: Circular Cross Section.

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18. Ghosh: "Measurement of Power and Absolute Calibration of a Detector in the Microwave Region", M.S. Thesis, 1942.

19. Ottinger: "History of UHF Measurements", Seminar, 1943.

20. Van Meter: "Losses in Cavity Resonators at 3000 Megacycles", M.S. Thesis, 1943.

21. Wohlwill: "Study of Rectifier Crystals as Nonlinear Circuit Elements", B.S. Thesis, 1943.

* * * * *

Chapter VIII

CONSTRUCTION DRAWINGS

Attached is a set of working drawings of microwave demonstration equipment, showing the construction of all parts of the microwave kit and the harmonic 10 cm oscillator, constructed for the colleges giving UHF laboratory courses. The drawings may be useful for instruction purposes, for new design and construction work, or for eventual repair work. The colleges were supplied with an extra set of drawings on map-bond paper so that any additional copies, which they may desire, can be obtained directly by any standard printing process.

You will note that, while these drawings are fully dimensioned and detailed, they are not to scale. This has made possible the exaggeration of small details which might otherwise be overlooked and enabled us to do a speedier drawing job. In this way the shops involved were at no time delayed by the lack of working drawings.

Dates on these drawings indicate their final release for printing after the parts concerned had been fabricated, thereby insuring that minor last-minute changes have been included. In the dimensioning of these drawings, standard conventions on tolerances have been followed: that is, where definite limitations must be observed, these limitations are given; otherwise fractional dimensions indicate a tolerance of ± 1/64 inch, and decimal dimensions indicate a tolerance of ± 0.005 inch.

To familiarize the experimenter with the microwave equipment, additional assembly drawings were made up. They are attached to their chapters, and illustrate the setup of various experiments, assembled from different standard parts.

* * * * *

WORKING DRAWINGS

OF

MICROWAVE DEMONSTRATION EQUIPMENT

Massachusetts Institute of Technology

February, 1943

TABLE OF CONTENTS

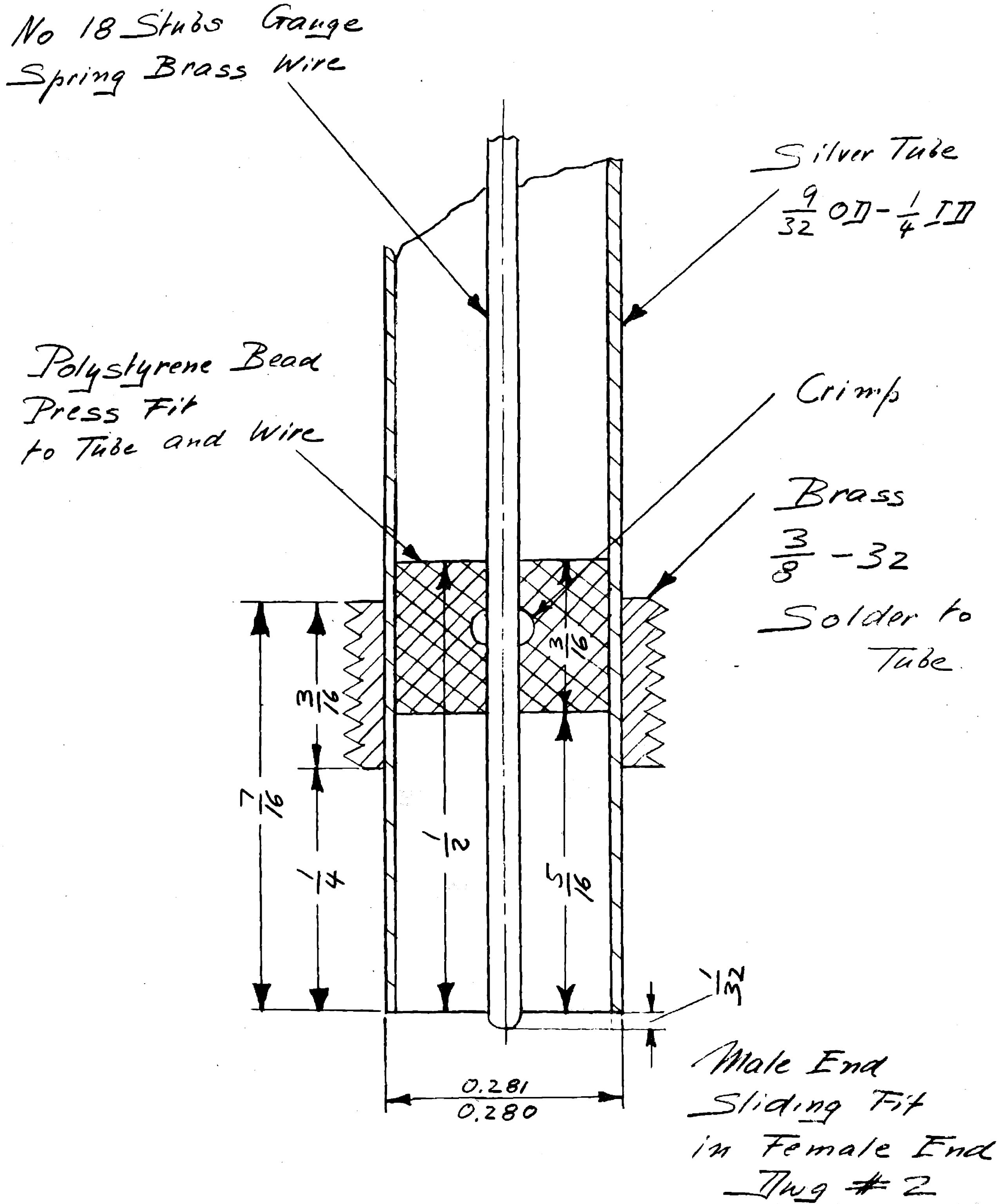
MICROWAVE DRAWINGS:
(Serially)

Complete Set: 61 Dwgs.
Selected Set: 29 Dwgs. (see *)

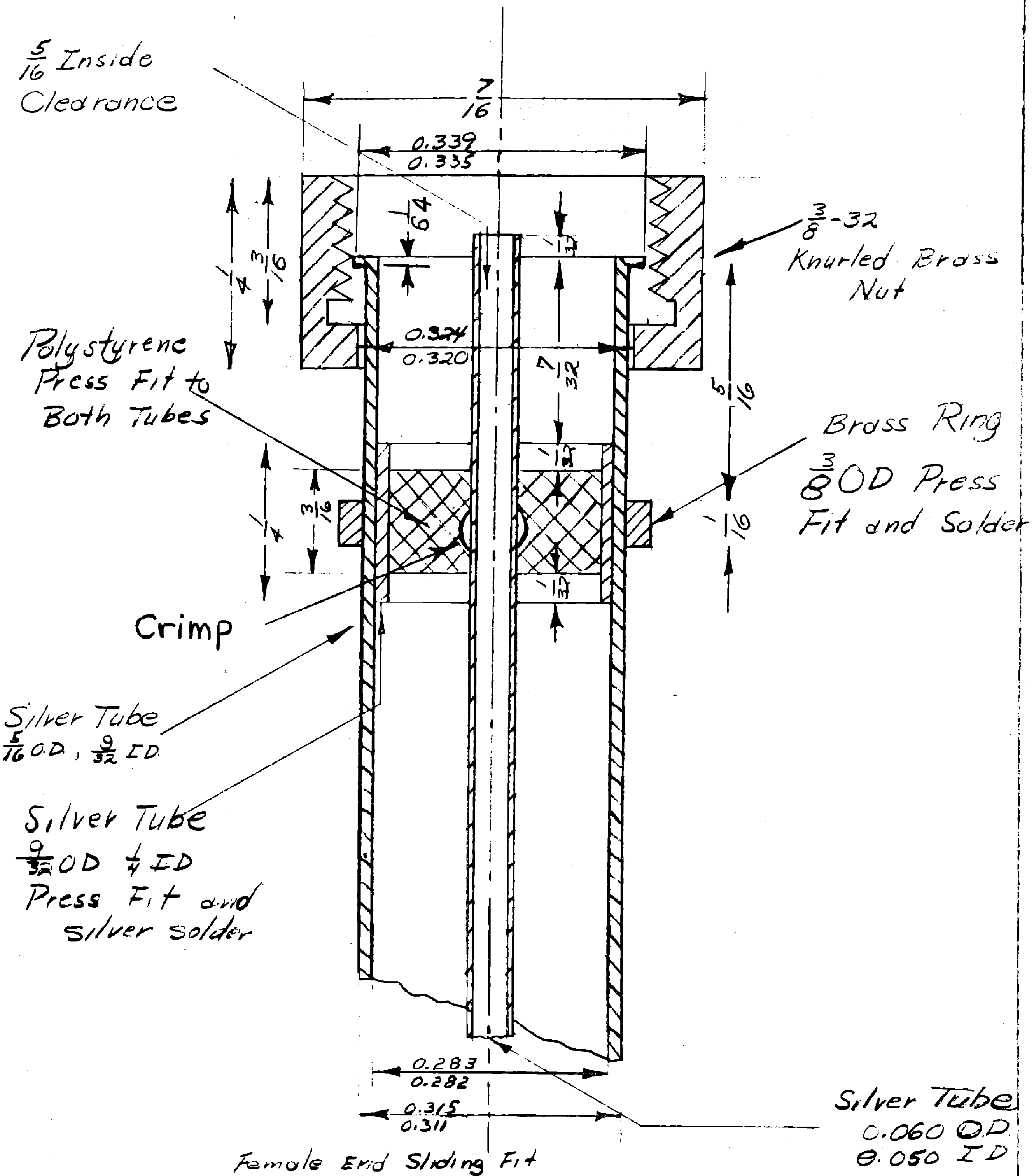
Table of Contents (cont'd)

MICROWAVE DRAWINGS:
(Alphabetically - Cross Referenced)

Table of Contents (cont'd)



Standard Male End	Not to Scale	Std ME
	2-9-43	1
	Dr: K Ch. #	



Female End Sliding Fit
Over Male End - Dwg #1

Standard Female End

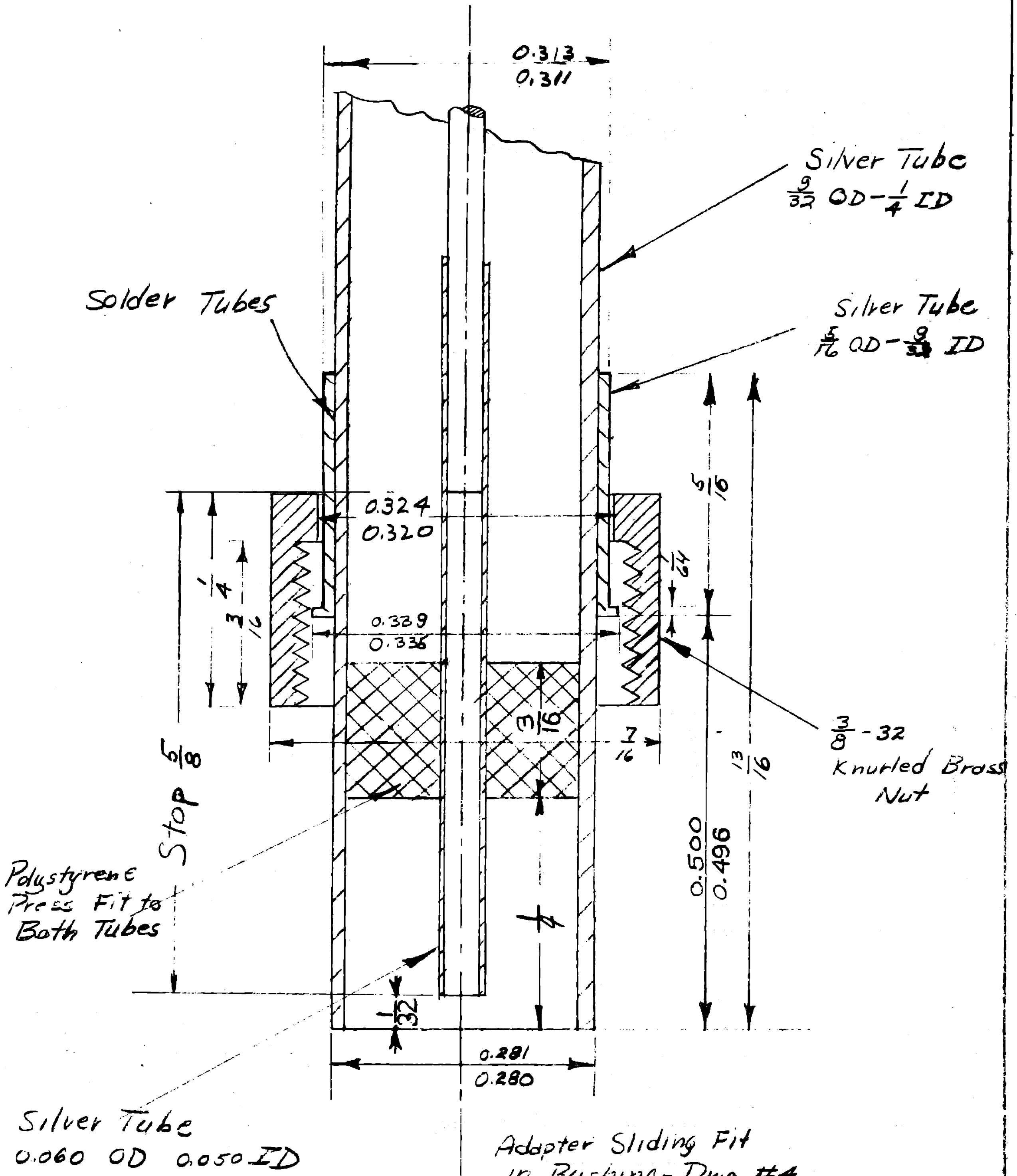
Not To Scale

2-4-43

Dr. BP, Ch. H

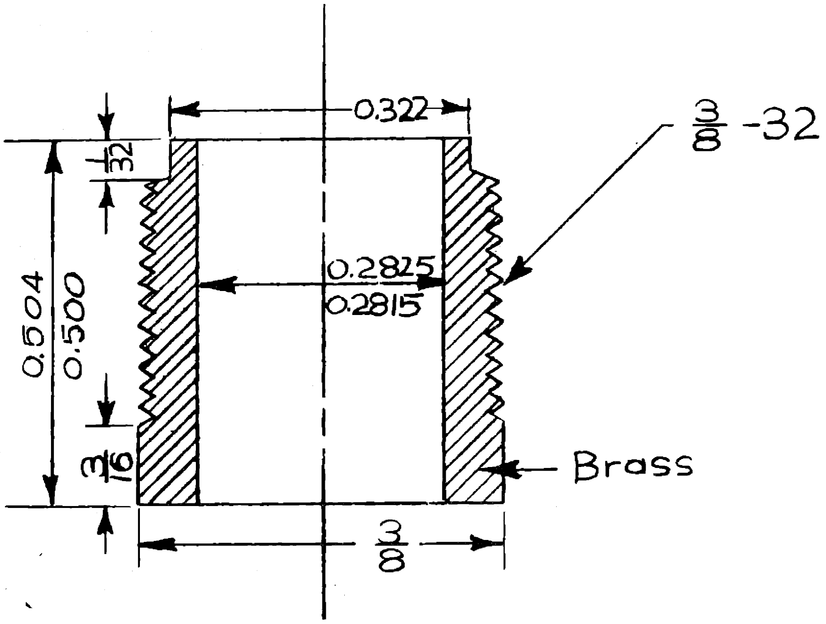
ST'D FE

2



Adapter Sliding Fit
in Bushing - Dwg. #4

Standard Adapter	Not To Scale	Std A
	2-4-43	3
	Dr.- BP Ch.- #	



Not To Scale

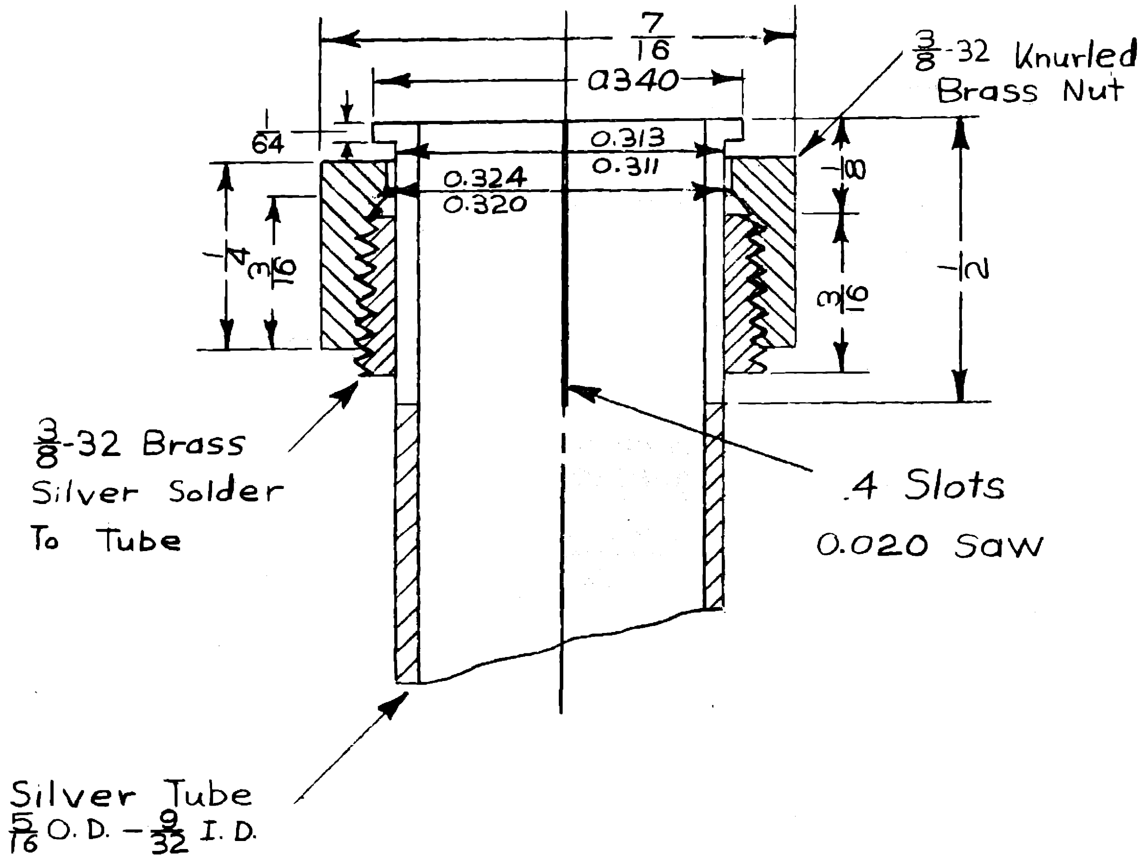
1-30-43

Dr. J.L. Ch.

Standard Bushing

ST'D Bu

4



Not To Scale

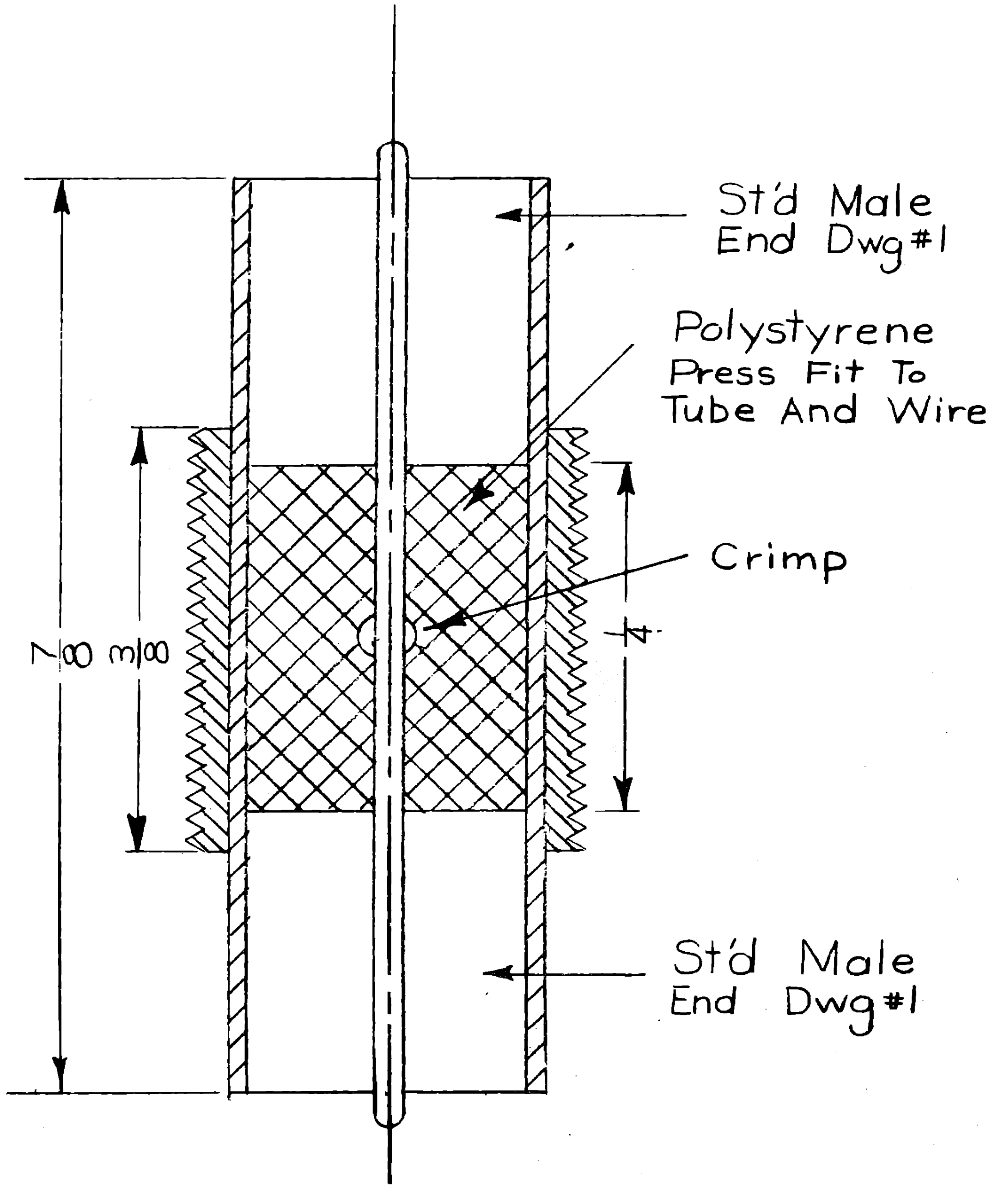
1-30-43

Dr. J.L. Ch: #

Std LN

5

Standard Locking Nut



Male-Male Adapter	NoT To Scale	MM
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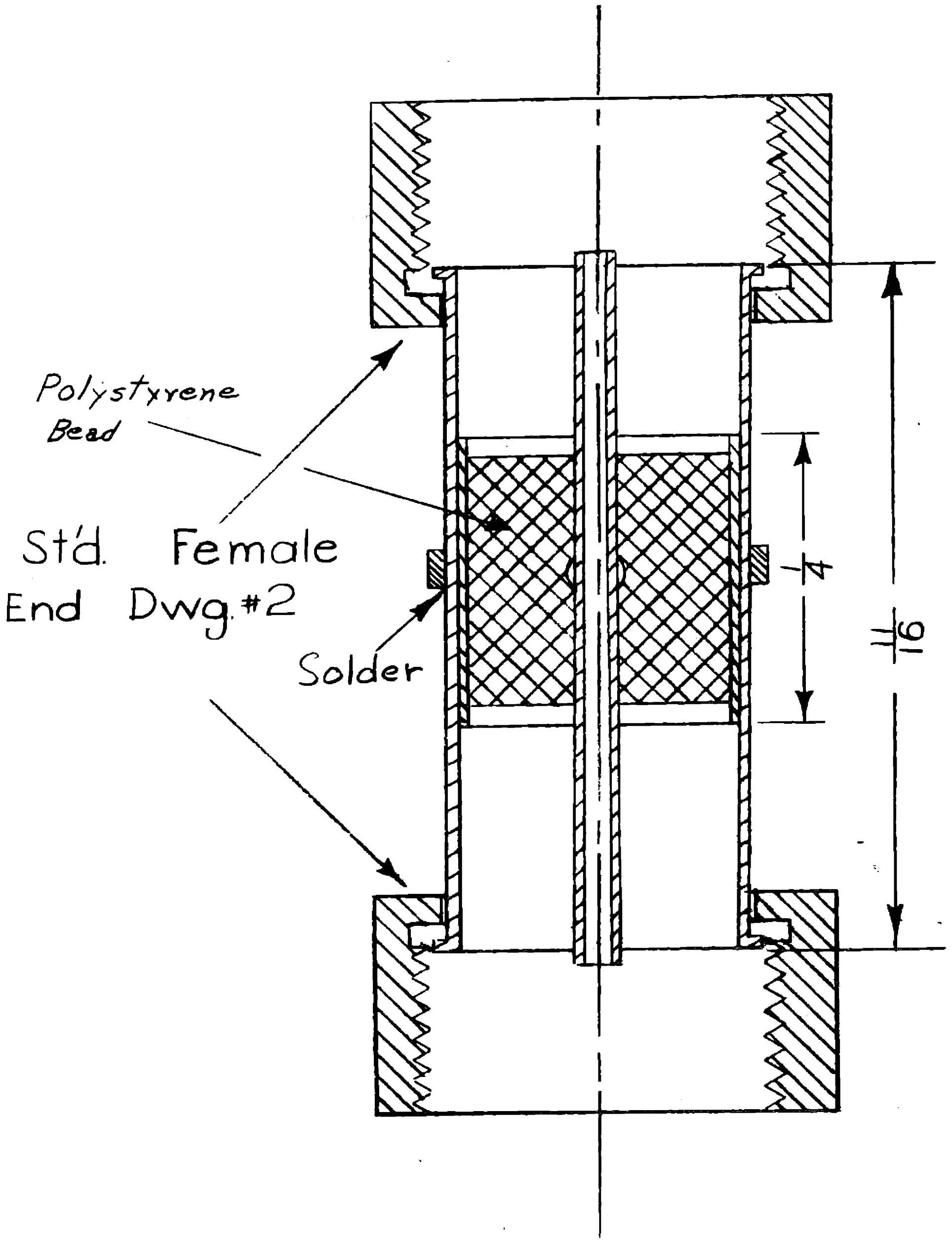
	Dr. J.L. Ch. #	



