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Millimeter Attenuation and Reflection Coefficient Measurement System

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Millimeter Attenuation and Reflection Coefficient Measurement System

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Institute for Basic Standards
Boulder, Colorado



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MILLIMETER ATTENUATION AND REFLECTION COEFFICIENT
MEASUREMENT SYSTEM

B.C. Yates and W. Larson

Abstract

This paper presents the details to implement a WR15 attenuation and reflection coefficient magnitude measurement system. A discussion of precision and of systematic error is given along with equations for estimating limits of the error. Machine drawings are provided to fabricate the waveguide standards and necessary hardware not commercially available.

Key words: Attenuation; Measurement system; Millimeter; Reflection coefficient, VSWR.

1. Introduction

In the Electromagnetics Division of the National Bureau of Standards, Boulder, Colorado, work is proceeding toward the establishment and extension of calibration services at frequencies in the millimeter region. Among the work completed at this time is a system for the measurement of attenuation and reflection coefficient magnitude on waveguide devices in WR15 waveguide. The purpose of this report is to describe this calibration system and include the instrumentation, measurement procedure, and error analysis employed in the system development and evaluation.

2. System Description and Measurement Procedures

The system can be conveniently broken into two parts for the purposes of description and discussion. The part (sub-system) dealing with measurement of reflection coefficient will be described first.

2.1 Magnitude of Reflection Coefficient¹

Immense improvements in reflectometer techniques over the past few years have made this method most accurate for the measurement of microwave and millimeter impedance (VSWR and reflection coefficient)² [1,2]³. In particular, the

¹The reflection coefficient Γ at a single frequency, and for a single mode of propagation having a sinusoidal time variation, is the ratio of the incident to reflected wave amplitudes at a given terminal plane in a uniform waveguide. The reflection coefficient is a complex number having both a modulus (magnitude) and argument (phase).

²The voltage standing-wave ratio (VSWR), in terms of the above-defined reflection coefficient, is given by the relation,

$$\text{VSWR} = \sigma = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

The converse relation (i.e., $|\Gamma|$ in terms of σ) is

$$|\Gamma| = \frac{\sigma - 1}{\sigma + 1}$$

A more complete discussion of reflection coefficient and VSWR is given by Beatty [2].

Note: The symbol σ is widely used to denote conductivity, but is used in this note only to designate VSWR.

³Figures in brackets indicate the literature references at the end of this paper.

tuned modified reflectometer, a single directional coupler with associated waveguide tuners, offers the best performance and accuracy over a large dynamic range. Untuned reflectometer techniques [3] have also been developed which provide a reasonable accuracy.

2.1.1 Subsystem Description

Figure 1 is a block diagram of the reflection coefficient magnitude calibration subsystem presently in use at NBS. The measurement system incorporates two microwave oscillators, the master oscillator (MO) and the sawtooth-modulated local oscillator (LO). The MO is tuned to the calibration frequency and controlled with an AFC circuit. The LO center frequency is tuned to either 30 MHz above or 30 MHz below the MO frequency.

MO energy is propagated to the reflectometer where it is reflected from the item under test and is applied to a mixer. LO energy is also coupled directly to this mixer to produce an i-f response of 30 MHz. The i-f response is then transmitted through a monitor network, which also provides a ground return for the mixer diode, and into a 30 MHz waveguide below-cutoff (WBCO) piston attenuator. Next, the attenuator output is amplified, detected, and filtered. The filtered voltage is then applied to a monitor scope and a strip chart recorder. For a dynamic range greater than 40 dB, the sawtooth audio modulation is amplified following the i-f amplifier and synchronously detected.

Figures 2, 3, are more detailed diagrams of the system.

In order to provide a coherent scope response, system stability, and wide dynamic range, a sawtooth voltage is superimposed upon the LO repeller voltage to frequency modulate (± 2 MHz) the LO. If better system stability than the modulated method provides is required, the LO can be controlled by an AFC circuit to maintain the i-f center frequency at a fixed 30 MHz. This can be accomplished by employing a separate AFC loop such as shown in figure 3. For more detail on system stability see section 3.3.2.

2.1.2 Measurement Procedure

The measurement is performed by: 1) attaching the unknown test item, Γ_u , to the reflectometer, 2) adjusting the gain of the amplifier to obtain a convenient reference response on a recorder (meter), 3) replacing the test item by a reflection coefficient standard ($|\Gamma_s| \approx 1$), and 4) adjusting the 30 MHz standard attenuator to obtain the original output on the recorder. The reflection coefficient magnitude can then be calculated by using the formula,

$$L_R = 20 \log_{10} \frac{|\Gamma_s|}{|\Gamma_u|}, \quad (1)$$

where L_R is the measured relative return loss (the attenuation difference between $|\Gamma_s|$ and $|\Gamma_u|$). Tables are available to

facilitate the calculation of $|\Gamma_u|$ [4]. Alternately, $|\Gamma_u|$ can be calculated from the equations,

$$L_R = -20 \log_{10} |\Gamma| \quad (2)$$

and

$$|\Gamma_u| = |\Gamma_s| \cdot |\Gamma|. \quad (3)$$

When measuring terminations having a sliding load (fig. 4) as a terminating element, both the maximum and minimum reflection coefficients are measured. Usually the reflection coefficient of the termination is taken as the average of these measurements.

Terminations having a small reflection coefficient ($|\Gamma| \leq 0.01$) and a sliding load $|\Gamma_L|$ as a terminating element are difficult to measure. Since both reflections are small, it is not possible to immediately identify whether the average reflection coefficient $|\Gamma|_{\text{ave}}$ belongs to the sliding load or to a discontinuity (fig. 4) associated with the termination. (For the case ($|\Gamma| > 0.01$), $|\Gamma|_{\text{ave}}$ is equal to the reflection coefficient of the discontinuity $|\Gamma_D|$ (to an order of $|\Gamma_L|^2$) provided that $|\Gamma_D| > |\Gamma_L|$). This is because the average value of reflection coefficient is associated with that element which has the largest reflection (see Appendix A).

The usual method to separate the two reflection coefficients is to insert a low-loss discontinuity either inside the termination or attached to the waveguide flange of the

termination in order to provide a reflection which is large compared to that of the sliding load. A flat metal plate with dimensions smaller than nominal waveguide dimensions and which has a VSWR ≈ 1.2 can easily be attached to the termination and also provide the necessary discontinuity. An alternate method is to use two different sliding loads inside the termination if it is physically practical.

The measurement procedure is to attach the plate to the termination, measure the maximum and minimum reflection coefficients as a function of the sliding load, and calculate the respective VSWR's, ${}^d\sigma_{\max}$ and ${}^d\sigma_{\min}$. (The d superscript is used here to denote the VSWRs measured with the discontinuity (plate) attached.)

The VSWR of the load σ_L is calculated from the equation [5]

$$\sigma_L = \sqrt{{}^d\sigma_{\max} / {}^d\sigma_{\min}}. \quad (4)$$

Next, measurements of the maximum and minimum reflection coefficients are made with the discontinuity (plate) removed, and the maximum and minimum VSWRs (σ_{\max} and σ_{\min}) are calculated. Here, σ_{\max} and σ_{\min} are not to be confused with the VSWRs in eq. 4 but pertain only to the VSWRs with the discontinuity (plate) removed. Substitution of σ_{\max} and σ_{\min} into the equations,

$$\sigma_1 = \sqrt{\sigma_{\max} / \sigma_{\min}}, \quad (5)$$

and

$$\sigma_2 = \sqrt{\sigma_{\max} \sigma_{\min}}, \quad (6)$$

yields the VSWRs of the termination discontinuity and the sliding load where σ_1 and σ_2 are the VSWRs of the elements with the smallest and largest reflection, respectively. Comparison of eq. 5 and eq. 6 with eq. 4 removes the ambiguity as to which VSWR is associated with the sliding load and which VSWR is associated with the termination discontinuity.

When measuring terminations or nominally nonreflecting one-ports⁴ which have a return loss greater than the dynamic range of the measurement system, other measurement procedures must be used. Four suitable techniques are described below. The last two methods to be described (rf and i-f substitution) can be also implemented for measuring attenuators over an extended attenuation range. Details on direct substitution attenuation measurements are given in reference [6]. All methods assume that adequate signal power is available.

The first method is to measure the return loss in two steps, first calibrating the reflection coefficient of a transfer standard having a return loss of about 32 dB ($|\Gamma| = 0.025$) by the method described previously. Then, with the power level at the measurement port increased to compensate

⁴A nominally nonreflecting one-port is a termination which is intended to produce no reflection or nearly no reflection ($|\Gamma| \leq 0.001$).

for the return loss of the transfer standard (32 dB), the unknown $|\Gamma_u|$ is compared to the transfer standard. $|\Gamma_u|$ is calculated from eq. 1 where $|\Gamma_s|$ is the reflection coefficient magnitude of the transfer standard. Alternately, the return loss of the transfer standard can be added to the measured return loss to obtain the return loss of the unknown.

The second method utilizes a reflection coefficient standard that is fairly close in magnitude to the unknown termination. In this case only a relatively small return loss measurement which is within the dynamic range of the system need be measured. Some excellent possibilities of reflection coefficient standards of low VSWR are discussed in section 4.1.

The third method utilizes a calibrated rf attenuator isolated from and located between the generator and reflectometer. This method makes a direct comparison between the standard of reflection coefficient ($|\Gamma_s| \approx 1$) and the unknown. When the unknown is compared to the standard, a portion of the substituted return loss is placed in the rf attenuator and a portion in the i-f 30 MHz standard attenuator and the losses summed. The unknown is calculated from eq. (1).

Since the rf attenuation in the third method is not always accurately known, the fourth procedure makes use of the i-f attenuator to determine the attenuation in the rf

attenuator. To do this the i-f attenuation is transferred to a second auxiliary rf attenuator. Next, the attenuation in the original (third method) rf attenuator is measured with the i-f attenuator. The sum of the two i-f attenuator losses is then used in eq. (1) to calculate $|\Gamma_u|$. Although this method is tedious, it has been found by experience to be more accurate than the third method.

2.1.3 Brief Modified Reflectometer Theory and Tuning Procedure

For the measurement procedures outlined previously to be valid, the output response from the modified reflectometer must be proportional to the reflection coefficient of the device located at the measurement plane. In order to obtain this output response, the imperfections in the directional-coupler-tuner assembly and the reflections from the equivalent generator are eliminated or minimized by appropriate tuning adjustments as will be described.

When a signal originating from the generator is incident on a device presenting a reflection coefficient, Γ_L , at terminal surface T_2 (fig. 5) in a reflectometer, a portion of the reflected signal is coupled to the output arm of the coupler. The output response b_3 can be expressed by the equation [1],

$$b_3 = c' \frac{\frac{1}{K} + \Gamma_L}{1 - \Gamma_{2i} \Gamma_L}, \quad (7)$$

where Γ_{2i} is the reflection coefficient of the equivalent source impedance looking back from T_2 and

$$|K| \approx |S_{21}| 10^{D/20} \quad (8)$$

D is the directivity of the reflectometer and the transmission coefficient, S_{21} , is defined as the ratio of the wave amplitude at T_2 to that at T_1 when T_2 is terminated by a nonreflecting device. S_{21} has magnitude values of approximately 0.707, 0.95, and 0.995 for a 3 dB, 10 dB, and 20 dB coupler, respectively. Thus, when employing a coupler with a directivity of 40 dB, $\frac{1}{|K|}$ is approximately 0.01 to 0.014 (3-20 dB coupler). These values of $\frac{1}{|K|}$ can be equal to or larger than $|\Gamma_L|$ so that from eq. (7) it can be seen that considerable error could result if the assumption were made that b_3 was proportional to Γ_L . In the denominator of eq. (7), the magnitude of $\Gamma_{2i}\Gamma_L$ is relatively small but still gives an appreciable error which will be discussed later.

Since both the directivity and Γ_{2i} errors are significant in the detected reading of the reflectometer, it is necessary to reduce their effects by appropriate tuning operations which are to raise the directivity of the reflectometer and to reduce Γ_{2i} to a negligible value. Reduction of Γ_{2i} to zero implies the elimination of multiple reflections at terminal plane, T_2 . If one could make the directivity infinite and

$\Gamma_{2i} = 0$, eq. (7) would become

$$b_3 = c' \Gamma_L \quad (9)$$

In other words, the output would be directly proportional to the reflection coefficient of the device connected to T_2 , and the ratio of the $|b_3|$ response from the device to the response from a standard of reflection coefficient would give the proper value of Γ_L (see eq. (1)). Although in principle these conditions are realizable, in practice it is possible only to approach them. However, one can approach them so nearly that only a small residual error remains. This deviation from perfect tuning conditions causes what is called the tuning error. The section on measurement errors gives the formulas to calculate the limits of tuning error. For a more detailed discussion of tuning theory see [1,2].

Various techniques can be employed in raising the directivity of the reflectometer and reducing Γ_{2i} to a negligible value. The individual techniques which are preferred by most metrologists are reviewed here.

The directivity of the reflectometer is raised by inserting a sliding load of small reflection coefficient (VSWR of 1.01 to 1.001) into the uniform precision waveguide (fig. 5) and adjusting tuner A for a null response at the detector. (It is possible to obtain a false tuning adjustment

if the null is not obtained first). Next, while the sliding load is moved (at least a half wavelength) to obtain the maximum-minimum variations, tuner A is adjusted to make these variations as small as possible. Usually a variation of 0.5 to 1 dB is considered satisfactory.

After making the directivity adjustment, a sliding short circuit is substituted for the sliding load in the precision waveguide to make the Γ_{2i} adjustment. Tuner B is adjusted to minimize variations in $|b_3|$ in the same manner as tuner A except that a detector null is not obtained originally. The adjustment is usually continued until the Γ_{2i} variation is less than 0.005 dB. An automated carriage has been devised to facilitate the tuning procedures [7] and its use or a similar device is highly recommended for tuning at millimeter frequencies.

It is always necessary to repeat the directivity adjustment (tuner A), after adjusting tuner B, but the Γ_{2i} adjustment (tuner B) usually need not be repeated again if the output variation is reduced to 0.002 dB or less originally. These adjustments should provide the necessary conditions that the output signal is proportional to the reflection coefficient of the device at T_2 , so that the measurement methods outlined can be used.

Machine drawings for fabricating the tuners, sliding load, and sliding short are given in Appendices D, E, and F respectively.

2.2 Attenuation⁵

The i-f substitution technique is most widely accepted as the most accurate and most versatile method of performing attenuation measurements over a wide range of frequencies. Several system configurations are possible with this measurement technique [6]. The most commonly used is the series i-f substitution system shown in figure 6 and described below.

2.2.1 Subsystem Description

The basic series i-f substitution system for measurement of attenuation incorporates the hardware of the reflection coefficient subsystem; the insertion point for attenuators being located at the terminal plane for reflection coefficient measurements. The reflectometer provides a "matched generator" and is also used to tune the receiver port so that there are no multiple reflections between the input and output ports of the device-under-test and the system into which it is inserted.

⁵Attenuation is a general transmission term used to denote a decrease of signal magnitude, usually resulting from either a dissipative or reflective loss. In this note, the term attenuation also implies a non-reflecting system at the place where the attenuator is inserted.

A signal from the MO is propagated through the reflectometer and device-under-test (insertion point) and frequency converted (heterodyned) to 30 MHz by mixing with the LO. After the 30 MHz signal is attenuated by the WBCO standard attenuator, it is amplified, detected and displayed on a monitor scope and chart recorder.

With this system configuration a change in attenuation (e.g., an increase) in the device-under-test requires a corresponding change (decrease) in the WBCO attenuator. Thus, this configuration is called a series i-f substitution system.

2.2.2 Measurement Procedure

Preparatory to making a measurement the reflectometer in the RF source portion of the waveguide system is tuned by the procedures outlined in section 2.1.3 in order to present a matched generator to the test device. The RF detector section (fig. 7) contains a precision waveguide and a waveguide tuner which is the output port of the insertion point. After the reflectometer is properly tuned, the insertion point is closed and aligned. The waveguide tuner in the RF detector section is then adjusted for a reflectometer null response (i.e., no i-f detector response). This completes the tuning adjustments necessary to present the device-under-test with a matched insertion point.

The measurement is performed by: 1) inserting the device under test into the system at the insertion point, 2) adjusting the gain of the i-f amplifier to obtain a convenient detected reference response on a recorder (meter) (Note: when measuring variable attenuators, the gain is adjusted with the rf attenuation inserted), 3) removing the rf attenuation, and 4) substituting i-f attenuation from the WBCO standard to restore the detected response to the reference value to obtain a direct measure of the rf attenuation.

When setting either the standard or a rotary vane attenuator, the dial should always be turned in the direction of increasing attenuation to avoid backlash effects from the gear mechanisms.

Alternate methods for making attenuation measurements when the dynamic range of the detector system is exceeded are described in section 2.1.2.

It should be noted that alignment of the flanges between the device-under-test and the insertion point should be as exact as possible in order to obtain repeatable measurements.

3. Systematic Measurement Errors

The discussion of the limits of systematic measurement errors encountered is divided into three parts. The first part deals with errors in the measurement of reflection coefficient. The second part deals with errors due to mismatch

in measuring the attenuation. And the third part deals with errors common to the measurement of both attenuation and reflection coefficient. Estimated systematic error limits for NBS WR15 components and systems are summarized in appendices B and C.

3.1 Reflectometer Errors

3.1.1 Tuning Errors

Evaluation of the tuning errors in a tuned reflectometer is very important. Since the ideal conditions of $K = \infty$ and $\Gamma_{2i} = 0$ will not be realized in practice, the relation $b_3 = c'\Gamma_L$ will not be exact, and a residual error is present in the measurement.

The maximum relative error in an unknown test item, $|\Gamma_u|$, due to $K \neq \infty$ and $\Gamma_{2i} = 0$ is given by the equation,⁶

$$\frac{|d\Gamma_u|}{|\Gamma_u|} < \frac{1}{|K|} \frac{|\Gamma_s| + |\Gamma_u|}{|\Gamma_u\Gamma_s| - \left|\frac{\Gamma_u}{K}\right|} \quad (10)$$

where $|K|$ is approximated by eq. 8 and $|\Gamma_s|$ is the reflection coefficient magnitude of the standard.

To obtain the approximate magnitude of K , a load of small known reflection coefficient, Γ_L , is placed in the precision waveguide section and its phase is varied by sliding it more than one-half wavelength. Next, the attenuation difference, R , in decibels between maximum and minimum output

⁶Equation (10) contains a typographical error in reference [2].

signal variation is noted. This is the variation observed when raising the directivity of the reflectometer (section 2.1.3). Then, $|K|$ is calculated from the equation,

$$|K| = \frac{10^{R/20} + 1}{(10^{R/20} - 1) |\Gamma_L|}. \quad (11)$$

The estimation of $1/|K|$ is facilitated by figure 8.

A typical value that can be obtained when sliding a load ($|\Gamma_L| = 0.001$) is $R = 0.5$ dB so that $|K| \approx 3.5 \times 10^4$. This corresponds to raising the directivity of the reflectometer to greater than 90 dB. At millimeter wave frequencies 80 dB is usually the upper directivity limit that can be maintained for a three to four hour time interval without readjustment, while 90 dB can be maintained over the same interval for microwave frequencies.

The maximum relative error due to $\Gamma_{2i} \neq 0$ but $K = \infty$ is given by the relation,⁷

$$\frac{|d\Gamma_u|}{|\Gamma_u|} \leq \frac{(|\Gamma_u| + |\Gamma_s|) |\Gamma_{2i}|}{1 - |\Gamma_{2i} \Gamma_u|}, \quad (12)$$

where $|\Gamma_{2i}|$ is obtained from the equation,

$$|\Gamma_{2i}| = \frac{10^{R/20} - 1}{(10^{R/20} + 1) |\Gamma_L|} \quad (13)$$

in which R is now the output dB variation observed when a short circuit ($|\Gamma_L| \approx 1$) is slid more than one-half wavelength. Typical values are $|\Gamma_L| = 0.996$, and $R = 0.003$ so that

⁷Equation (12) contains a typographical error in reference [2].

$|\Gamma_{2i}| \approx 0.0002$. The estimate of $|\Gamma_{2i}|$ is facilitated by figure 9.

The above results should not be difficult to obtain provided good tuners and reasonable system stability are available. As a word of caution, the tuning conditions are sharply frequency sensitive and cannot be accurately maintained unless the master oscillator is frequency controlled.

Equations (10), (11), (12), and a form of (13) were presented in reference [2].

3.1.2 Precision Section Error

Although the precision section of waveguide used in the reflectometer is carefully constructed and considered to be a standard transmission line, and thus could be discussed in the section on standards, it is also an integral part of the reflectometer. Thus, the errors associated with that waveguide section are presented here.

A major portion of the reflectometer error is caused by the cross-sectional deviation of the precision section from standard waveguide dimension. It should be noted that this particular error is the limiting factor in obtaining better accuracy in waveguide impedance measurements, because it is possible to reduce the tuning errors to a value much smaller than the precision section error. Although present fabrication techniques make possible a waveguide tolerance of ± 50 microinch, this error can be significant. The quoted limit of

error from this source may be actually too conservative, and a future reduction may be possible if and when a more rigorous mathematical analysis of this type of problem can be performed.

The residual reflection coefficient magnitude caused by dimensional deviations Δa and Δb in the a and b dimensions respectively, is given by the formula,

$$\Delta\Gamma = 2 \left[\left(\frac{\lambda_g}{\lambda_c} \right)^2 \frac{|\Delta a|}{4a} + \frac{\sigma}{(1 + \sigma)^2} \frac{|\Delta b|}{b} \right], \quad (14)$$

where

a = the broad waveguide dimension,

b = the narrow waveguide dimension,

λ_g = the guide wavelength,

λ_c = the cutoff wavelength,

σ = the measured VSWR of the item under test. (Not to be confused with conductivity of the metal).

This formula considers only the change in characteristic impedance of the waveguide. Also, the respective error terms are derived while holding the other waveguide dimension constant at the nominal dimension. The "a" dimension error term is believed correct to 2 percent. The "b" dimension is correct to 1 percent for VSWR's less than or equal to 1.1 and varies to 10% for VSWR's of 2. Graphs of the respective errors for WR15 waveguide are given in figure 10 and figure 11.

Another possible error is due to the fact that the inside corners of the waveguide are filleted and not sharp.

The reflection from the junction of standard rectangular waveguide to filleted waveguide has been derived [8] and is given by the expression,

$$\Delta\Gamma = \left[\frac{\lambda_g R}{a} \right]^2 \cdot \frac{4 - \pi}{8ab} \quad (15)$$

where R is the radius of curvature of a filleted corner and the other parameters are as given for the previous equation.

Machine drawings for fabricating brass and invar precision waveguide sections are given in Appendix G.

3.2 Attenuation Error

3.2.1 Mismatch Errors

The error due to mismatch must be considered in making attenuation measurements because the attenuator is not always inserted in a perfectly matched system.

The attenuation difference of a variable or rotary-vane attenuator is measured by moving the vane from a zero or reference angular position to the desired vane angle or attenuation. The mismatch error [9] is expressed for the attenuation difference measurement by the equation,

$$\epsilon(\text{dB}) = 20 \log_{10} \frac{|(1 - {}^{(f)}\Gamma_i \Gamma_g)(1 - {}^{(f)}S_{22} \Gamma_L)|}{|(1 - {}^{(i)}\Gamma_i \Gamma_g)(1 - {}^{(f)}S_{22} \Gamma_L)|} \quad (16)$$

where the frontscripts (i) and (f), refer to the initial and final values, respectively, and Γ_i is the input voltage reflection coefficient of the variable attenuator when the attenuator is terminated with a load (receiver) of reflection coefficient, Γ_L . Γ_g is the reflection coefficient of the generator, and S_{22} is the reflection coefficient at the output port when the input port is terminated with a load $|\Gamma_L| = 0$.

For insertion loss measurement of a fixed attenuator the mismatch error [6] is given by the equation,

$$\varepsilon(\text{dB}) = 20 \log_{10} \frac{|(1 - S_{11}\Gamma_g)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_L\Gamma_g|}{|1 - \Gamma_g\Gamma_L|}, \quad (17)$$

where S_{11} is the attenuator input reflection coefficient, and S_{12} and S_{21} are the attenuator transmission coefficients.

Figure 12 can be used to quickly estimate the mismatch error for fixed attenuators having attenuation of 20 dB or more.

A typical value of mismatch error is approximately 0.008 dB for WR15 attenuators (fixed or variable) with a system VSWR of 1.02 at the insertion point. The magnitude of this error is approximately 50 percent of the total systematic error for attenuation measurements from zero to 30 dB, and approximately 20 percent for a 50 dB measurement (see also Appendix 3).

3.3 System Measurement Errors -- Attenuation and/or Reflection Coefficient Magnitude

3.3.1 Converter Linearity

A knowledge of the degree of linearity of the power conversion of the mixer is essential in the i-f measurement system. When using a diode mixer in heterodyne receivers, nonlinearity is always present. This nonlinearity is a function of the ratio of the local oscillator power to the master oscillator power. Empirically, it has been shown in the NBS WR15 waveguide system that a 27 dB ratio (i.e., the MO power 27 dB down from the LO power) will give a nonlinearity less than 0.003 dB over the measurement range of 0-50 dB when the LO power is set at 2-3 mW at the mixer. The deviation from linearity is reduced when the signal power in the mixer is decreased relative to the local oscillator power. These results are in good agreement with the theory [10] (see figure 13).