Female-Female Adapter

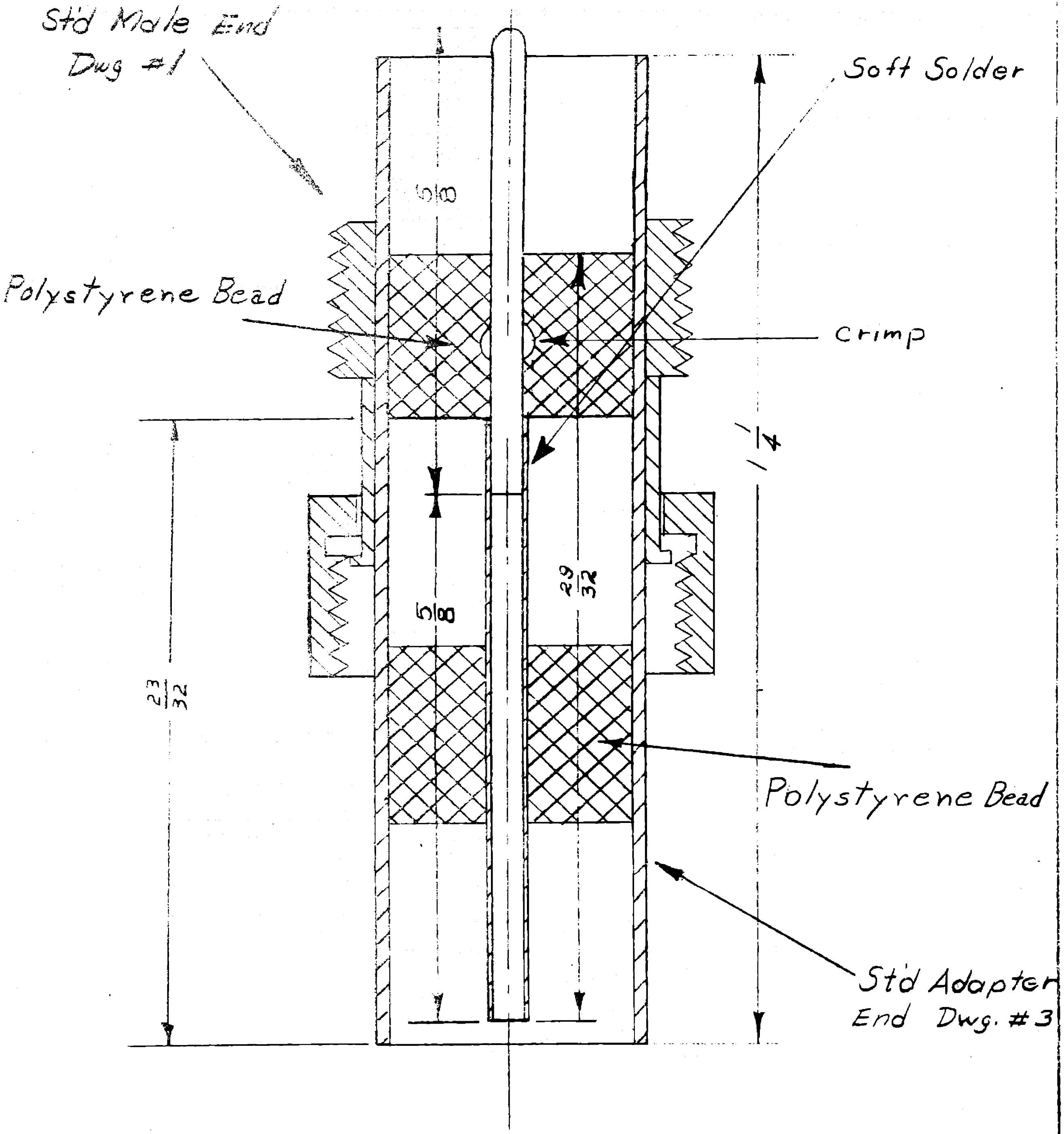
Not To Scale

1-30-43

Dr. J.L. Ch: #

FF

7



Not To Scale

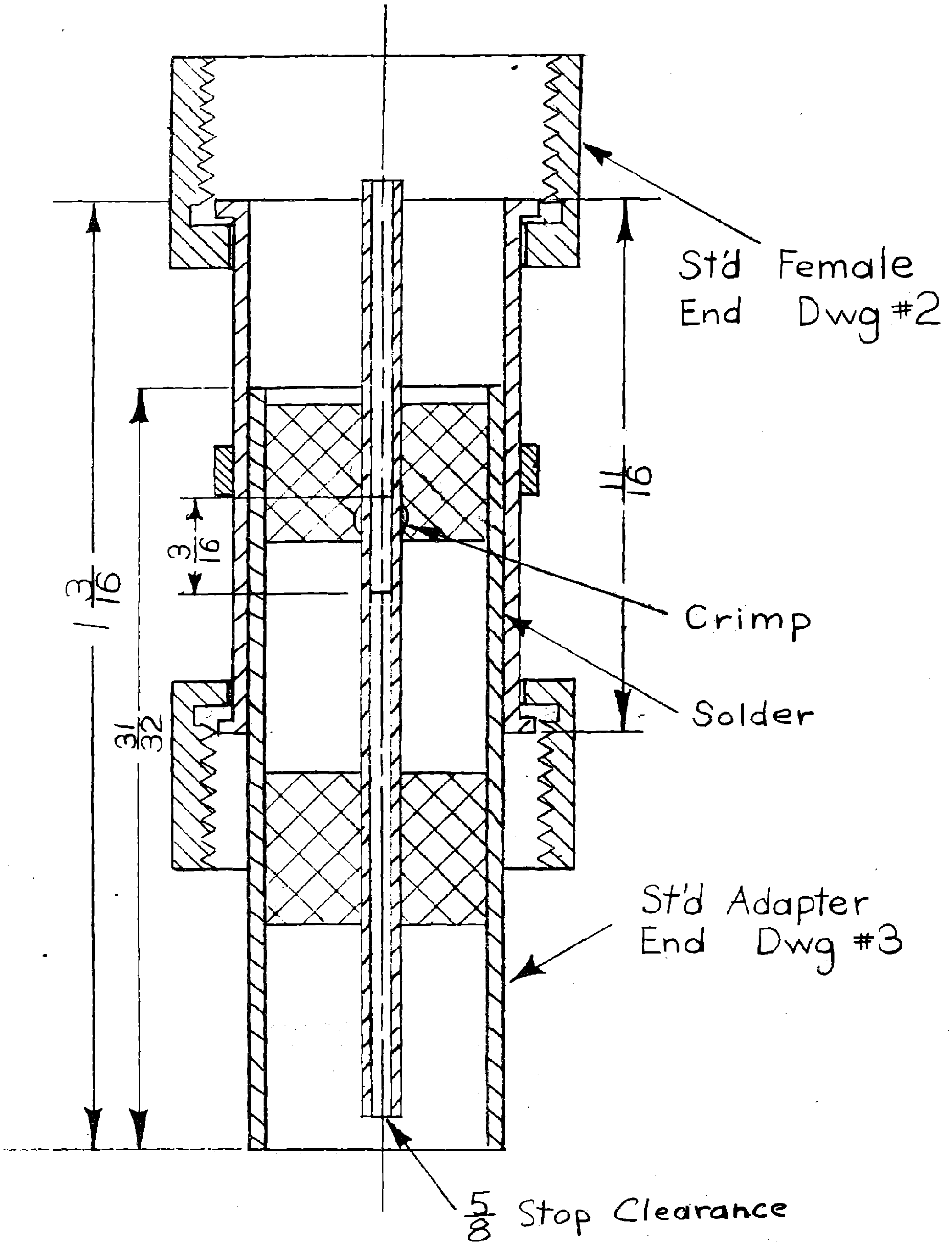
Male Adapter

2-4-43

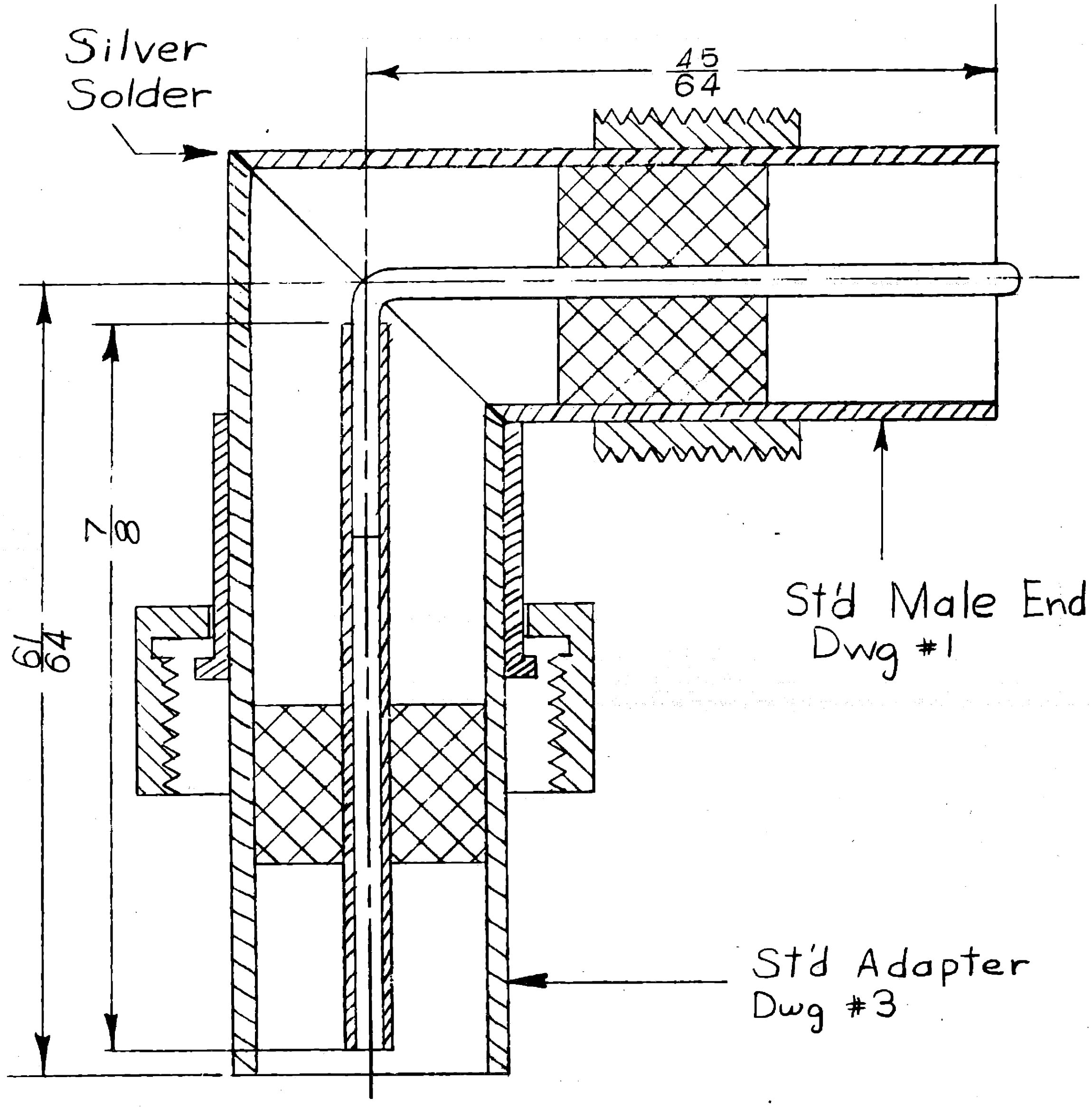
Dr. BP Ch. A

MA

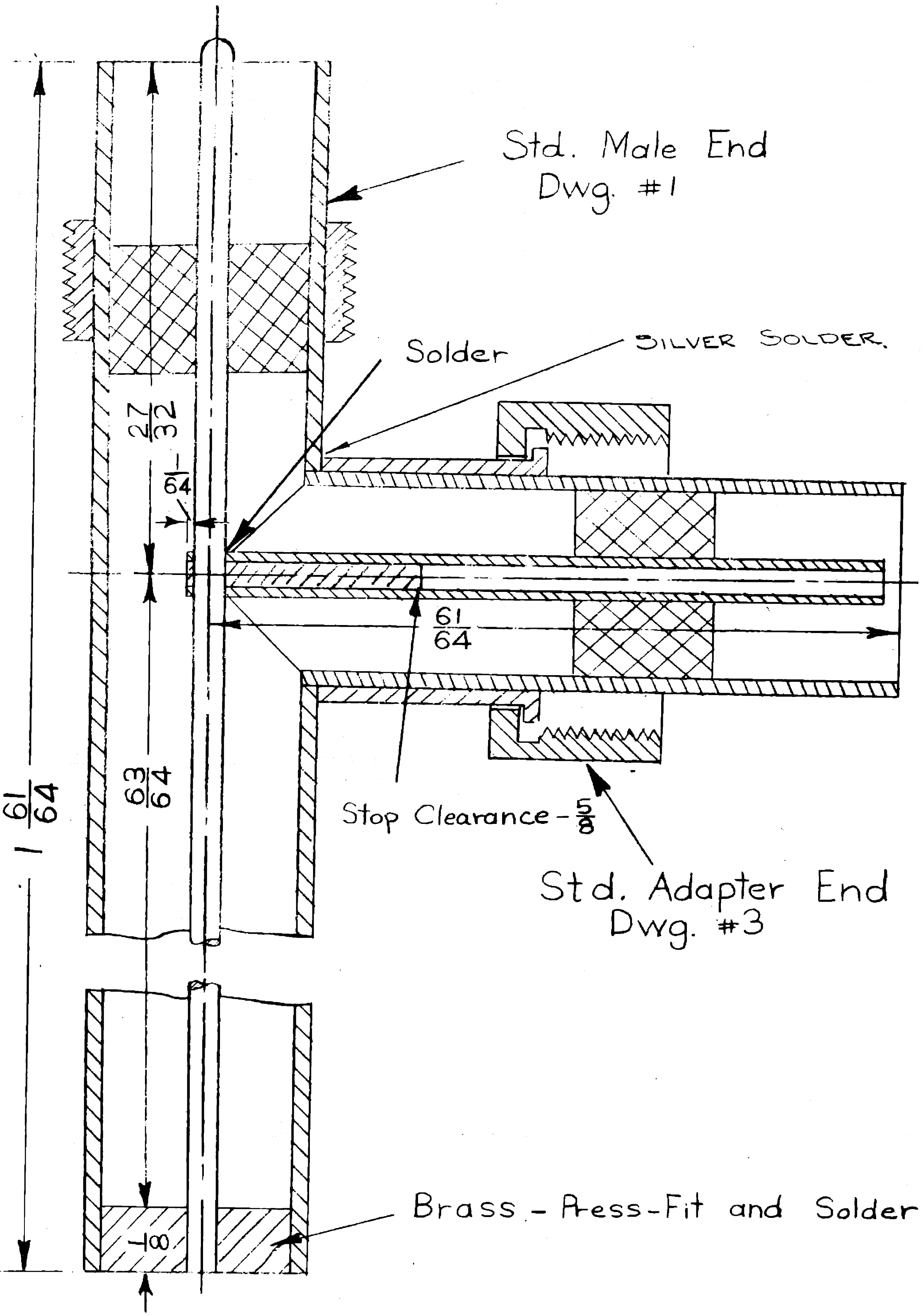
8



Female Adapter	Not To Scale	FA
	2-1-43	9
	Dr. J.L. Ch: #	



Male Corner Adapter	Not To Scale	MCA
	2-1-43	10
	Dr. J.L. Ch: #	

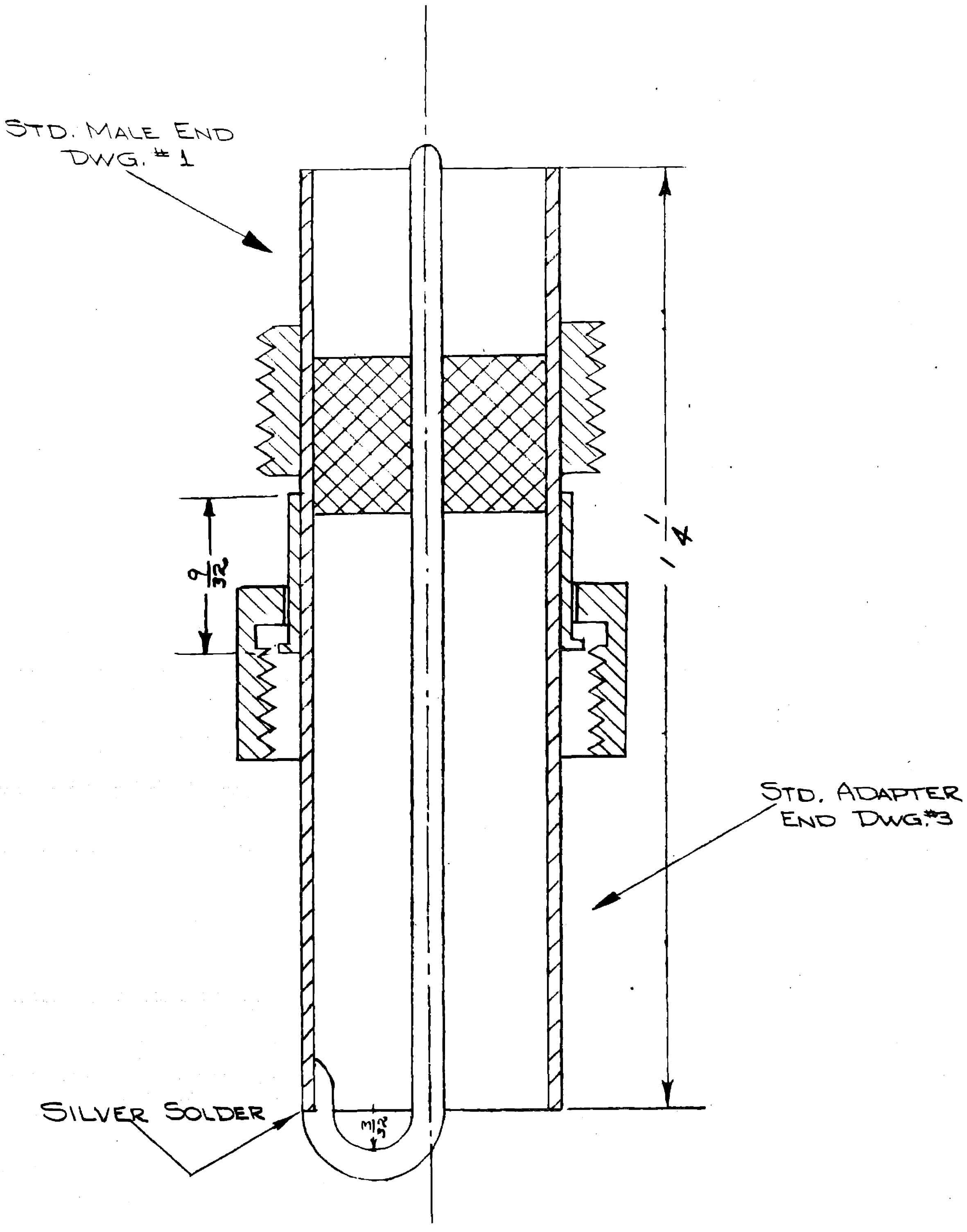


Quarter Wave Adapter

Not To Scale
10-10-42
5-3-43
Dr: J.L. Ch:

$\frac{\lambda}{4}$ A

11

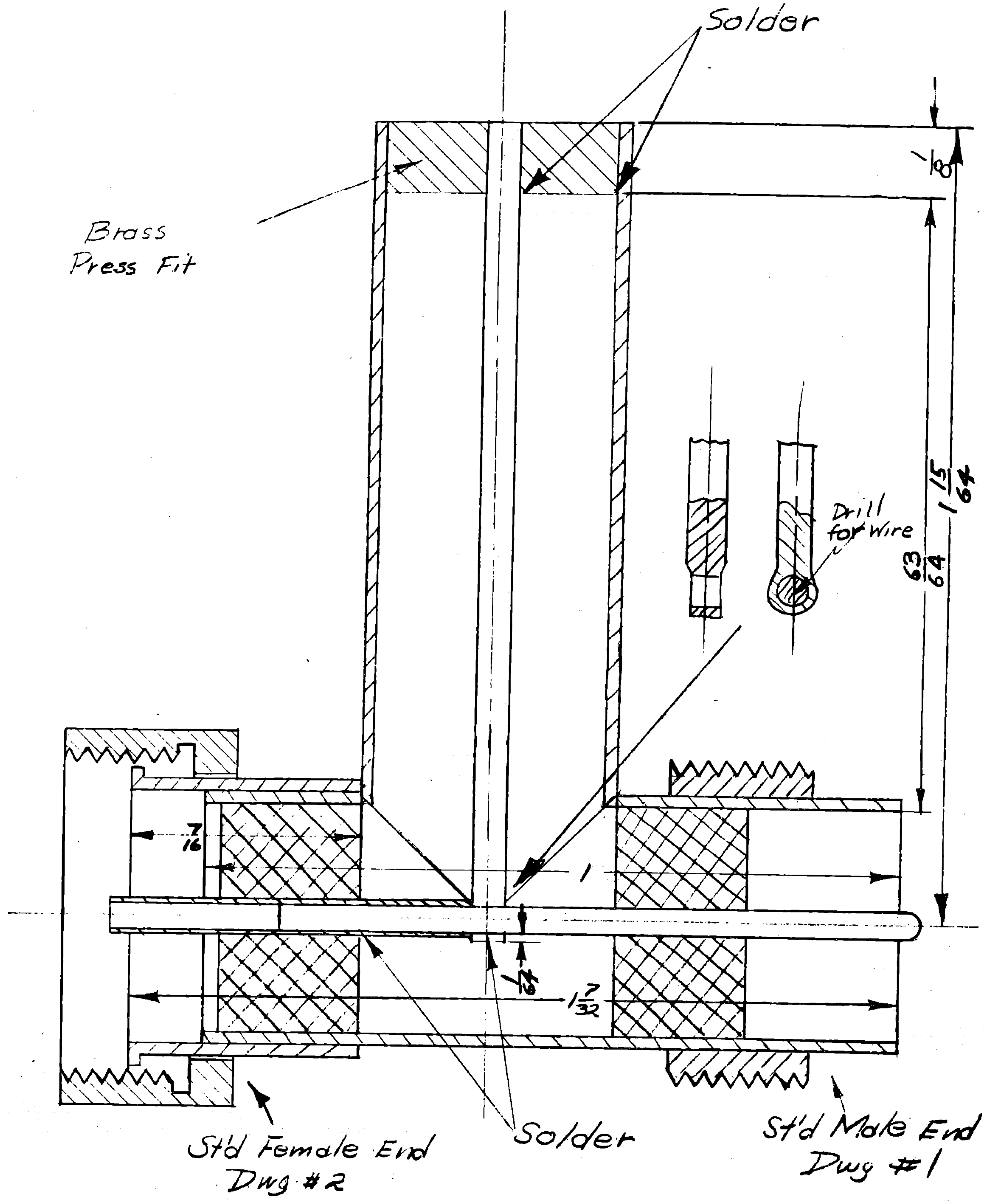


Male Loop

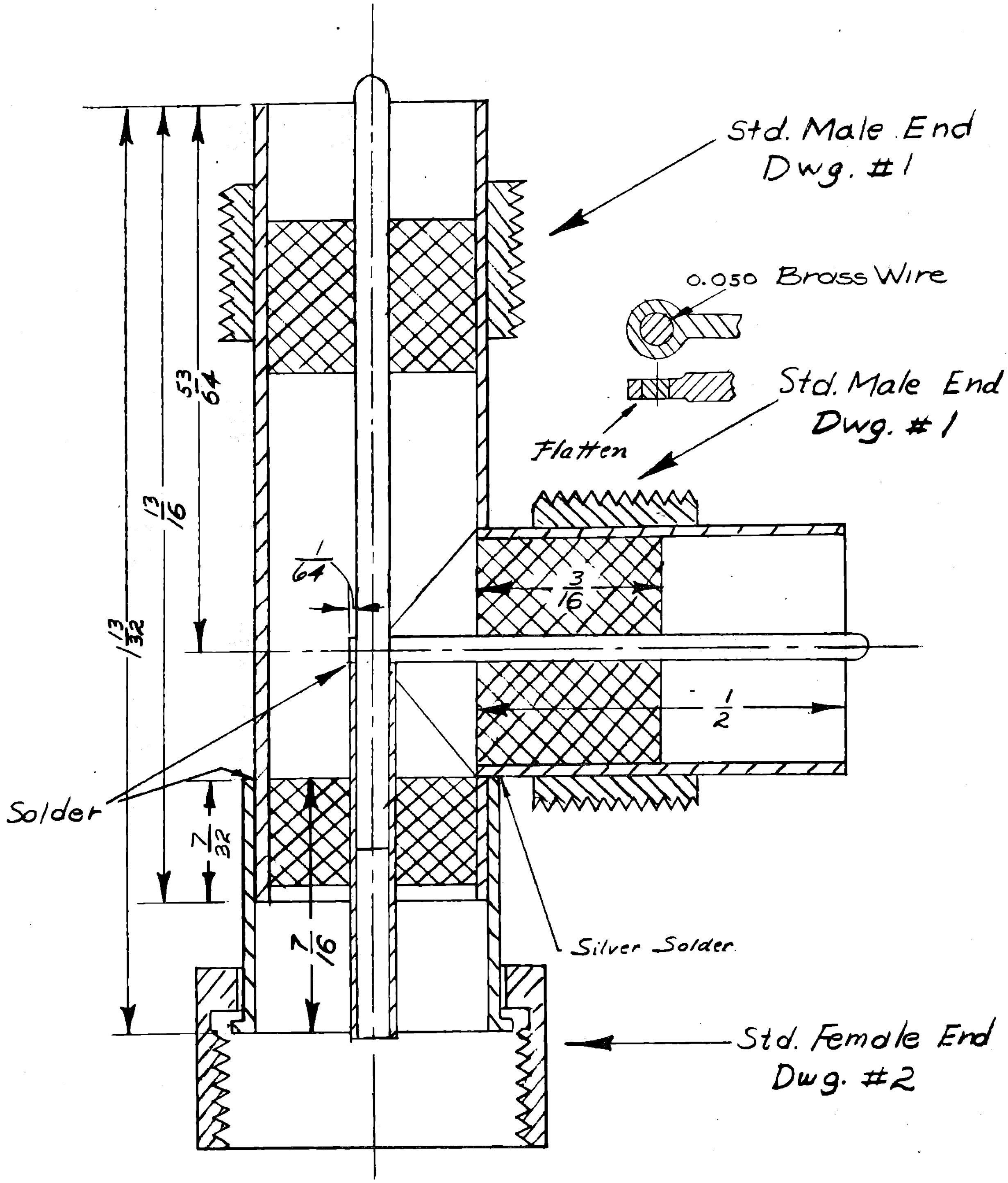
Not To Scale
10-12-42
5-3-43
Dr BP Ch #

ML

12



Quarter Wave Stub	Not To Scale	λ/4 S
	2-4-43	
	Dr. EP Ch #	17



Male T Section	Not To Scale	MT
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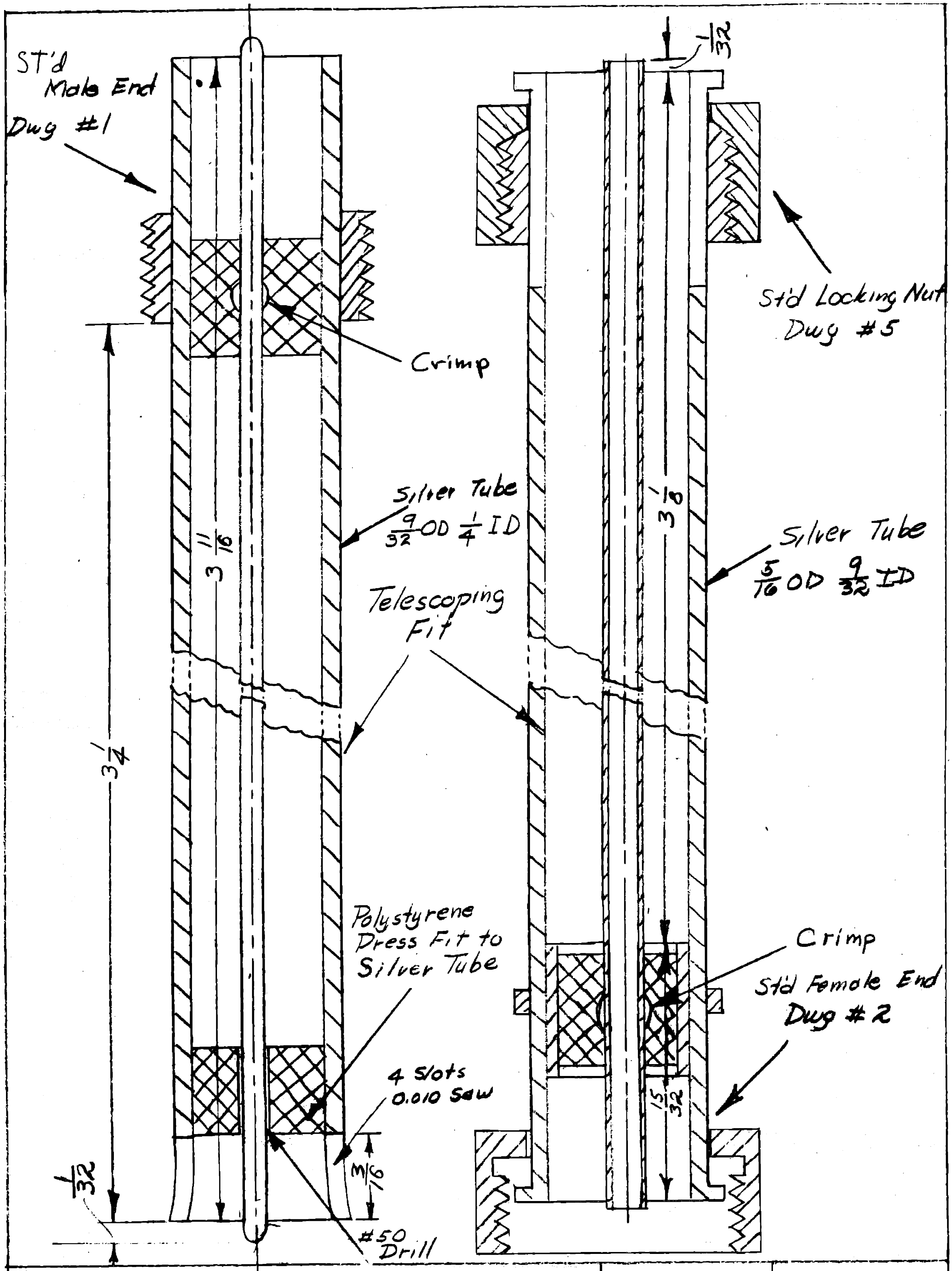
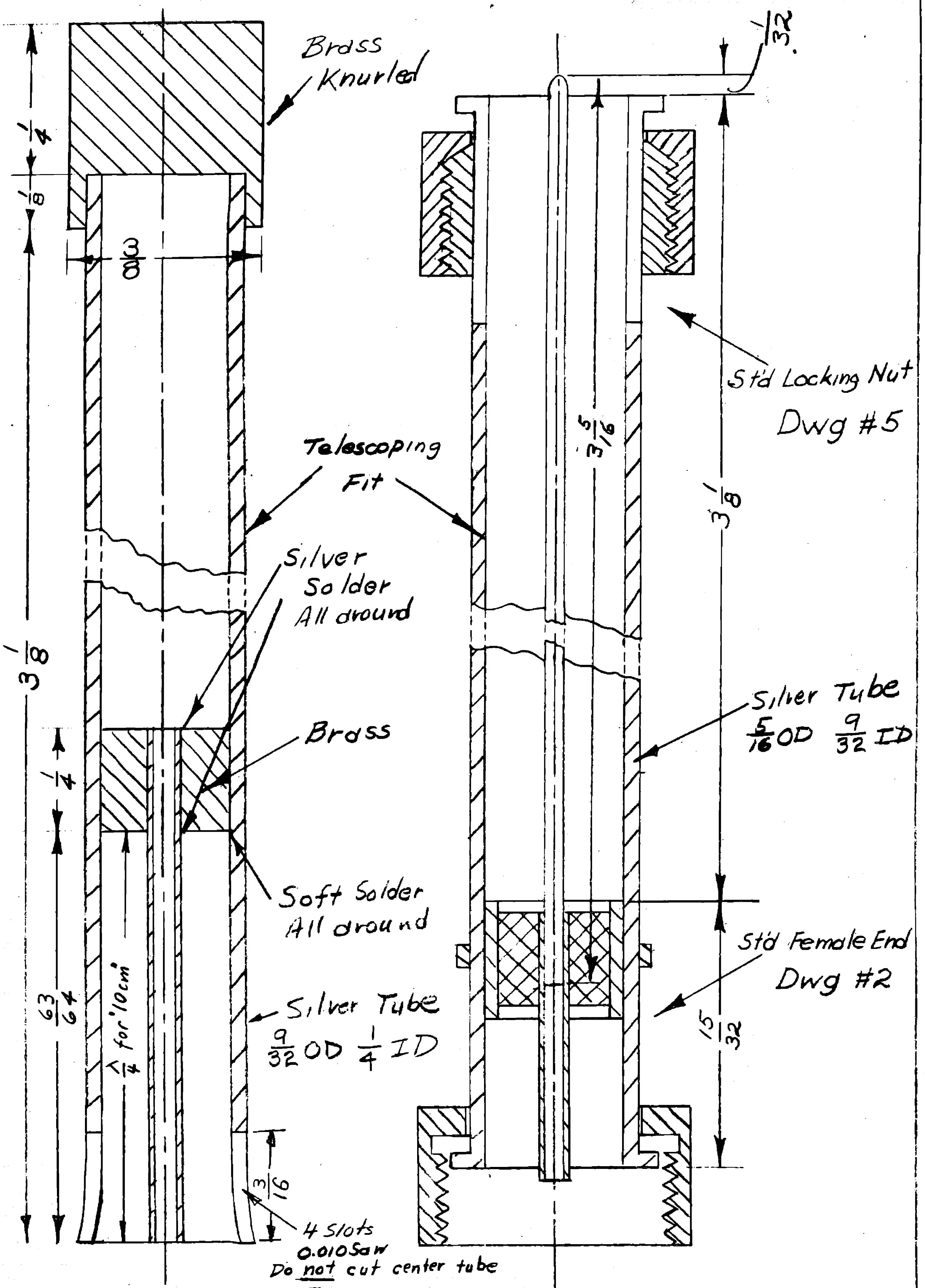
	Dr. B.P. Ch #	



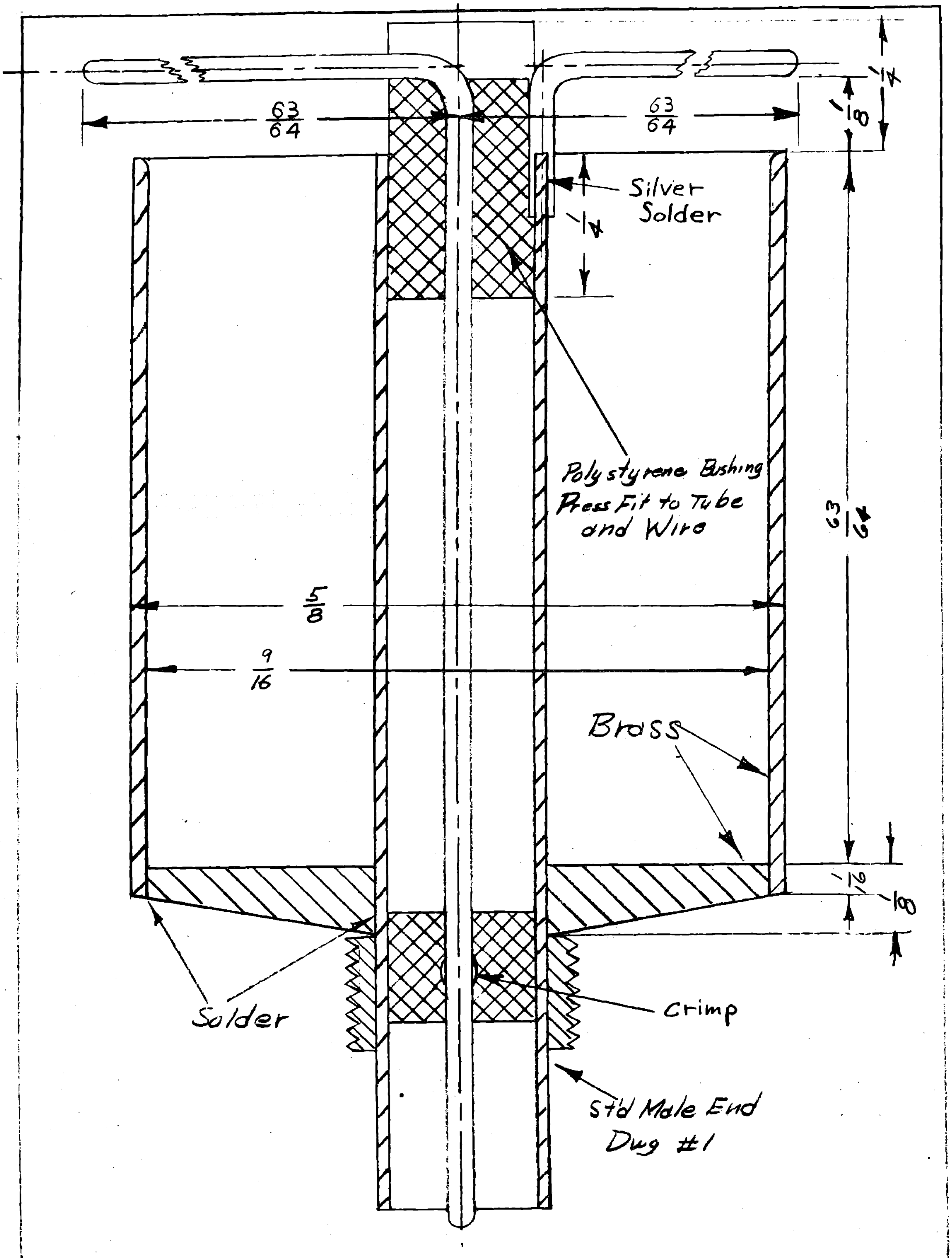
Variable Length Section	Not to Scale	VLS
	2-4-43	
	Dr. BECh #	20