In practice, the degree of linearity is established by measuring the same known attenuation step (e.g., 5 or 10 dB) at various power levels over the required measurement range. The difference between the measured value at the higher level and the value of attenuation at low levels, Δ dB (decibel), is the converter nonlinearity.

The relative error in reflection coefficient magnitude due to nonlinearity is calculated from the formula,

$$\frac{|\Delta\Gamma|}{|\Gamma|} = 0.115 \Delta\text{dB} \quad (18)$$

where ΔdB (decibel) is the deviation from linearity. The error for an attenuation measurement is ΔdB .

3.3.2 System Instability

Instability errors caused by power or frequency fluctuations are dependent on the particular generators, amplifier, detectors, power supply, and frequency stabilizer used and cannot be predicted in advance for a particular system. The variation of the output signal from an average power level can be held to less than ± 0.1 dB with a stable power supply and water cooling of the rf source (klystron). Phase locking the signal klystron to a stable source operating at a lower frequency (fig. 3) can hold the i-f output level fluctuations to approximately ± 0.005 dB for a 30-60 second interval. The two-loop AFC used here accomplishes this stability with only a water-cooled LO. When the two-loop AFC was applied to the LO also, the stability was held to better than ± 0.002 dB for a 1-2 minute interval. Frequency stability of this system (WR15) is approximately 1-2 kHz short-term and 5-10 kHz daily drift.

Instability errors are usually treated as random errors of measurement, a value being assigned after several hundred random measurements are made. When only a few measurement data are available, the error is formulated from eq. (18).

Connect-disconnect instabilities and repeatabilities of flanges, attenuators, and terminations are discussed in Section 5.1 and 5.2.

3.3.3 Leakage

3.3.3.1 RF Leakage

The effect of rf leakage becomes noticeable and increases the measurement error when measuring an attenuation ratio of 35-40 dB or more. This applies to a typical system where no special precaution has been made to control the leakage. The maximum attenuation error can be computed from the equation [11],

$$\Delta\text{dB} = 20 \log_{10} \left(1 \pm \sqrt{\frac{P_L}{P_S}} \right) \quad (19)$$

where P_S and P_L represent the signal power and leakage power, respectively. The reflection coefficient error is given by applying the results of eq. (19) to eq. (18).

In practice eq. (19) is not easily utilized, because an accurate measure of the leakage power cannot be made, but it can be applied to yield approximate error limits. A suggested method is to use a RF receiver (e.g., the attenuation

LO receiver) with an incorporated dial readout attenuator attached. This receiver is mobile enough to be placed near possible sources of leakage and can give an indication of the leakage signal. The receiver can be "calibrated" by the usual attenuation measurement system.

The leakage can be eliminated or minimized by several trial-and-error techniques. Placing the signal sources in shielded containers will usually sufficiently reduce this leakage source. Waveguide joints can be wrapped with steel wool or metal foil, and polytetrafluoroethylene-metal gaskets [12] have been used at microwave frequencies. Also, if the system is of a permanent nature, painting joints with a solution containing a high silver content will eliminate the leakage. Unfortunately, a major source of leakage may be the test item (e.g., a rotary vane attenuator). In the case of some commercial attenuators, the leakage power is down only 40 dB from the incident power in the waveguide and it is rarely down more than 60 dB. Fabrication techniques for NBS rotary-vane attenuators using absorbing material have been devised to reduce the leakage to more than 120 dB below the incident power [13]. Leakage in an NBS fabricated WR15 rotary-vane attenuator was shown to be at least 80 dB below the incident power.

3.3.3.2 Intermediate Frequency Leakage

I-f leakage is present around the standard attenuator, i-f amplifier, converter, and the associated i-f coaxial cables. The leakage from the standard attenuator can be contained by proper fabrication techniques. The i-f amplifier should be placed in a shielded container which has filtered power input connectors. The coaxial cable connector leakage can be reduced by wrapping the joint with lossy cloth and metal foil, but the suggested procedure is to use a conductive silver paint on threaded connectors and pack metal foil around the outer walls of BNC type connectors.

A field strength meter and probe or alternately an additional i-f receiver can be used to detect this type of leakage.

If the i-f leakage cannot be controlled adequately (30-50 dB range), a rf substitution in conjunction with the i-f substitution (similar to the method used for nonreflecting terminations (see Section 2.1.2)) will usually overcome the problem, since the signal power will be much larger than the leakage power. Although this method requires an additional calibration, it may yield a more accurate attenuation measurement. The technique is to remove approximately 20-25 dB of attenuation from the attenuator which holds the MO-LO 30 dB ratio (for power linearity) to an auxiliary attenuator. The unknown item is then calibrated by using the attenuations of the rf and i-f attenuators.

At least 20-25 dB (the amount removed previously) must be measured by the rf attenuator. If the i-f leakage cannot be reduced to a negligible amount, an estimate of its Δ dB attenuation change can be treated as a systematic error as in the case of rf leakage.

3.3.4 Signal-to-Noise Error

In the series i-f substitution system used at NBS, it has been demonstrated experimentally that attenuation measurement error due to noise is not significant. This is because the principal noise present in the 30 MHz detection system originates from the i-f amplifier and not the mixer. Thus, since the i-f amplifier receives a constant signal level from the 30 MHz attenuator, as is the case with the series i-f substitution, no apparent signal-to-noise error arises. The latter statement assumes a 50 dB range only. (There may be some range greater than 50 dB where the mixer noise dominates).

An error due to noise that may be significant is that due to loss of readout resolution (i.e., the true signal level is not readily determined from the random variations caused by noise). This problem can usually be corrected by using a long time-constant filter after the amplifier detector when measuring over a dynamic range of 0-50 dB. Also, the resolution can be improved by increasing the signal power and using the i-f and rf substitution technique described previously.

The measurement error from random variations due to a small signal-to-noise ratio is the observed readout variation in decibels for attenuation measurements, and the associated reflection coefficient error is given by eq. (18).

4. Standards

4.1 Reflection Coefficient Magnitude Standards

The standard of reflection coefficient used for impedance measurements at NBS is the quarter-wavelength short-circuited waveguide, more commonly called the quarter-wave short circuit (fig. 14).

The main advantages of this type of standard are: 1) the reflection coefficient magnitude can be calculated from derived formulas given in references [14], [15] if conductivity or attenuation measurements [16], [17] of the waveguide are available. Relatively crude measurements of conductivity will suffice to obtain the reflection coefficient to excellent accuracy (fig. 15). For example, a 20 percent error in the conductivity measurement will result in only a 0.015 percent error in the standard; 2) the axial component of current vanishes a quarter-wavelength from the shorting plate (fig. 16) which makes the dissipative loss in the waveguide joint negligible; and 3) small dimensional variations in the waveguide cross section have a negligible effect on the reflection coefficient. An increase in height of 0.001 inch causes 0.0008

percent change in reflection coefficient (fig. 17) at 62.5 GHz; an increase in width of 0.001 inch causes approximately a 0.001 percent change at the same frequency (fig. 18). NBS short circuits are fabricated from electroformed silver or copper to a tolerance of ± 0.0002 inch for the narrow and wide waveguide dimensions.

The critical dimension of a short circuit is the length (ideally a quarter wavelength). The length of the short circuit must be accurately dimensioned in the fabrication process in order to achieve the vanishing of the axial component of current at the connector surface. If the electrical length is different from that at the design frequency, current will flow across the discontinuity and result in a loss of power, so that the reflection coefficient will be less than the calculated value.

The proper length of the short circuit corrected for the change in phase factor due to guide attenuation [18] is given by the equations,

$$l = \frac{1}{(1 + \alpha_m/\beta)} \left(\frac{\lambda_g}{4} - \frac{\alpha_m}{\beta} l_{ep} \right) \quad (20)$$

and

$$l_{ep} = \frac{b(\lambda/\lambda_g)^2}{[2(b/a)(\lambda/\lambda_c) + \epsilon_r]} \quad (21)$$

where:

α_m = the measured waveguide attenuation constant,

$\beta = \frac{2\pi}{\lambda_g} =$ the wave phase factor,

$\lambda_g =$ the guide wavelength,

$\lambda_c =$ cutoff wavelength,

$\lambda =$ free space wavelength,

$b =$ narrow inside dimension of waveguide,

$a =$ broad inside dimension of waveguide,

and $\epsilon_r =$ relative dielectric constant of the laboratory environment.

The reflection coefficient magnitude ($|\Gamma_s|$) is given by the equation,

$$|\Gamma_s| = 1 - 2\alpha(\ell + \ell_{ep}). \quad (22)$$

The attenuation constant is obtained by comparing the change in attenuation between a quarter-wave short circuit and a five-quarter-wave short circuit which is designed to operate at mid-frequency (mid-frequency is not essential) of the particular waveguide band. The attenuation at other frequencies in the particular waveguide size is given by the equation,

$$\alpha = \alpha_m \left(\frac{f}{f_m} \right)^{3/2} \left(\frac{\epsilon_r + 2(b/a)(\lambda/\lambda_c)^2}{\epsilon_r + 2(b/a)(\lambda_m/\lambda_{cm})^2} \right) \left(\frac{\lambda_g}{\lambda_{gm}} \right)^2 \quad (23)$$

where the m-subscripted parameters correspond to the parameter wavelength values at the mid-frequency f_m .

The reflection coefficient magnitude measurement error due to the quarter-wave short circuit is directly related to the error of the standard. In other words,

$$\frac{|d\Gamma|}{|\Gamma|} = \frac{|d\Gamma_s|}{|\Gamma_s|}.$$

The fractional error in the reflection coefficient of the NBS quarter-wave short circuits is estimated to be less than ± 0.03 percent.

Machine drawings for fabricating quarter-wave short circuits are given in Appendix H.

The previous discussion on quarter-wave shorts does not mean to imply that other reflection coefficient standards could not be fabricated in WR15 waveguide. Examples of several possibilities are half-round inductive obstacles [18, 19], waveguide irises, inductive and capacitive posts [20, 21] and waveguide holes [22].

4.2 Standard Attenuator

The IF substitution method has been used at NBS for comparison of attenuation difference and insertion loss in waveguide sizes WR28 to WR430 for many years. This method employs a waveguide below-cutoff (WBCO) attenuator operating at the selected frequency of 30 MHz. The WBCO is a continuously variable attenuation standard whose incremental attenuation may be closely predicted from a knowledge of its waveguide dimensions [23]. If the waveguide section is uniform, nearly lossless, and excited sinusoidally in only one mode, the field decays exponentially along the waveguide in a predictable manner.

Thus, a probe or pickup coil which is moved a known distance (with respect to an excitation coil) along the waveguide axis causes a calculable change in insertion loss. If certain constraints are applied regarding frequency of operation, resistivity of the waveguide, and the waveguide dimensions, the attenuator will constitute a nearly ideal standard.

Grantham and Freeman have published detailed theoretical factors affecting the design of the WBCO attenuator and its use as a standard attenuator [24]. The NBS Monograph 97 [6] treats the WBCO for general considerations, dimensional tolerances and accuracy of measurement of displacement, skin depth corrections, loading effects, and mode purity.

The errors in the NBS WBCO attenuator is estimated to be within $0.002 \text{ dB} + 0.002 \text{ dB}/20 \text{ dB}$. The error in reflection coefficient magnitude is given by application of eq. (18).

The machine drawings required to reproduce the NBS model VII WBCO standard attenuator are included in Appendix I.

Figure 19 is a photo of an NBS WBCO attenuator.

4.3 Interlaboratory Standards

4.3.1 Reflection Coefficient

The most frequently encountered type of interlaboratory standard (fig. 20) uses a change in height of the narrow waveguide dimension to achieve a calculable reflection coefficient. The ratio of waveguide heights is closely equal to the VSWR for

ratios less than 1.5. The frequency characteristic of this type of device is dependent on the capacitive effect of the waveguide discontinuity, but it is of second order. Formulas are available [20] for the capacitive correction terms. Thus, this type of standard has the desirable qualities of being more broadband than most types and having a calculable reflection coefficient. This type of device usually incorporates a low-reflection sliding load to terminate the structure.

Caution should be observed when selecting interlaboratory standards for measurement purposes. Two of the main sources of trouble in a poor quality standard are nonflatness of the connector (flange) surface (see fig. 4) and mechanical and electrical instability of the sliding load incorporated in the reflector.

A connector (flange) surface which has protrusions, bent surfaces or separated seams (where the device is fabricated from 2-4 separate pieces) does not mate properly so that there is excessive joint loss and leakage which will change with use of the standard, thereby changing the measured value. Another disadvantage of joint loss is the increased leakage signal which can effect the measurement accuracy. Also, protrusions on the connector (flange) surface can damage the fine surface finish of a precision waveguide section which will degrade the accuracy of the measurement system.

The electrical instability of the sliding load is the most common flaw in an otherwise good standard. It is possible to overcome this fault by improving the mechanical fit between the shaft and the shaft hole, or by providing a better sliding fit between the load supporting mechanism and the waveguide. The recommended procedure is to mount a pyramidal taper on a block which has teflon guides that provide a close fit with the waveguide walls. Both the taper and the block should be made from an rf absorbing material. If properly constructed, the electrical instability is virtually eliminated.

Other qualities to be considered in selection of a standard are: 1) accessibility to the reverse side of the connector (flange) surface to provide fast connect/disconnect, and 2) sturdy construction to eliminate flexing of the flange and associated waveguide.

Cautions to be observed before and after calibration are: 1) Inspect for flat front and reverse connector (flange) surfaces. This includes removal of paint and unevenness on the reverse side which can cause different pressures to be applied to the mating surface, 2) inspect interior waveguide walls for freedom from dust and lint, and 3) inspect connector surfaces for freedom from grease and corrosion.

4.3.2 Attenuation

There are two basic types of rf attenuation inter-laboratory standards, the fixed attenuator [25] for insertion loss and the variable attenuator for attenuation difference.

There are two designs of variable attenuators that are suitable for calibration. One type has a resistive vane which moves into the waveguide field from a side wall. The other type is the rotary-vane attenuator. Both types of attenuators have good resolution at low values of attenuation, but the rotary-vane attenuator has superior resolution at high values as compared to the first type. The rotary-vane attenuator is less frequency-sensitive and has less incremental phase change than the other type.

The rotary-vane attenuator which basically consists of a dissipative vane rotated in a circular waveguide is the preferred variable attenuation interlaboratory standard. It has the property that the "ideal" attenuation can be calculated by the expression

$$A = -40 \log \cos \theta + c \quad (25)$$

where θ is the angle between the rotating vane and the polarization of the circular TE_{11} mode, and c is the residual attenuation when $\theta = 0$.

Equation (25) is ideal because fabrication imperfections can cause deviations in actual attenuation for a known vane angle θ . Among the factors causing these deviations are

mismatch, misalignment of the rotating vane, insufficient attenuation of the vane, imperfections in the gear drive mechanisms, readout parallax, and a warped vane. Vane alignment techniques have been developed to reduce the errors from stator and rotating vane misalignment [26, 27, 28]. Likewise, fabrication techniques have also been improved so that the mechanical and physical imperfections are minimized [13].

Two main types of single-value attenuators are the fixed pad and the single-step attenuator. The disadvantage of the fixed pad is that it must be inserted and removed during a calibration, thus requiring good system stability and a repeatable connect-disconnect system assembly (see Section 5.2 for measurement results).

The step attenuator can remain in the system during its operation and thus overcomes the disadvantage of the fixed pad if its mechanical characteristics are stable and repeatable. The step attenuators usually consist of a movable resistive vane located between the two sets of coupling holes of an in-line directional coupler. When the vane is located in the center of the waveguide, energy is transmitted through the device via the coupling path, thus being attenuated in proportion to the design coupling factor. When the vane is located in the minimum electric field (against the wall) only a small residual attenuation results. Thus, with this device a fixed attenuation step can be measured without insertion and removal of the device. Other advantages of this device

are low VSWR and minor frequency sensitivity.

Precision calibrated attenuators used as interlaboratory standards require careful handling and should meet the following criteria to give satisfactory results. They should:

- 1) be electrically stable over several years time,
- 2) be mechanically rugged so that the electrical characteristics do not change through handling,
- 3) be electrically stable under environmental changes such as temperature, humidity, etc.,
- 4) be electrically stable for reasonable overloads (power),
- 5) have a VSWR of less than 1.2 (the nearer to 1.00, the better),
- 6) have input and output waveguide ports that are axially in line,
- 7) have a small to negligible leakage power, and
- 8) have excellent flanges or connector surfaces.

A more complete discussion of the above is found in reference [6].

5. Measurement Results

5.1 Reflection Coefficient Magnitude

Measurements were performed on two WR15 waveguide reflectors which were manufactured at the NBS. The reflection coefficient magnitudes were approximately 0.1 and 0.024. The devices

were measured each day for 10 days in order to obtain preliminary information on the standard deviations of individual runs (flange repeatability) and of day to day measurements (system random error).

The 0.024 device was made with a standard UG-385/U flange and the 0.1 device was made with a flat (non-bossed) mating surface. The waveguide precision section to which the devices were joined is a flat surface. Alignment pins were used on both flanges.

The results show that the device with the flat flange is more stable and repeatable. For the 0.1 device (flat flange) the standard deviation within runs (based on 4 individual determinations per run) was 0.02 percent of the reflection coefficient magnitude, and the standard deviation between daily averages was 0.015 percent giving a quadrature sum of 0.025 percent.

The 0.024 device exhibited some instability, and a plot of the results displays a "learning curve" (the standard deviation values decreased by an order of magnitude from start to finish) so that a components of variance analysis is not possible at present. Since the standard deviation of the daily averages for the 0.1 device is small (which implies that the measurement system is stable), the conclusion is that the UG-385/U flange is the contributing factor to the reflector instability and is indeed inferior in respect to measurement repeatability.

Additional measurements on the 0.024 device which consisted of tightening the flange bolts by proceeding in either a clockwise or counter clockwise direction around the flange by one operator reduced the standard deviation from 0.8 percent to 0.07 percent. However, when operators were changed, different values of reflection coefficient were obtained.

At present, measurements using this type of flange are unstable, and until further research on flange repeatability and the development of procedures to torque the flange bolts, no definite limits of the repeatability of reflection coefficient measurements using the UG-385/U flange can be reached.

5.2 Attenuation

The measurement of attenuation difference with a rotary-vane attenuator involves angular rotation of the center vane by a dial mechanism being set on several prescribed marks. The repeatability of such a measurement of attenuation involves these factors: (1) ability of the rotor vane to repeat the same angular displacement for a given dial setting, (2) the ability of the operator to set and read the same mark, and 3) system stability. Thus, the lack of repeatability introduces a random error in the process of several measurements. (A precise high resolution WR15 rotary-vane attenuator with a repeatability of .011 dB at a dial setting of 50 dB has been designed and constructed at the NBS.)

The procedure for an insertion loss measurement requires that the waveguide assembly be opened to accept the device-under-test. In both the closed and receptive position, the waveguide holes must be maintained in exact axial alignment to make precision measurements. The connect-disconnect and bolting of the flanges should be done with great care, especially in WR15 and smaller waveguide sizes. Laboratory benches are commercially available for holding waveguide assemblies in a stable and rigid position. The present NBS developed millimeter measurement system (fig. 21) for attenuation and impedance uses a commercial laboratory bench with moderate modifications. The attenuation calibration system is arranged in such a manner that fixed pads, inline multi-hole attenuators, directional couplers, and variable attenuators all can be inserted into the system with minimum effort.

At this time the estimate of the attenuation measurement system random error limits have not been completed, but some typical measurement results are presented in the following paragraphs.

Several commercially available waveguide devices were measured as fixed interlaboratory standards for insertion loss in WR15 waveguide measurement system at 62 and 64 GHz. One device, a directional coupler terminated with a matched load at one output port, was used as an inline fixed attenuator with a nominal value of 1 dB. The directional

coupler was measured in the condition that it was received in the laboratory, that is, with a slight bend in the flange of one port. The estimated value of $3S$ (three times the calculated standard deviation of the mean) for six determinations taken in this circumstance was 0.129 dB. After the flange of the damaged port was realigned by machining, the calculated values of $3S$ for five determinations was 0.009 dB. Thus, the above measurements of insertion loss illustrate that excellent alignment of the output flanges is a must for precision measurements in millimeter waveguide.

Two fixed attenuators in WR15 waveguide measured at 62 and 64 GHz were of nominal values of 10 and 20 dB. The calculated values of $3S$ for five determinations of the 10 dB attenuator at 62 GHz and of a 20 dB attenuator at 64 GHz was 0.023 dB and 0.012 dB, respectively. The measurement precision was better with the 20 dB attenuator due to better flange alignment.

The insertion loss or attenuation of a twenty-eight inch section of commercial silver WR15 waveguide was measured at 64 GHz. The value of $3S$ for five determinations was 0.012 dB. The nominal value of attenuation of the twenty-eight inch section was 1.5 dB, or about 0.05 dB/inch.

The authors extend their appreciation to R.W. Beatty for his helpful suggestions regarding this paper and to G.C. Counas and R.D. Hunter for their help in the system instrumentation and measurements.

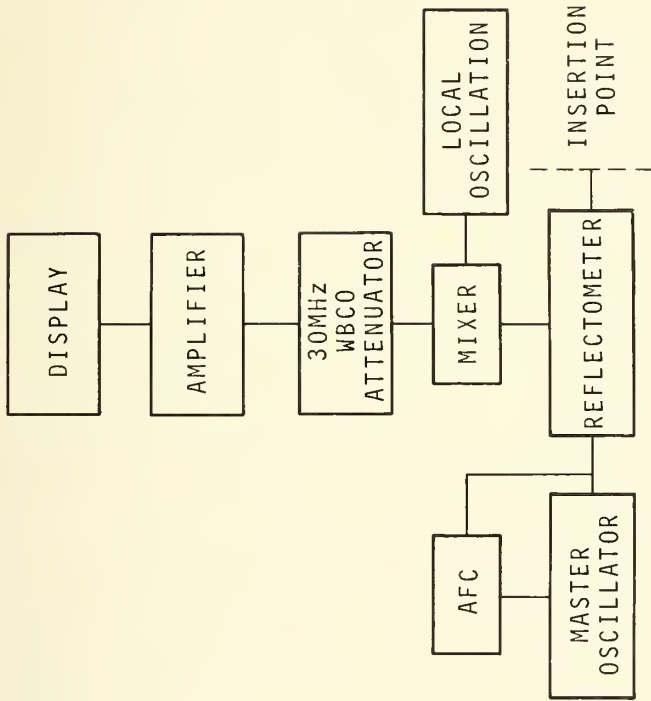


Figure 1. Block diagram of the reflection coefficient magnitude subsystem using an i-f receiver.

MODIFIED REFLECTOMETER

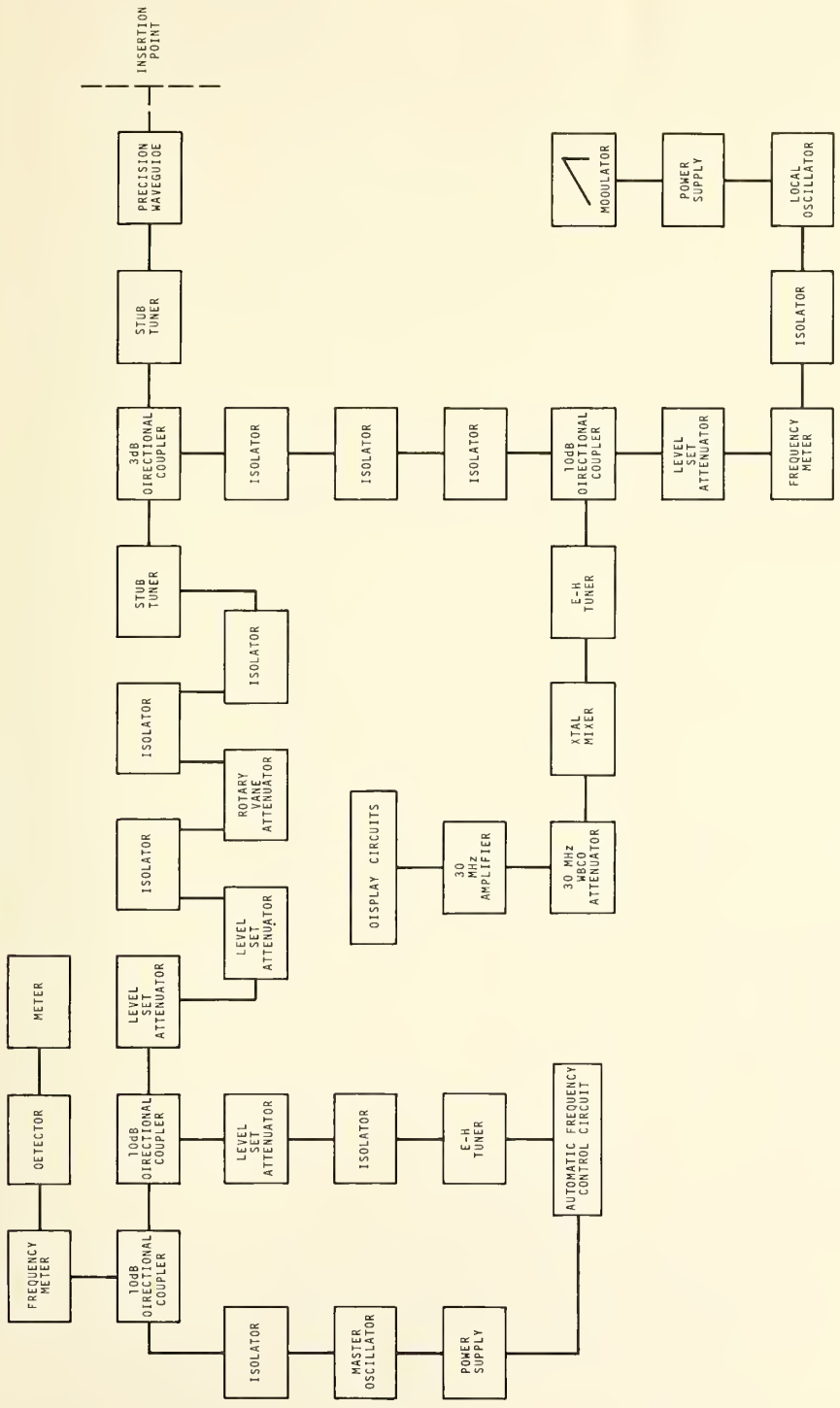


Figure 2. Detailed diagram of the reflection coefficient magnitude subsystem.

TWO LOOP AFC CIRCUIT

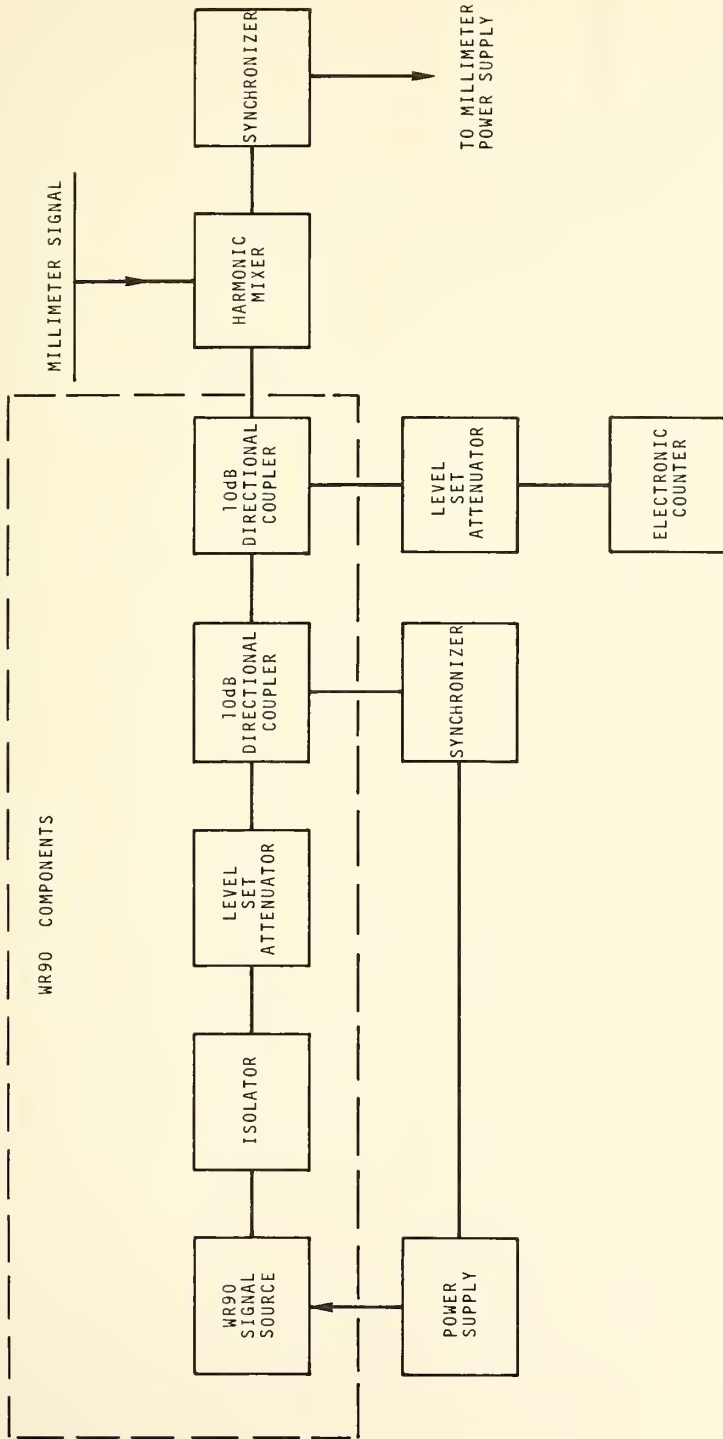


Figure 3. Detailed diagram of the two-loop automatic frequency control network.

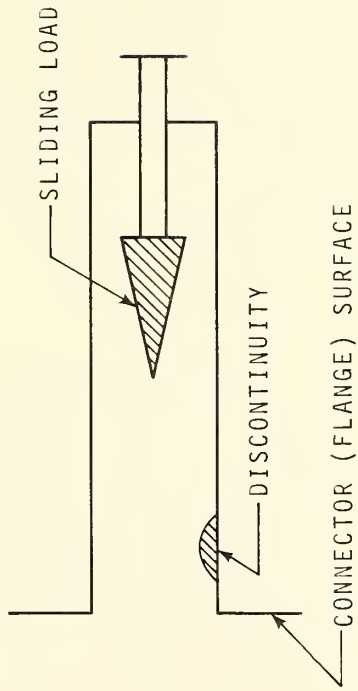


Figure 4. Waveguide termination.

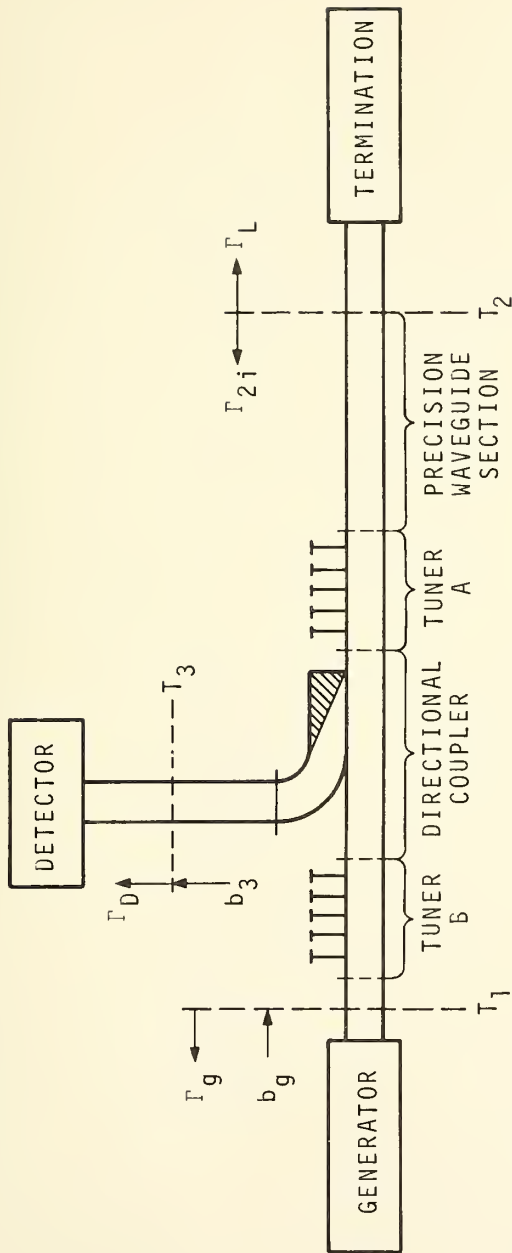


Figure 5. Diagram of a tunable, single-directional coupler reflectometer (modified reflectometer).

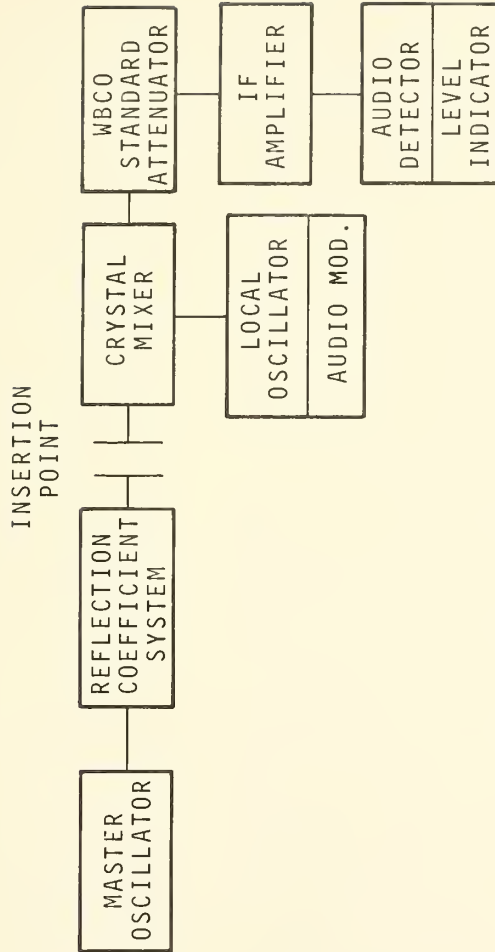


Figure 6. Block diagram of the i-f series substitution attenuation subsystem.

LOCAL OSCILLATOR AND MIXER ARM

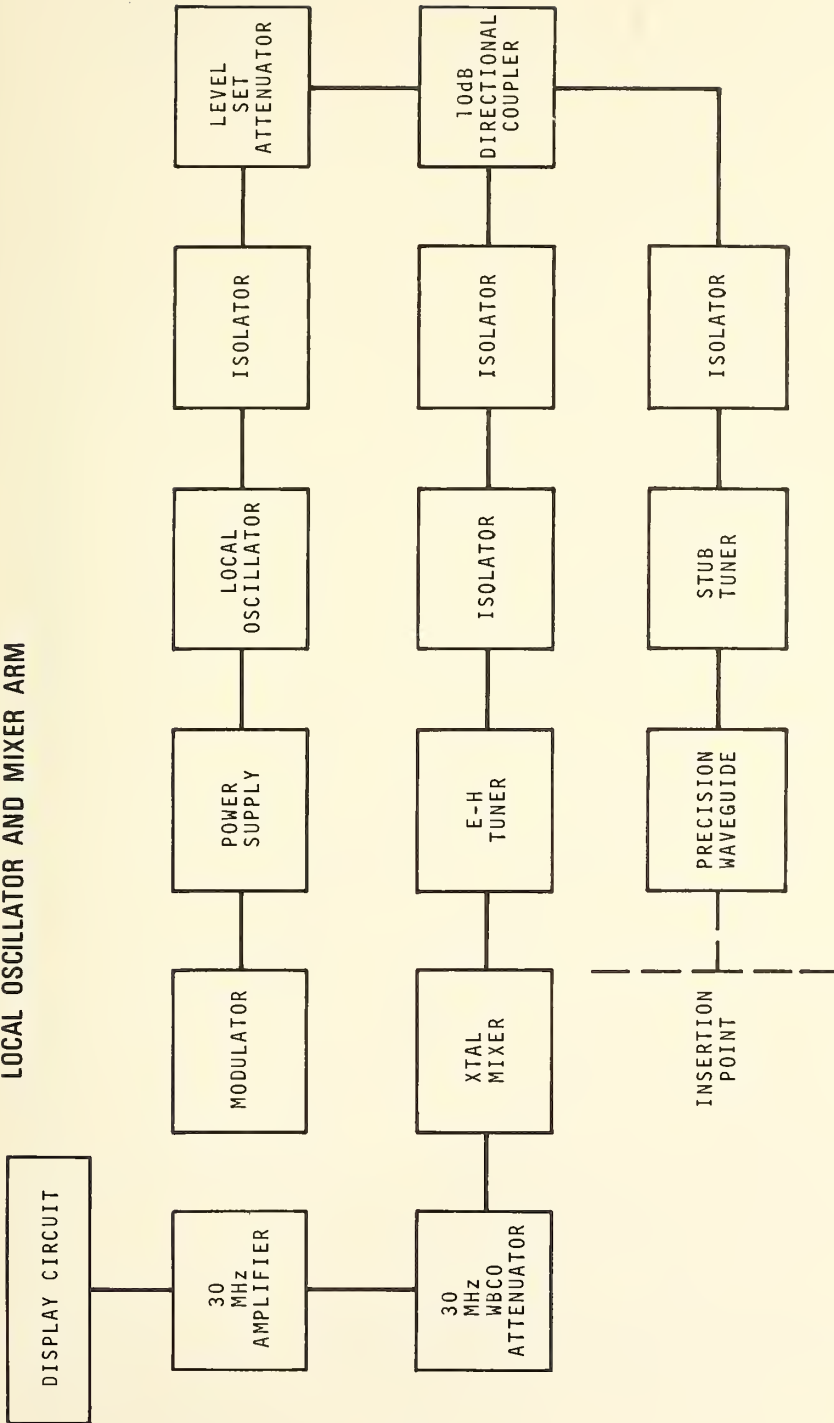


Figure 7. Detailed diagram of the rf receiver of the attenuation subsystem.

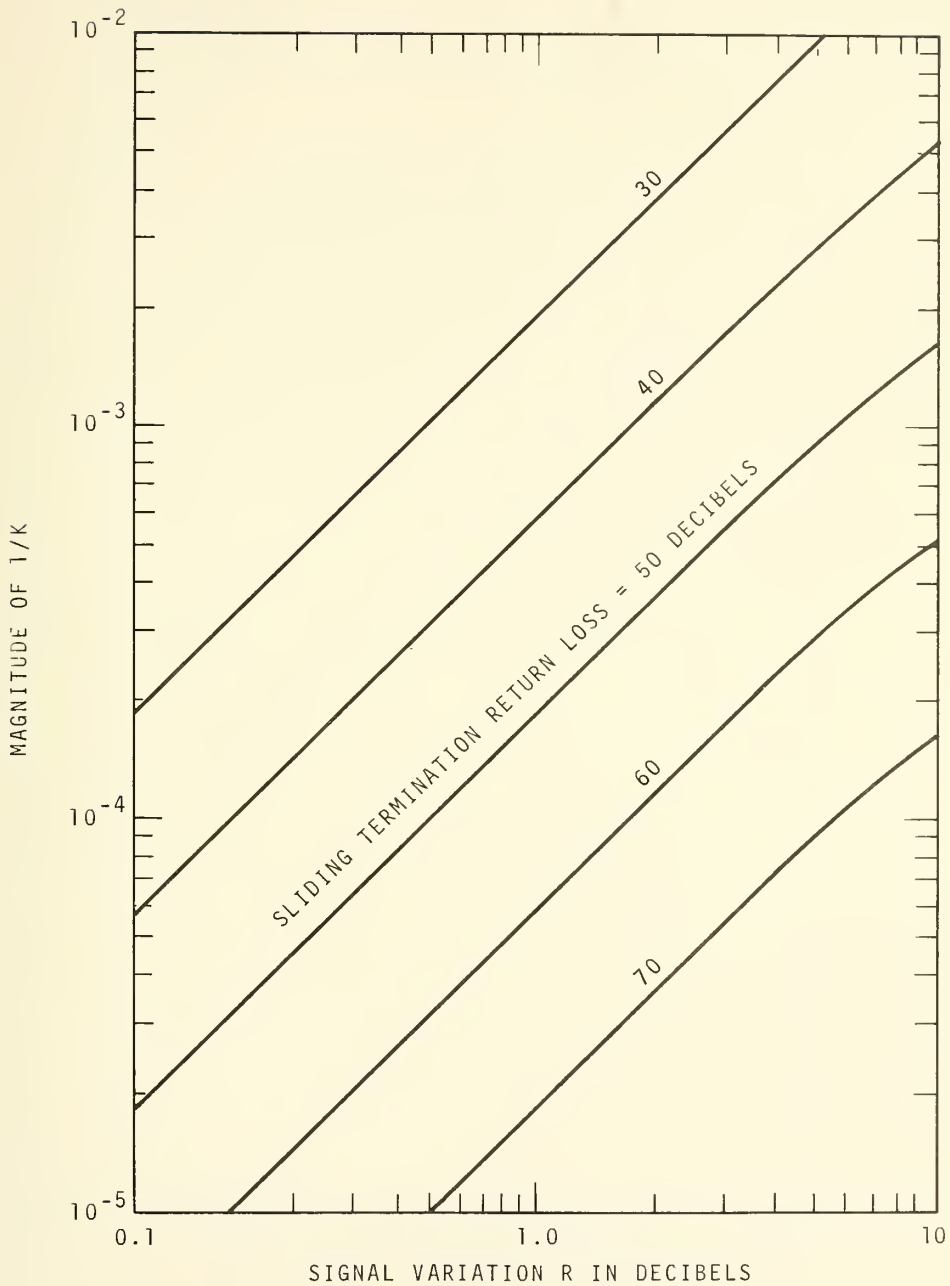


Figure 8. Graph for estimating the magnitude of $1/K$ given a response variation R when sliding a load with return losses of 30 to 70 decibels.

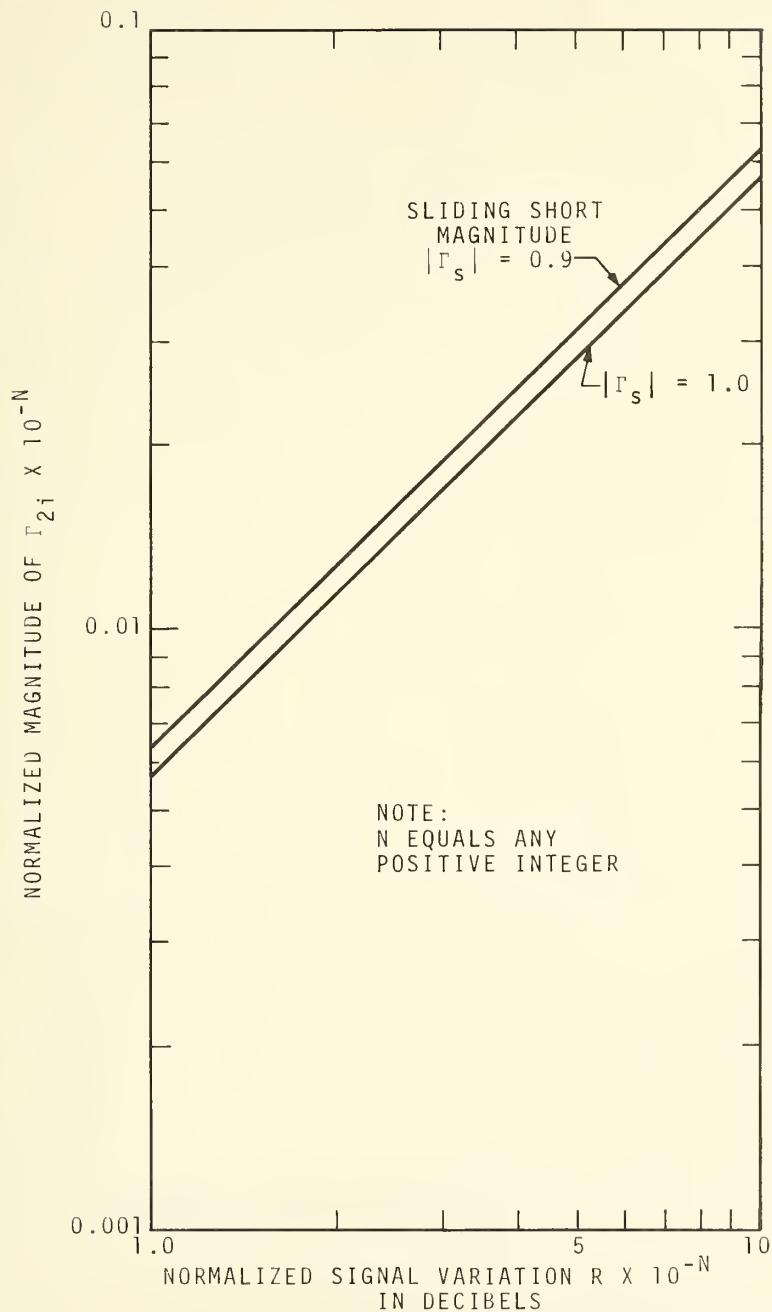


Figure 9. Graph for estimating the equivalent generator impedance for a given response variation $R \times 10^{-N}$ when sliding a short-circuit termination.

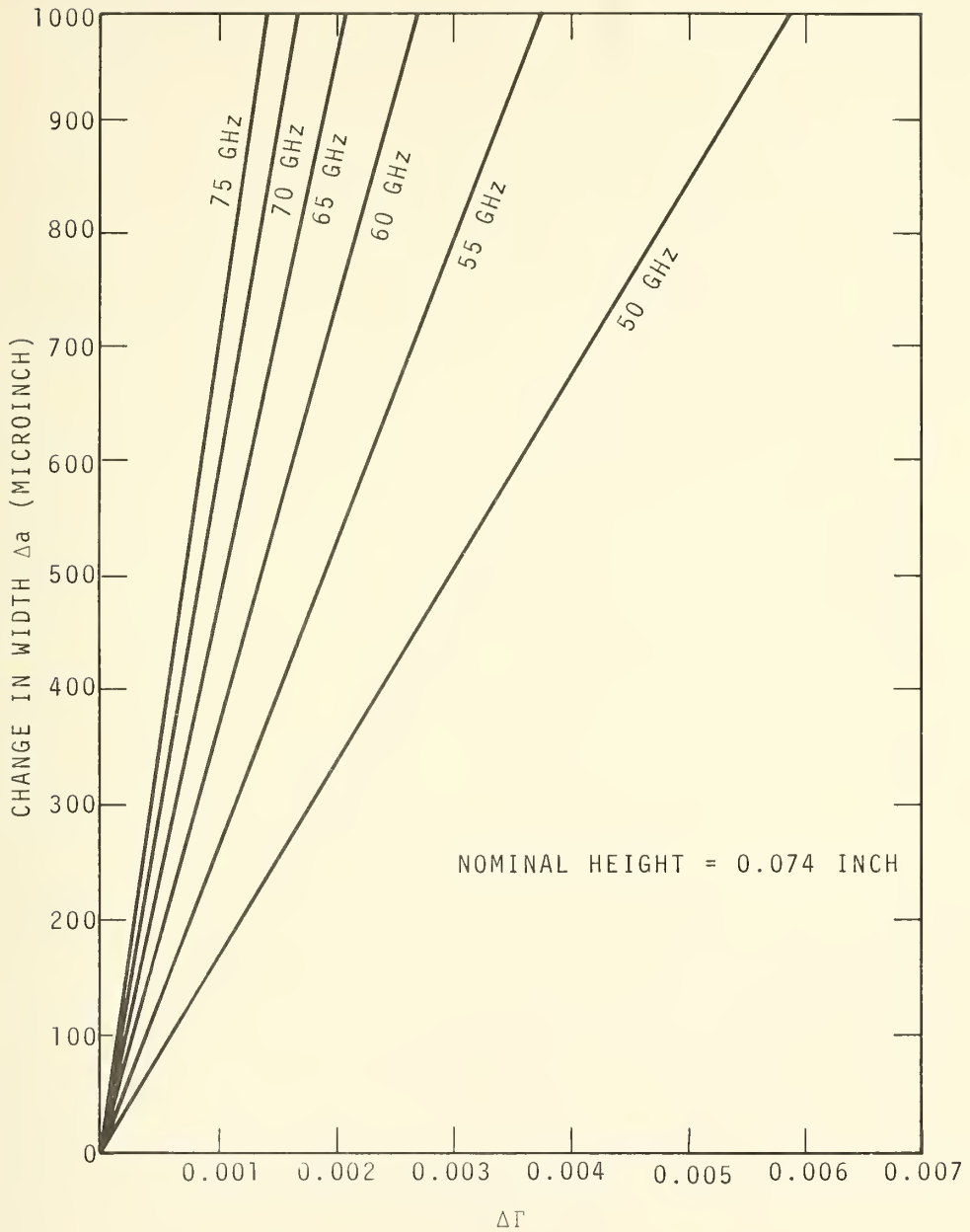


Figure 10.

Change in reflection coefficient magnitude versus dimension change in the nominal waveguide width of 0.148 inch.