Short Circuiting Stub

Not To Scale
2-4-43
Dr BP Ch #

SS
21



λ/2 Antenna

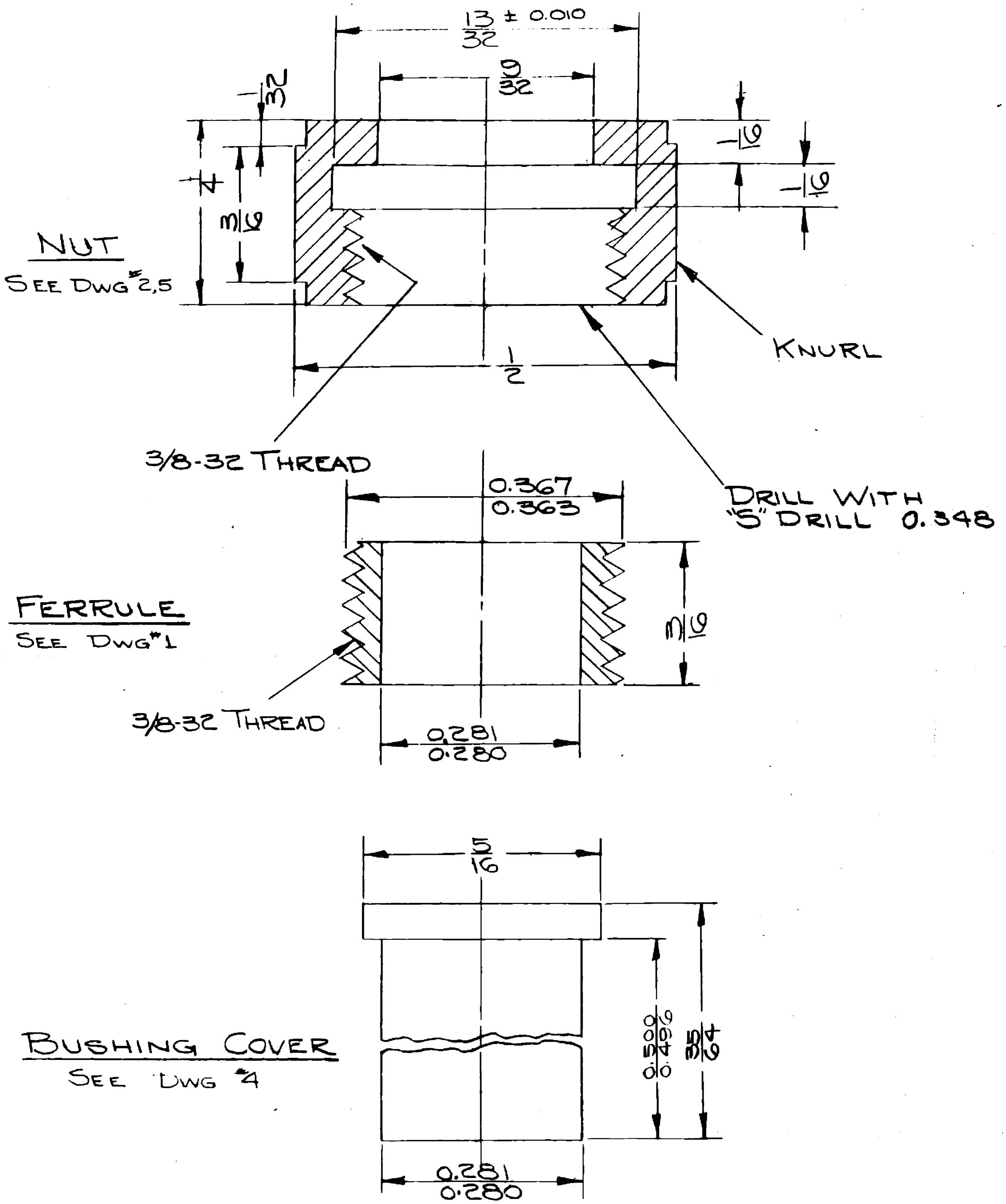
Not To Scale

2-4-43

Dr BP Ch-H

λ/2

22



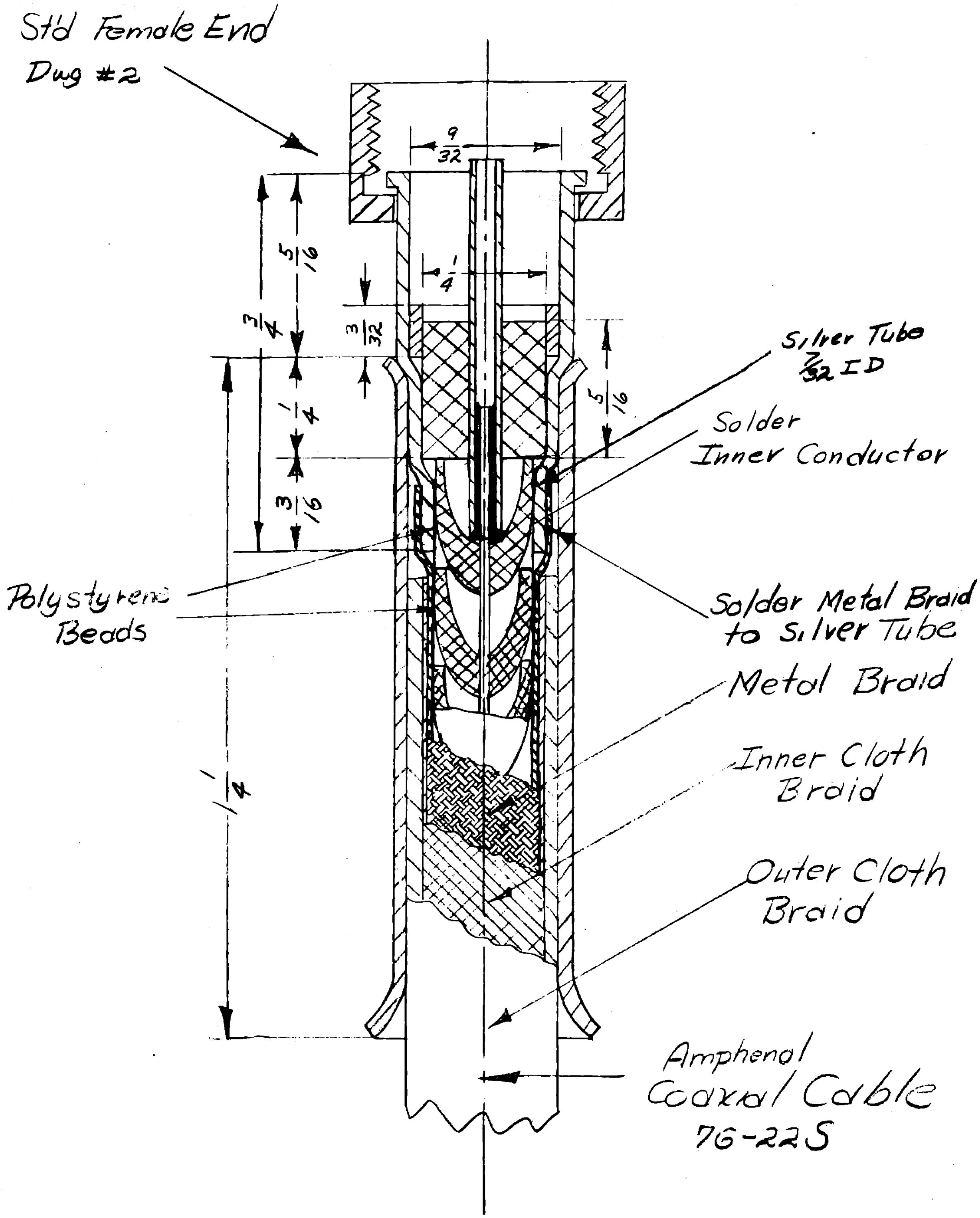
BRASS

STANDARD NUT, FERRULE,
BUSHING COVER

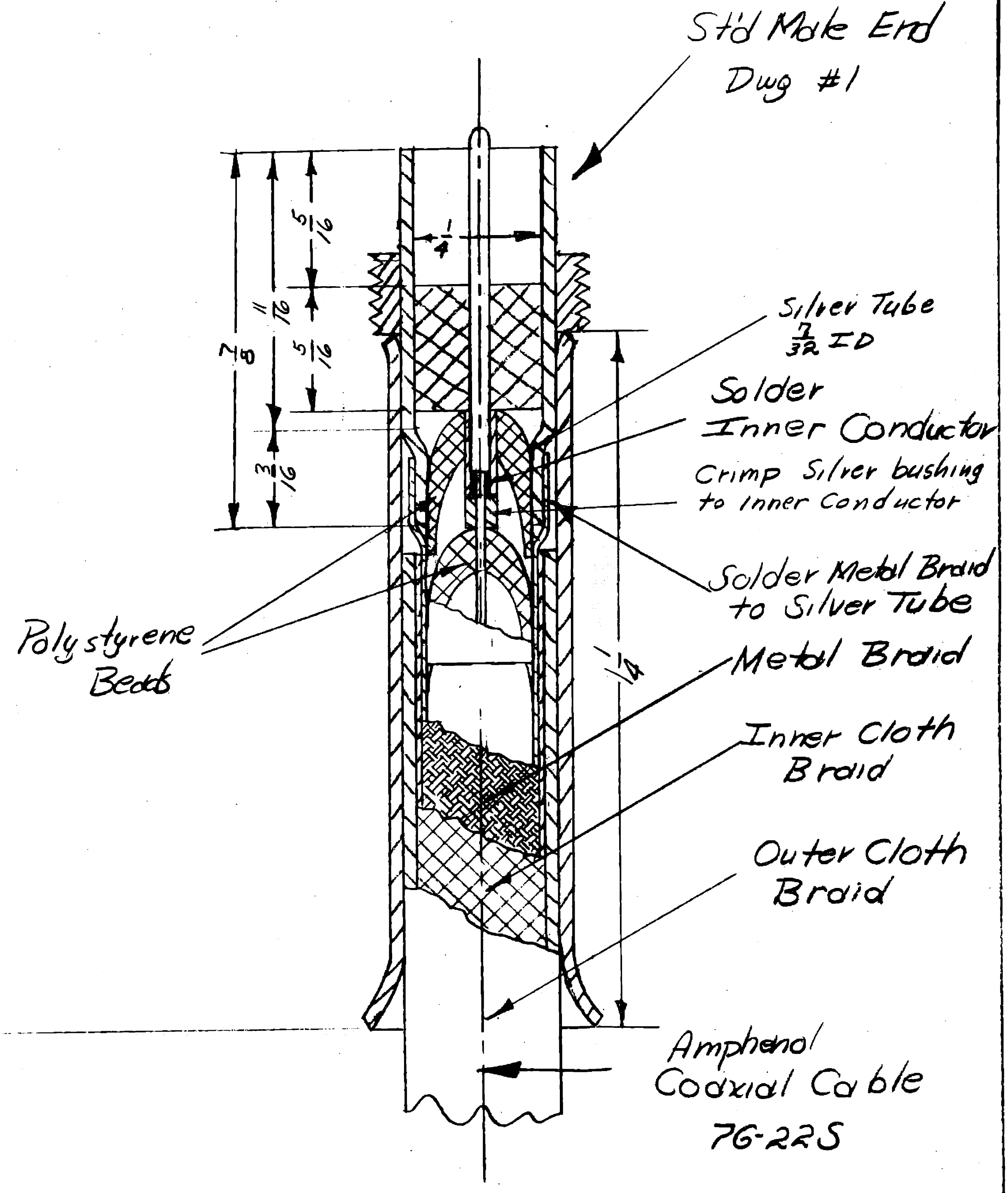
NOT TO SCALE
10-16-42
5-3-43
CH. BY #

STD. NU.
FE BCOV

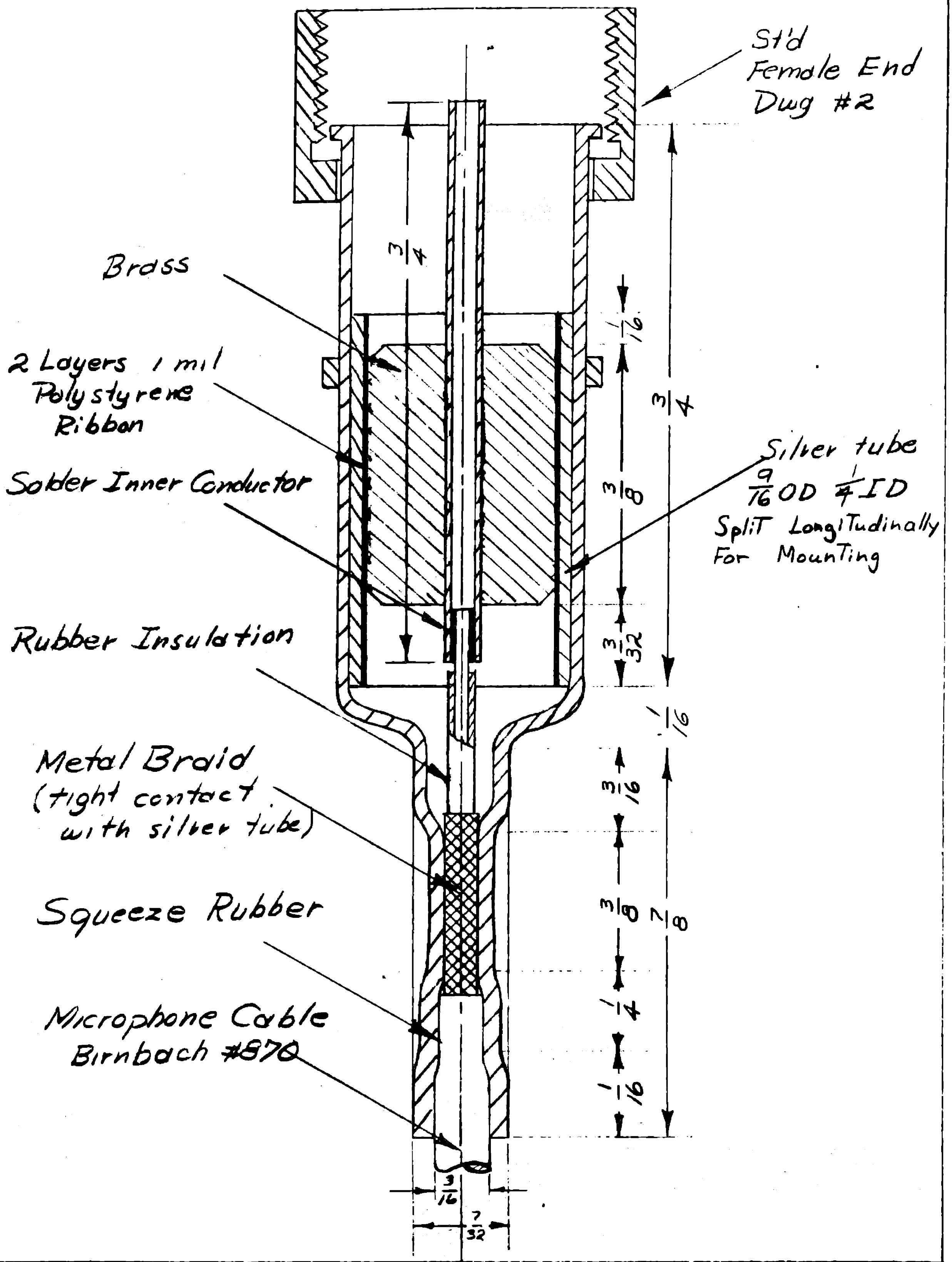
23



Female Cable End	Not To Scale	FC
	2-4-43	24
	Dr BP Ch#	



Male Cable End	Not To Scale	MC
	2-4-43	25
	Dr BP Ch L	



Coaxial D-C End

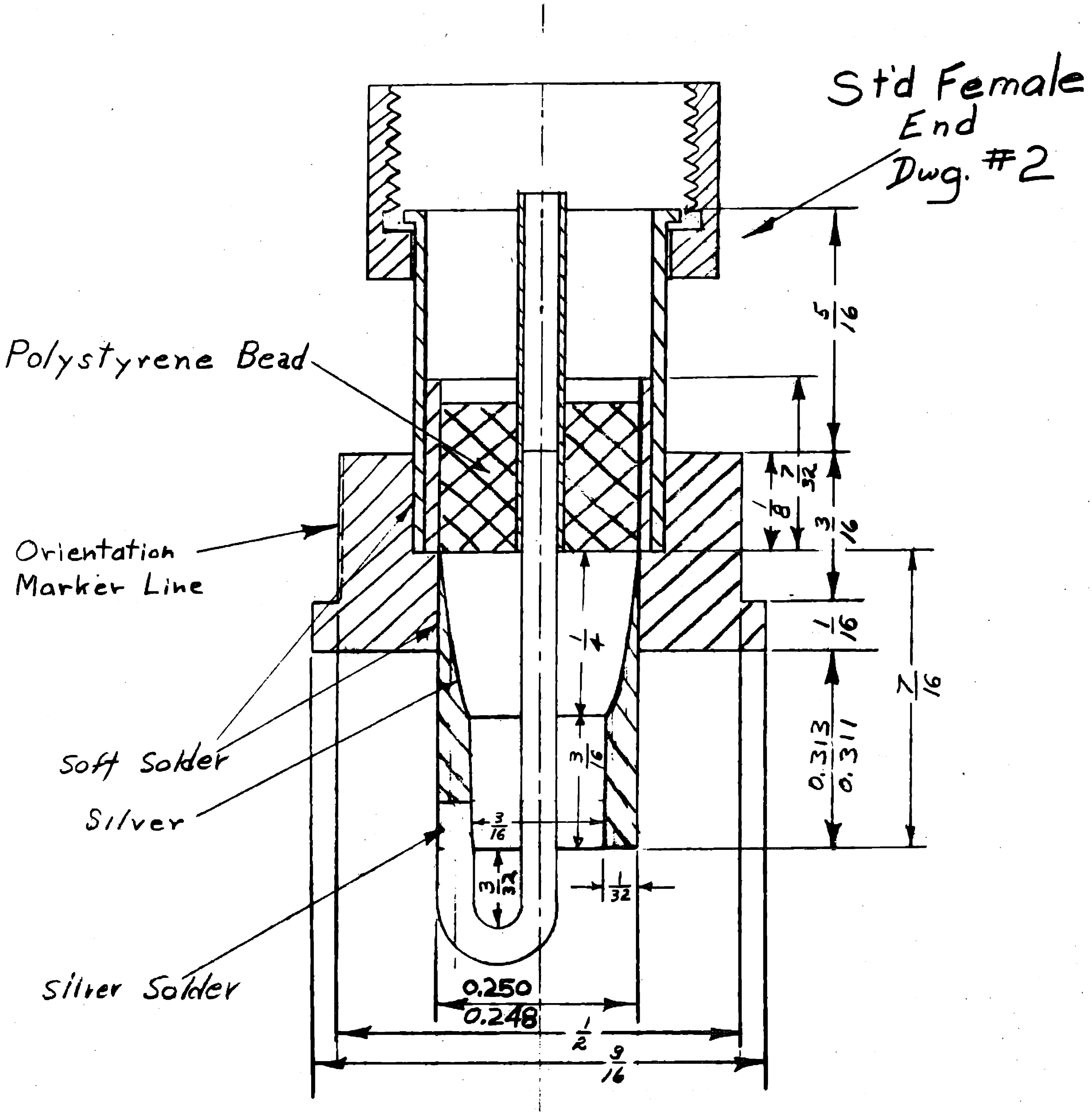
Not To Scale

2-4-43

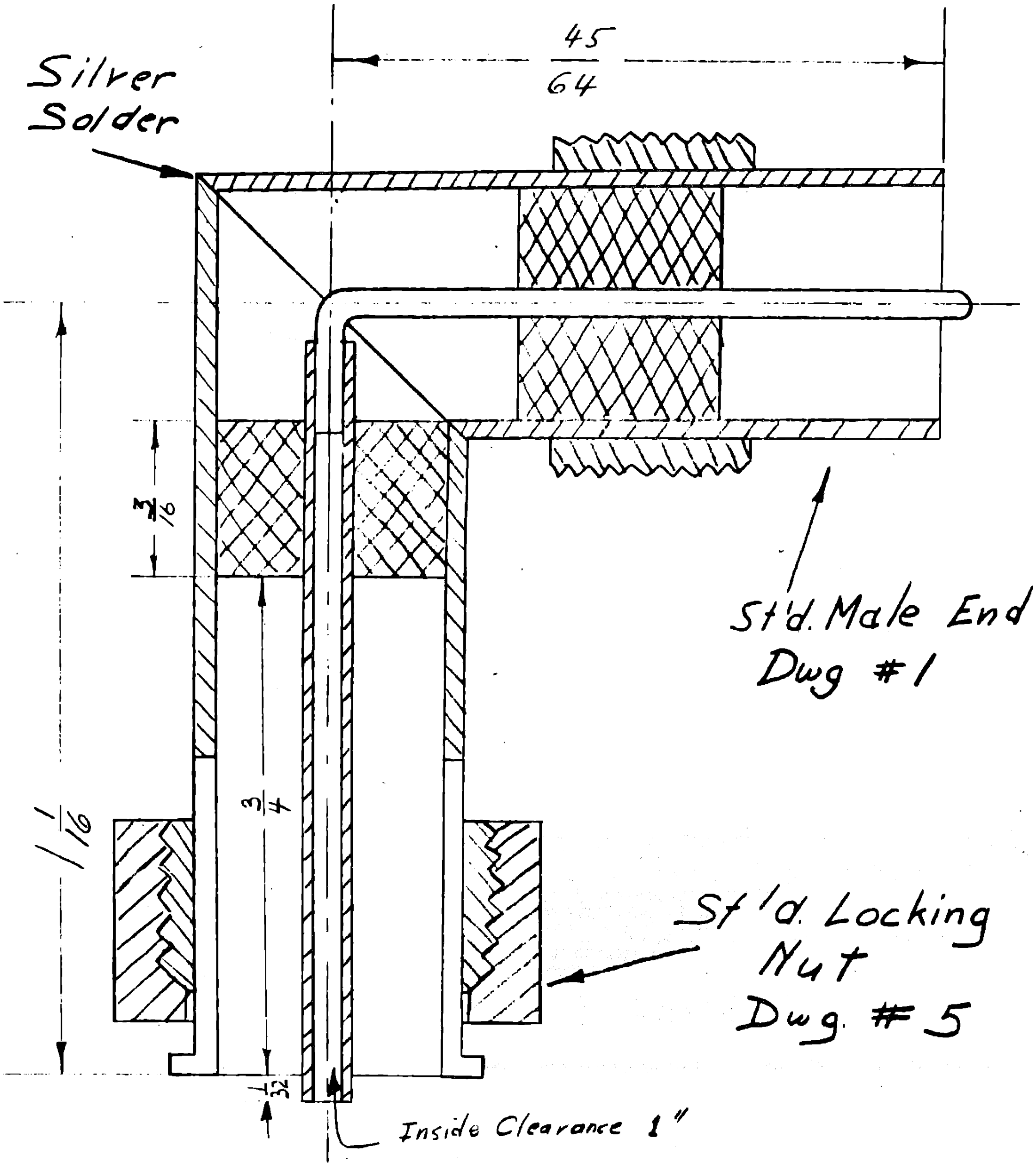
Dr BPCh #

CDC

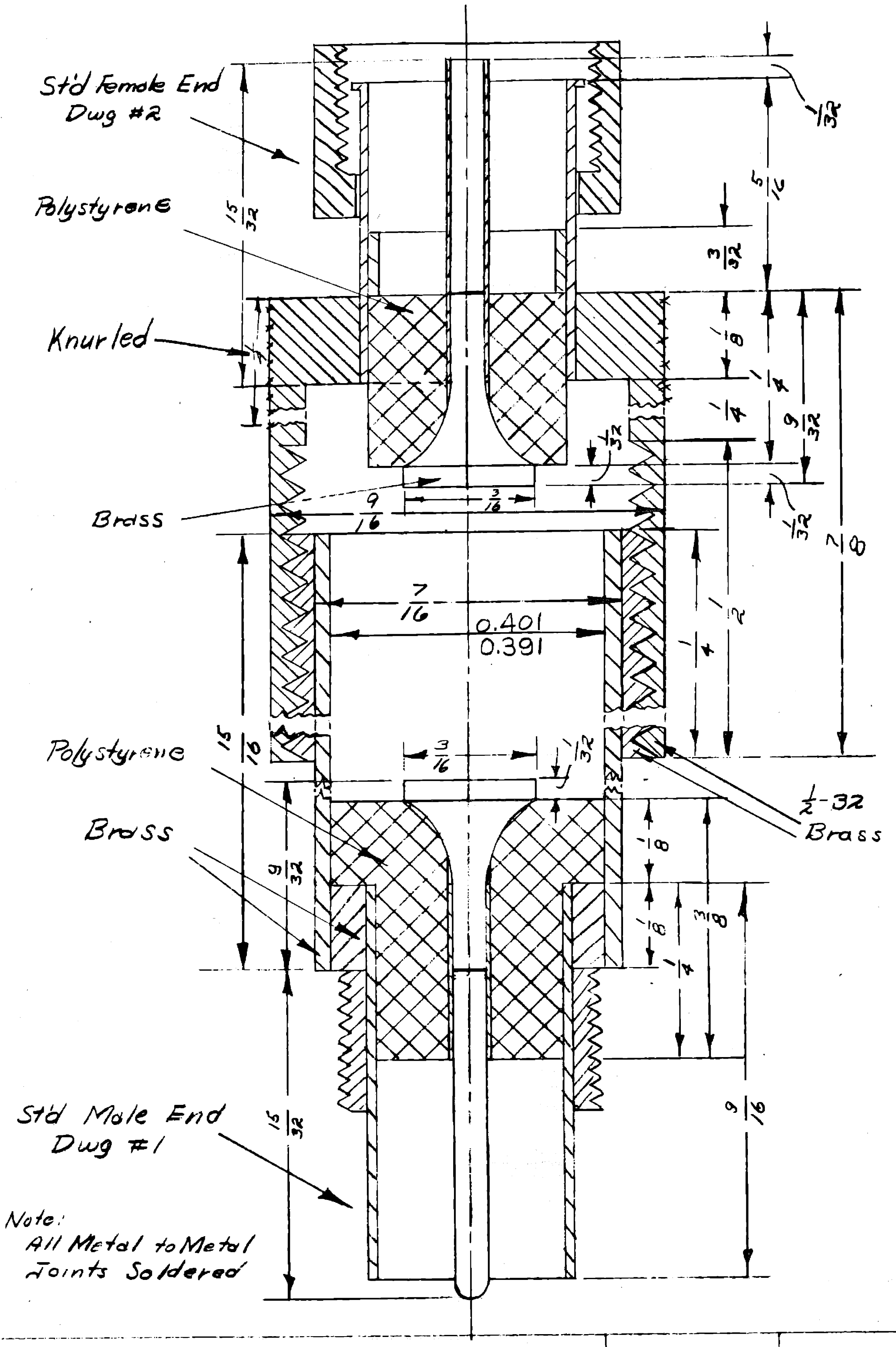
26



Wavemeter Loop	Not To Scale	WL
	4-2-43	27
	Dr BP Ch	



Male Corner AnTenna Adapter	Not To Scale	MCAA
	2-4-43	
	Dr. S Ch. #	28



Note:
All Metal to Metal
Joints Soldered

Element Holder

Not To Scale

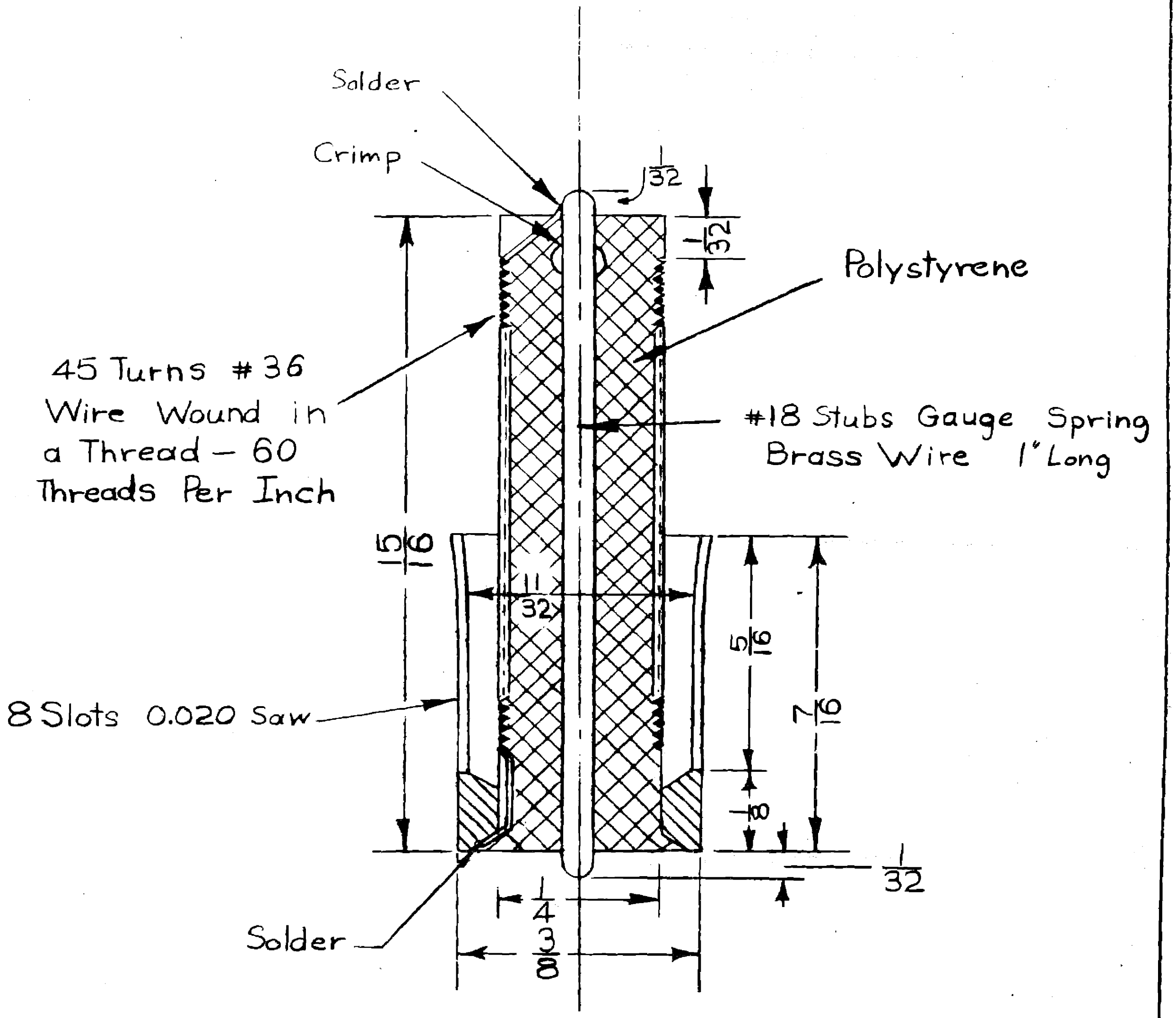
2-4-43

Dr BP Ch #

EH

29

Note: To Be Inserted in Element Holder Dwg. #29

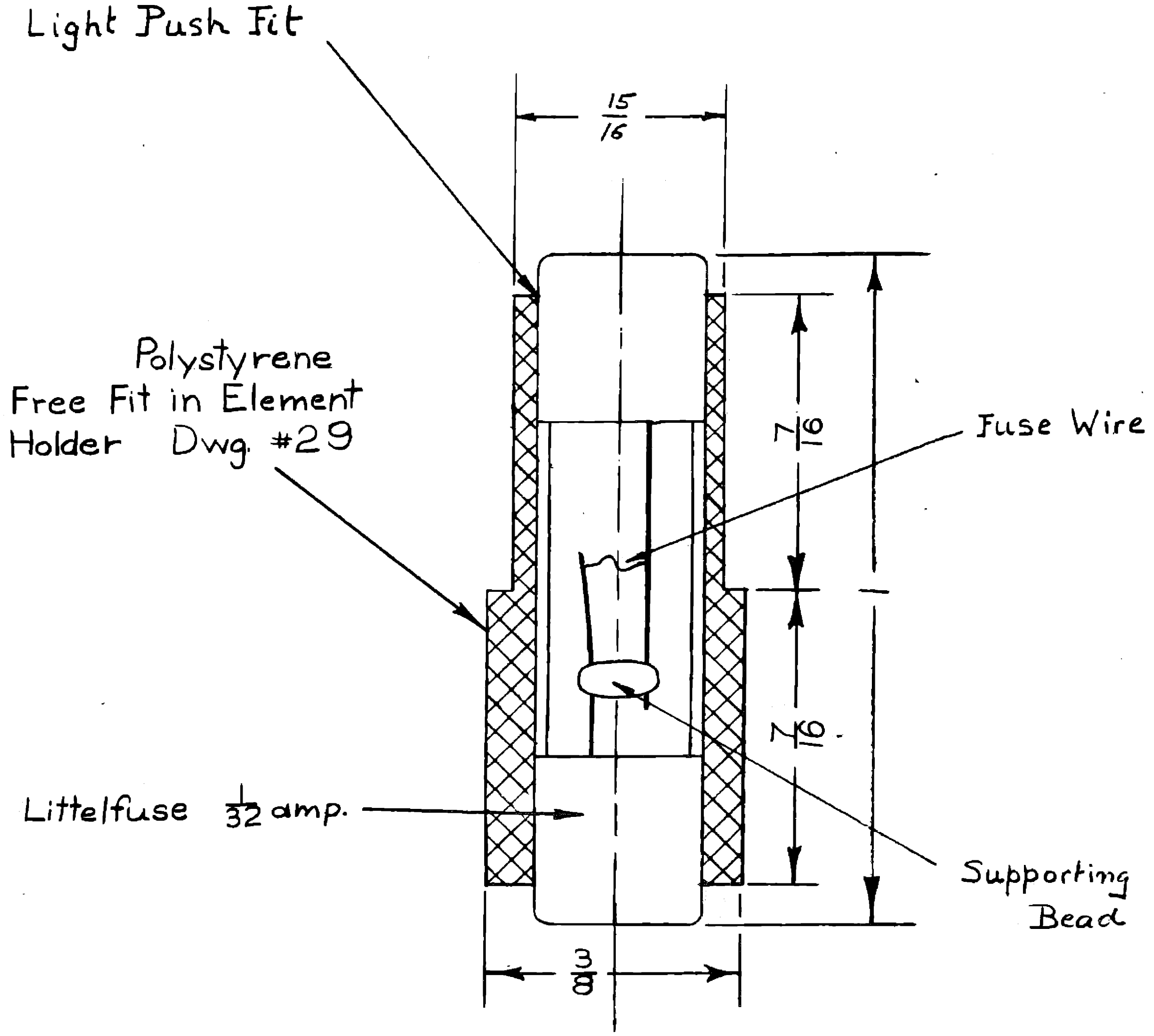


Choke

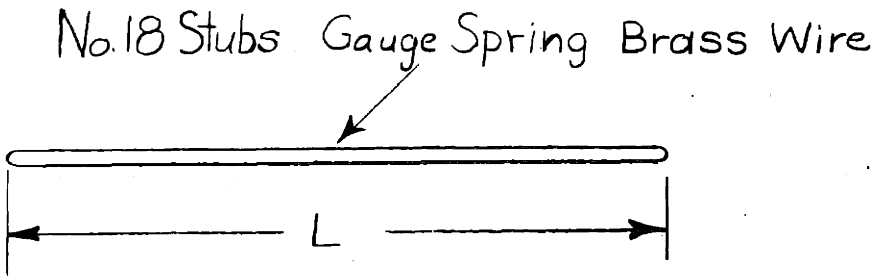
Not To Scale
3 - 5 - 43
5 - 3 - 43
Dr: J. L. Ch: #

Cho

31

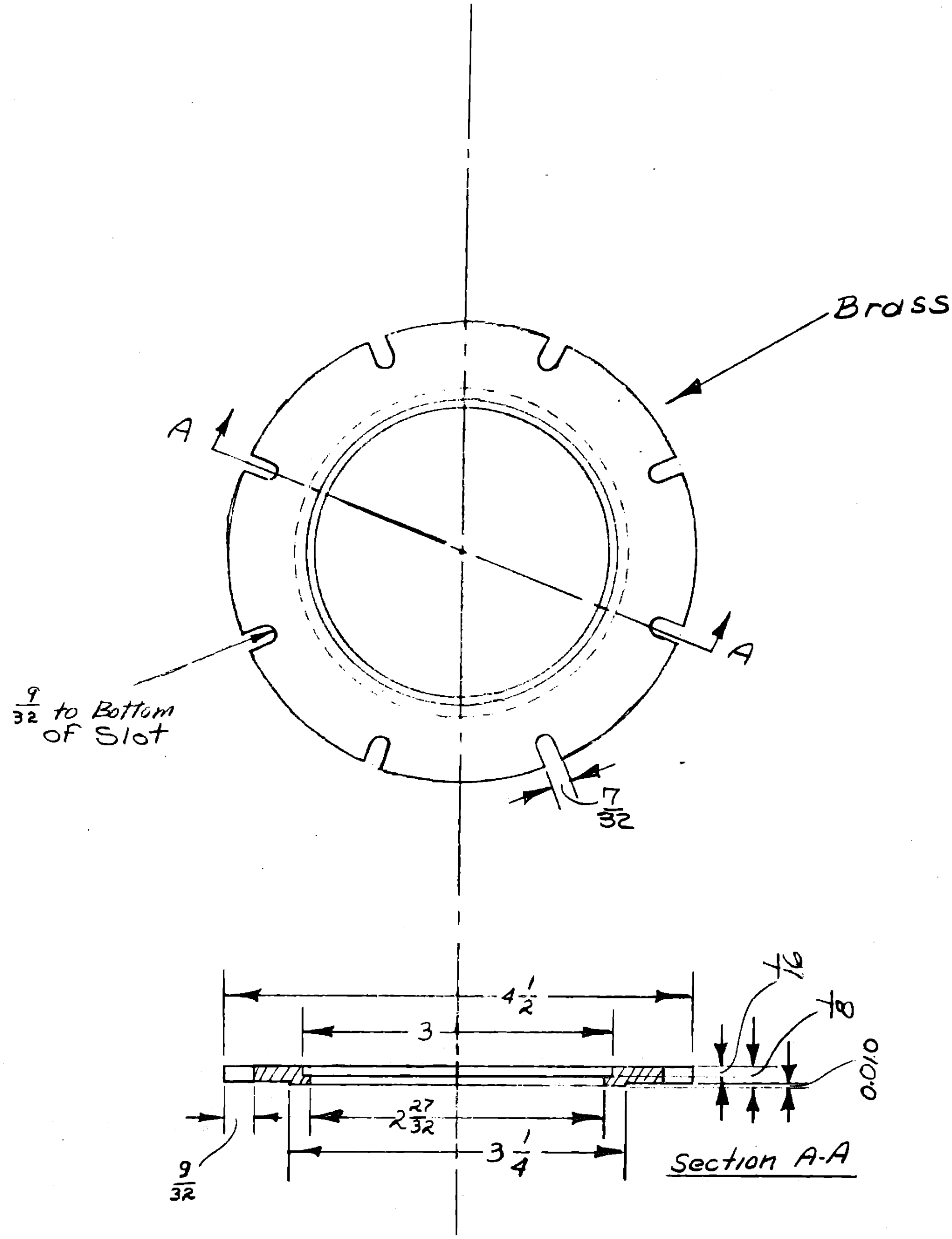


Resistance	Not To Scale	Res
Littelfuse $\frac{1}{32}$ Amp.	3 - 8 - 43 5 - 4 - 43	32
	Dr: J.L. Ch:	



Description	Code	Length	No. Per Set
Small Electrostatic Probe	SEP	$\frac{11}{16}$	4
Large Electrostatic Probe	LEP	$1\frac{1}{8}$	4
Driver Rod For Rectangular Pipe	RDR	$2\frac{1}{2}$	3
Driver Rod For Circular Pipe	CDR	4	4

Electrostatic Probes and Driver Rods	Not To Scale	EP DR
	2-4-43	33
	Dr: J. L. Ch: #	



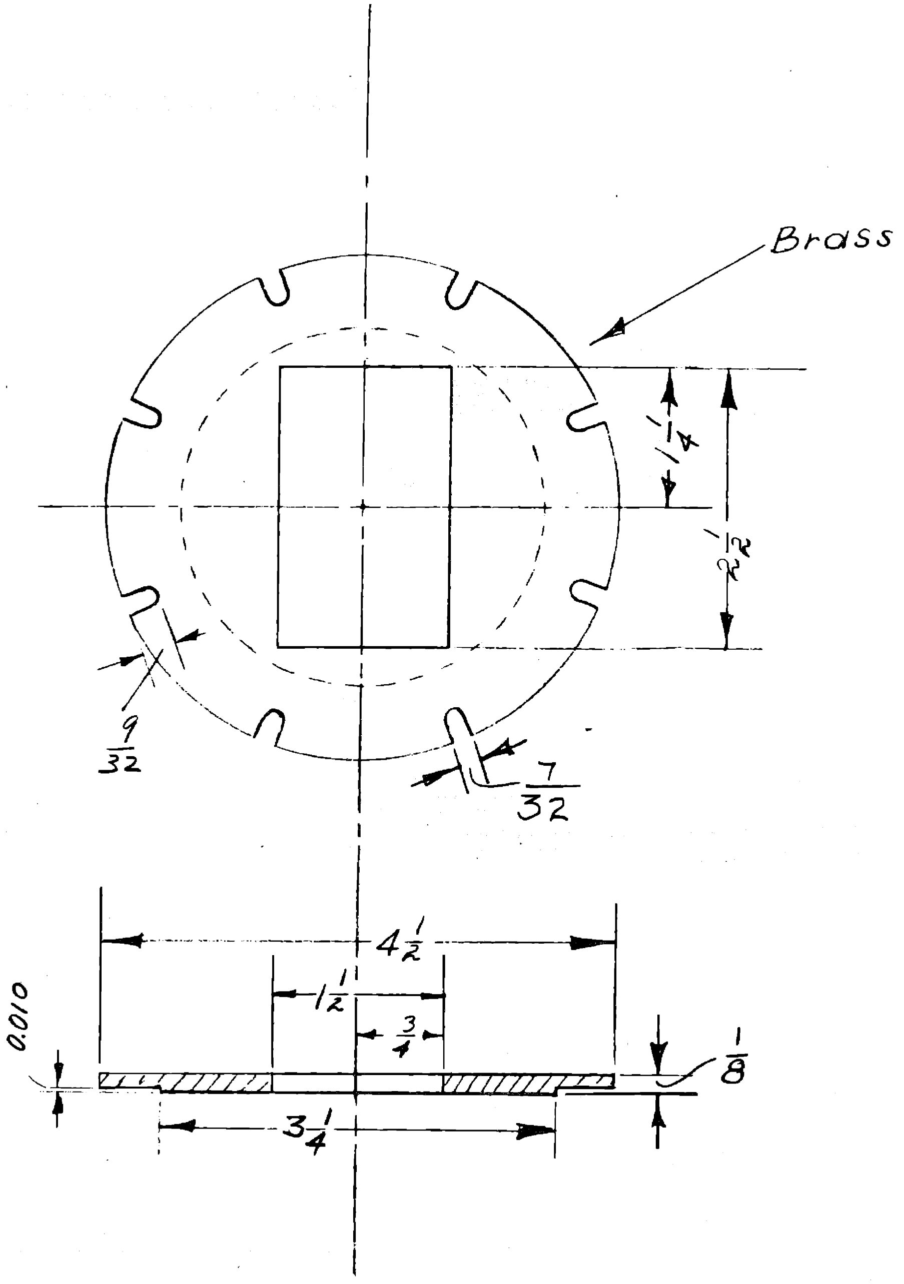
Standard
Circular Flange

Not To Scale
10-22-42
5-3-43
Dr BP Ch#

Std C FL

34

NOTE: FOR SECTORAL HORN,
DWG. #42, RECTANGLE HAS
DIMENSIONS 1.34 x 2.34

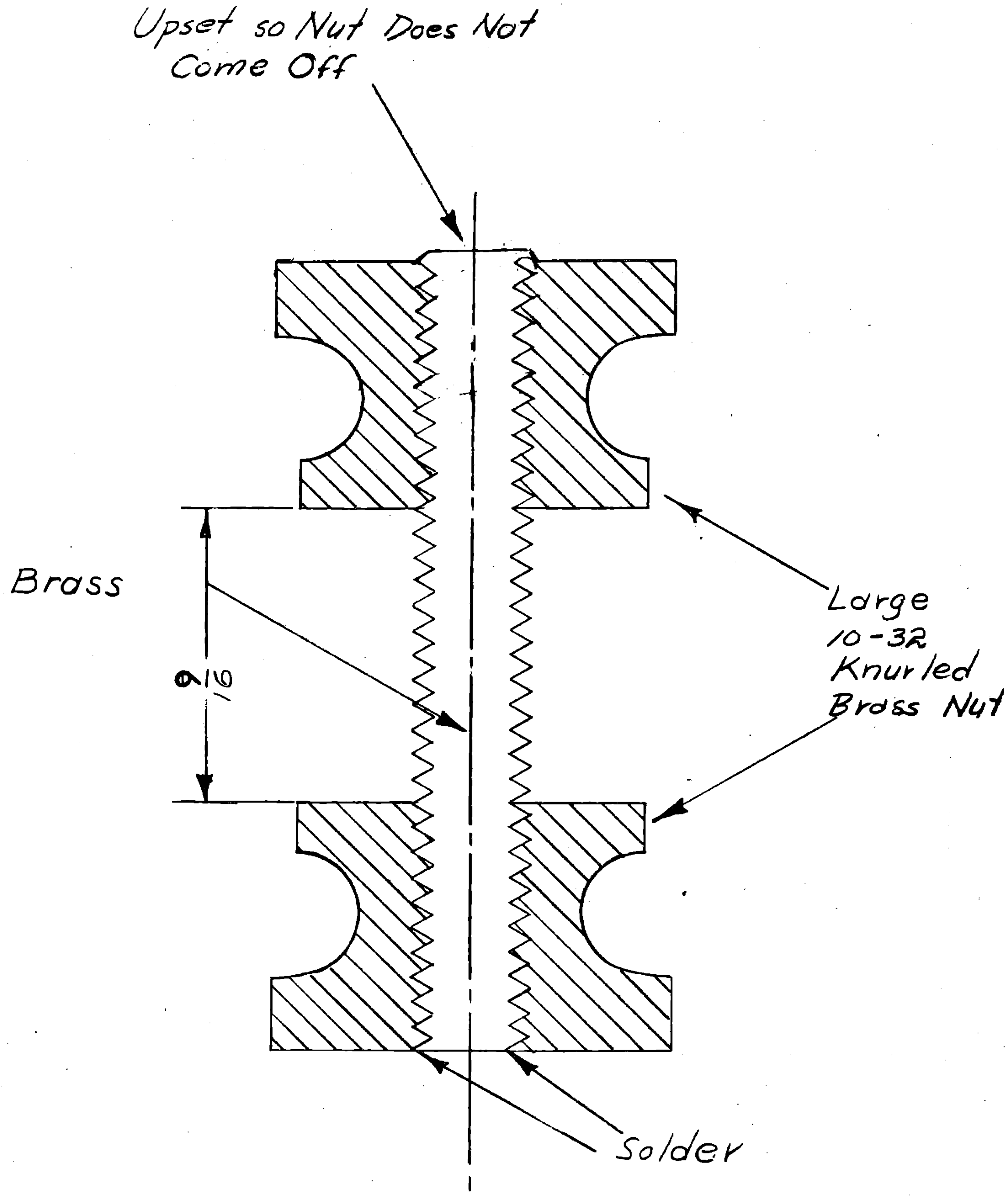


Standard Rectangular Flange

Not To Scale
10-22-42
5-3-43
Dr. BP Ch. #

Std RFL

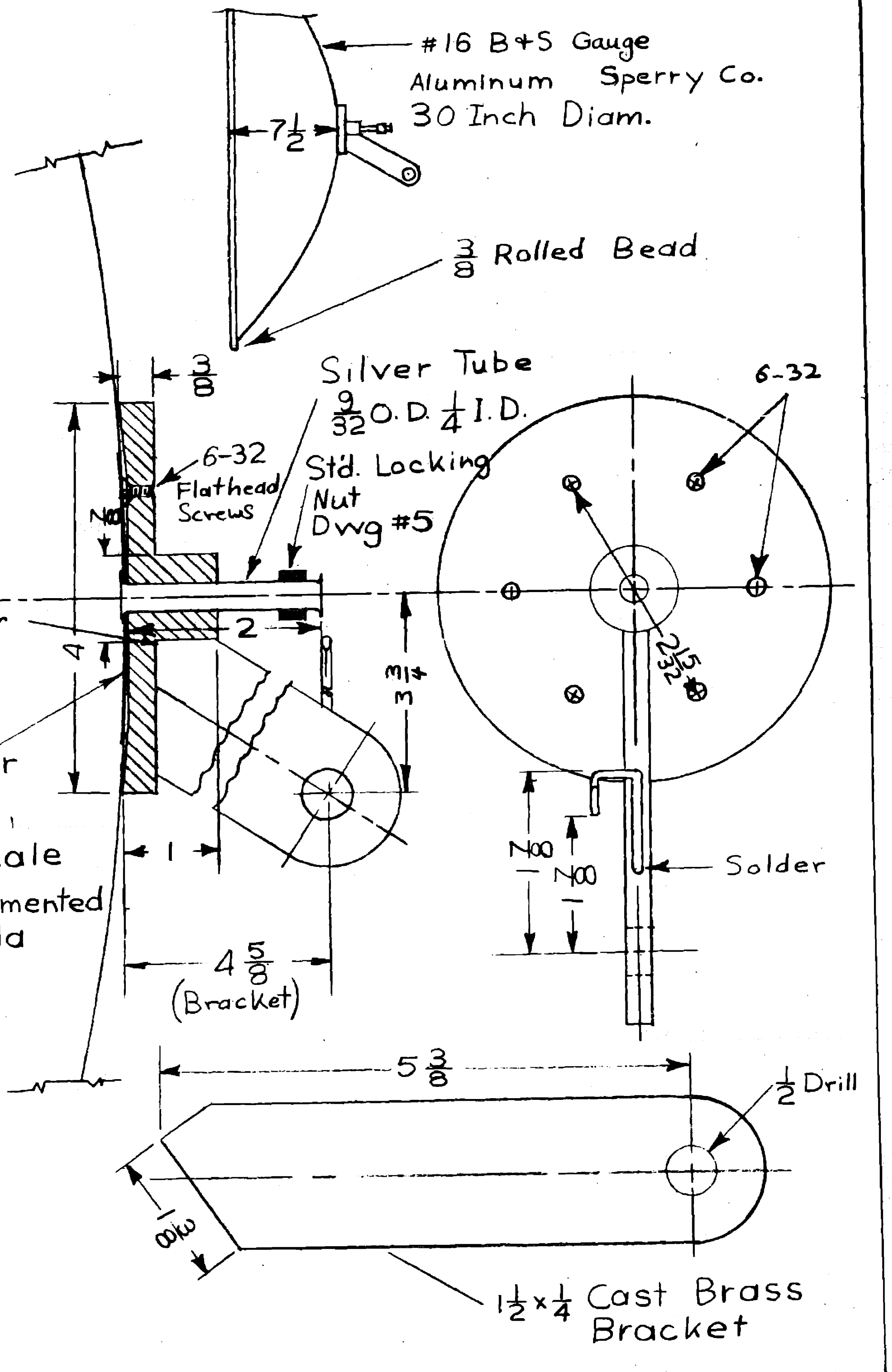
35



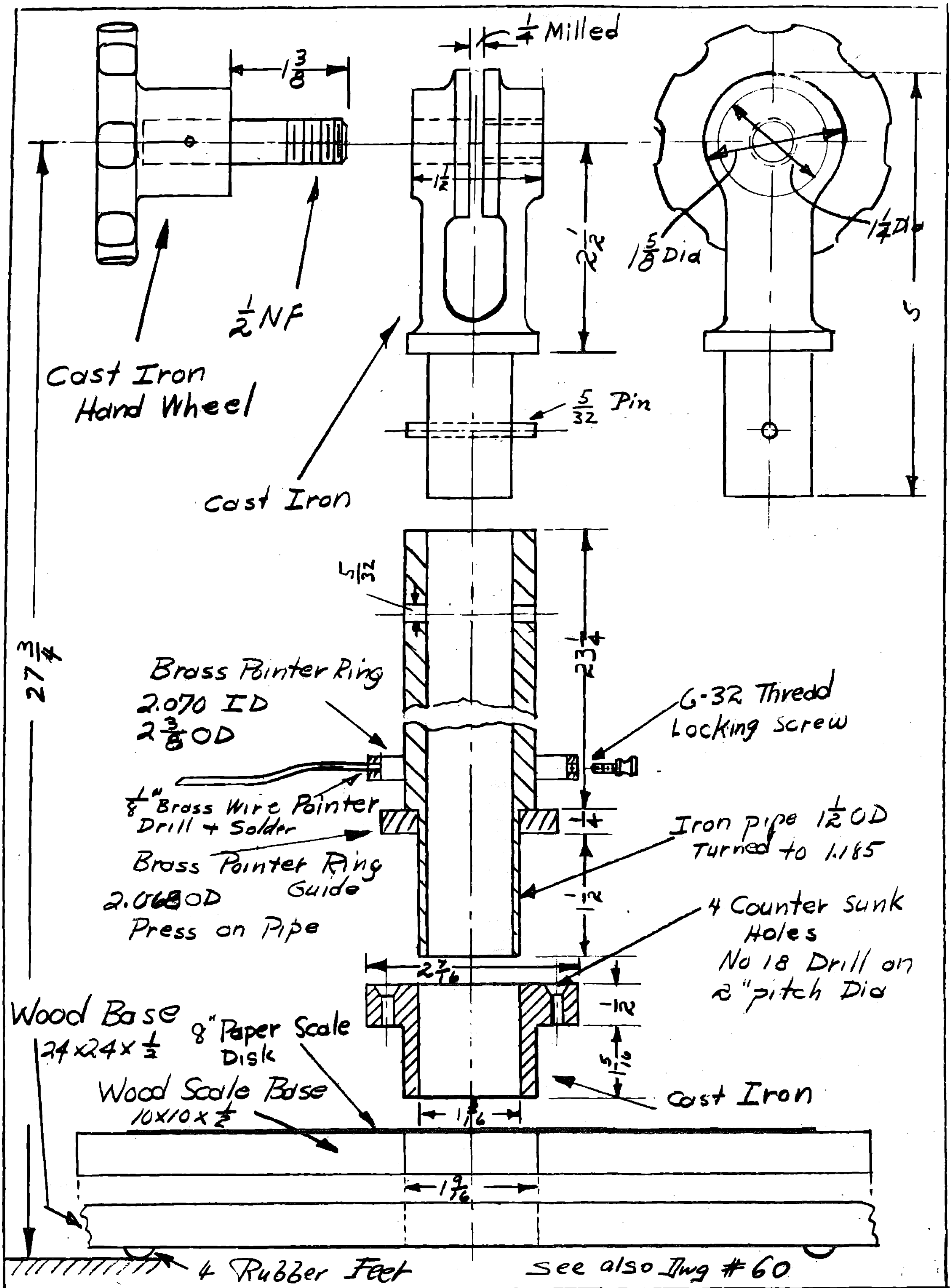
Flange Clamp

Not to Scale
2-4-43
Dr. BP Ch. E

Std. Fl Cl.
36

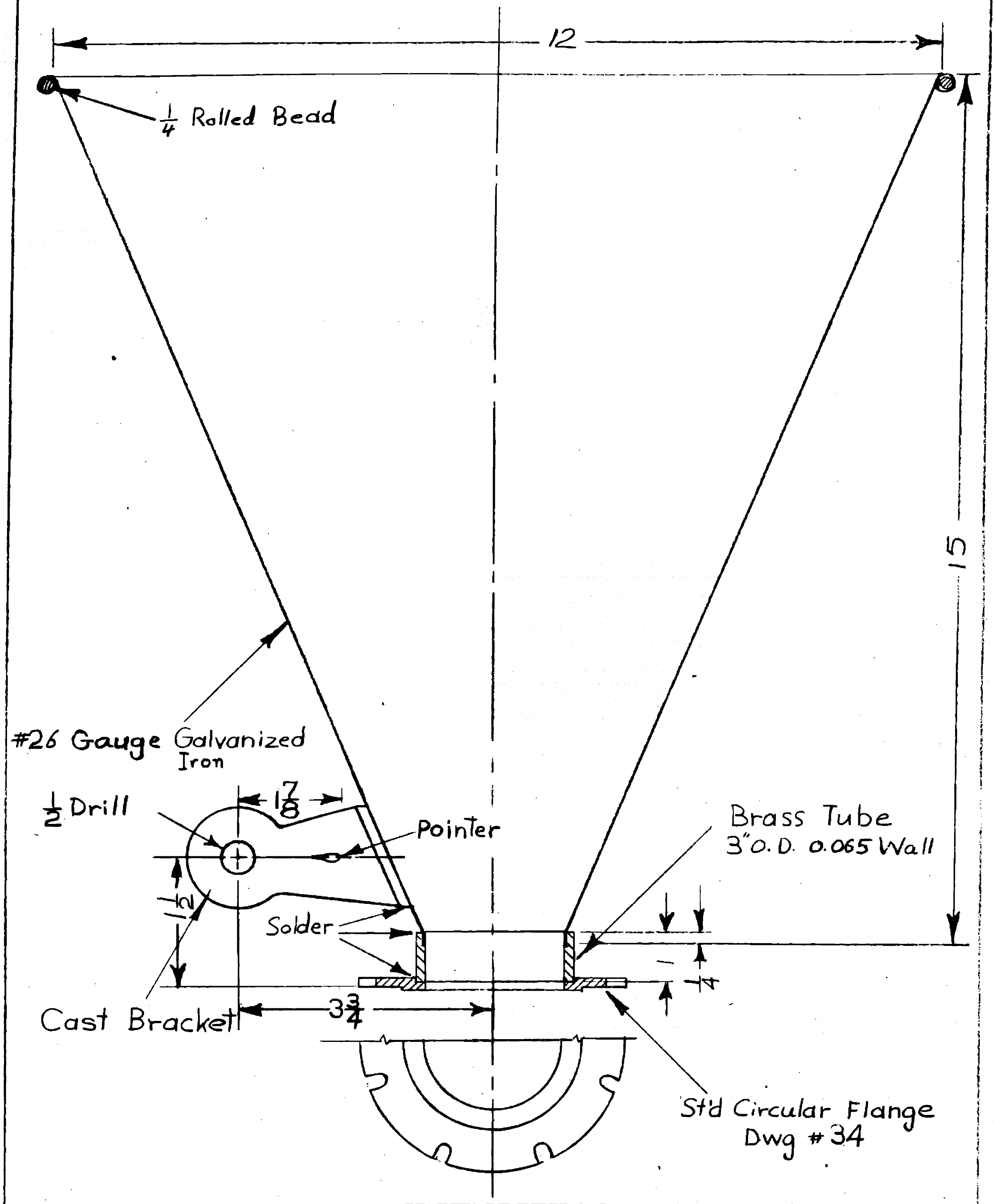


Parabola Reflector	Not To Scale	Par.
	1-30-43	38
	Dr. J.L. Ch.#	



Radiator Stand

Not to Scale	Ra. St
1-30-43	39
Dr. B.P. Ch: #	



Circular Horn

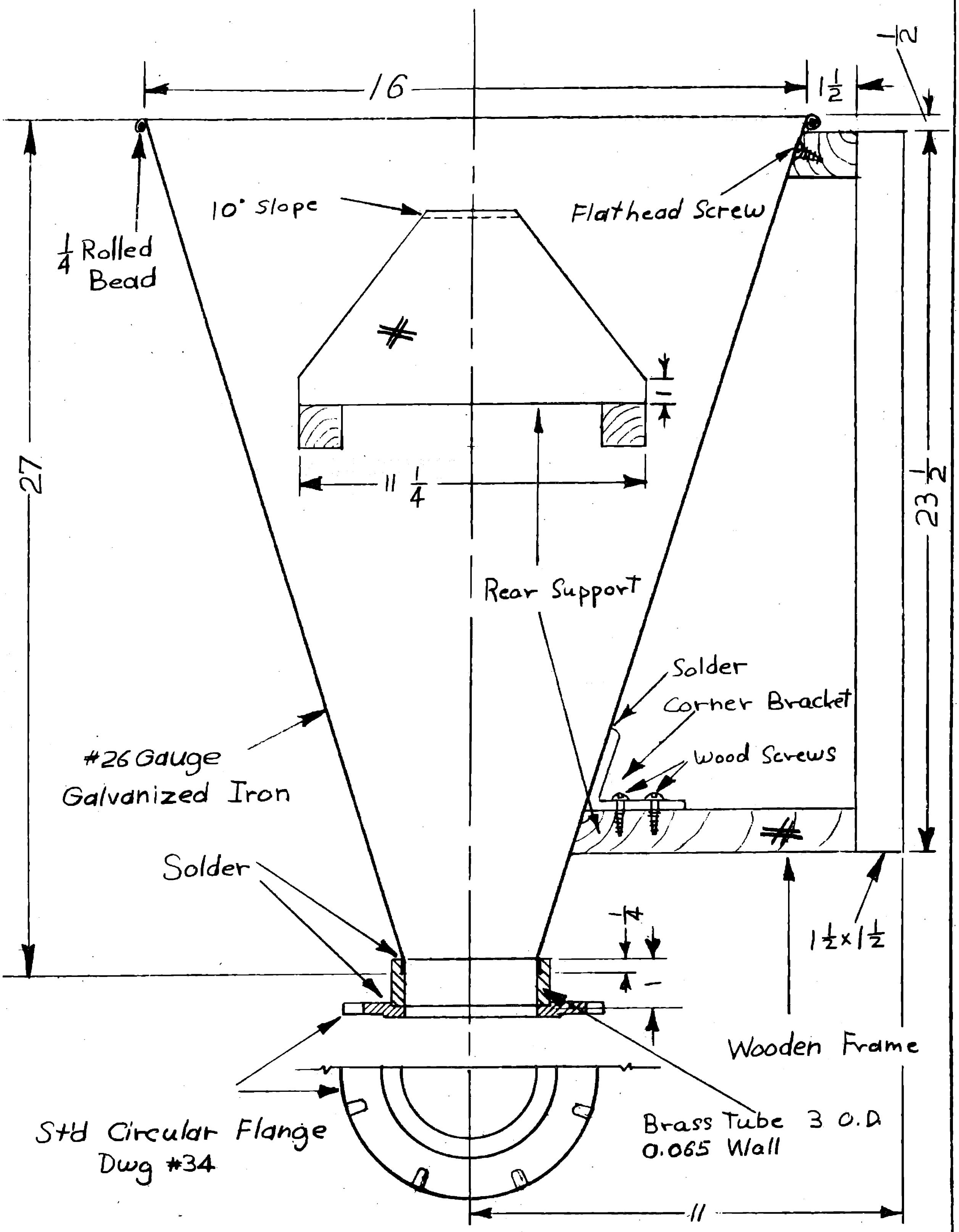
Not To Scale

2-1-43

Dr. J.L. Ch: #

CH

40



Not To Scale

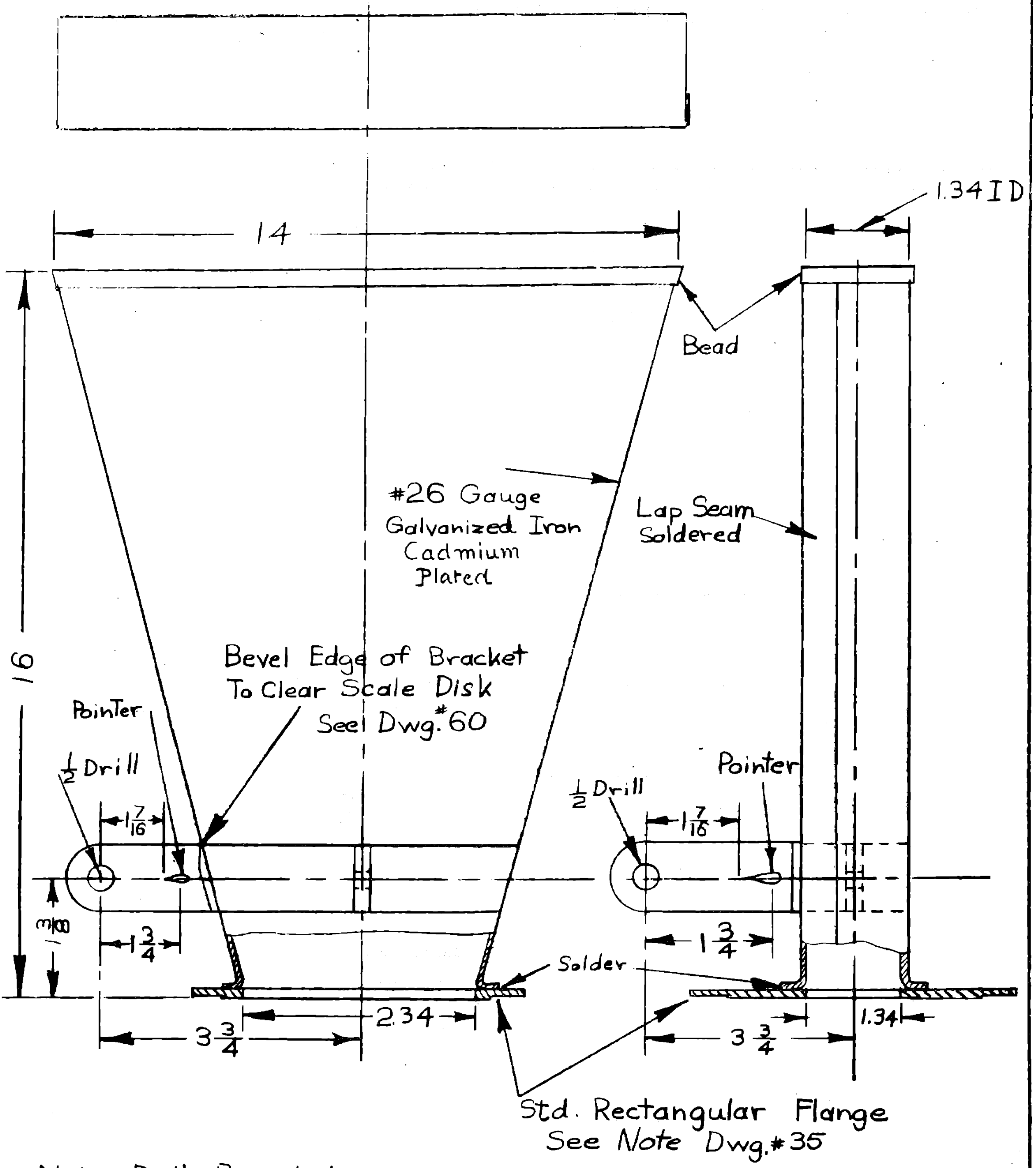
2-2-43

Dr. J.L. Ch: #

LCH

41

Large Circular Horn

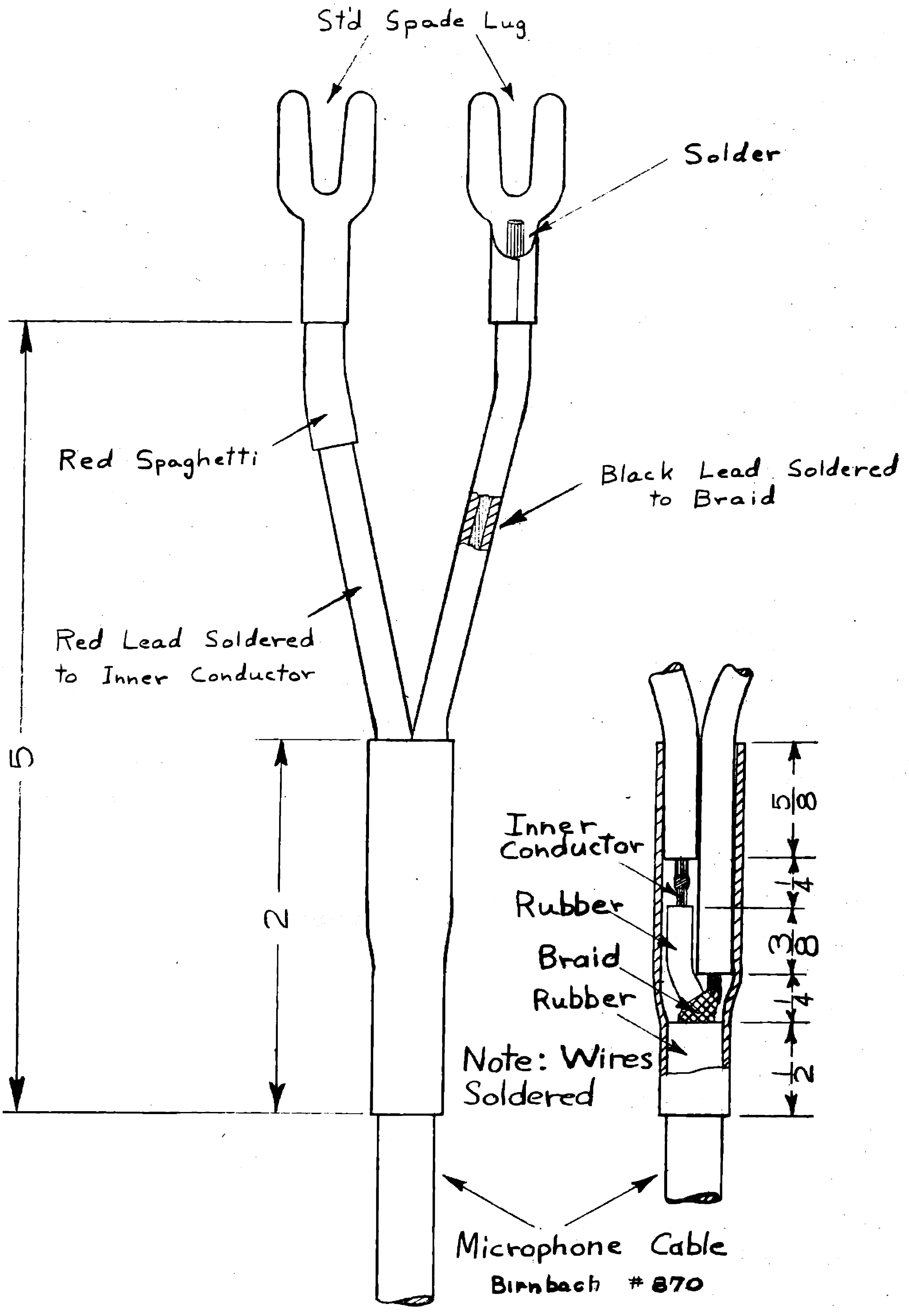


Note: Both Brackets
Cut From $1\frac{1}{2} \times \frac{1}{4}$ Strap Brass

Sectoral Horn

Not To Scale
11-9-42
5-3-43
Dr: J. L. Ch: #

SH
42



Coaxial D-C Cable
D-C End

Not to Scale

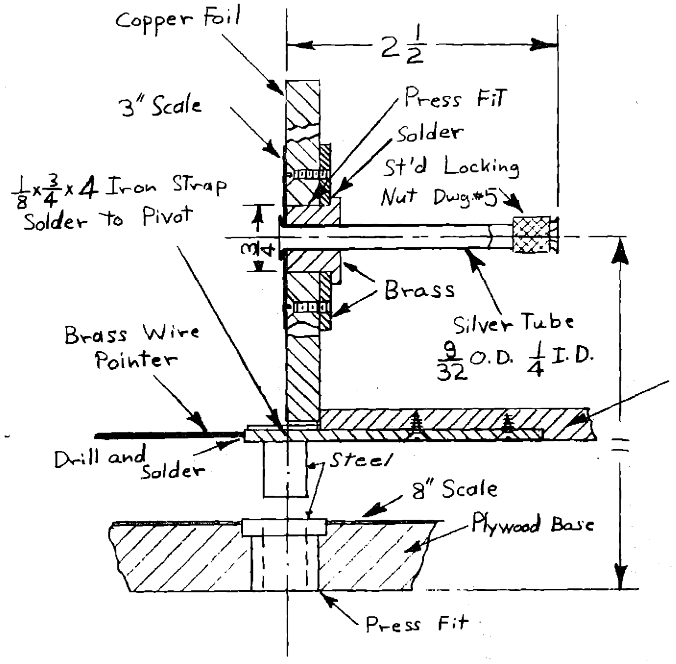
1-29-43

D- J.L. Ch. #

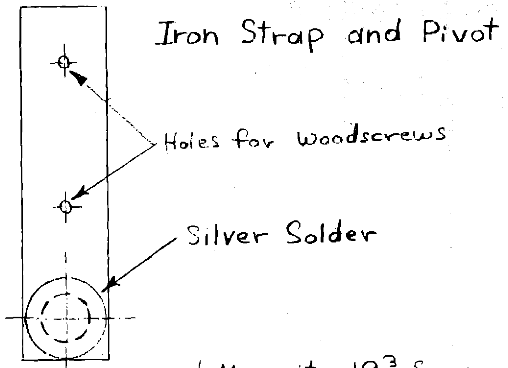
CDC

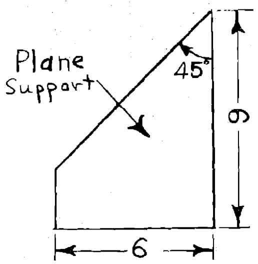
43

Pivot Assembly

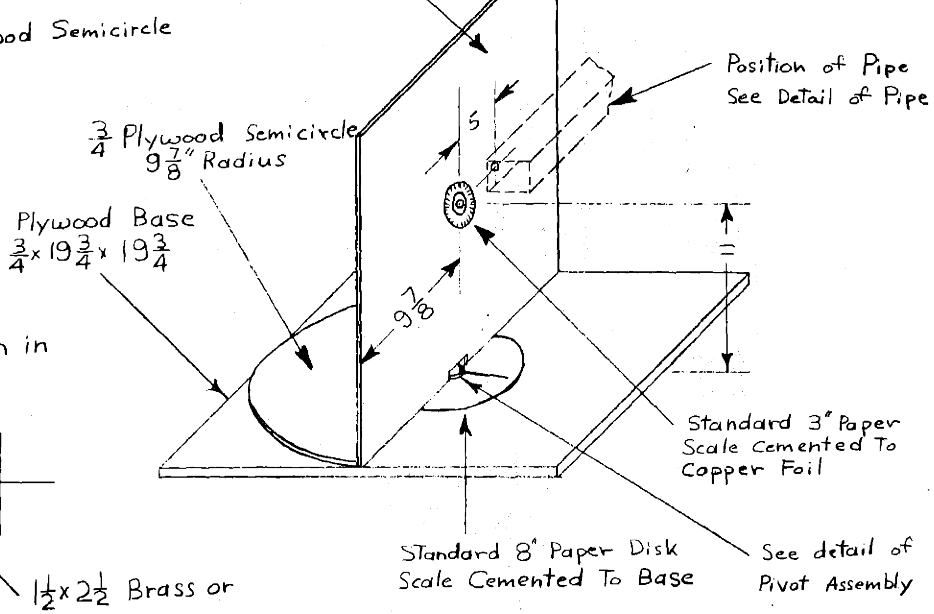