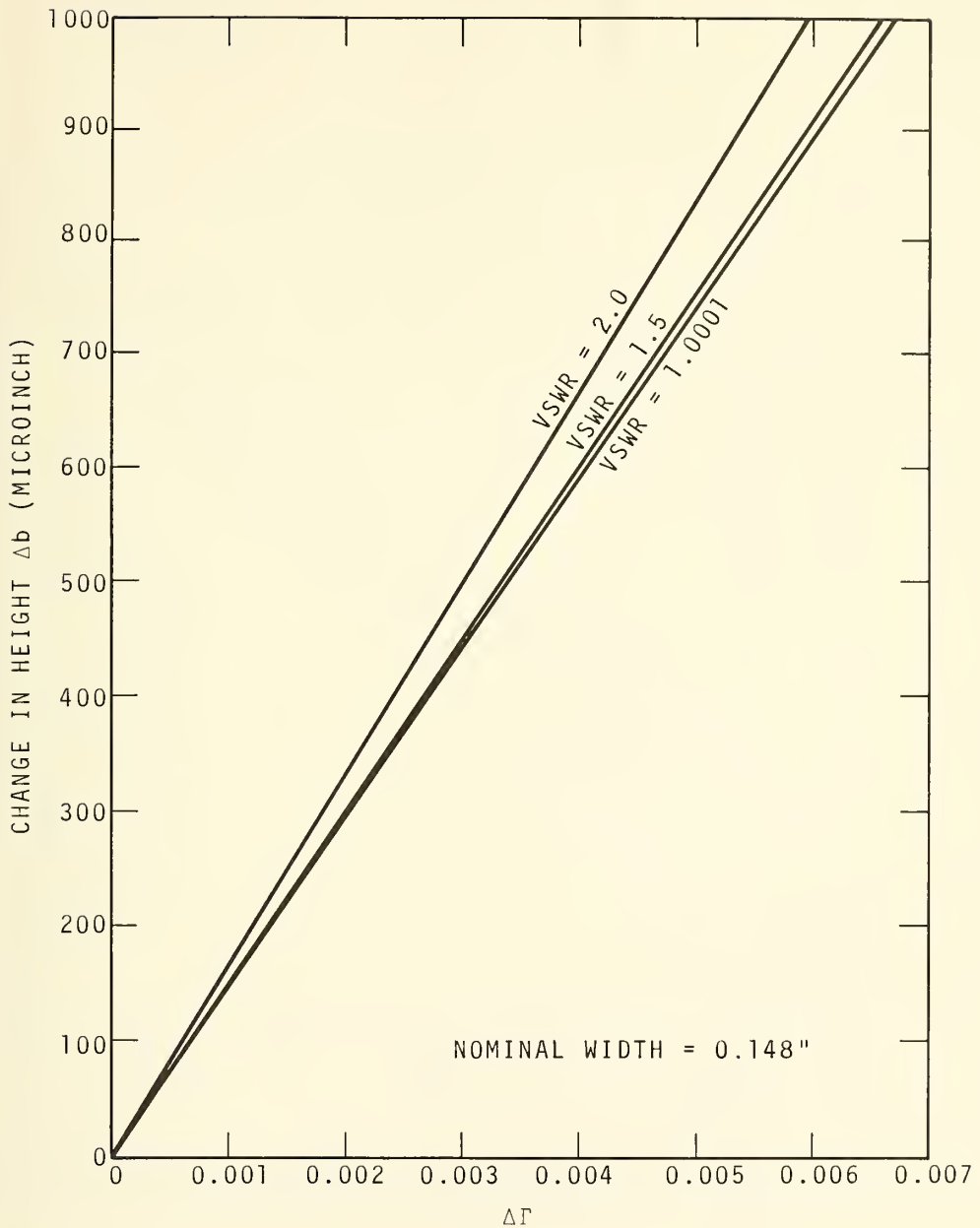


Figure 11. Change in reflection coefficient magnitude versus dimensional change in the nominal waveguide height of 0.074 inch.

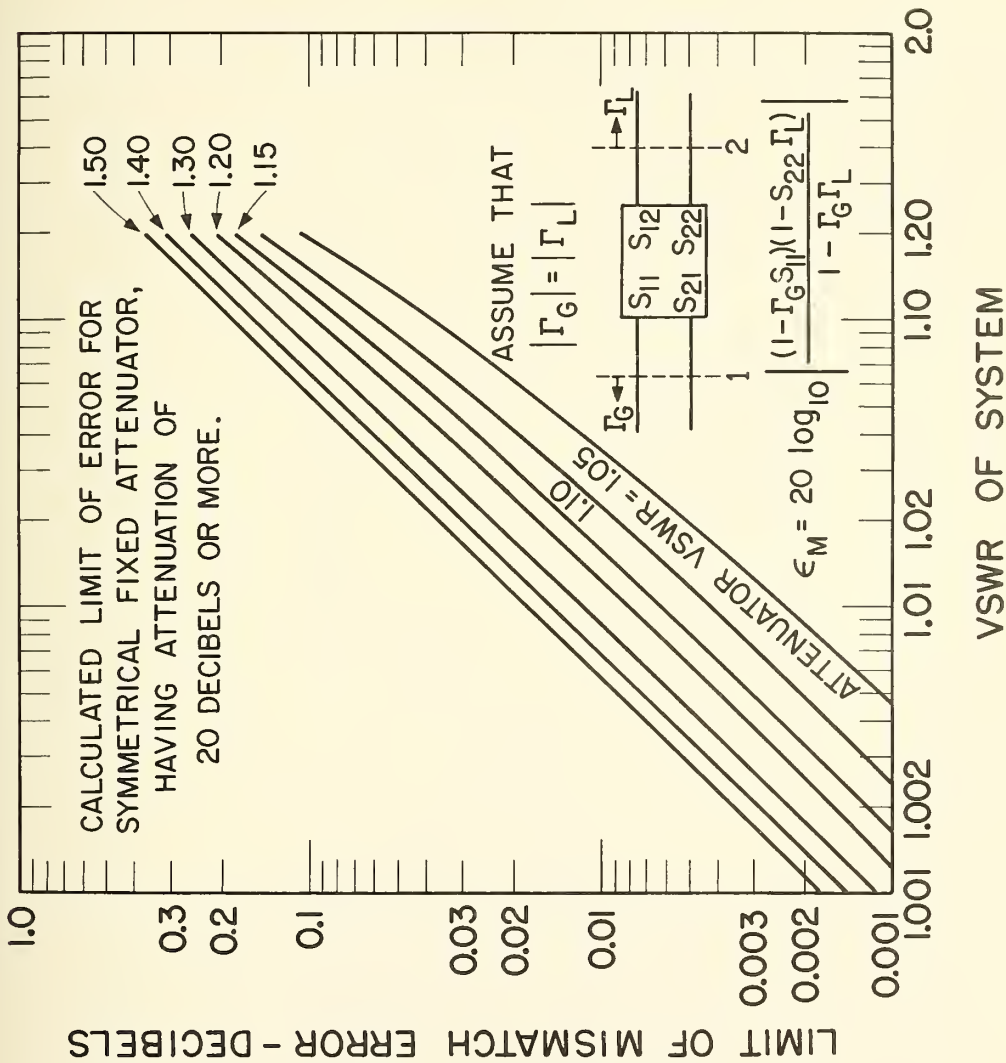


Figure 12. Graph for estimating mismatch error limits when the attenuation and system VSWR is given.

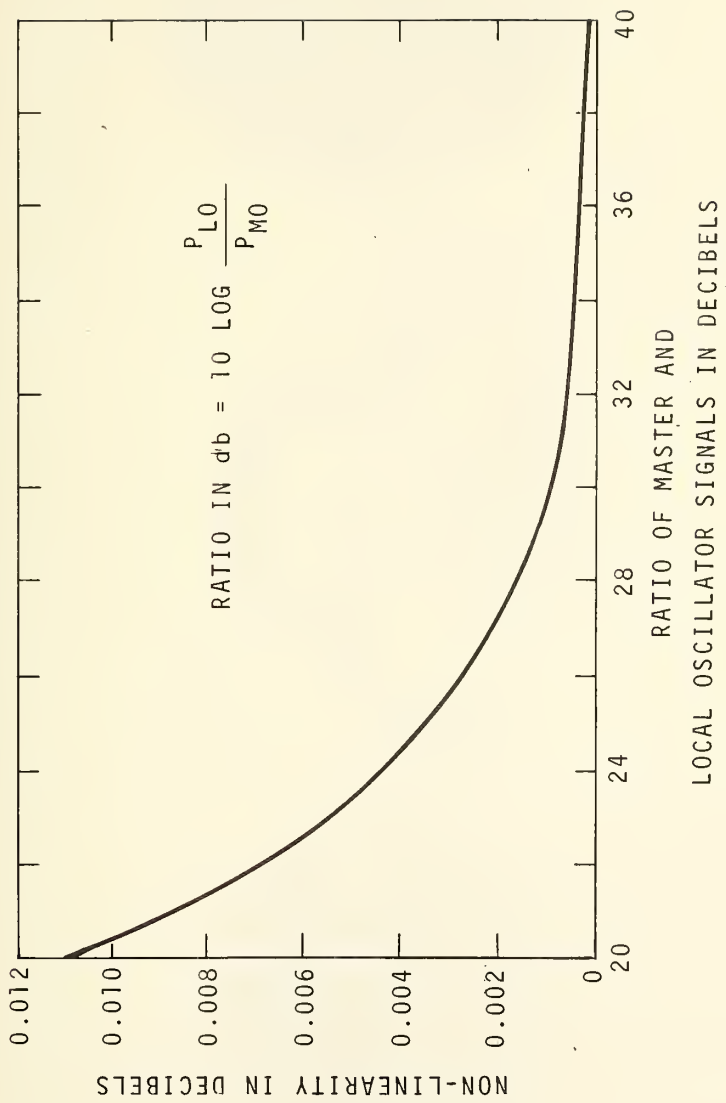


Figure 13. Theoretical mixer power conversion non-linearity versus master-local oscillator power ratio.

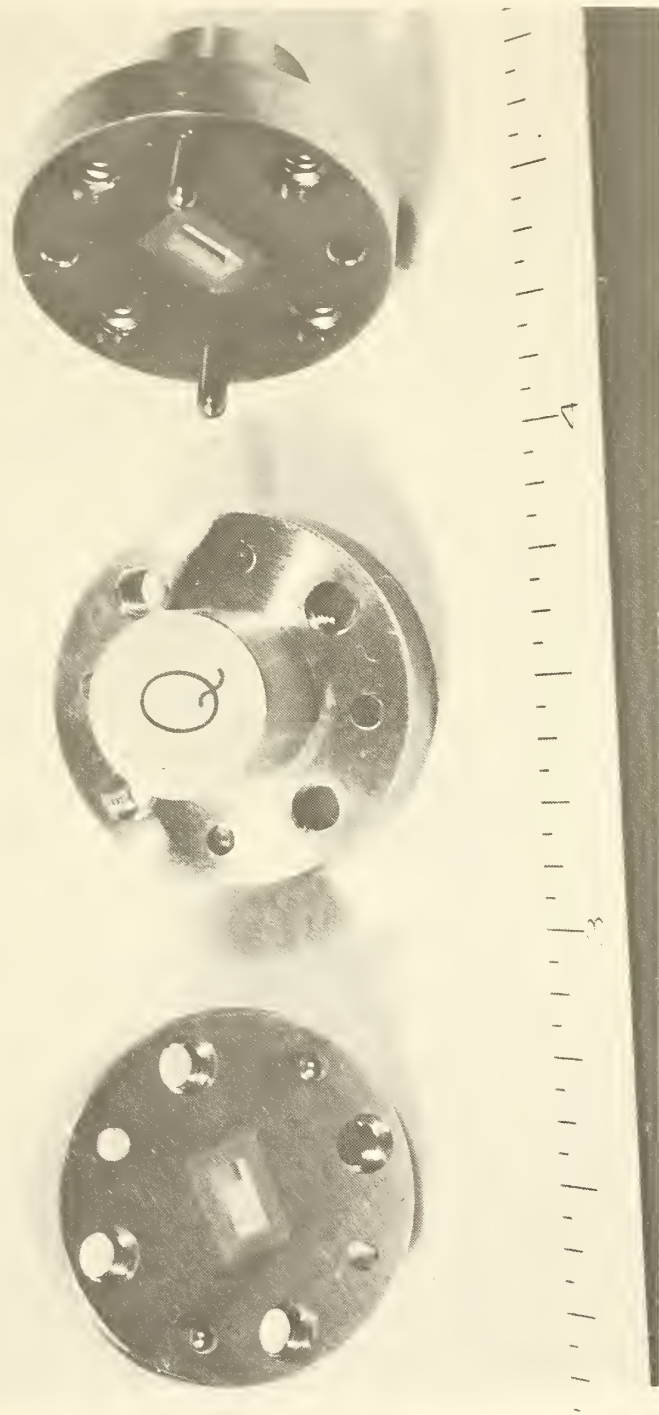


Figure 14. Quarter-wavelength short-circuited waveguide standards.

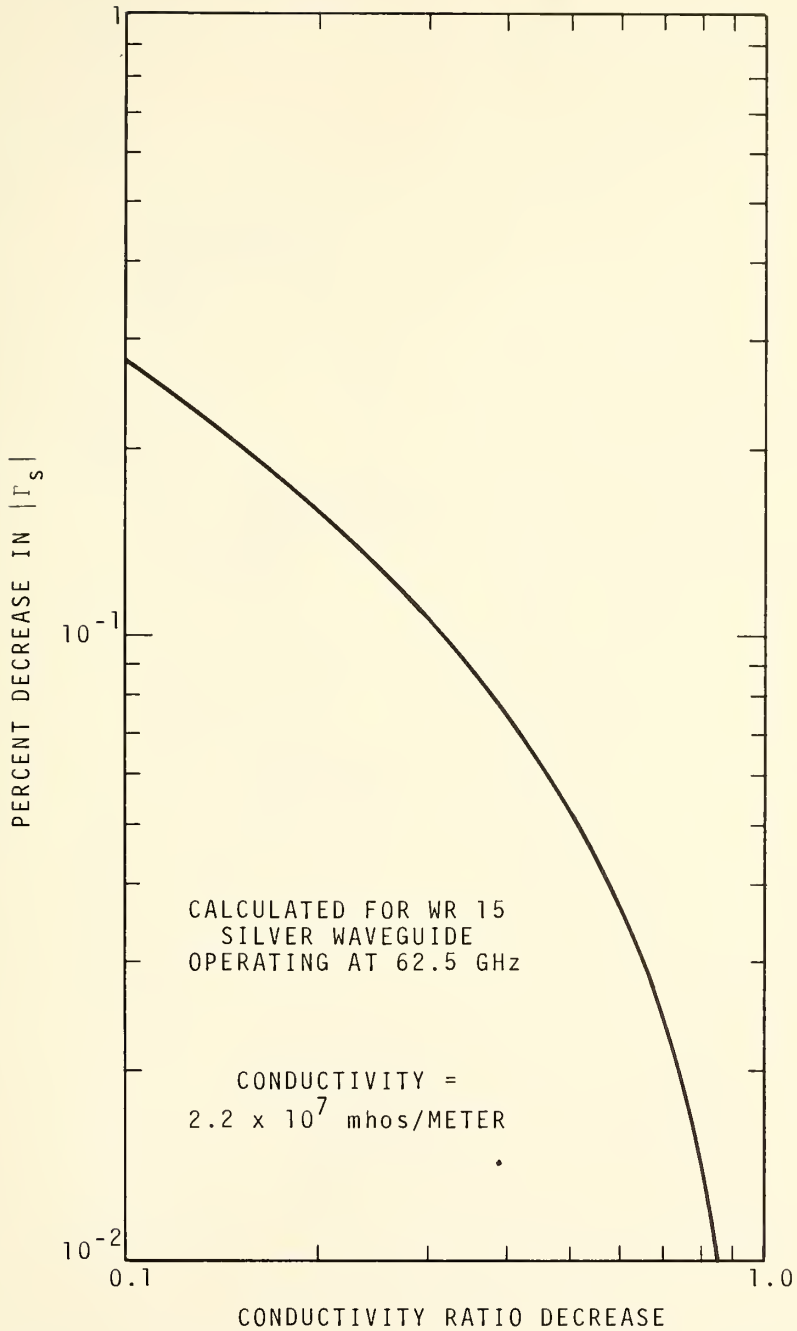


Figure 15. Graph for estimating the change in reflection coefficient of a quarterwave short circuit versus conductivity confidence interval (the relative error subtracted from unity).

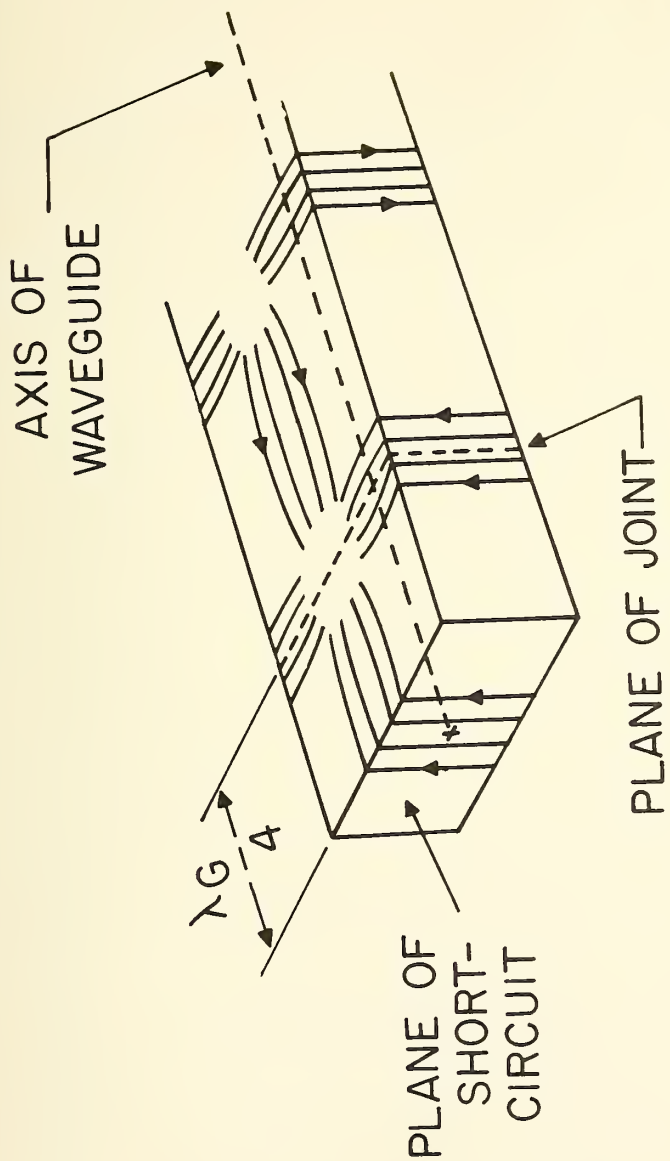


Figure 16. Current distribution for a rectangular TE₁₀ mode short-circuited waveguide.

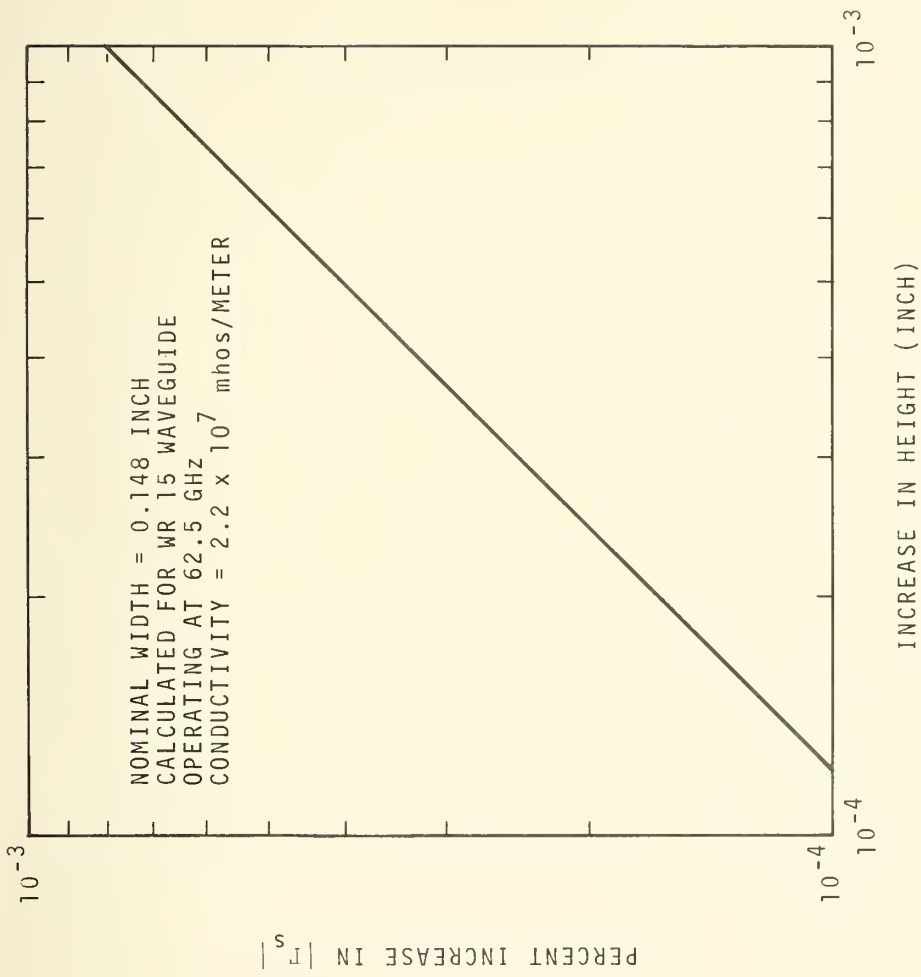


Figure 17. Graph for estimating the change in reflection coefficient magnitude of a quarterwave short circuit versus dimensional deviation from height dimension of 0.074 inch.

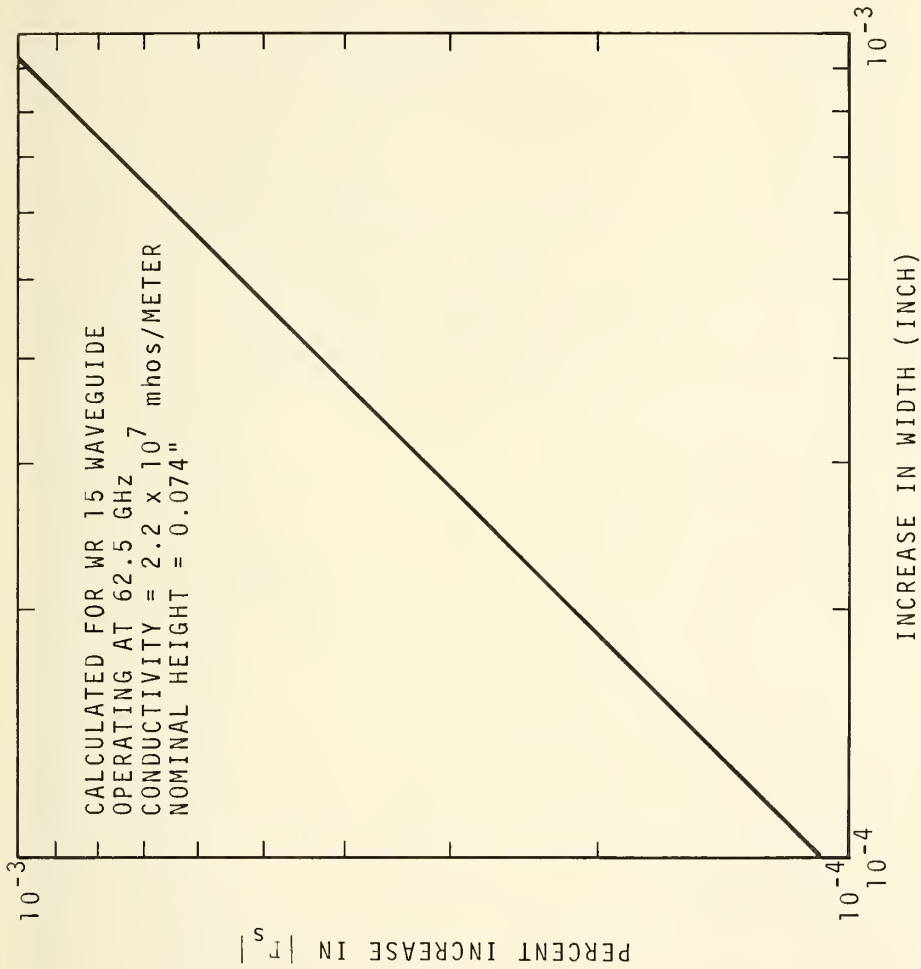


Figure 18. Graph for estimating the change in reflection coefficient magnitude of a quarterwave short circuit versus dimensional deviation from nominal width dimension of 0.148 inch.

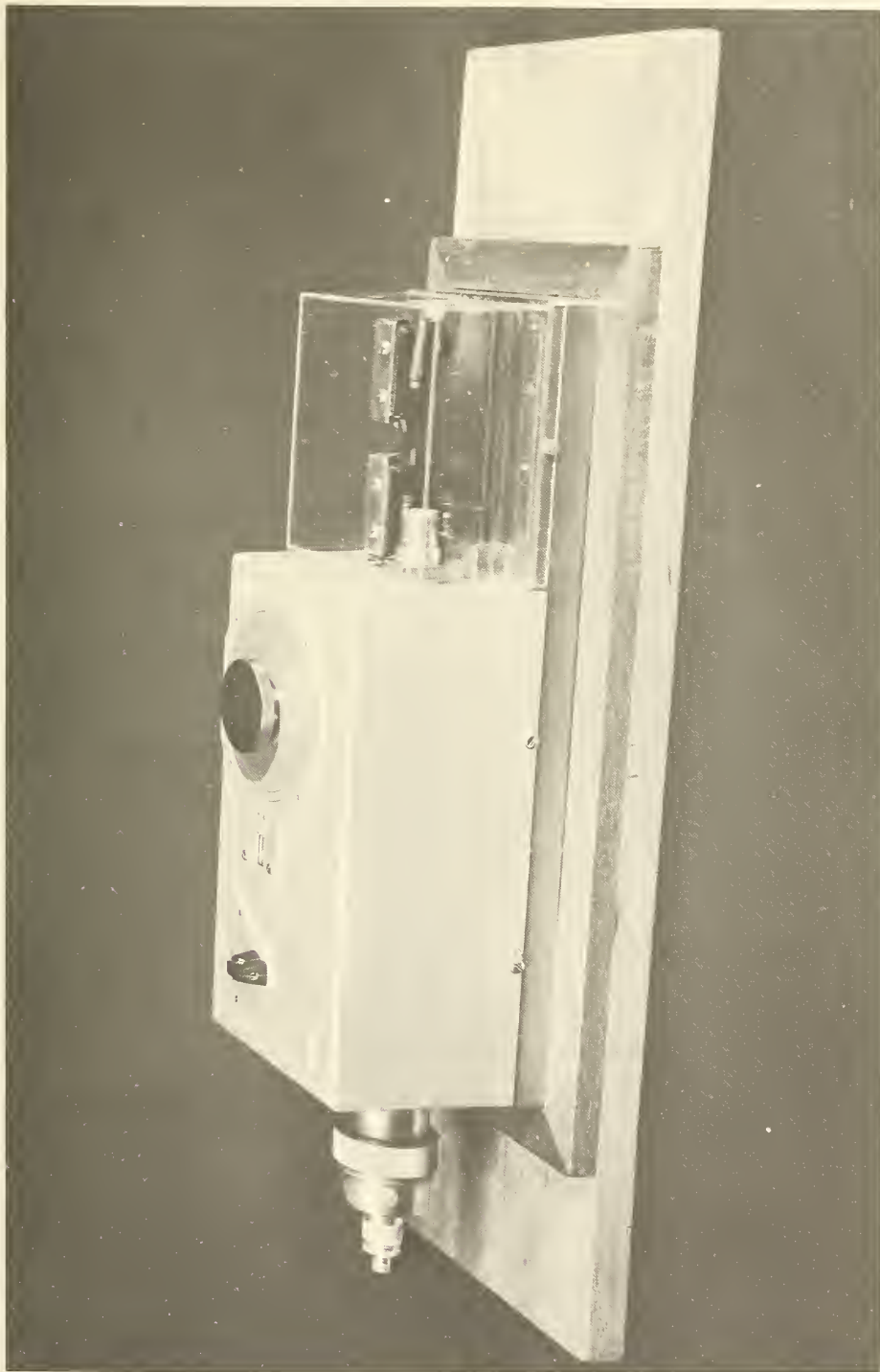


Figure 19. Waveguide-Below-Cutoff attenuator.

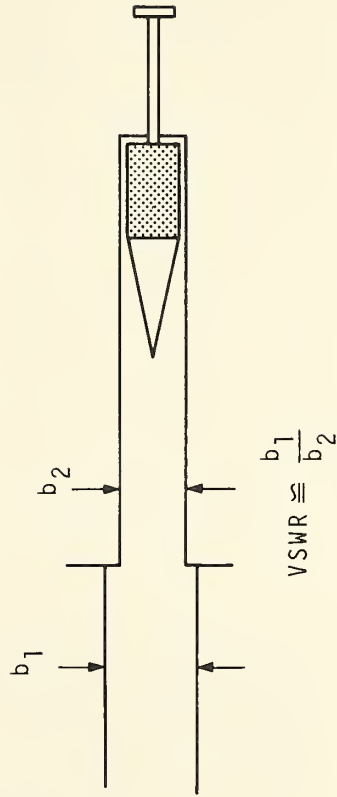


Figure 20. Typical change in narrow dimension of rectangular waveguide used for interlaboratory reflection standards.

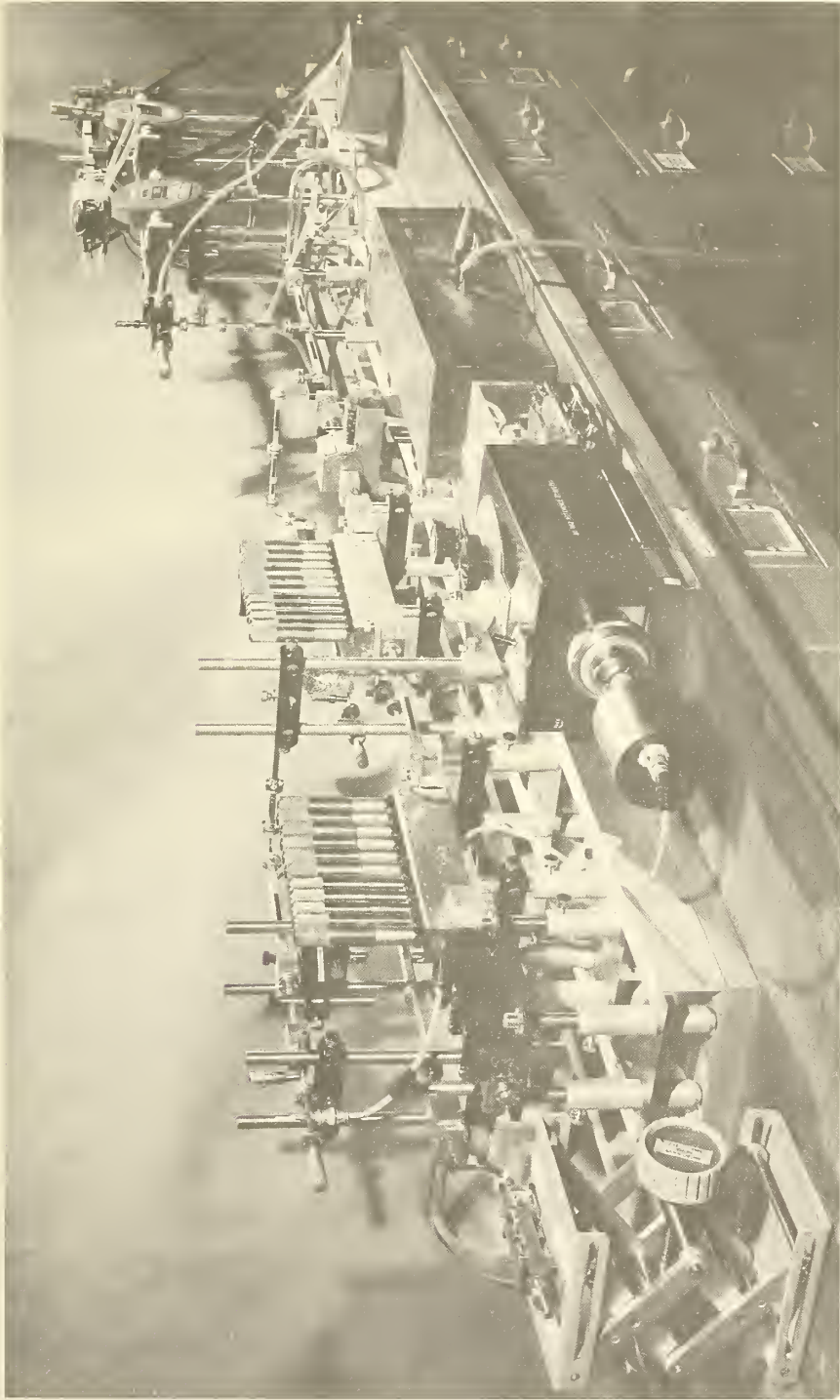


Figure 21. WR15 reflectometer and associated support hardware.

APPENDIX A

To illustrate the statement in section 2.1.2 that the average reflection coefficient magnitude $|\Gamma|_{\text{ave}}$ is associated with that element which has the largest reflection, consider the following lossless case (for definitions of losslessness see [29], p. 48) of a termination with a fixed discontinuity Γ_D and a sliding load Γ_L .

It can be shown [30, 31] that

$$|\Gamma|_{\text{max}} = \frac{|\Gamma_D| + |\Gamma_L|}{1 + |\Gamma_D \Gamma_L|}$$

and

$$|\Gamma|_{\text{min}} = \frac{|\Gamma_D| - |\Gamma_L|}{1 - |\Gamma_D \Gamma_L|} \quad |\Gamma_D| > |\Gamma_L|$$

or

$$|\Gamma|_{\text{min}} = \frac{|\Gamma_L| - |\Gamma_D|}{1 - |\Gamma_D \Gamma_L|} \quad |\Gamma_L| > |\Gamma_D|$$

where $|\Gamma|_{\text{max}}$ and $|\Gamma|_{\text{min}}$ correspond to the measured maximum and minimum reflection coefficients. Then, the average reflection coefficient magnitude

$$\begin{aligned} |\Gamma|_{\text{ave}} &= \frac{1}{2} \left(|\Gamma|_{\text{max}} + |\Gamma|_{\text{min}} \right) \\ &= |\Gamma_D| \frac{(1 - |\Gamma_L|^2)}{1 - |\Gamma_D \Gamma_L|^2}, \quad |\Gamma_D| > |\Gamma_L| \end{aligned}$$

or

$$= |\Gamma_L| \frac{(1 - |\Gamma_D|^2)}{1 - |\Gamma_D \Gamma_L|^2}, \quad |\Gamma_L| > |\Gamma_D|$$

is in either case a first order approximation to the largest reflection coefficient.

APPENDIX B

Estimated Systematic Error Limits for WR15 Attenuation Measurements

The following estimated error limits are based on tolerances for the NBS WR15 components and systems.

Converter (Mixer) Error	±0.003
Noise up to	
{ 40 dB } measured	±0.004
{ 50 dB } attenuation	±0.020 dB
30 MHz Standard Attenuator	
Loading effects	±0.001 dB
Mode purity	±0.001 dB
Dimensional Tolerance	±0.002 dB/20 dB

Mismatch Error vs. Attenuator VSWR

(System VSWR at insertion point = 1.02)

Attenuator VSWR	Mismatch Error (dB)
1.05	±0.005
1.10	±0.008
1.15	±0.013
1.20	±0.017

Total Systematic Error (dB) Attenuator VSWR

Dial Setting (dB)	1.05	1.10	1.15	1.20
10	±0.012	±0.015	±0.020	±0.024
20	±0.012	±0.015	±0.020	±0.024
30	±0.014	±0.017	±0.022	±0.026
40	±0.018	±0.021	±0.026	±0.030
50	±0.036	±0.039	±0.044	±0.048

APPENDIX C

Estimated Systematic Error Limits ($\Delta\Gamma$) for
WR15 Reflection Coefficient Magnitude ($|\Gamma|$) Measurements

The following estimated error limits are based on tolerances for the NBS WR15 components and systems.

$$|\Gamma| \geq 0.025$$

Tuning Error

Directivity	$\pm 0.00015 (1 + \Gamma)$
Γ_{2i}	$\pm 0.00012 (1 + \Gamma)$
Converter Error	$\pm 0.00035 \Gamma $
30 MHz Standard Attenuator	$\pm 0.00046 \Gamma $
Reflection Coefficient Magnitude Standard	$\pm 0.0003 \Gamma $
Precision Section	± 0.0006
Total Error	$\pm 0.00087 + 0.00138 \Gamma $
Reported Estimated Error	$\Delta\Gamma = \pm(1 + 1.5 \Gamma) \times 10^{-3}$

$$|\Gamma| < 0.025$$

Converter Error	$\pm 0.00105 \Gamma $
30 MHz Standard Attenuator	$\pm 0.00138 \Gamma $
Total Error	$\pm 0.00087 + 0.0030 \Gamma $
Reported Estimated Error	$\Delta\Gamma = \pm(1 + 3 \Gamma) \times 10^{-3}$

APPENDIX D

Machine drawings for 11 stub tuner

for 55-65 GHz, WR15.

Figures 22(a), 22(b), 22(c).

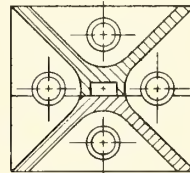
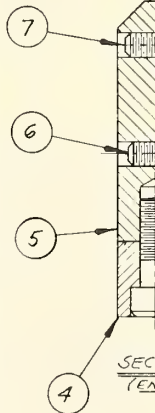
Certain commercial equipment and materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

ORIGINAL DATE OF DRAWING			
REVISIONS			
NO	E C N	CHANGE	DATE
1			
2			
3			
4			

LIST OF PARTS

* STOCK ITEMS

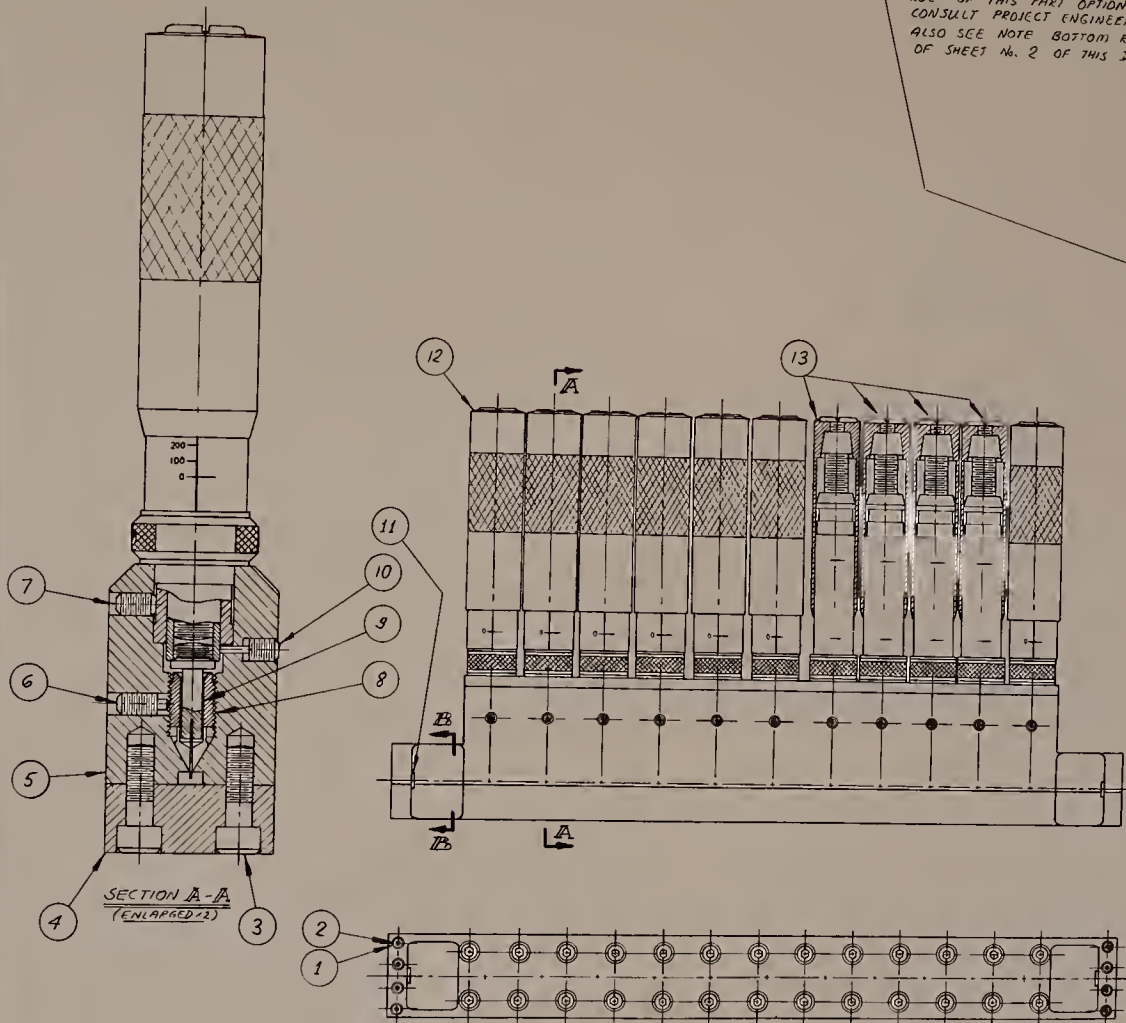
13	DIFFERENTIAL SCREW TRANSLATOR (MICROMETER 0'-0.050) LANSING PRODUCT CAT. 306-1/69 # 22505 (MODIF. '8')	4
12	DIFFERENTIAL SCREW TRANSLATOR (MICROMETER 0'-0.050) LANSING PRODUCT CAT. 306-1/69 # 22505 (MODIF. '9')	7
11	BUSHING MAT'L - HARDENED STEEL	8
10	"NO-MAR" STAINLESS STEEL SET SCREW, # 6-32 UNC, 3/8" LONG PIC CAT. NO. CS-15 (MODIFIED: NYLON REPLACED BY .050 D. BRASS PIN)	11
9	SPINDLE TIP WITH STUB MAT'L - SPINDLE TIP: FREE CUTTING BRASS; STUB: DRILL ROD	11
8	CONTACT SPRING MAT'L - PHOSPHOR BRONZE	11
7	STEEL SET SCREW # 6-32 UNC, 1/4" LONG FLAT POINT	11
6	"NO-MAR" STAINLESS STEEL SET SCREW # 6-32 UNC 3/32" LONG PIC CAT. NO. CS-15 (MODIFIED: MACH REARCED BY BRASS)	11
5	HOUSING, TOP SECTION MAT'L - FREE CUTTING BRASS	1
4	HOUSING, BOTTOM SECTION MAT'L - FREE CUTTING BRASS	1
3	STEEL HEX. SOCKET HEAD SCREW, # 8-32 UNC 1/2" LONG	22
2	STEEL HEX. SOCKET HEAD SCREW, # 3-48 UNC 5/8" LONG	8
1	HELICOIL INSERT # 3-48 UNC, STAINLESS STEEL 0.248 LONG	8
PCE NO.	NOMENCLATURE	NO. REQ'D



SECTION TB-TB
(ENLARGED x 2)

PICE NO.	NOMENCLATURE	NO. REQ'D
NATIONAL BUREAU OF STANDARDS		
RADIO STANDARDS LABORATORY, BOULDER, COLORADO, 80502		
11 STUB TUNER		
FOR 55-65 GHz, WR-15 (RC-98/U)		
MODEL I	TYPE	SCALE 1/1
DIMENSIONS IN INCHES (Unless otherwise specified)	DRAFTSMAN Vernie LEVINSON	CHECKER
TOLERANCES (Unless otherwise specified)	PROJECT ENGR BILL C. YATES	PROJECT ENGR R. P. WEIDMAN
DECIMALS ±.000	SUBMITTED BY	
FRACTIONS ±.016	CHIEF DES.	
ANGLES ±.4°	EXAMINED BY	
DO NOT SCALE THIS PRINT	CHIEF ENGINEER	
DIV. SEC.	THIS PRINT ISSUED	APPROVED BY
272		CHIEF, DIV.
40		

Figure 22(a)

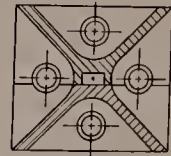


USE OF THIS PART OPTIONAL
CONSULT PROJECT ENGINEER,
ALSO SEE NOTE BOTTOM R.H. CORNER
OF SHEET No. 2 OF THIS DRAWG.

ORIGINAL DATE OF DRAWING			
REVISIONS			
NO	REASON	CHANGE	DATE
1			
2			
3			
4			

LIST OF PARTS * STOCK ITEMS

13	DIFFERENTIAL SCREW TRANSLATOR (MICROANETER 0-050) LANSING PRODUCT CAT. 306-1/69 # 22505 (MODIF. '8')	4
12	DIFFERENTIAL SCREW TRANSLATOR (MICROMETER 0-050) LANSING PRODUCT CAT. 306-1/69 # 22505 (MODIF. '7')	7
11	BUSHING MAT'L - HARDENED STEEL	8
10	"NO-MAR" STAINLESS STEEL SET SCREW, # C-32 UNC, 1/4 LONG PIC CAT No. CS-15 (MODIFIED. WHEN REPLACED BY 000 D. BRASS P.H.)	11
9	SPINDLE TIP WITH STUB MAT'L - SPINDLE TIP: FREE CUTTING BRASS, STUB: BRILL ROD	11
8	CONTACT SPRING MAT'L - PHOSPHOR BRONZE	11
7	STEEL SET SCREW # C-32 UNC, 1/4 LONG FLAT POINT	11
6	"NO-MAR" STAINLESS STEEL SET SCREW # C-32 UNC 3/32 LONG PIC CAT. No. CS-15 (MODIFIED. WHEN REPLACED BY 000 D.)	11
5	HOUSING, TOP SECTION MAT'L - FREE CUTTING BRASS	1
4	HOUSING, BOTTOM SECTION MAT'L - FREE CUTTING BRASS	1
3	STEEL HEX. SOCKET HEAD SCREW, # 8-32 UNC 1/2 LONG	22
2	STEEL HEX. SOCKET HEAD SCREW, # 3-48 UNC 5/8 LONG	8
1	HELICOIL INSET # 3-48 UNC, STAINLESS STEEL 0.248 LONG	8
PIECE NO. NOMENCLATURE		NO. QUANT.



PIECE NO.	NOMENCLATURE	NO. QUANT.
NATIONAL BUREAU OF STANDARDS RADIO STANDARDS LABORATORY, BETHESDA, GEORGETOWN, MD 20815		
11 STUB TUNER		
FOR 55-65 GHz, WR-15 (NC-3216)		
MODEL 1	TYPE	SCALE 1/1
DESIGNED IN INCHES (Unless otherwise specified)	DRAWN BY VICTOR LECHNER	CHECKED
TOLERANCES (Unless otherwise specified)	PROJECT ENG. BILL C. YATES	PROJECT ENG. R.P. WIDMANN
DECIMALS ± .000	SUBMITTED BY	
FRACTIONS ± .010	CHIEF ENG.	
ANGLES ± 1'	EXAMINED BY	
DO NOT SCALE THIS PRINT	CHIEF ENGINEER	
REV. NO.	THIS PRINT ISSUED	APPROVED BY
272		CHIEF DIV.
90		

Figure 22(a).

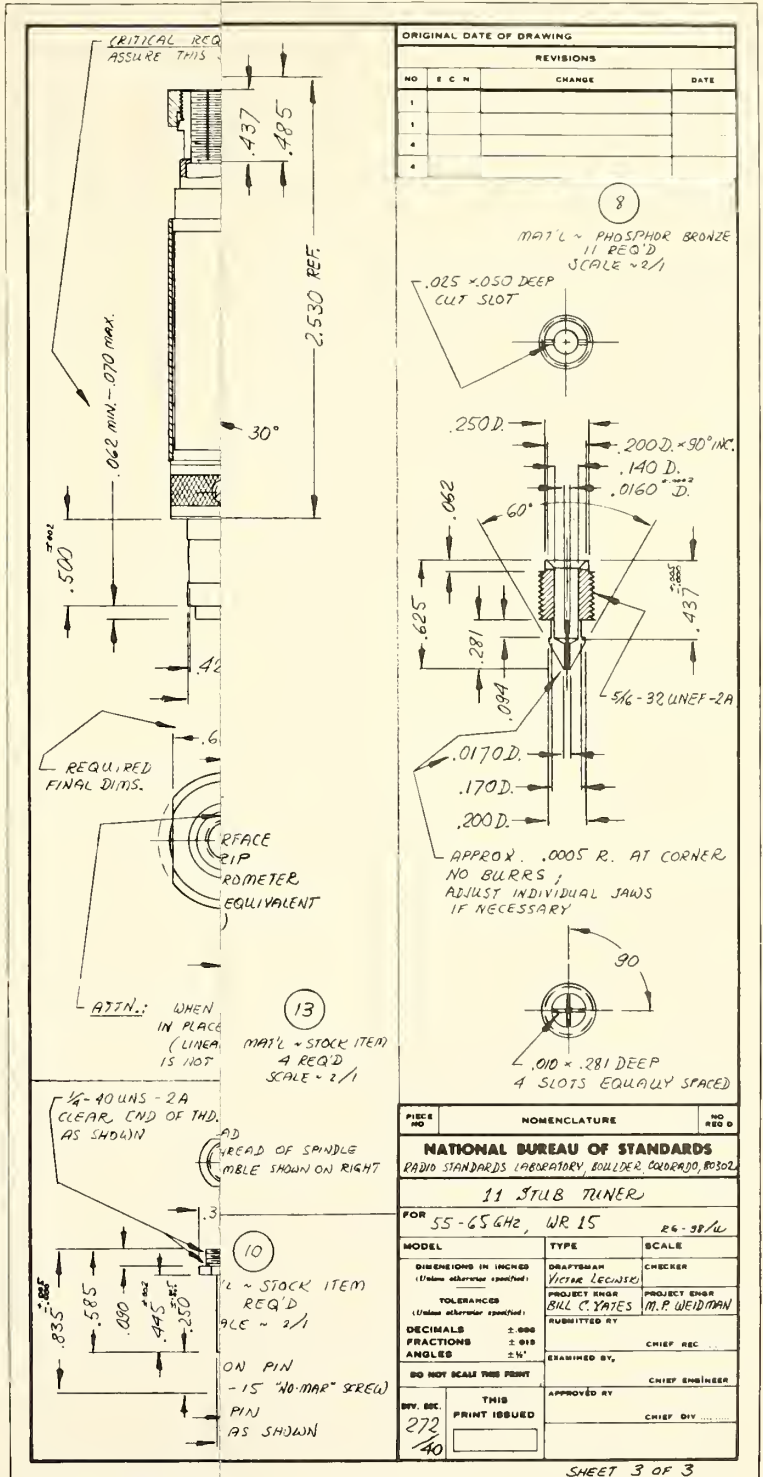


Figure 22(c)

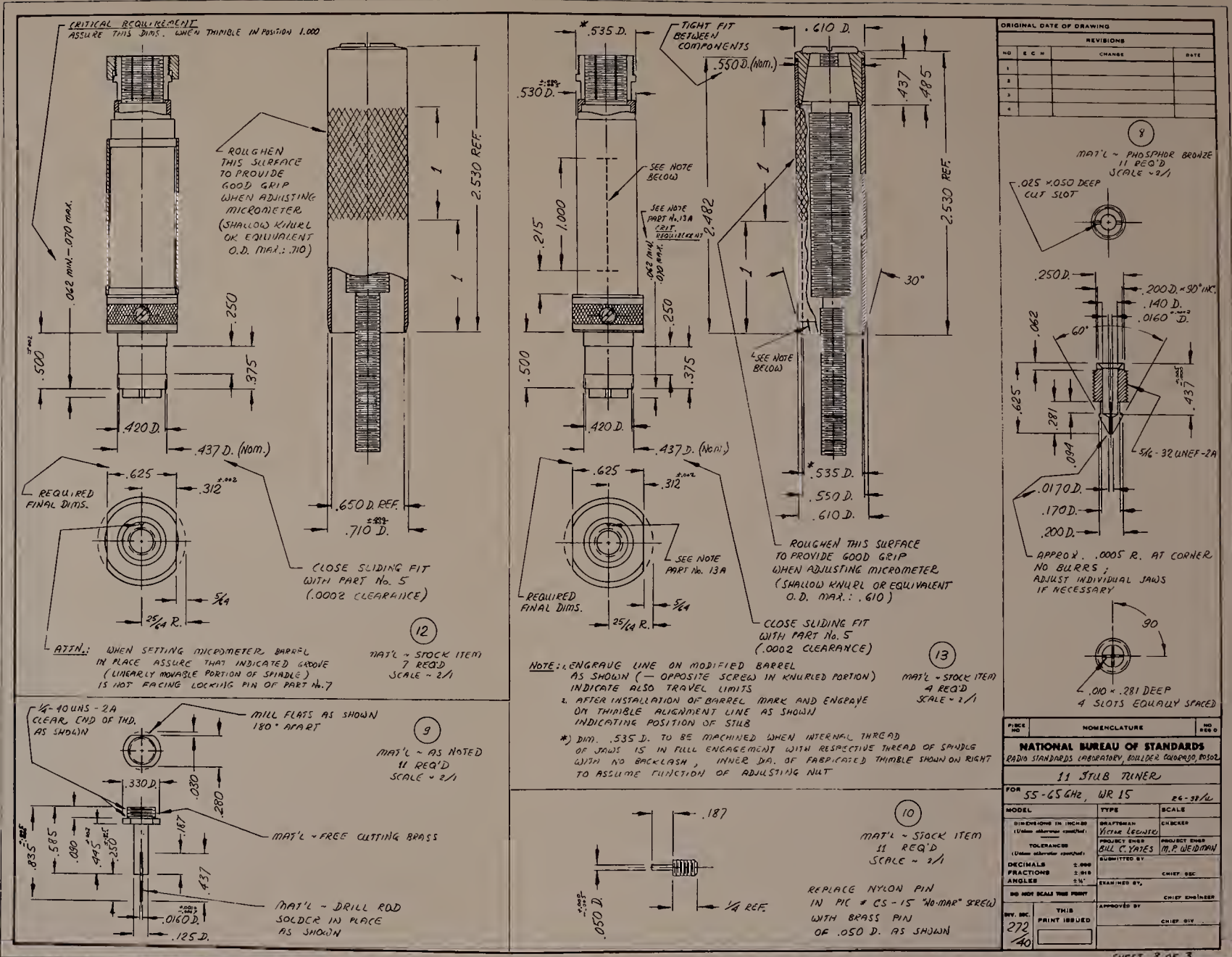


Figure 22(c).