Iron Strap and Pivot

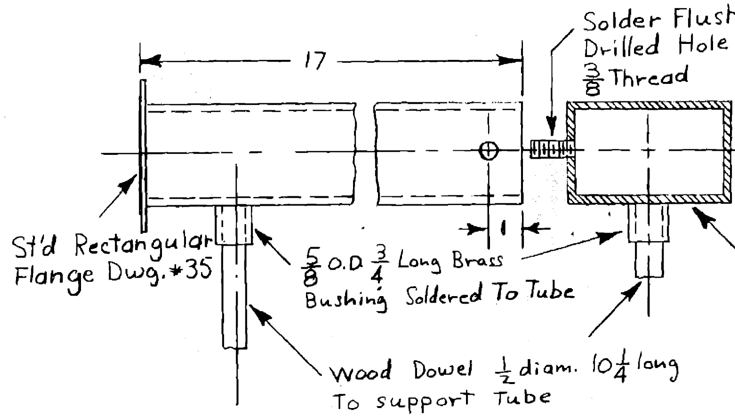




Note: Masonite Plane Fastened To Semicircle With two Triangular Pieces of Wood.



Note: Three Thumbtacks Evenly Spaced in Bottom of Semicircle. Four Rubber Buttons on Bottom of Base

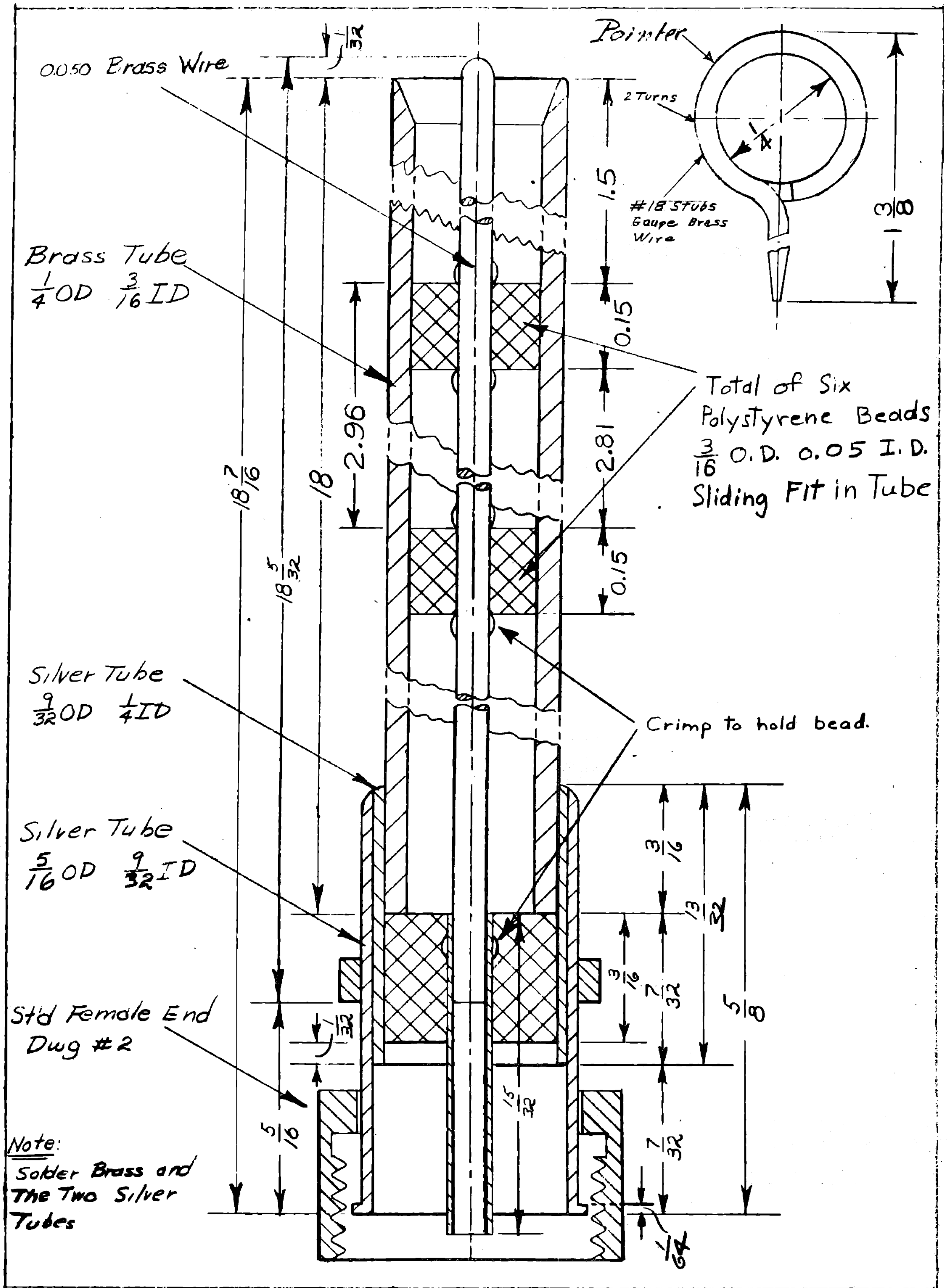


Rectangular Pipe Section

Reflecting Plane

Not To Scale
2 - 3 - 43
Dr: J.L. Ch: #

RfPl
44



Antenna Rod

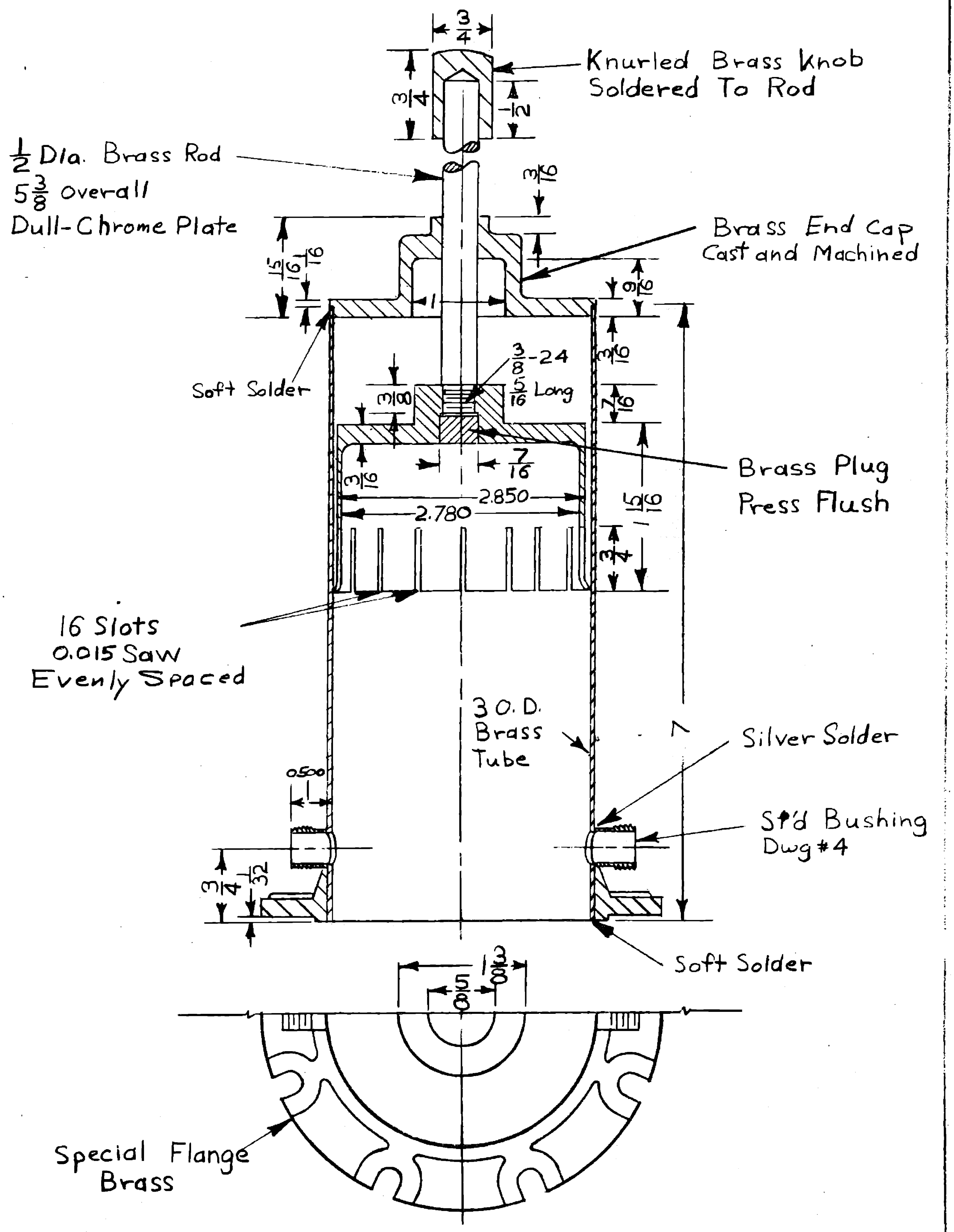
Not to Scale

1-29-43

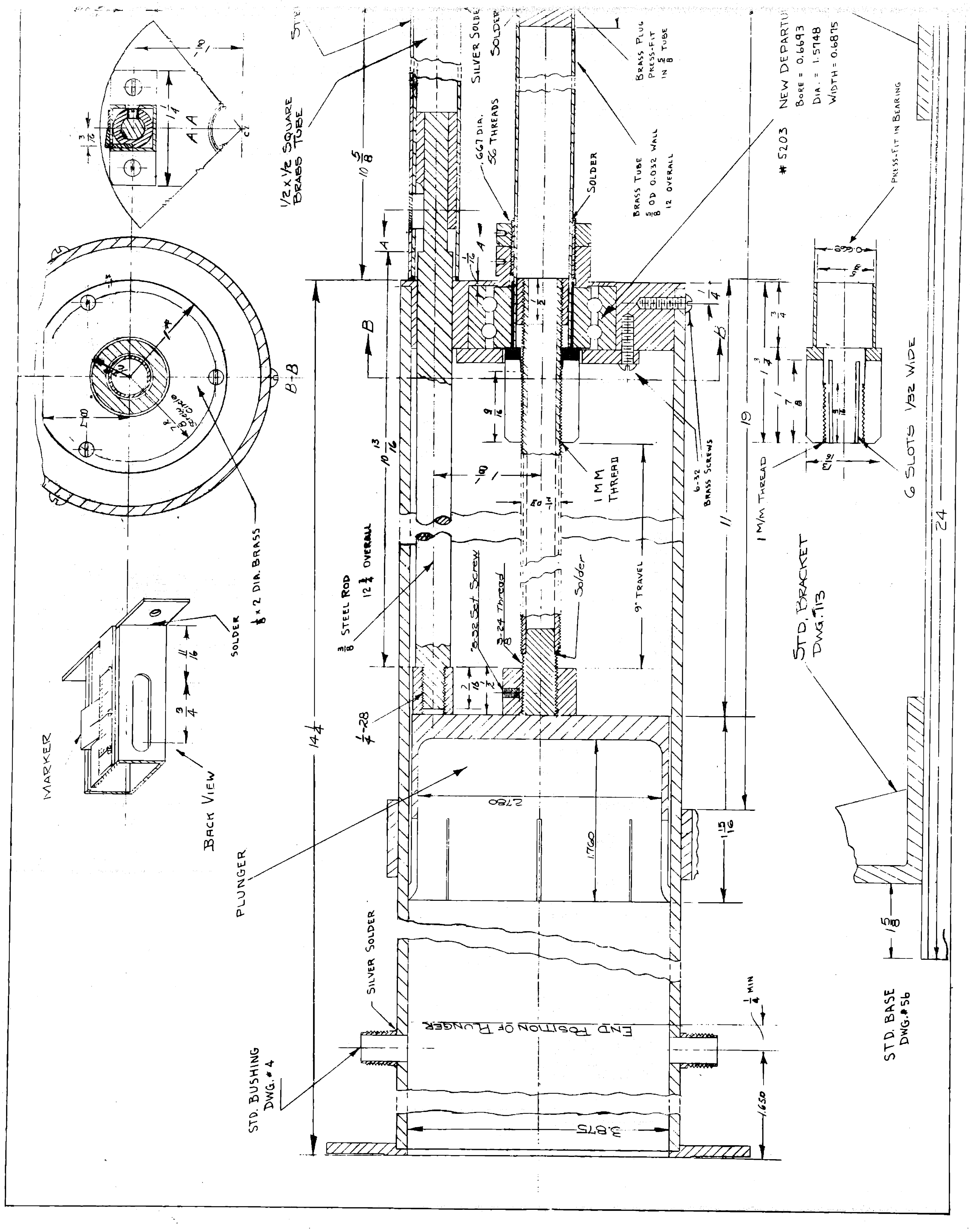
Dr Ch #

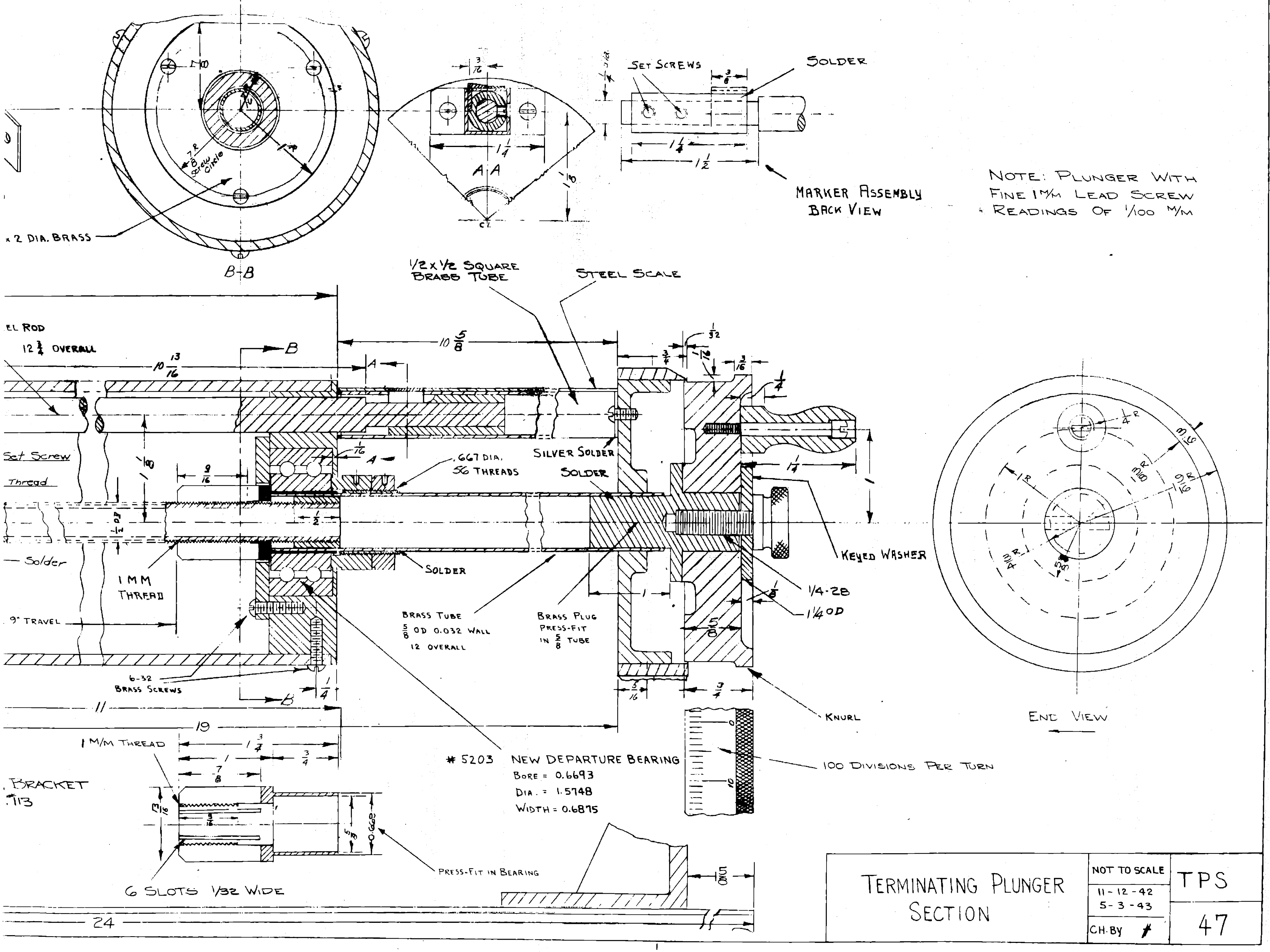
AR

45



Circular Driver	Not To Scale 2-4-43 Dr: J.L. Ch: #	CD 46


MARKER
BACK VIEW
SOLDER
11/16
3/4
1/8 x 2 DIA. BRASS
B-B
A-A
1 1/4
3/16
PLUNGER
STD. BUSHING DWG. # 4
SILVER SOLDER
END POSITION OF PLUNGER
3.875
1.650
1/4 MIN
STD. BASE DWG. #56
1 5/8
24
STD. BRACKET DWG. 113
2.780
1.760
1 15/16
14 1/4
3/8 STEEL ROD 12 1/4 OVERALL
1/4-28
8-32 Set Screw
3/8-24 Thread
Solder
9" TRAVEL
10 13/16
1 MM THREAD
6-32 BRASS SCREWS
11
19
1 M/M THREAD
6 SLOTS 1/32 WIDE
PRESS-FIT IN BEARING
1 3/4
7/8
3/4
9/16
1/16
1/4
1/2
1/2 x 1/2 SQUARE BRASS TUBE
10 5/8
.667 DIA. 56 THREADS
SOLDER
BRASS TUBE 5/8 OD 0.032 WALL 12 OVERALL
BRASS PLUG PRESS-FIT IN 5/8 TUBE
SILVER SOLDE
SOLDER
# 5203 NEW DEPARTU
BORE = 0.6693
DIA. = 1.5748
WIDTH = 0.6875