APPENDIX E

Machine drawing for sliding load
for WR15 waveguide.

Figure 23

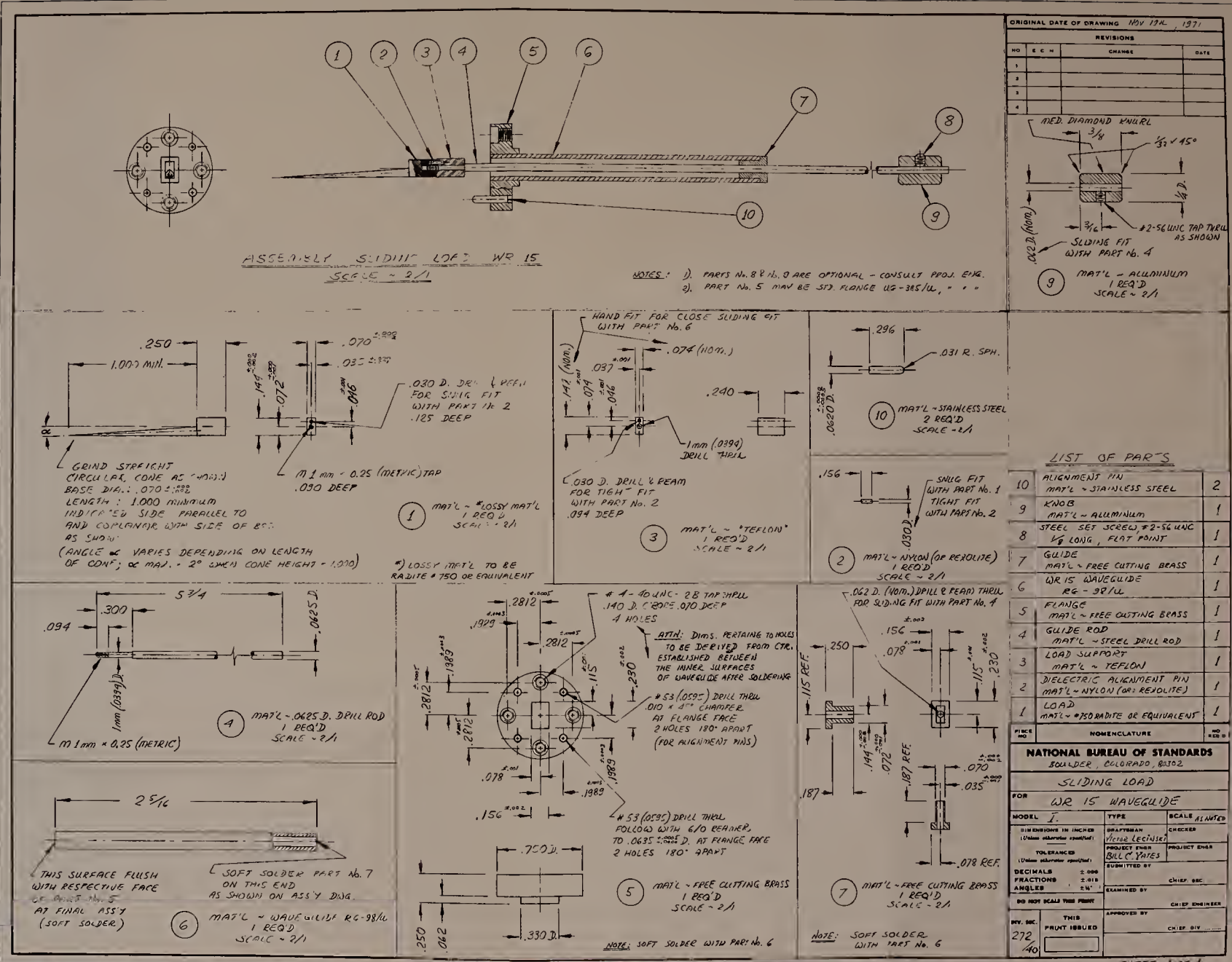


Figure 23.

APPENDIX F

Machine drawing for sliding dumbbell short
for WR15 waveguide.

Figure 24

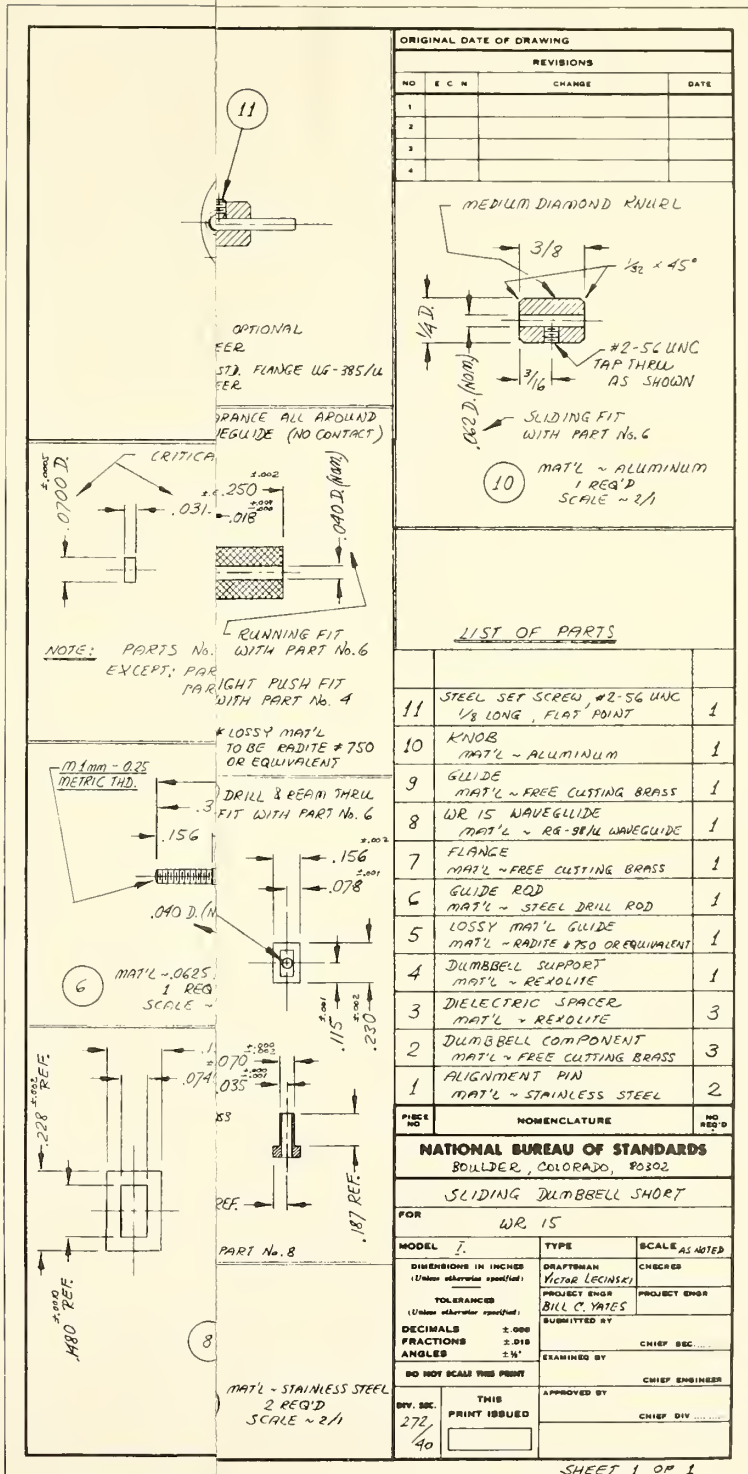
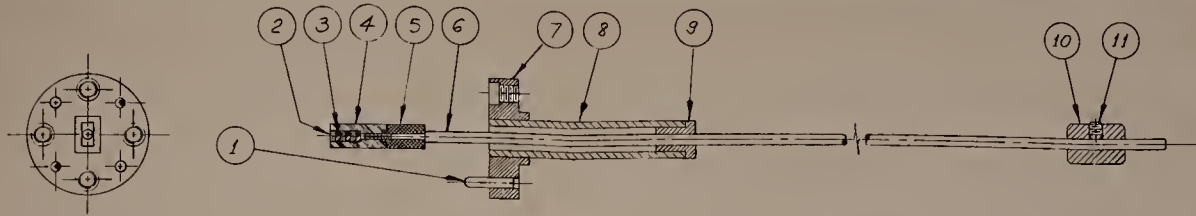


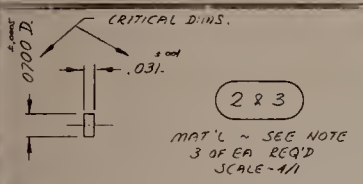
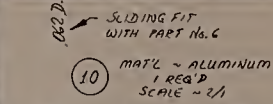
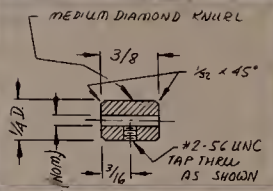
Figure 24



ASSEMBLY DUMBELL - SHIRT WR 15
SCALE - 2/1

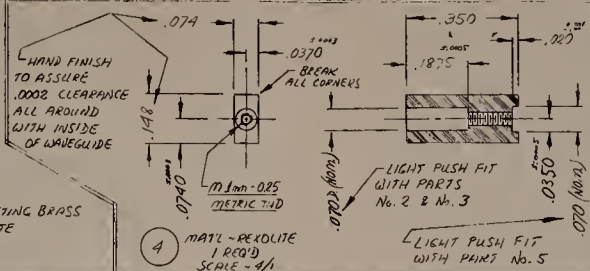
NOTES: 1) PARTS No. 10 & 11 ARE OPTIONAL
CONSULT PROJ. ENGINEER
2) PART No. 7 MAY BE .573 FLANGE UG-385/U
CONSULT PROJ. ENGINEER

ORIGINAL DATE OF DRAWING			
REVISIONS			
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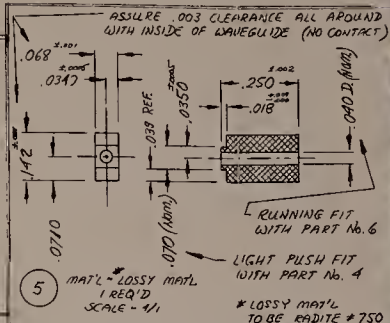
2 3 4
MATERIAL - SEE NOTE 3 OF EA REQ'D
SCALE - 4/1

NOTE: PARTS No. 2 & 3 ARE IDENTICAL EXCEPT: PART No. 2 MATERIAL - FREE CUTTING BRASS PART No. 3 MATERIAL - REOLITE



4 MATERIAL - REOLITE 1 REQ'D
SCALE - 4/1

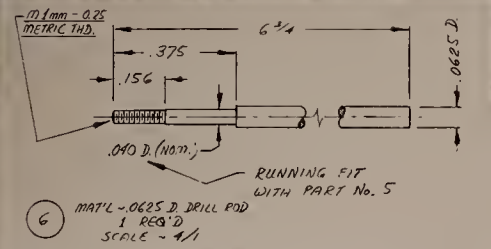
LIGHT PUSH FIT WITH PARTS No. 2 & No. 3
LIGHT PUSH FIT WITH PART No. 5



5 MATERIAL - LOSSY MATERIAL 1 REQ'D
SCALE - 4/1

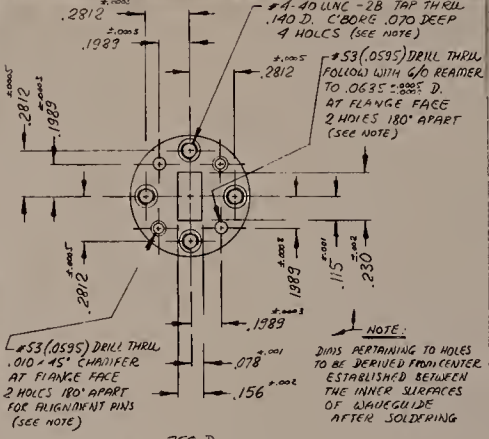
ASSURE .003 CLEARANCE ALL AROUND WITH INSIDE OF WAVEGUIDE (NO CONTACT)

* LOSSY MATERIAL TO BE RADITE # 750 OR EQUIVALENT
RUNNING FIT WITH PART No. 6
LIGHT PUSH FIT WITH PART No. 4



6 MATERIAL - .0625 D DRILL ROD 1 REQ'D
SCALE - 4/1

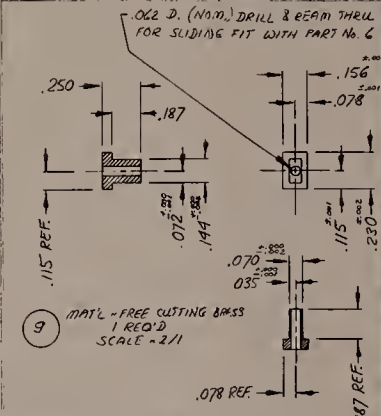
RUNNING FIT WITH PART No. 5



#1-40 UNC - 28 TAP THRU .140 D. C-BORE .070 DEEP 4 HOLES (SEE NOTE)
#53 (.0595) DRILL THRU FOLLOW WITH 6/0 REAMER TO .0635 ± .0005 D. AT FLANGE FACE 2 HOLES 180° APART (SEE NOTE)

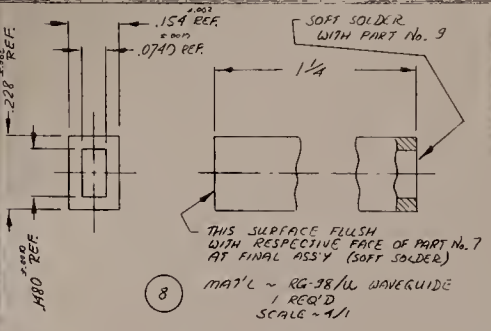
NOTE: DIMS PERTAINING TO HOLES TO BE DERIVED FROM CENTER ESTABLISHED BETWEEN THE INNER SURFACES OF WAVEGUIDE AFTER SOLDERING

7 MATERIAL - FREE CUTTING BRASS 1 REQ'D
SCALE - 2/1



9 MATERIAL - FREE CUTTING BRASS 1 REQ'D
SCALE - 2/1

NOTE: SOFT SOLDER WITH PART No. 8



THIS SURFACE FILLSH WITH RESPECTIVE FACE OF PART No. 7 AT FINAL ASSY (SOFT SOLDER)

8 MATERIAL - RG-38/U WAVEGUIDE 1 REQ'D
SCALE - 4/1

LIST OF PARTS

11	STEEL SET SCREW #2-56 UNC 1/2 LONG - FLAT POINT	1
10	KNOB MATERIAL - ALUMINUM	1
9	GLIDE MATERIAL - FREE CUTTING BRASS	1
8	WR 15 WAVEGUIDE MATERIAL - RG-38/U WAVEGUIDE	1
7	FLANGE MATERIAL - FREE CUTTING BRASS	1
6	GUIDE ROD MATERIAL - STEEL DRILL ROD	1
5	LOSSY MATERIAL GLIDE MATERIAL - RADITE # 750 OR EQUIVALENT	1
4	DUMBELL SUPPORT MATERIAL - REOLITE	1
3	DIELECTRIC SPACER MATERIAL - REOLITE	3
2	DUMBELL COMPONENT MATERIAL - FREE CUTTING BRASS	3
1	ALIGNMENT PIN MATERIAL - STAINLESS STEEL	2

PIECE NO.	NOMENCLATURE	NO. REQ'D
-----------	--------------	-----------

NATIONAL BUREAU OF STANDARDS
BOULDER, COLORADO, 80502

SLIDING DUMBELL SHIRT
FOR WR 15

MODEL I	TYPE	SCALE AS SHOWN
DWG. NO. 272/40 <td>THIS PRINT ISSUED <td></td> </td>	THIS PRINT ISSUED <td></td>	
DATE	APPROVED BY	CHIEF DTL

Figure 24.

APPENDIX G

Machine drawing for four piece brass
and invar precision waveguide section for WR15.

Figures 25(a), 25(b), 25(c).

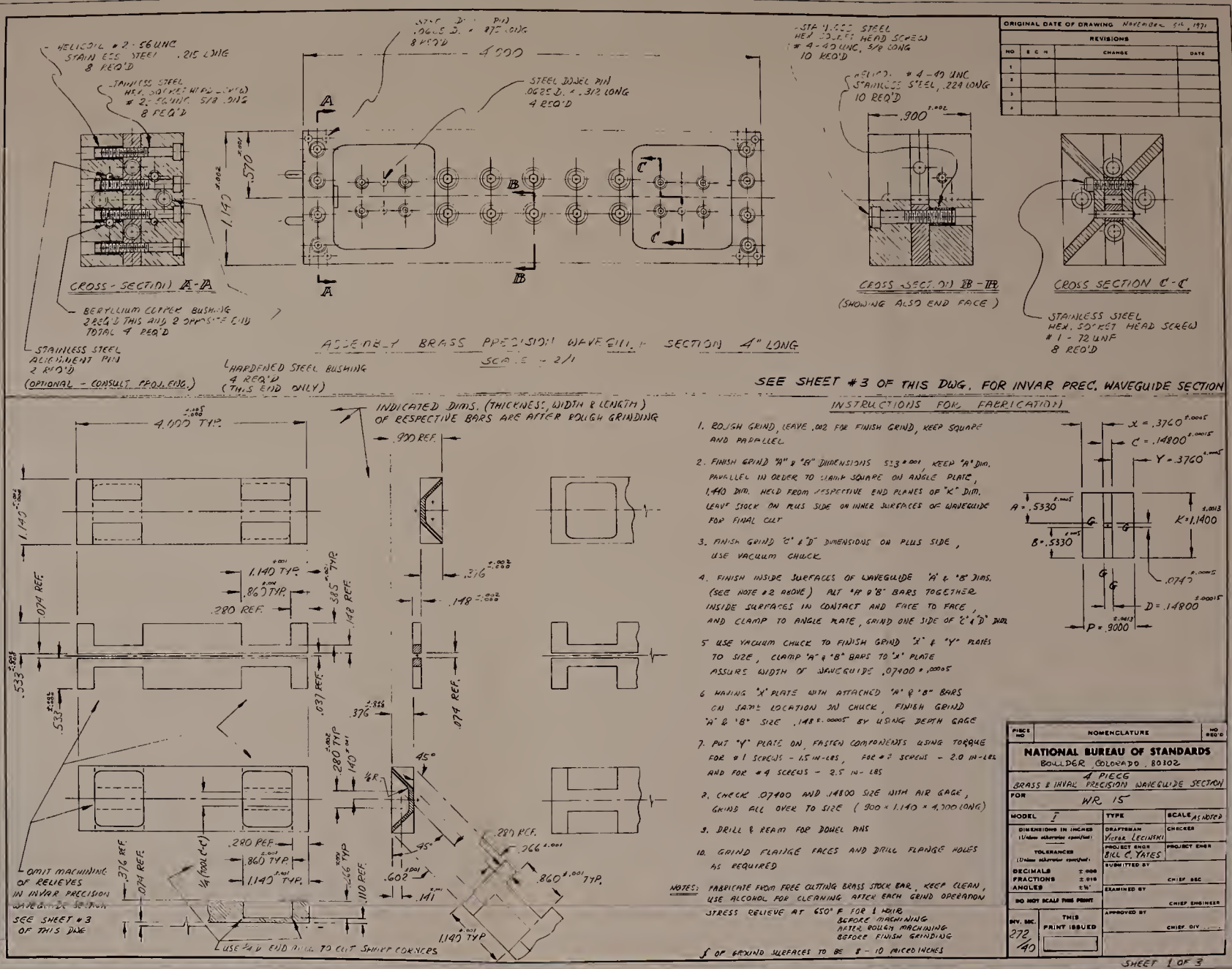


Figure 25(a).

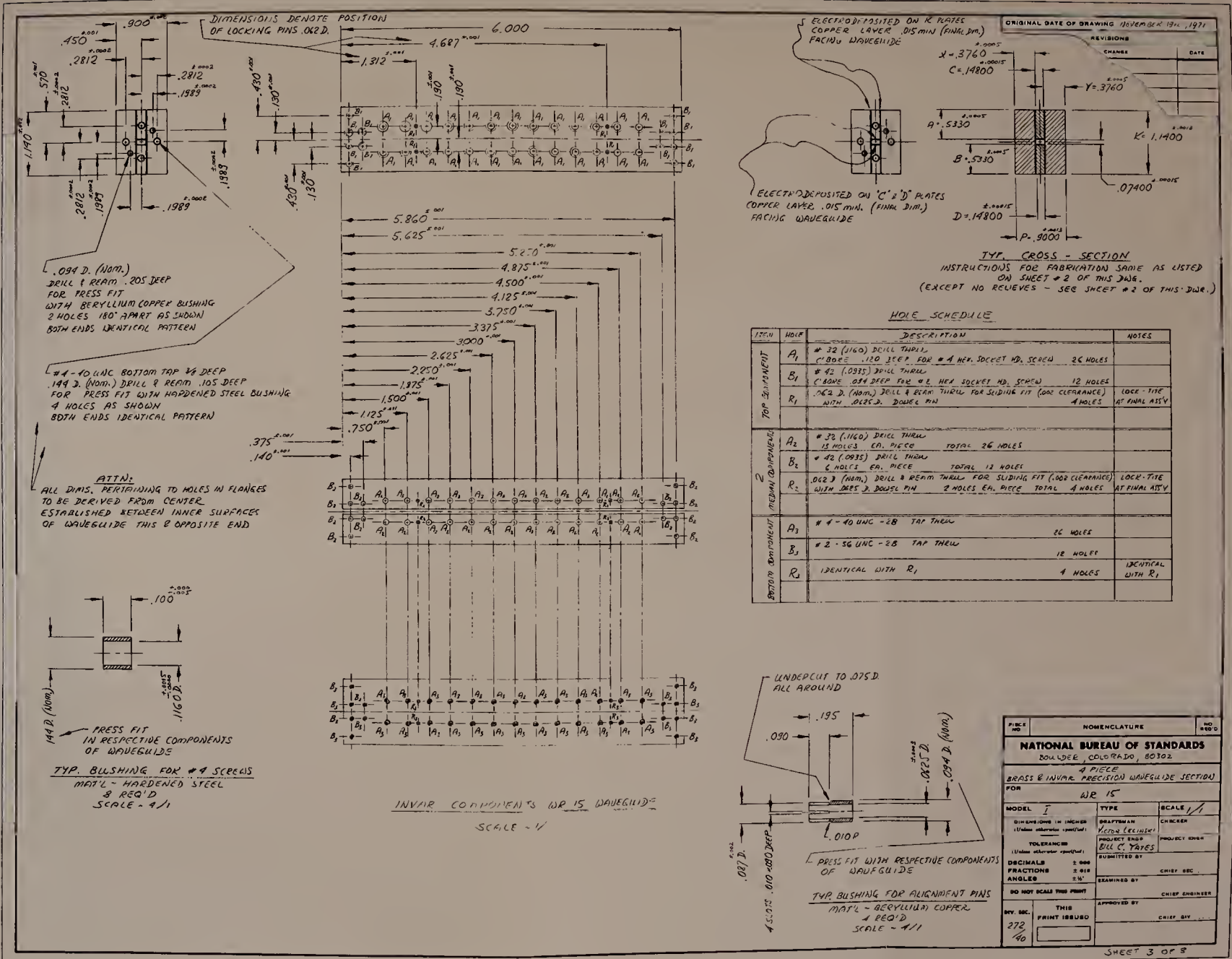


Figure 25(c).

APPENDIX H

Machine drawing for quarter-wave short circuit
for WR15 waveguide.

Figure 26

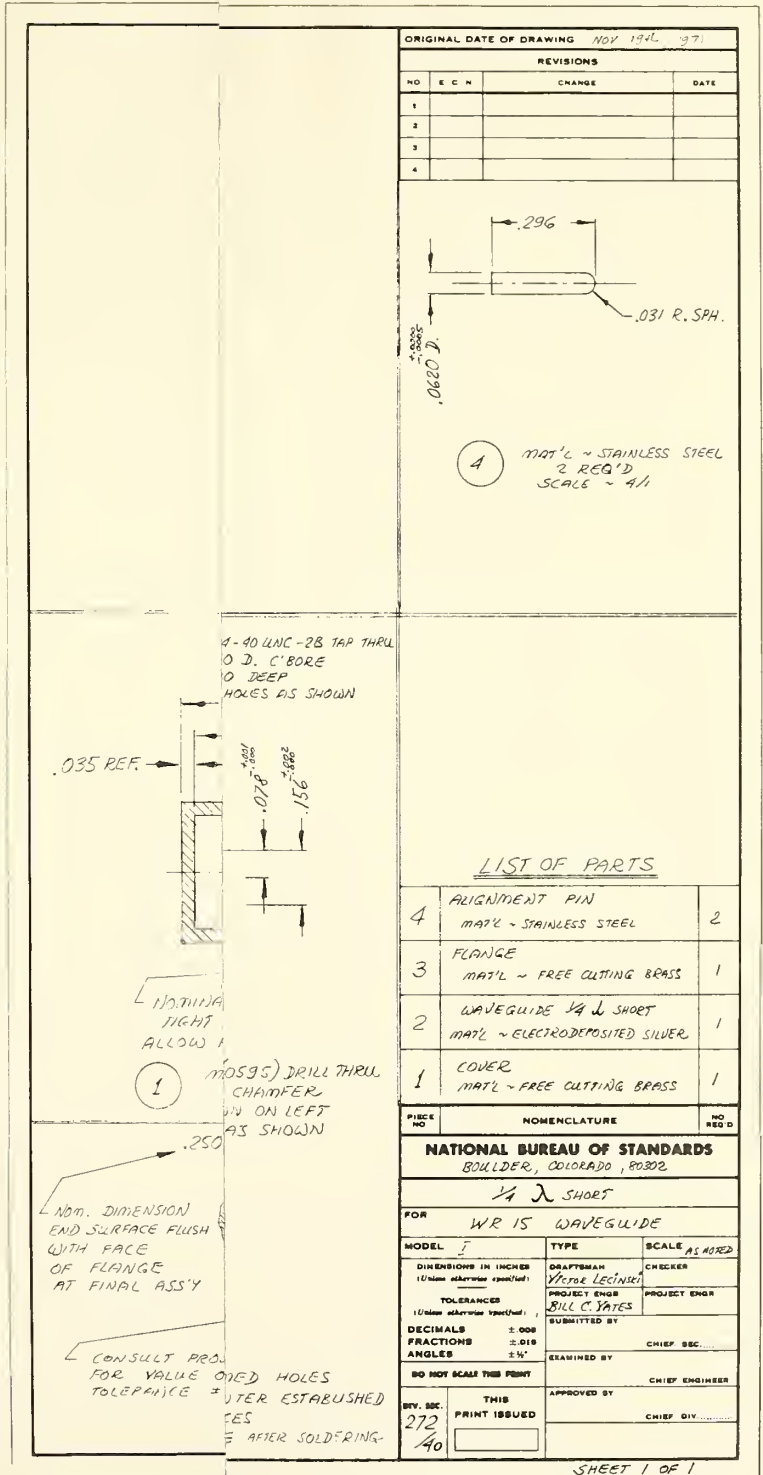
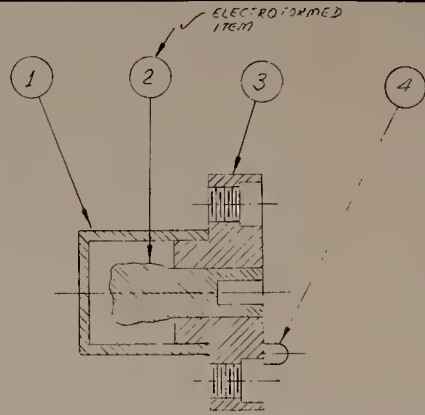
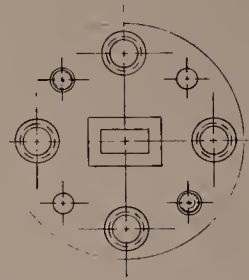


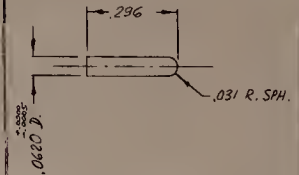
Figure 26.



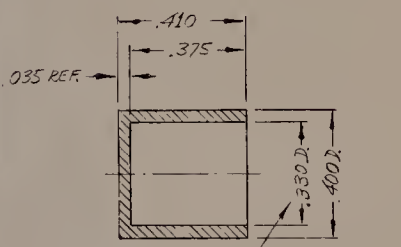
ASSEMBLY 1/4 λ SHORT WR 15
SCALE - 4/1



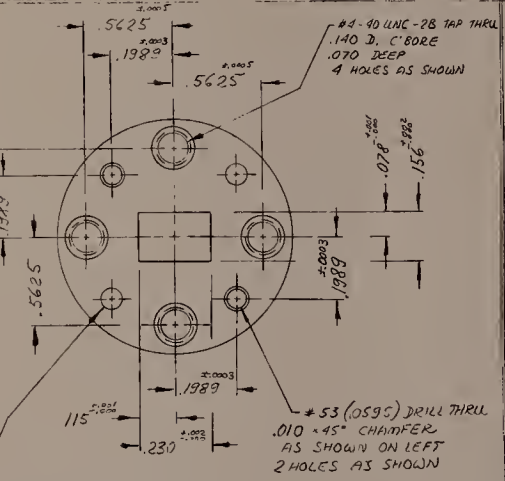
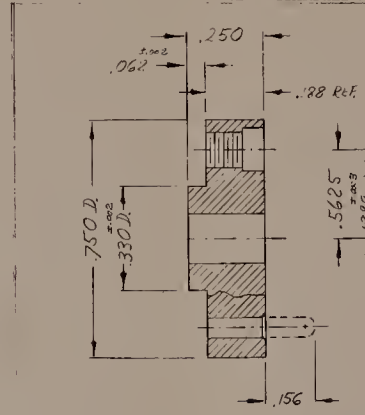
REVISIONS			
NO	E C N	CHANGE	DATE
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3			
4			



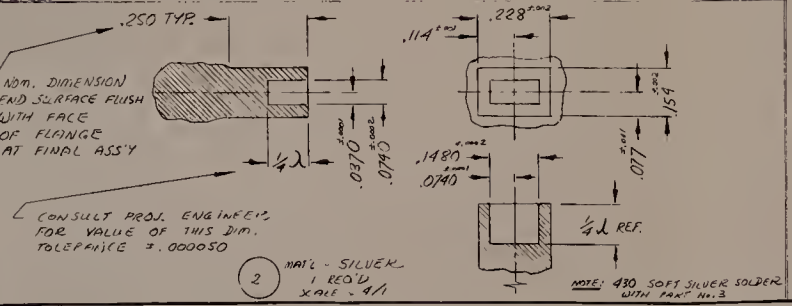
4 MAT'L - STAINLESS STEEL
2 REQ'D
SCALE - 4/1



1 MAT'L - FREE CUTTING BRASS
1 REQ'D
SCALE - 4/1



3 MAT'L - FREE CUTTING BRASS
1 REQ'D
SCALE - 4/1



2 MAT'L - SILVER
1 REQ'D
SCALE - 4/1

NOTE: 430 SOFT SILVER SOLDER WITH PART No. 3

LIST OF PARTS

PIECE NO	NOMENCLATURE	NO REQ'D
4	ALIGNMENT PIN MAT'L - STAINLESS STEEL	2
3	FLANGE MAT'L - FREE CUTTING BRASS	1
2	WAVEGUIDE 1/4 λ SHORT MAT'L - ELECTRODEPOSITED SILVER	1
1	COVER MAT'L - FREE CUTTING BRASS	1

NATIONAL BUREAU OF STANDARDS
BOULDER, COLORADO, 80302

FOR WR 15 WAVEGUIDE			
MODEL J	TYPE	SCALE	ALLIARD
DIMENSIONS IN INCHES (Unless otherwise specified)	DRAWN BY Victor Lechner	CHECKER	
TOLERANCES (Unless otherwise specified)	PROJECT ENG Bill C. Yates	PROJECT ENGR	
DECIMALS ± .000	SUBMITTED BY		CHIEF REC
FRACTIONS ± 1/16	EXAMINED BY		CHIEF ENGINEER
ANGLE ± 1/2°	APPROVED BY		CHIEF DIV
NO IND SCALE THIS PRINT	THIS PRINT ISSUED		
REV. 272	40		

CRITICAL REQUIREMENT:
DIMENSIONS INDICATED ABOVE FOR TAPPED, DRILLED & REAMED HOLES TO BE DERIVED FROM CENTER ESTABLISHED BETWEEN THE INNER SURFACES OF ELECTROFORMED WAVEGUIDE AFTER SOLDERING.

Figure 26.

APPENDIX I

Machine drawing for circular waveguide below-cutoff
attenuator for nominal 30 MHz operation.

Figures 27(a) thru 27(n)

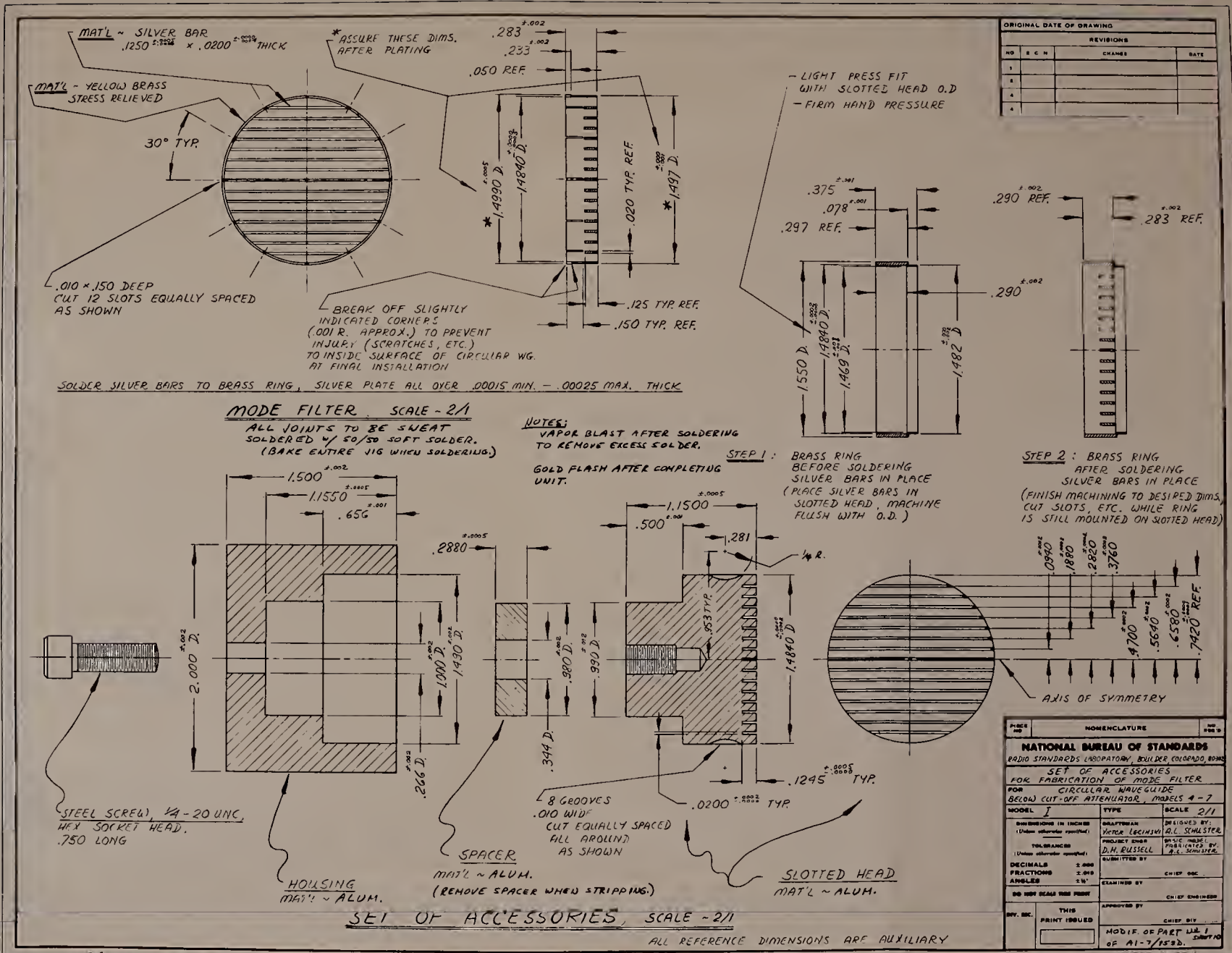
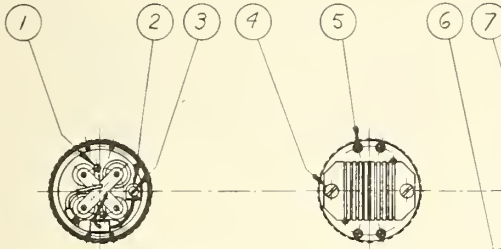


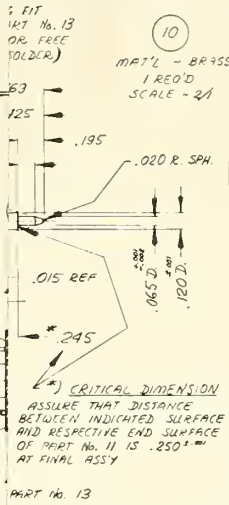
Figure 27(a).

SUB-ASS'Y: PICK UP

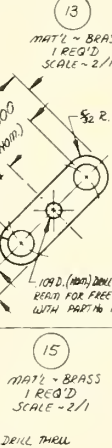
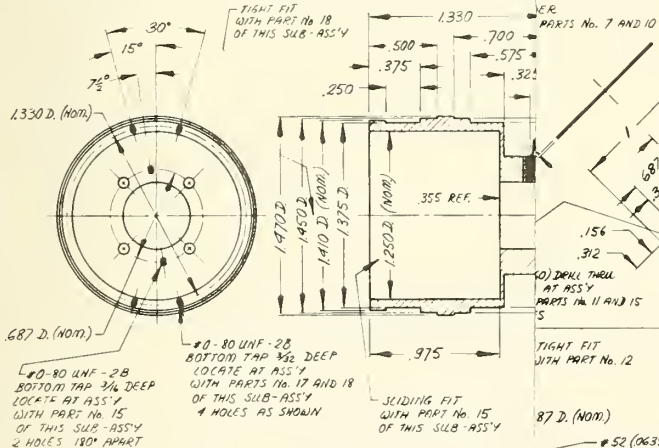
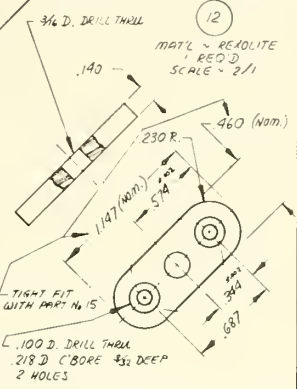
SCALE = 1/1



SECTION A-A

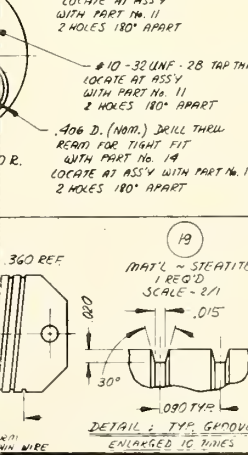
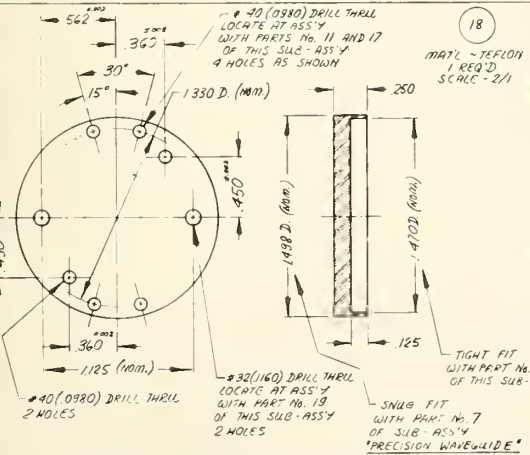


ORIGINAL DATE OF DRAWING			JULY 31, 1967		
REVISIONS					
NO	DESCRIPTION	DATE	NO	DESCRIPTION	DATE
1					
2					
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5					



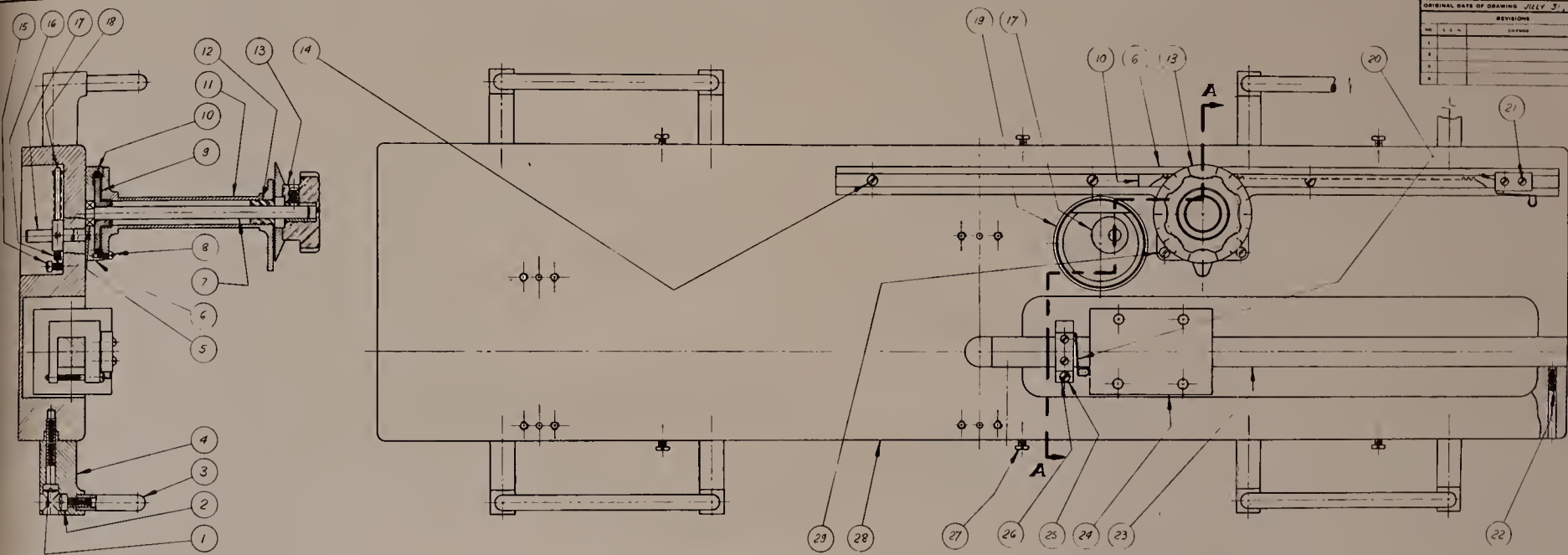
LIST OF PARTS

NO	DESCRIPTION	QTY	STOCK ITEM
21	COPPER WIRE .050 D., BARE 4' LONG	1	
20	MANGANIN WIRE # 26, 1/16 DIA W/B DR. REG. HEAD, 4' LONG	1	
19	COIL SUPPORT	1	
18	DIELECTRIC GUIDE	1	
17	COVER	1	
16	CONTACT PLATE	1	
15	CAPACITOR MOUNT	1	
14	DIELECTRIC BUSHING	2	
13	CONTACT PLATE	1	
12	DIELECTRIC COVER	1	
11	HOUSING	1	
10	CTR. CONDUCTOR CONTACT PIN	1	
9	STEEL SET SCREW # 4-40 UNC 1/16 L, PLAT PT	1	
8	FINGER CONTACT STRIP INSTRUMENT SPECIFICATIONS G. # 97-223, 1/4"	1	
7	ADJUSTABLE CAPACITOR JFD NMC 601 6638	4	
6	CAPACITOR .33 PF	1	
5	BRASS SCREW # 8-32 UNC 1/8 L FILLISTER HD	4	
4	NYLON SCREW # 4-40 UNC 1/8 L FILLISTER HD	2	
3	BRASS SCREW # 2-56 UNC 3/8 L FILLISTER HD	1	
2	BRASS SOLDERING CUS (70 PCT # 2 SCREW)	1	
1	BRASS SCREW # 0-80 UNC 1/16 L FILLISTER HD	2	

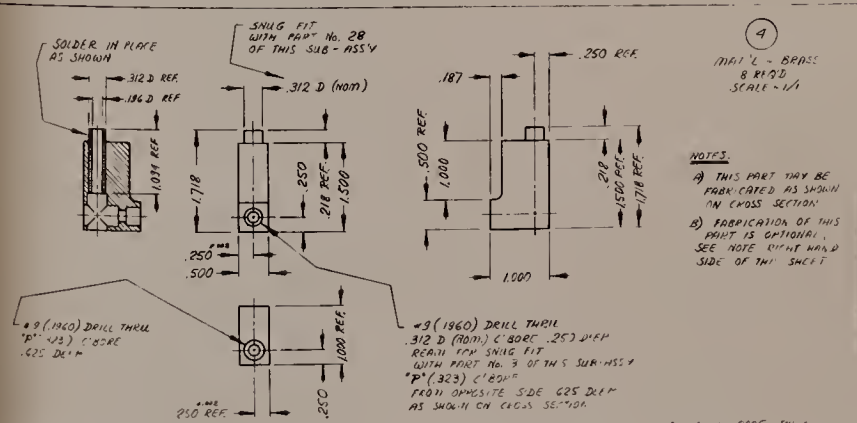


NATIONAL BUREAU OF STANDARDS			
RADIO TRANSMISSIONS (ARBITRARY) AUXILIARY (CONV. 400-4000 KHZ)			
OPERATING WAVELENGTH BELOW CUTOFF OF ATTENUATOR			
FOR ADDITIONAL 30 MHz OPERATION			
MODEL	TYPE	SCALE	DATE
771	TYPE	SCALE	DATE
DIMENSIONS IN INCHES		DRAWN BY	
TOLERANCES		CHECKED BY	
ANGLES		APPROVED BY	
NO NET SCALE SHOWN		APPROVED BY	
BY: ETC		PRINT ISSUED	
250		21	
		AI - 7/153 D	

Figure 27(d).