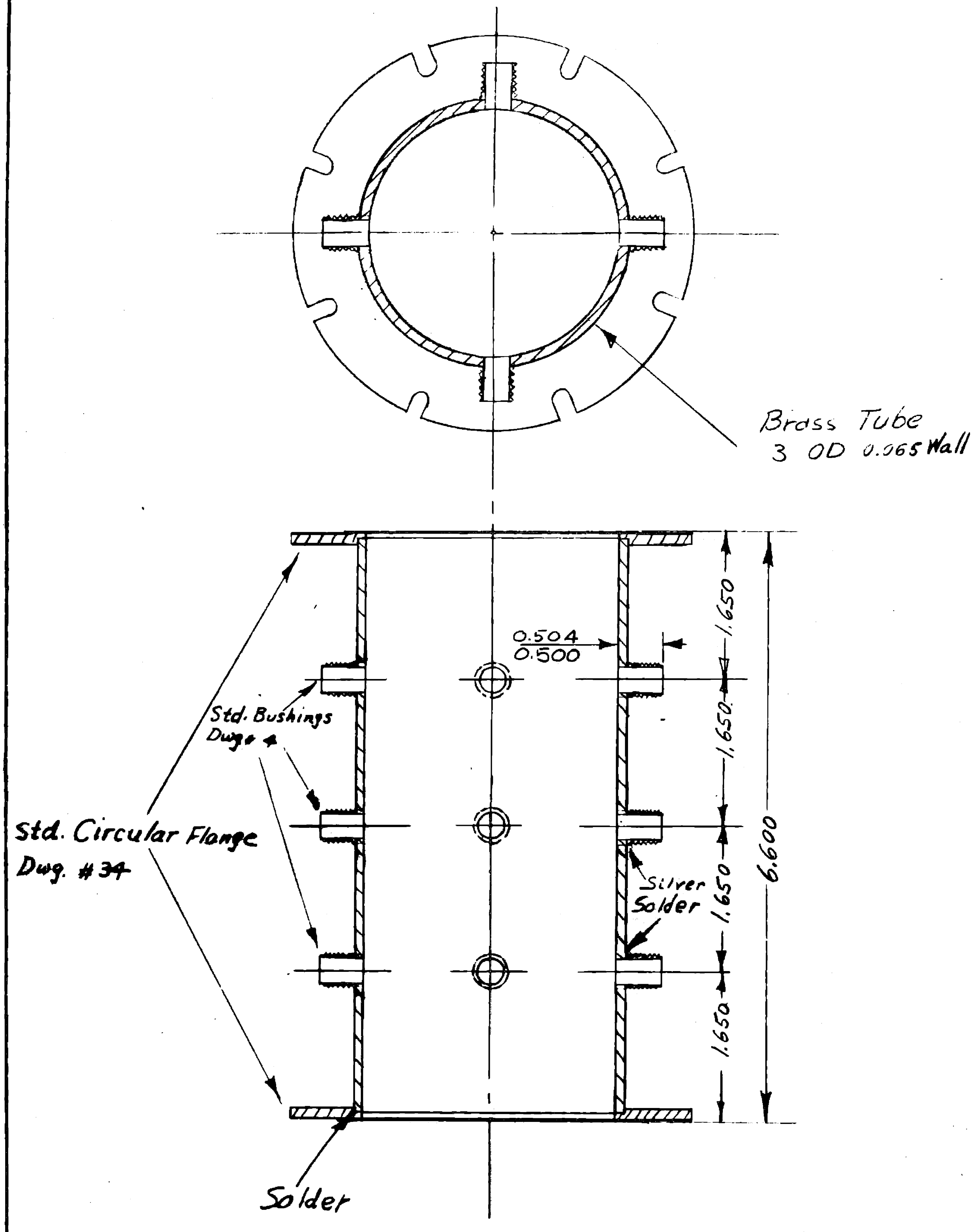
NOTE: PLUNGER WITH FINE 1 M/M LEAD SCREW
READINGS OF 1/100 M/M

TERMINATING PLUNGER SECTION

NOT TO SCALE
11-12-42
5-3-43
CH. BY

TPS

47



Transfer Section

Not To Scale

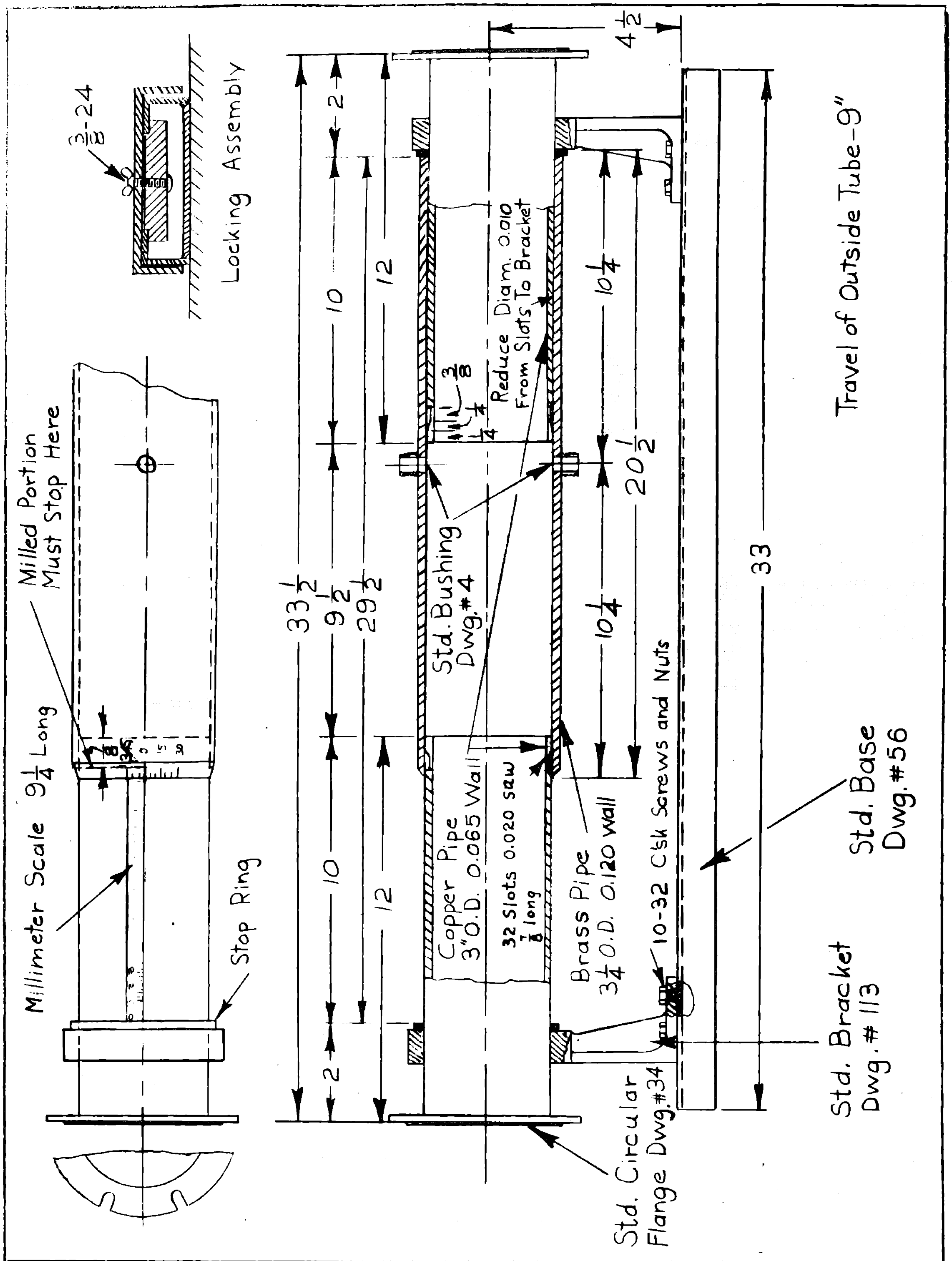
10-30-42

5-3-43

Dr BP Ch #

Tr S

48

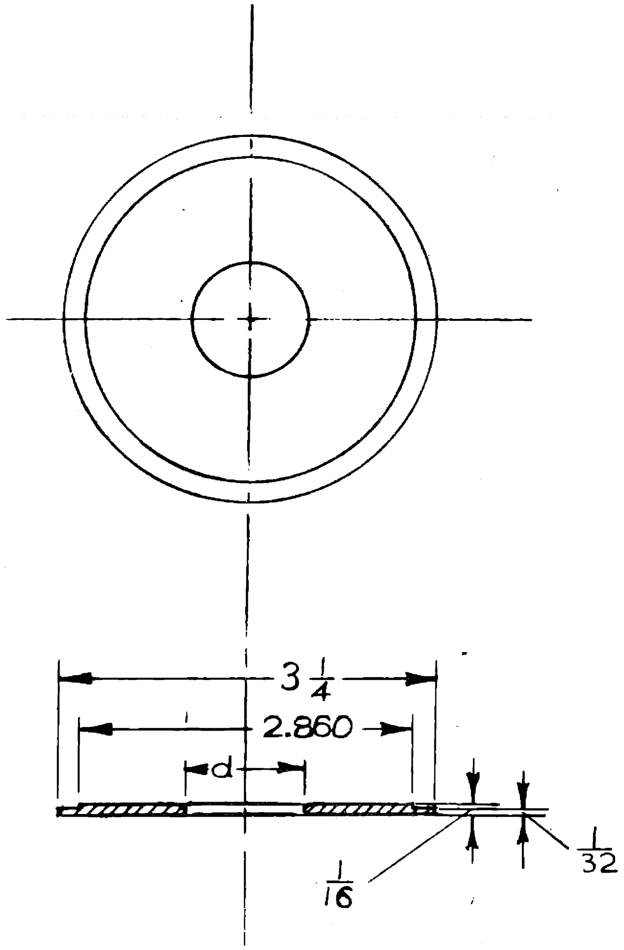


Traveling Detector
Section

Not To Scale
2-28-43
5-3-43
Dr: J.L. Ch:

TDS
49

COUPLING UNIT FOR CIRCULAR WAVE GUIDE CAVITY



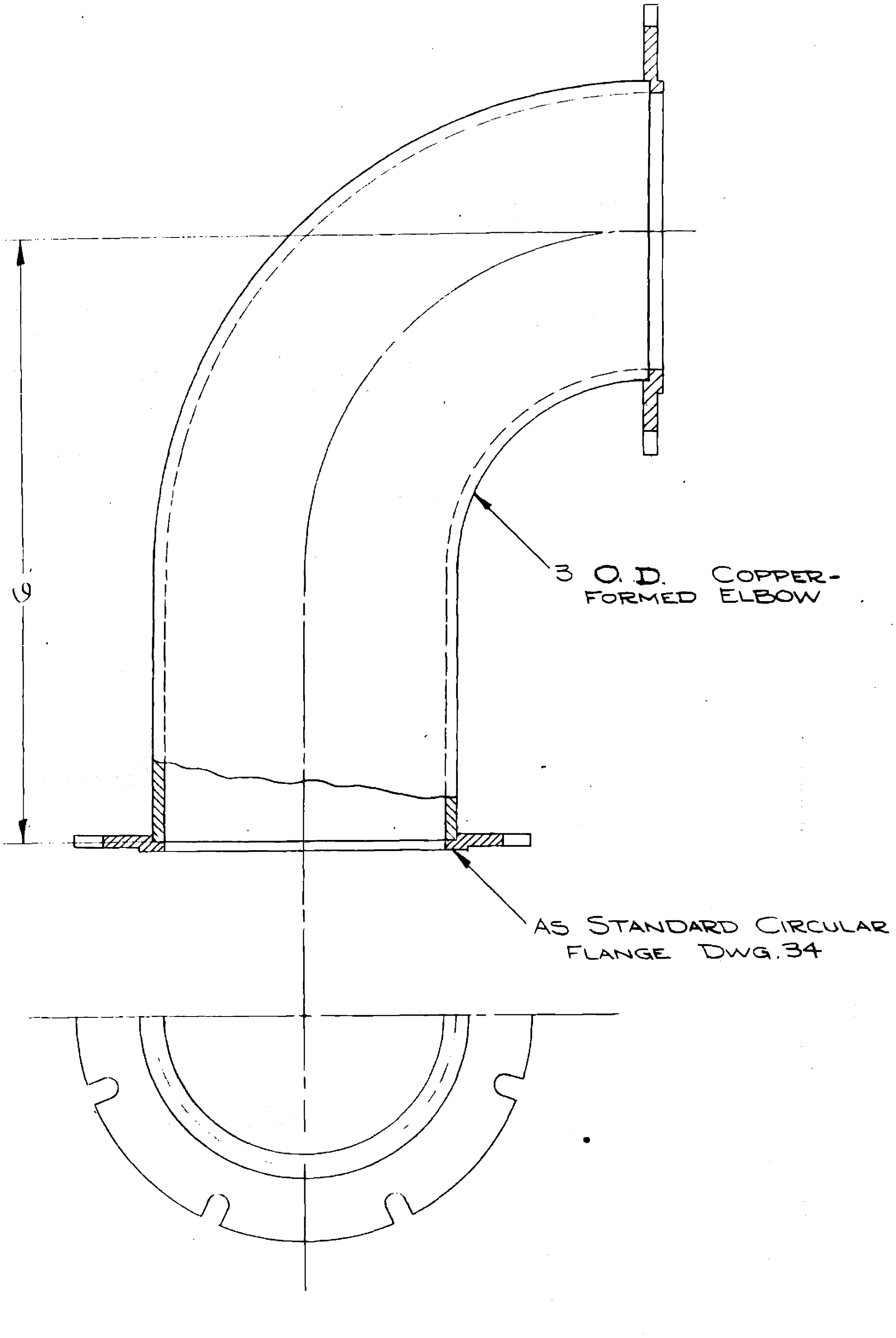
BRASS

d	0	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	1$\frac{1}{4}$	1$\frac{1}{2}$	2

Iris

Not To Scale
10-30-42
5-3-43
Dr. J.L. Ch:

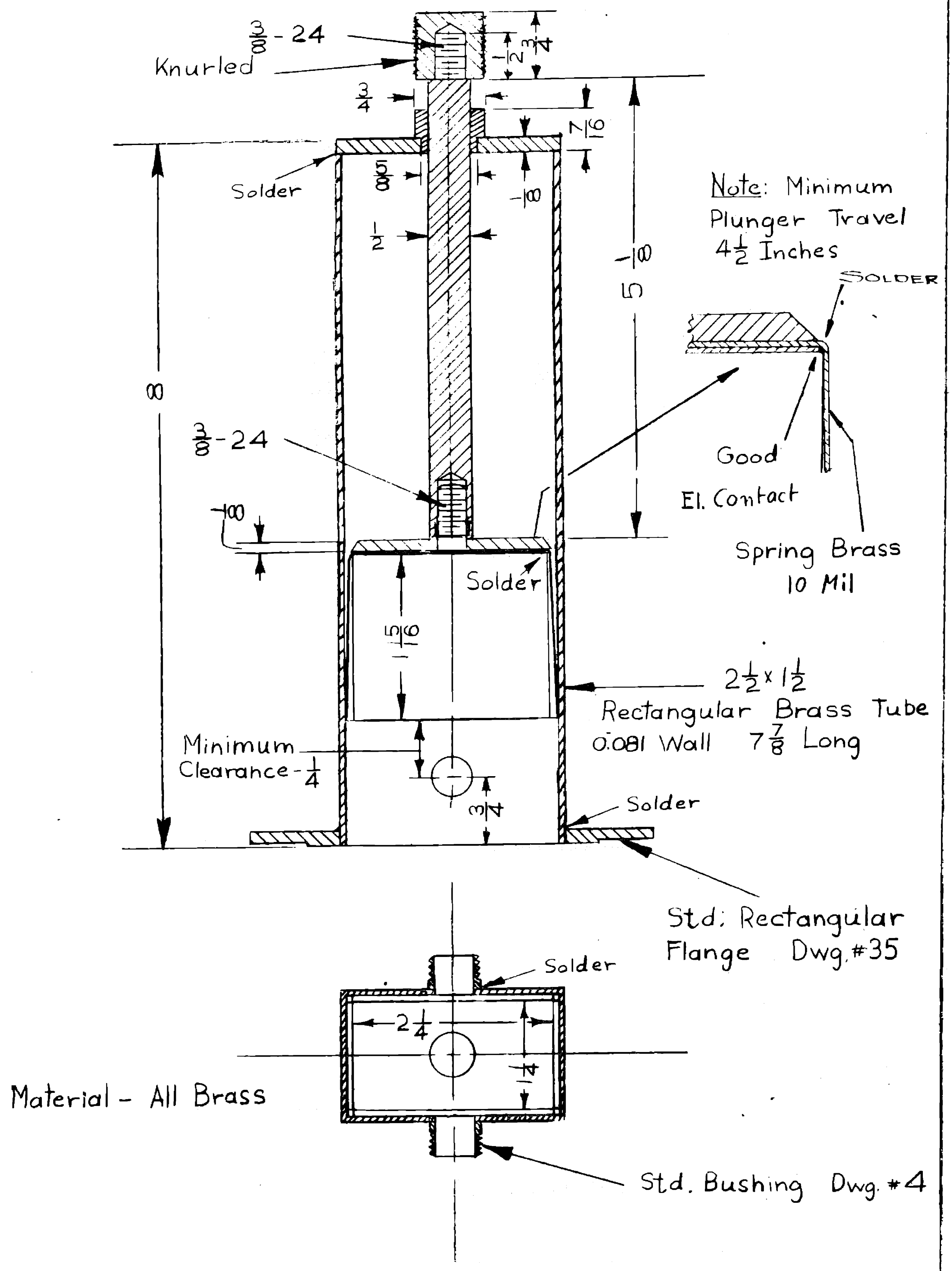
Ir
50



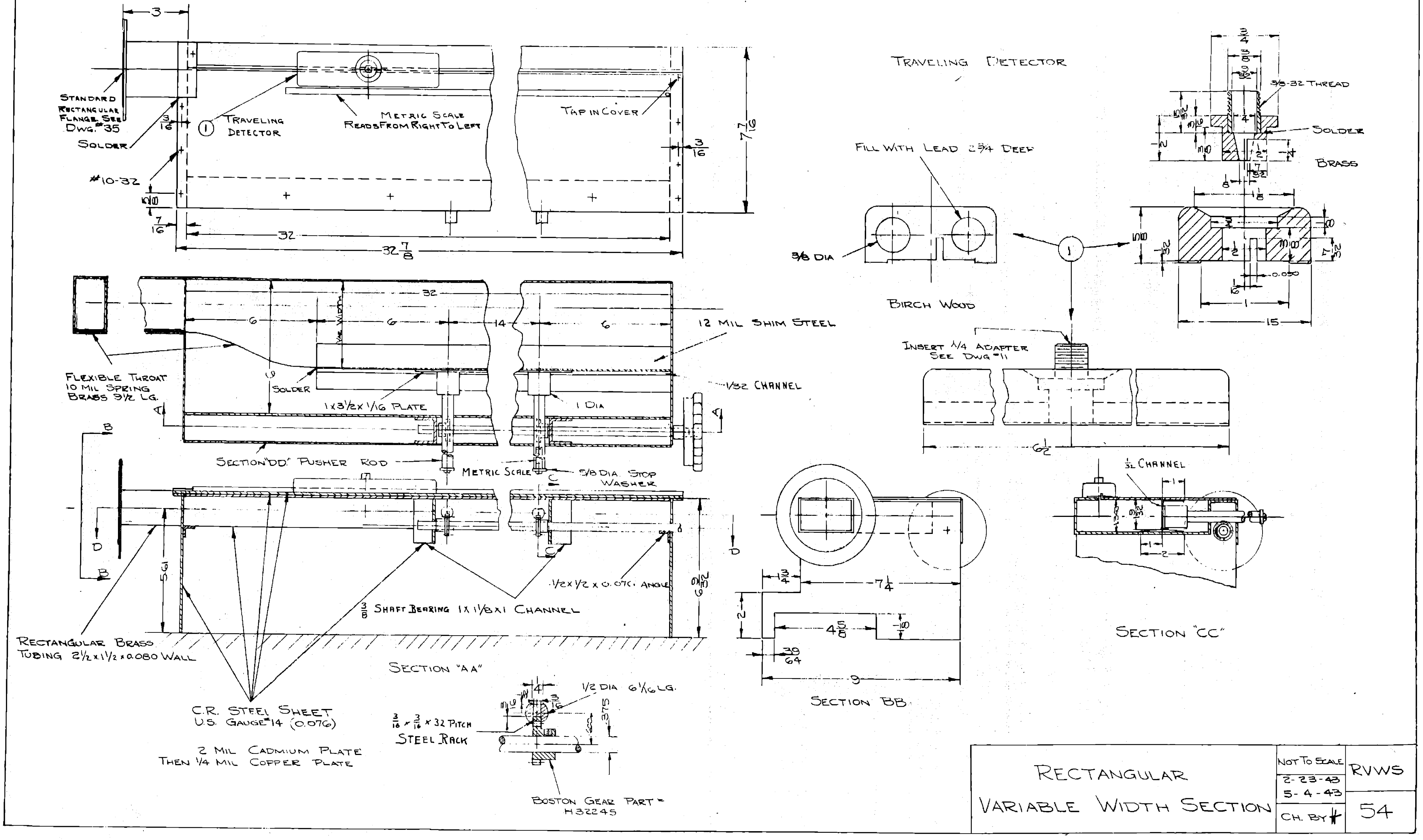
CIRCULAR BEND

NOT TO SCALE
4-17-43
CH. BY #

CB
51



Rectangular Driver	Not To Scale	RD
	3-8-43 5-4-43	52
	Dr: J.L. Ch: #	

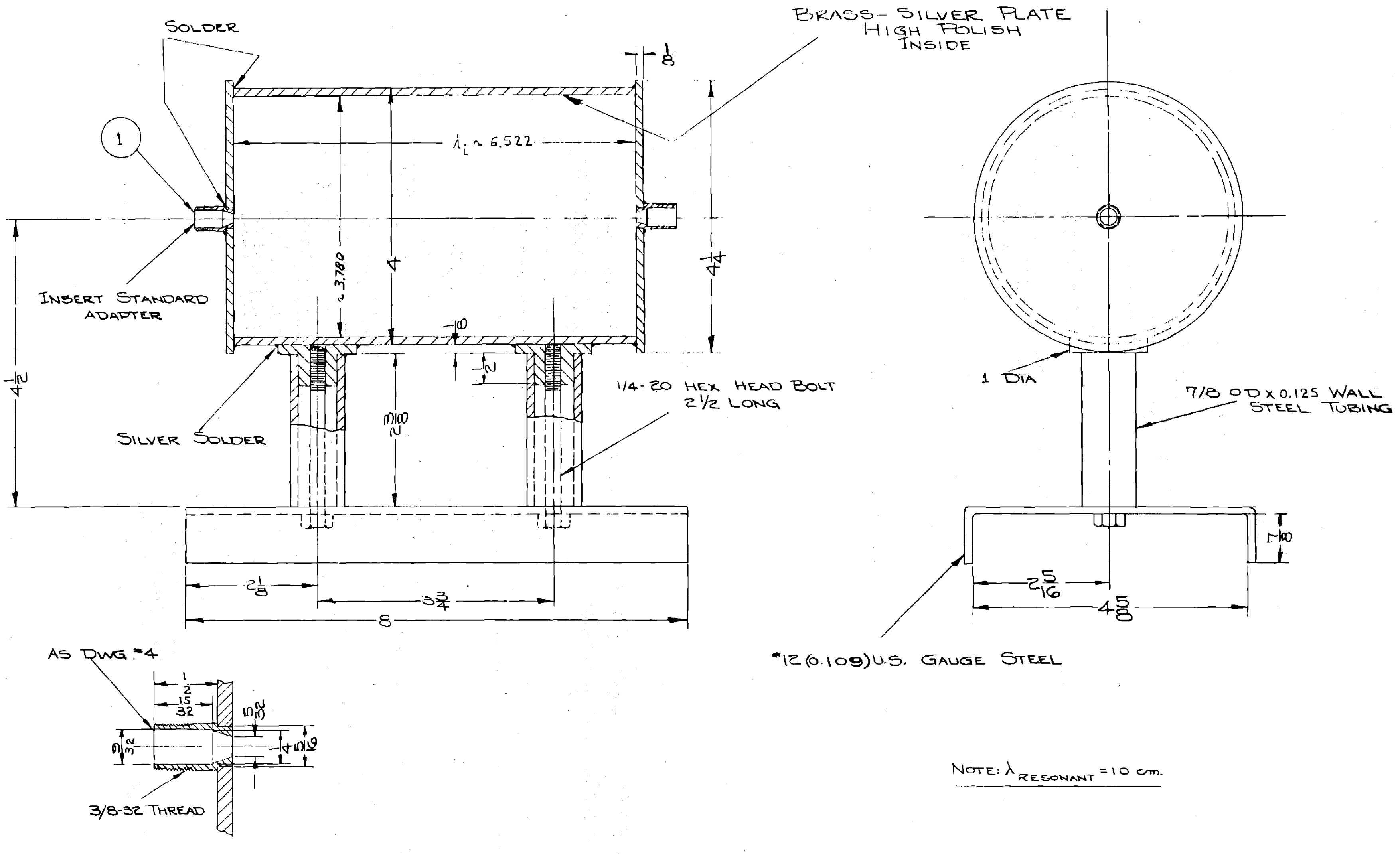


RECTANGULAR
VARIABLE WIDTH SECTION

NOT TO SCALE
2-23-43
5-4-43
CH. BY

RVWS

54



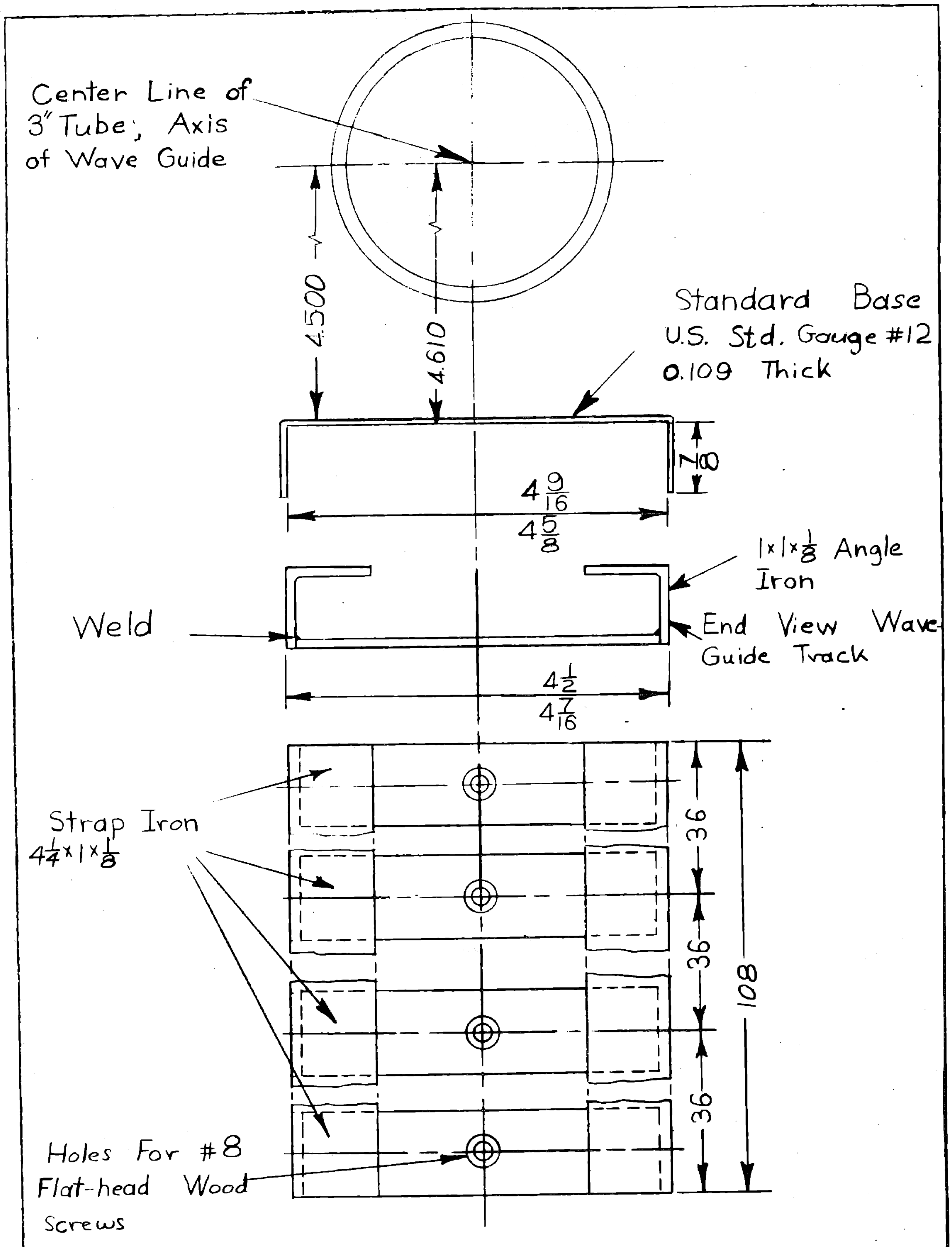
Note: $\lambda_{\text{resonant}} = 10$ cm.

① Scale - 2 x Size

CAVITY RESONATOR
WAVE STANDARD

NOT TO SCALE
5-1-43
5-4-43
CH. BY #

W STD.
55

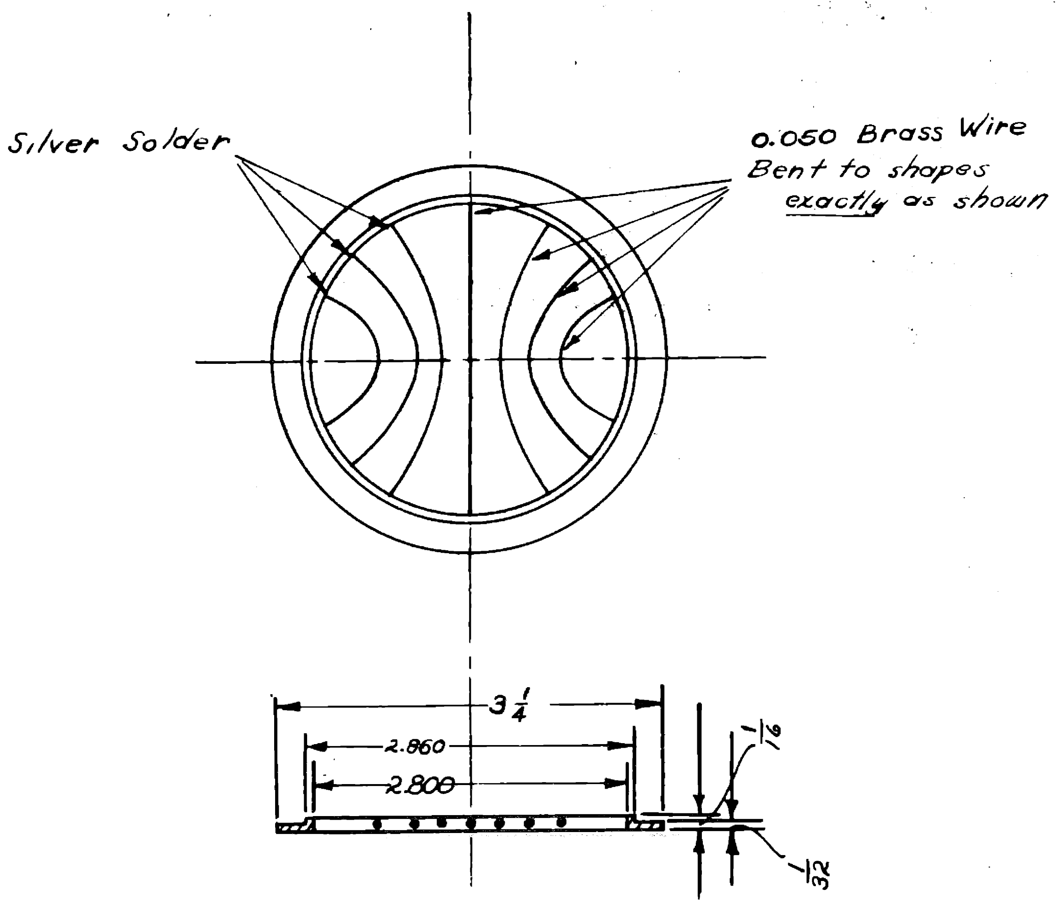


Wave Guide Track

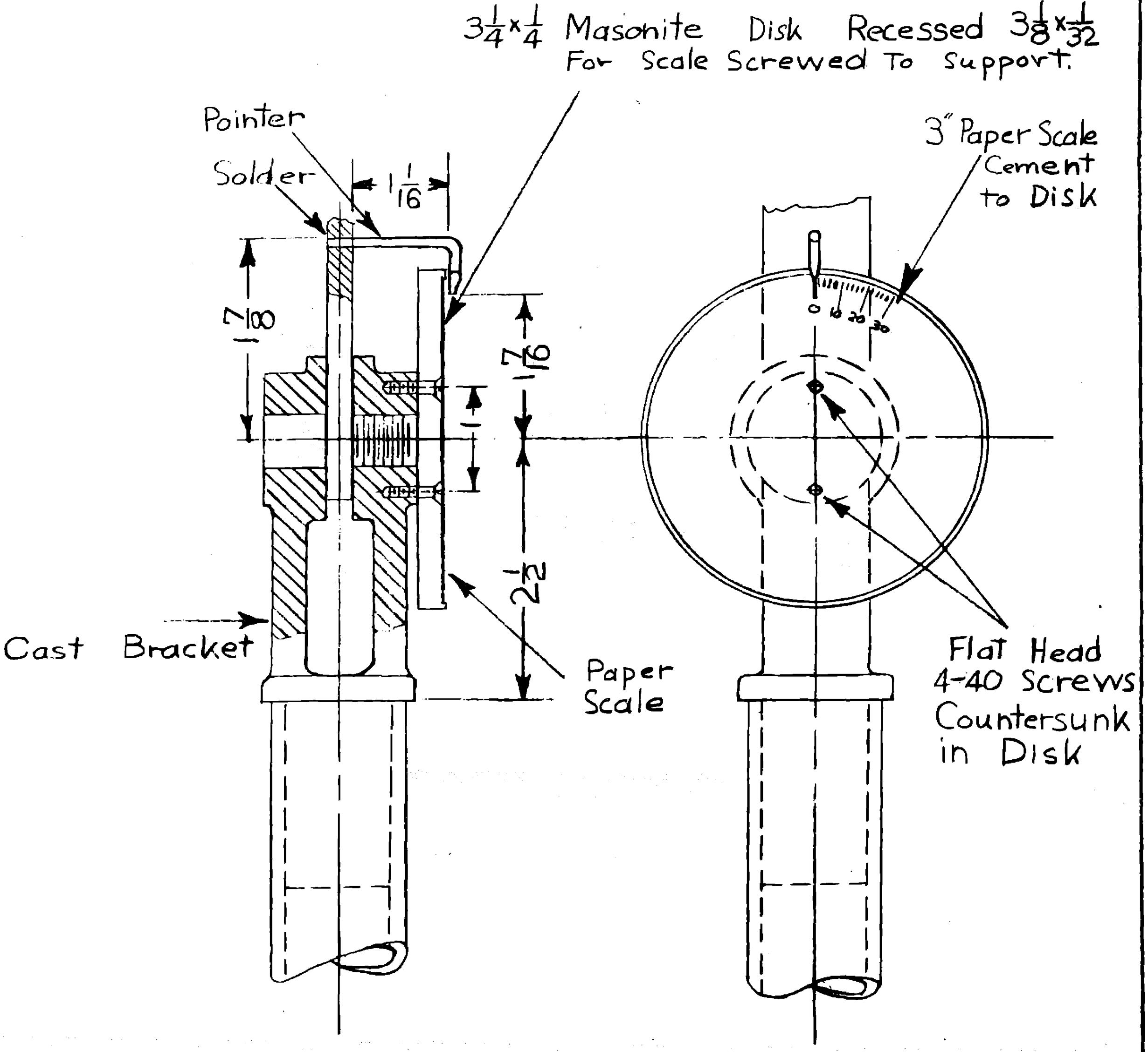
Not To Scale
10-29-42
5-3-43
Dr: J.L. Ch: #

WGTr
56

CIRCULAR WAVE GUIDE
$TE_{1,1}$ MODE

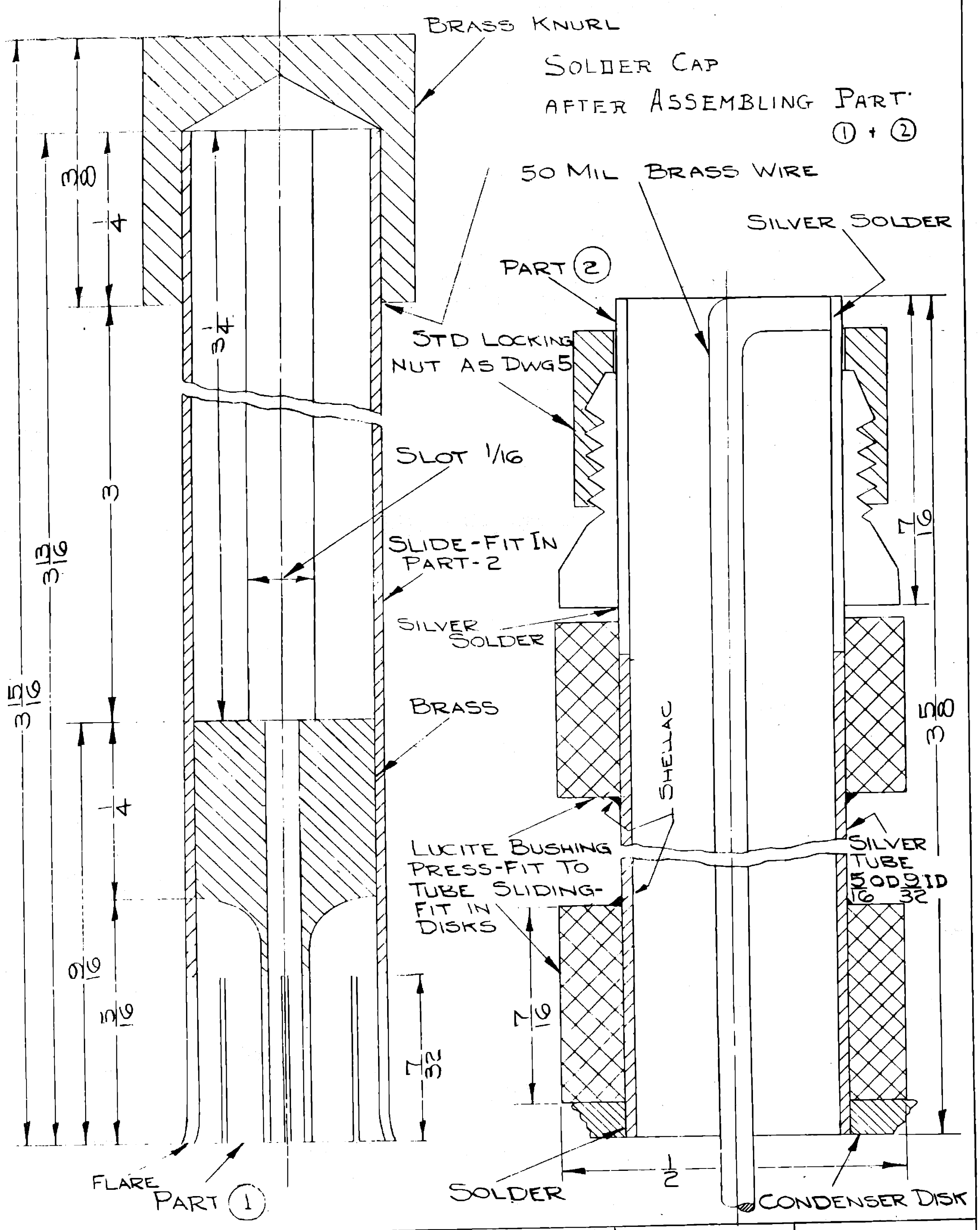


POLARIZATION GRID	Not to Scale	PG
	1-28-43 5-3-43	
	Dr BP Ch H	58

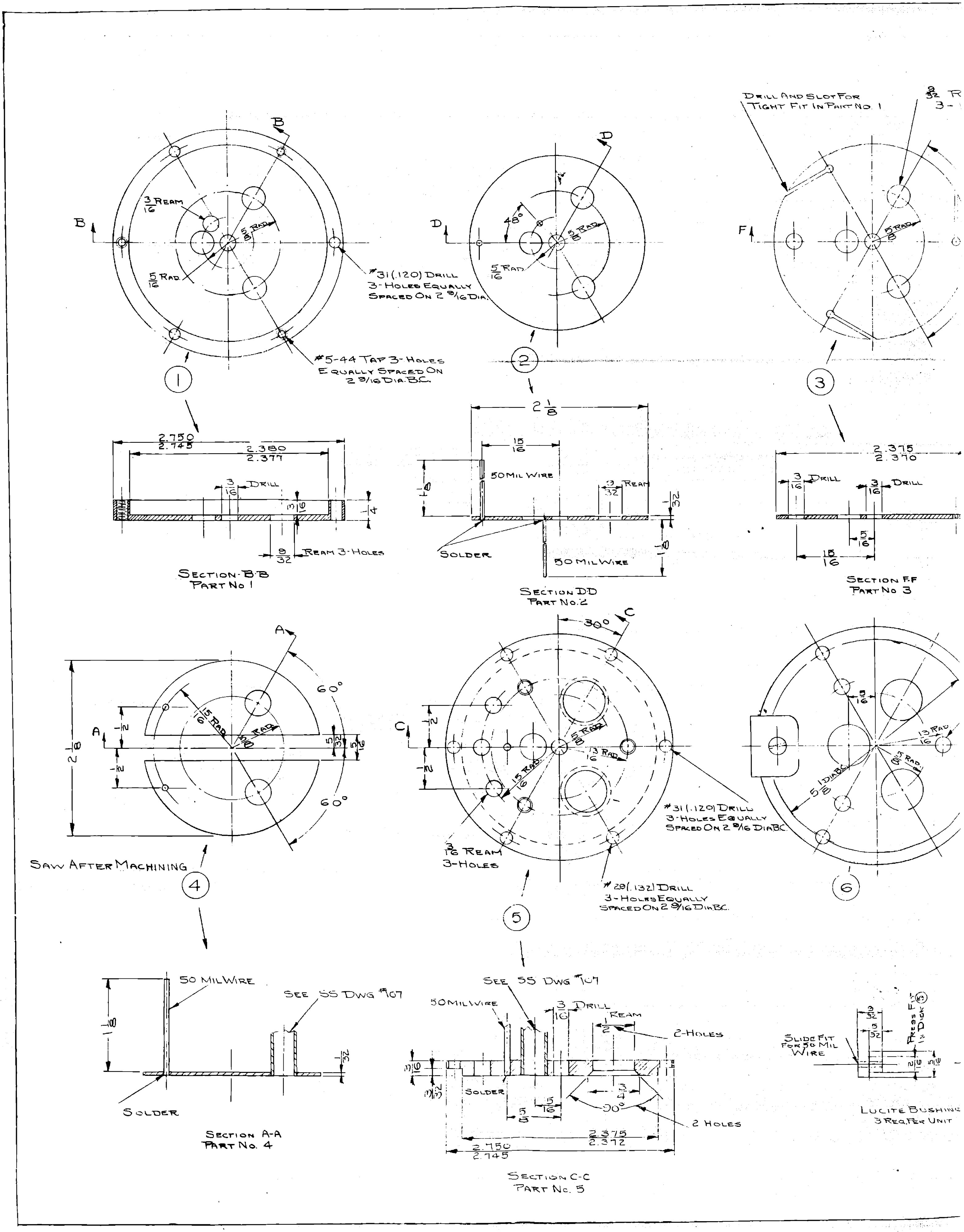


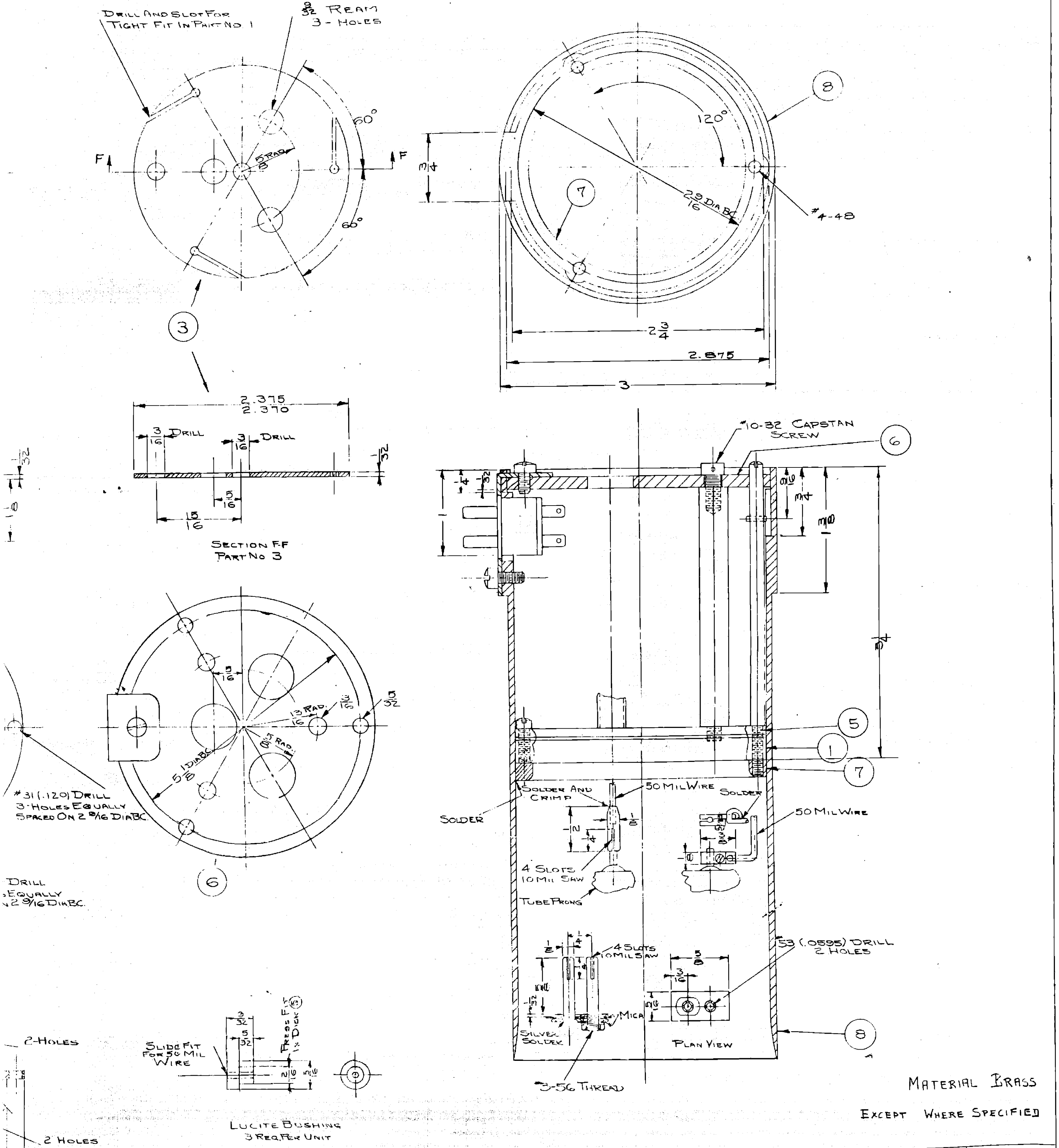
See also
Dwg #39

Radiator Stand Scale Disk	Not To Scale	Ra St
	2-2-43	60
	Dr: J.L. Ch: #	



368A Short-Circuiting Stub	No Scale	368A SS
	11-19-42 4-2-43	107
	Ch By H	

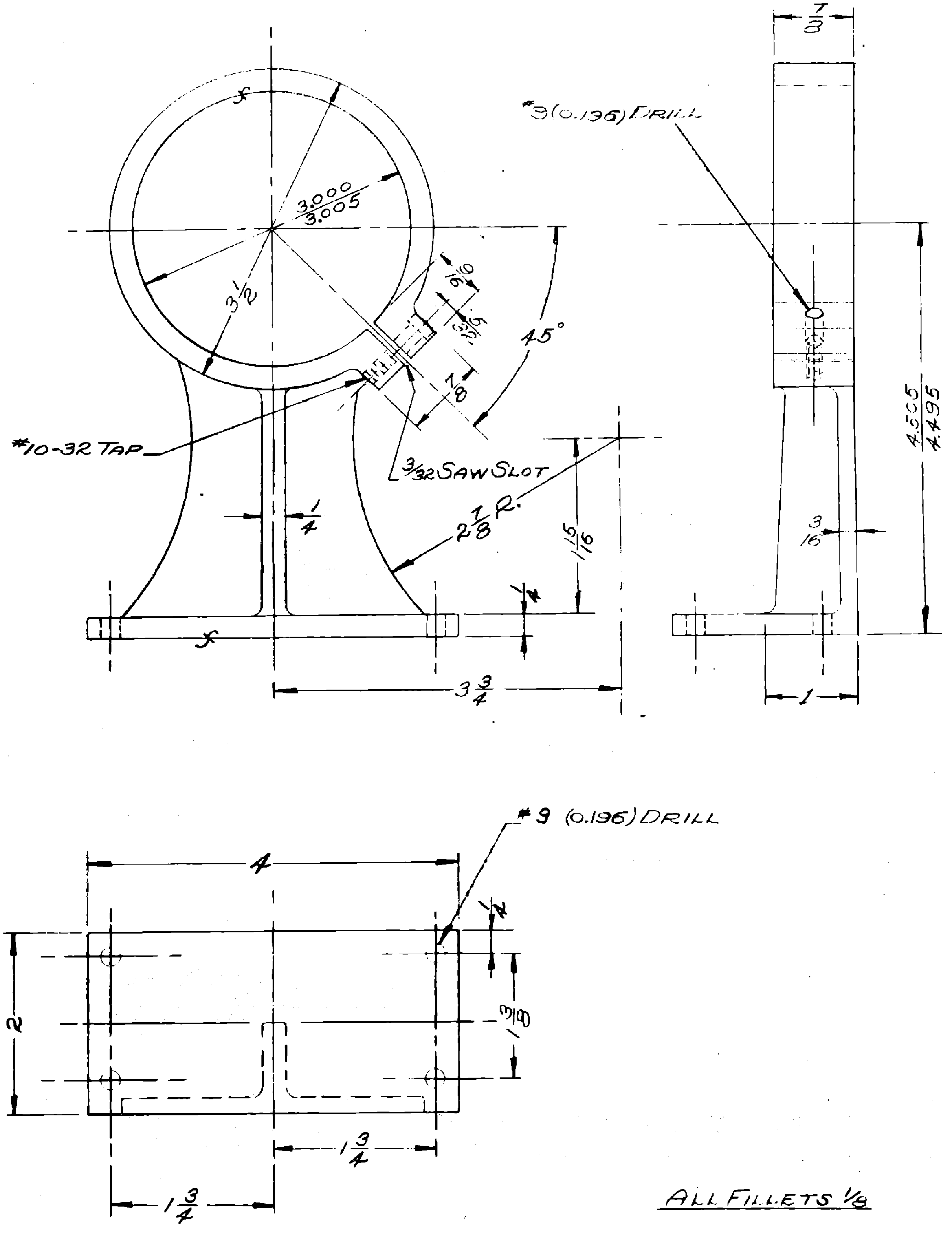

B
B
3/16 REAM
5/8 RAD.
5/16 RAD.
#31 (.120) DRILL 3-HOLES EQUALLY SPACED ON 2 9/16 DIA.
#5-44 TAP 3-HOLES EQUALLY SPACED ON 2 9/16 DIA. B.C.
①
D
D
48°
5/8 RAD.
5/16 RAD.
②
DRILL AND SLOT FOR TIGHT FIT IN PART NO. 1
3/32 R
3-
F
5/8 RAD.
③
2.750
2.745
2.380
2.377
3/16 DRILL
3/16
1/4
9/32 REAM 3-HOLES
SECTION-B-B
PART NO 1
2 1/8
15/16
50 MIL WIRE
1 1/8
9/32 REAM
1/32
SOLDER
50 MIL WIRE
1 1/8
SECTION DD
PART NO. 2
2.375
2.370
3/16 DRILL
3/16 DRILL
5/16
15/16
SECTION F-F
PART NO 3
A
A
60°
15/16 RAD.
3/8 RAD.
1/2
1/2
5/32
5/16
2 1/8
60°
SAW AFTER MACHINING
④
30°
C
C
1/2
1/2
5/8 RAD.
13/16 RAD.
15/16 RAD.
3/16 REAM 3-HOLES
#31 (.120) DRILL 3-HOLES EQUALLY SPACED ON 2 9/16 DIA BC
#29 (.132) DRILL 3-HOLES EQUALLY SPACED ON 2 9/16 DIA BC.
⑤
5/16
13/16 RAD.
5 1/8 DIA BC.
15/16 RAD.
⑥
50 MIL WIRE
1 1/8
SEE SS DWG #107
1/32
SOLDER
SECTION A-A
PART NO. 4
SEE SS DWG #107
50 MIL WIRE
3/16 DRILL
1/2 REAM
2-HOLES
3/16
3/32
SOLDER
3/4
90°
5/8
5/16
2 HOLES
2.375
2.372
2.750
2.745
SECTION C-C
PART NO. 5
9/32
5/32
PRESS FIT 1/2 DIA.
SLIDE FIT FOR 50 MIL WIRE
5/16
5/16
LUCITE BUSHING
3 REQ. PER UNIT



Material Brass

Except Where Specified

368 A Oscillator Condenser Section	Not To Scale	368 A
	3-19-42	Cond
	4-10-43	110
	Ch. By ✱	



ALL FILLETS 1/8

STANDARD BRACKET	NOT TO SCALE	STD BKT
	11-28-42 5-3-43	113
	CHECKED BY: H	