SUB-ASSY: ATTENUATOR BASE
SCALE = 1/1



* PARTS NO. 30 NOT INDICATED ON THE ABOVE DRAWING - THEY SCALE FOR FASTENING OF PART NO. 18 TO PART NO. 17 (RECD) AND OF PART NO. 13 TO PART NO. 18 (RECD)

LIST OF PARTS

NO.	DESCRIPTION	QTY	NO.	DESCRIPTION	QTY
30	STEEL SET SCREW #4-40 UNC 3/8 LONG, FLAT POINT	3	15	STEEL SCREW #6-32 UNC FLEXIBLE HEAD 1 1/2 LONG	1
29	BRASS SCREW #4-40 UNC, BINDING HEAD, 1/2 LONG	2	14	BRASS SCREW #4-40 UNC BINDING HD 3/8 LONG	4
28	BASE	1	13	COMPARTMENT END (PART 11) WITH 0-10 DIAL & 3 SHIM HOLES	1
27	BRASS SCREW #6-32 UNC BINDING HEAD, 1/4 LONG	6	12	BUSHING	1
26	MIL-C-MECHANIZITE	1	11	GEAR COVER	1
25	MIL-C-75 UNFIN. SUPPORT	1	10	BRASS RACK GEAR 48 TEETH 1/8" P, SECTION AT IN. G 526	1
24	STEEL SCREW #4-40 UNC FLEXIBLE HEAD, 1/4 LONG	1	9	BRASS SILENT GEAR 48 TEETH 1500 P.D., 1/8" P, 1/4" P.H. SECTION AT IN. G 146	1
23	SQUARE WELDING W/AFINING COIL AND DIMPLES	1	8	BRASS SCREW #2-56 UNC, ROUND HEAD, 1/4 LONG	3
22	TUMBLER, SERIES SNG GEAR, 1/2" P	1	7	SHAFT	1
21	STEEL SET SCREW #8-32 UNC 1/2 LONG, FLAT POINT	2	6	GEAR HOUSING	1
20	BRASS SCREW #2-56 UNC ROUND HEAD, 3/8 LONG	4	5	MIL-C-75 UNFIN. BRASS	1
19	MIL-C-75 UNFIN. MOUNTING BRACKET WITH ALUMINUM HOLES AS SHOWN	2	4	BRASS TAPPING SCREW 77R 3	1
18	MIL-C-75 UNFIN. MOUNTING BRACKET WITH ALUMINUM HOLES AS SHOWN	1	3	HANDLE EXTENSION	8
17	MIL-C-75 UNFIN. MOUNTING BRACKET WITH ALUMINUM HOLES AS SHOWN	1	2	COMPARTMENT CHASSIS HANDLE	4
16	SPRING	1	1	MIL-C-75 UNFIN. BRASS	1
15	STEEL SCREW #6-32 UNC FLEXIBLE HEAD 1 1/2 LONG	1	1	BRASS SCREW #1-56 UNC FLEXIBLE HEAD 1/2 LONG	1
14	BRASS SCREW #4-40 UNC BINDING HD 3/8 LONG	4	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
13	COMPARTMENT END (PART 11) WITH 0-10 DIAL & 3 SHIM HOLES	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
12	BUSHING	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
11	GEAR COVER	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
10	BRASS RACK GEAR 48 TEETH 1/8" P, SECTION AT IN. G 526	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
9	BRASS SILENT GEAR 48 TEETH 1500 P.D., 1/8" P, 1/4" P.H. SECTION AT IN. G 146	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
8	BRASS SCREW #2-56 UNC, ROUND HEAD, 1/4 LONG	3	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
7	SHAFT	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
6	GEAR HOUSING	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
5	MIL-C-75 UNFIN. BRASS	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
4	BRASS TAPPING SCREW 77R 3	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
3	HANDLE EXTENSION	8	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
2	COMPARTMENT CHASSIS HANDLE	4	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1
1	MIL-C-75 UNFIN. BRASS	1	1	GEAR 155 SERIES #10 SLIP FITTED INTO MOUNTING	1

MIL. STANDS No. 1, 2, 3 AND 4 ARE OPTIONAL (U.S.D. FOR INDICATION ONLY)

NATIONAL BUREAU OF STANDARDS
PLATE STANDARDS LABORATORY, BUREAU OF STANDARDS

CERTIFICATE OF APPROVAL
BELOW LISTED MATERIALS
FOR MEASUREMENT OF THE OPERATION

MODEL NO.	TYPE	SCALE	DATE

APPROVED BY: [Signature]
DATE: [Date]

AI-7/153 D
SHEET 4 OF 13

Figure 27(e).

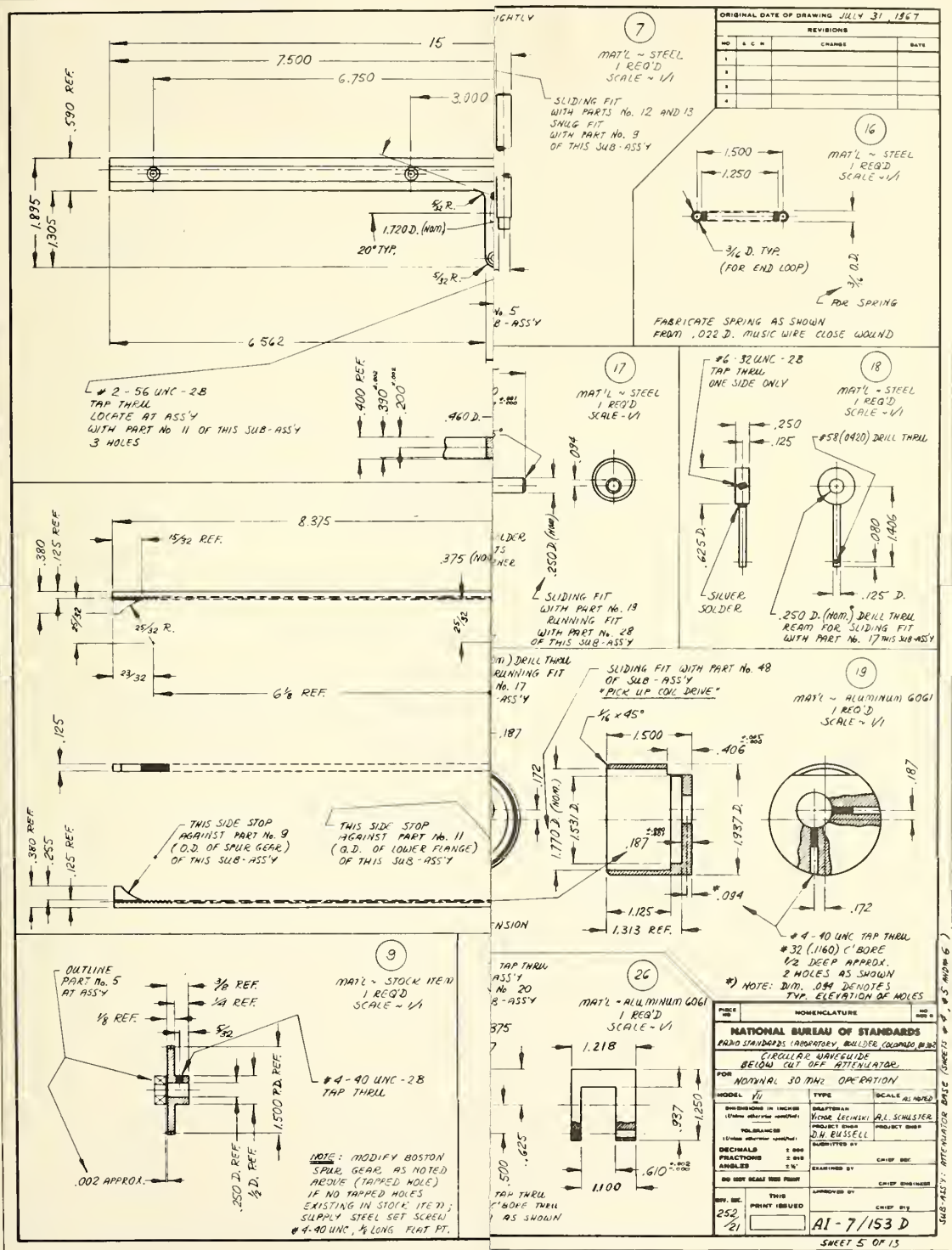


Figure 27(f).

SUB-ASSY: ATTENUATOR BASE (SHRINK FIT) (SEE PART 6)

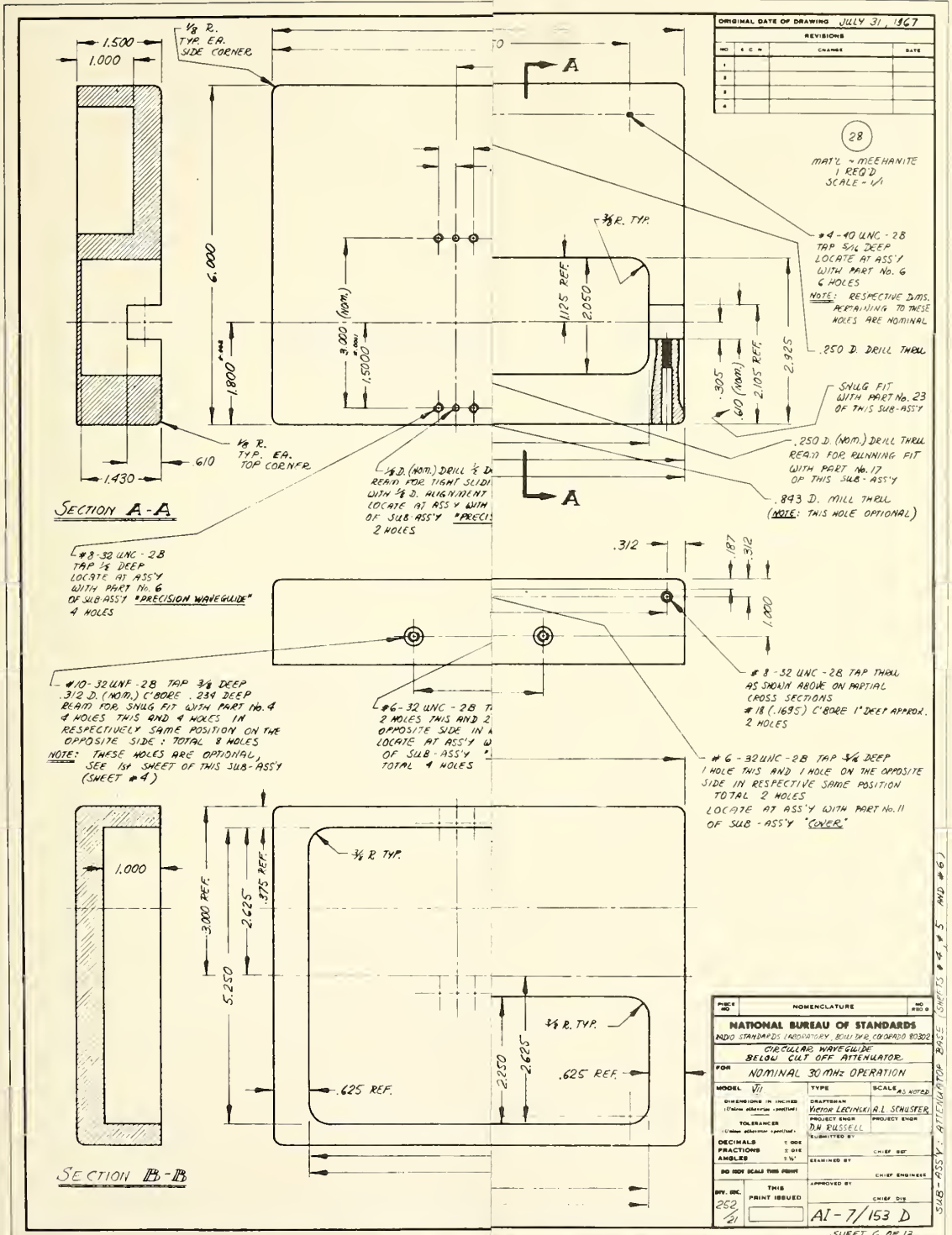
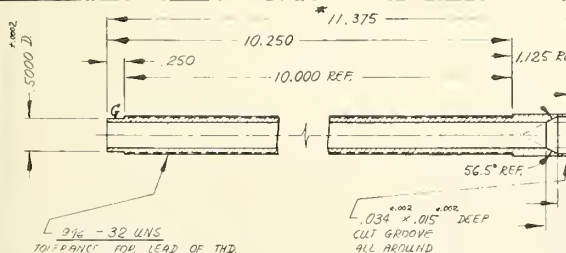
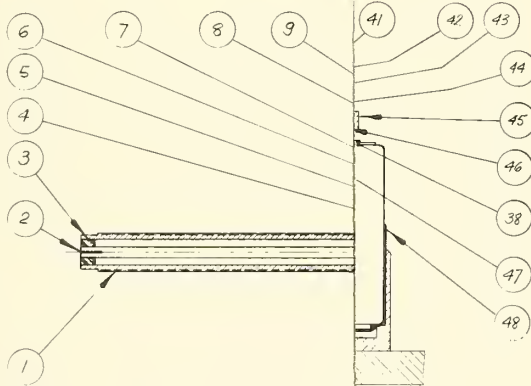
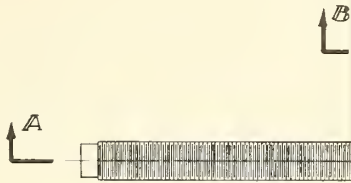


Figure 27(g).

SUB-ASS'Y: PICK UP COIL DRIVE

SCALE - 1/1



9% - 32 UNS
TO FINISH FOR LEAD OF THD.
SHALL NOT EXCEED .0002
ESTABLISH ANY TWO POINTS;
TOP 1/4 OF THD IS CRITICAL

NOTE: GRIND WHERE SHOWN INCLUDE
CONCENTRICITY OF ALL DIA'S

FINISH TO ASSY OF PARTS NO. 1, 2 AND 3
NO 2 SHALL BE FLUSH TO ODDS BEYOND
OF PART NO. 1 AT FINAL ASSY

FAK:IC

ORIGINAL DATE OF DRAWING JULY 31, 1967		
REVISIONS		
NO	A. C. N.	DATE
1		

LIST OF PARTS

* STOCK ITEMS	
50	TRIGGER, MICROSWITCH
49	TERMINAL STRIP 8 BBL 2-56 UNF
48	MOTOR CONTACT AND DEVICES
47	DRIVE WHEEL
46	O-RING
45	DIAL
44	KNOB INSULATOR
43	STEEL SET SCREW
42	KNOB
41	BEVEL GEAR
40	STEEL KEY
39	BEVEL GEAR
38	STEEL SET SCREW
37	BRACKET
36	BEARING SLEEVE TYPE MAIN
35	SHAFT EXTENSION COLLATER
34	BASE SCREW
33	INDEX PLATE
32	BRASS SCREW
31	SWIMMY
30	COLLATER
29	COLLAR
28	BEARING SLEEVE TYPE
27	DRIVE SHAFT
26	STEEL KEY
25	HELICAL GEAR
24	HELICAL GEAR
23	GEAR HOUSING
22	THRUST WASHER
21	STEEL SCREW
20	GUIDE
19	STEEL SCREW
18	STEEL SCREW
17	ANTI BACKLASH NUT
16	STEEL SCREW
15	RETAINER RING
14	BRASS SCREW
13	STEEL SCREW
12	ALIGNMENT RING
11	STEEL SCREW
10	BEARING HOUSING
9	SPACER
8	SINGLE ROW BALL BEARING
7	RETAINER RING
6	STEEL SET SCREW
5	WIPER
4	THRUST NUT
3	DIELECTRIC SPACER
2	CENTER CONDUCTOR
1	MOTION TRANSDUCING SCREW

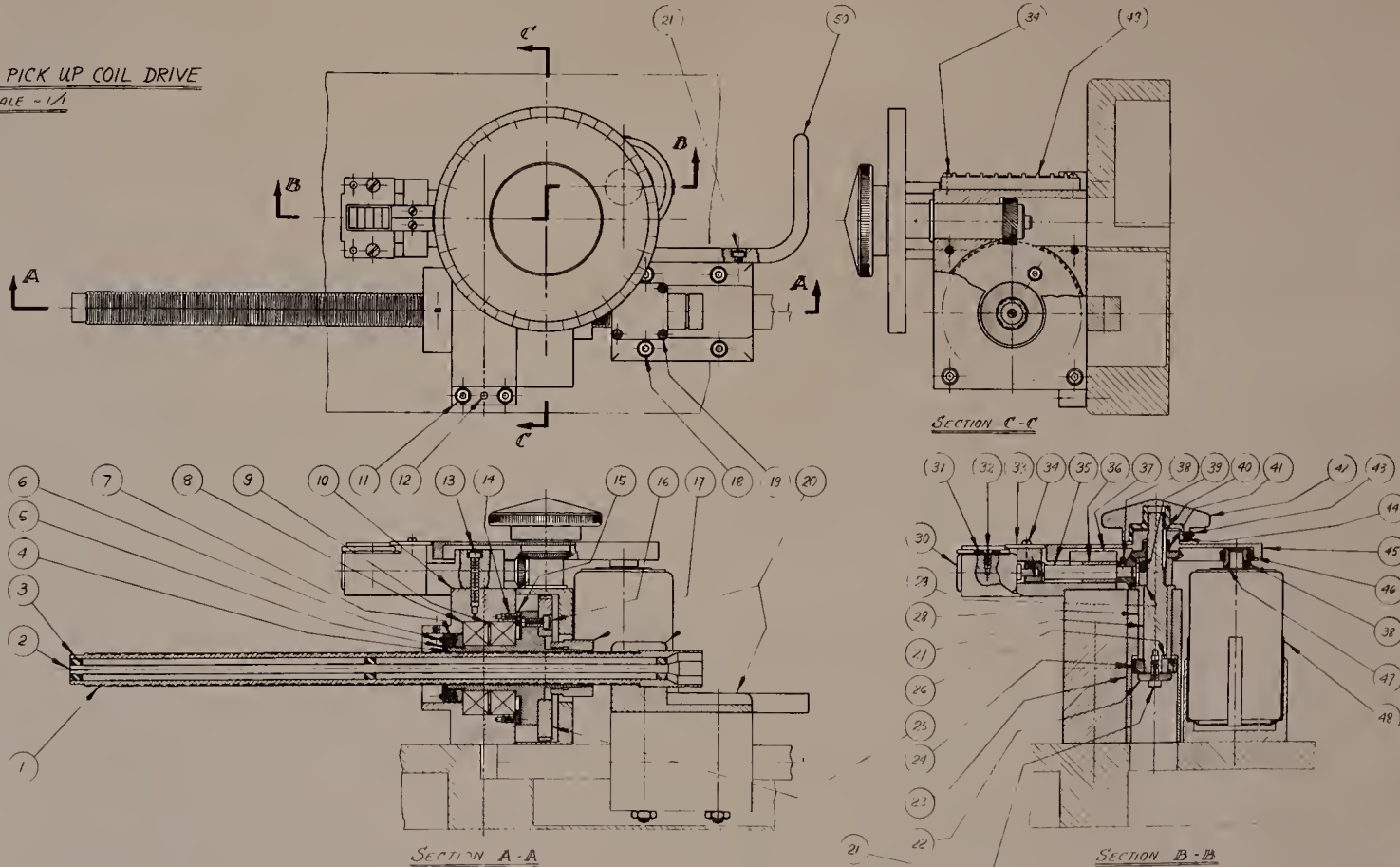
FIG. NO.	NOMENCLATURE	NO.

NATIONAL BUREAU OF STANDARDS			
R200 STANDARDIZATION, REVISIONS, 80502			
CIRCULAR MANUFACTURE			
BELOW CUT OFF ATTENUATOR			
FOR NOMINAL 30 MHz OPERATION			
MODEL NO.	TYPE	SCALE	AS SHOWN
DIMENSIONS IN INCHES	DRAFTSMAN		
(Unless otherwise specified)	MEMO LETTERS	A. L. SCHUSTER	
TOLERANCES	PROJECT ENGR		
(Unless otherwise specified)	D. H. BISHOP		
DECIMALS	1.000		
FRACTIONS	2.018		
ANGLES	1/2°		
BY SEC	THIS	APPROVED BY	CHIEF ENGINEER
252	PRINT ISSUED		
21		AI-7/153 D	

Figure 27(h).

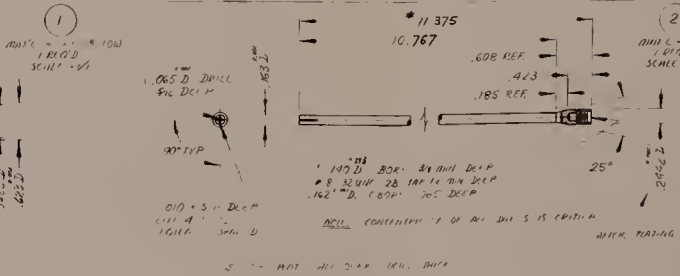
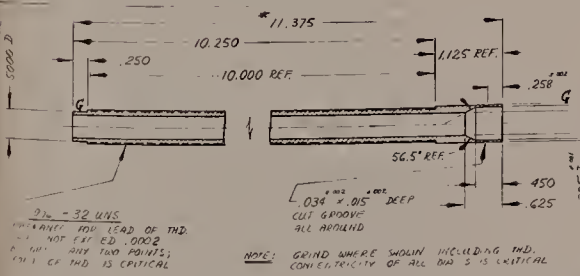
SUB-ASSY: PICK UP COIL DRIVE

SCALE - 1/1



ORIGINAL DATE OF DRAWING: JULY 31, 1967		
REVISIONS		
NO.	DESCRIPTION	DATE
1		

LIST OF PARTS			QTY	STOCK ITEMS
50	ADJUST. WIPER	ALUMINUM	1	
49	TOP PLATE	STEEL	1	
48	WIPER	ALUMINUM	1	
47	WIPER	ALUMINUM	1	
46	O-RING	NBR	2	
45	WIPER	ALUMINUM	1	
44	WIPER	ALUMINUM	1	
43	STEEL SET SCREW	# 4-40 UNF	1	
42	WIPER	ALUMINUM	1	
41	BEVEL GEAR	BOSTON # 6-48 Y	1	
40	STEEL SET SCREW	# 6-48 Y	1	
39	BEVEL GEAR	BOSTON # 6-48 Y	1	
38	STEEL SET SCREW	# 4-40 UNF	1	
37	WIPER	ALUMINUM	1	
36	DRIVING SHAFT	STEEL	1	
35	SHAFT	STEEL	1	
34	BEVEL GEAR	BOSTON # 6-48 Y	2	
33	INDEX PLATE	ALUMINUM	1	
32	BEVEL GEAR	BOSTON # 6-48 Y	2	
31	WIPER	ALUMINUM	2	
30	COIL WINDING	STEEL	1	
29	COIL WINDING	STEEL	1	
28	DRIVE SHAFT	STEEL	1	
27	BEARING	STEEL	1	
26	STEEL SET SCREW	# 4-40 UNF	1	
25	WIPER	ALUMINUM	1	
24	WIPER	ALUMINUM	1	
23	WIPER	ALUMINUM	1	
22	WIPER	ALUMINUM	1	
21	STEEL SET SCREW	# 4-40 UNF	3	
20	GUIDE	STEEL	1	
19	STEEL SET SCREW	# 4-40 UNF	1	
18	STEEL SET SCREW	# 4-40 UNF	1	
17	WIPER	ALUMINUM	1	
16	STEEL SET SCREW	# 4-40 UNF	3	
15	RETAINER	STEEL	1	
14	BEVEL GEAR	BOSTON # 6-48 Y	1	
13	STEEL SET SCREW	# 4-40 UNF	1	
12	ALIGNMENT PIN	STEEL	1	
11	STEEL SET SCREW	# 4-40 UNF	1	
10	BEARING HOUSING	STEEL	1	
9	SHOULDER	STEEL	1	
8	WIPER	ALUMINUM	1	
7	RETAINER	STEEL	1	
6	STEEL SET SCREW	# 4-40 UNF	2	
5	WIPER	ALUMINUM	1	
4	THRUST WIPER	STEEL	1	
3	ELECTRIC LEAF	STEEL	1	
2	CENTER	STEEL	1	
1	PROTENT TENSIONING SCREW	STEEL	1	

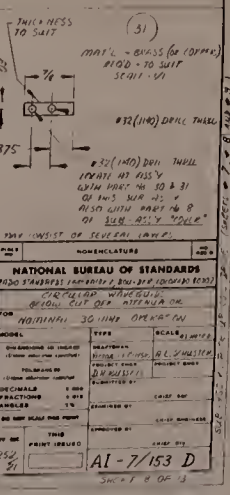
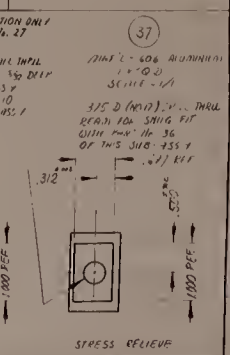
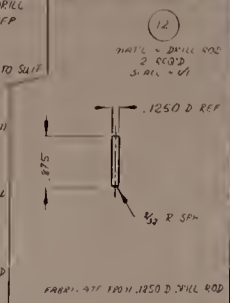


NO.	DESCRIPTION	DATE
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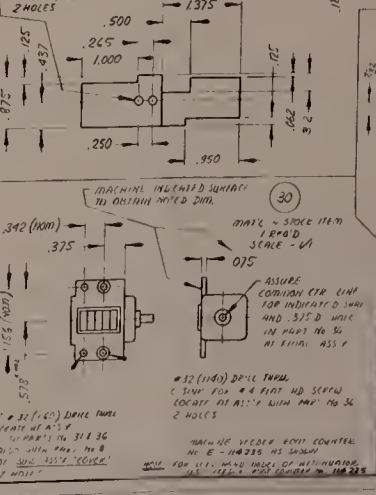
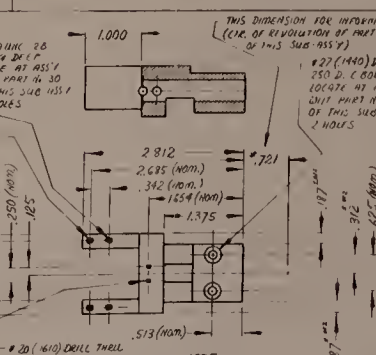
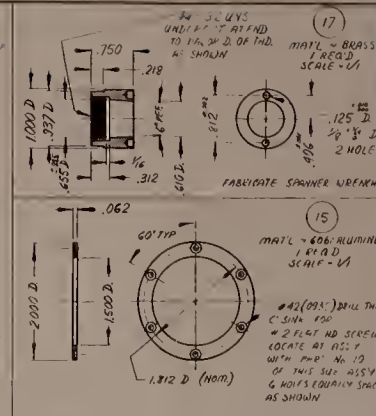
NATIONAL BUREAU OF STANDARDS	
FEDERAL BUREAU OF INVESTIGATION	
CIRCULAR 115-10	
RECORD COPY OF SPECIFICATION	
FORM	REVISION
115-10	30 MAY OPERATION
MODEL	TYPE
DESCRIPTION	SCALE
DETAILED	SCALE
APPROVED	DATE
NO. OF SHEETS	TOTAL SHEETS
1	1
BY	DATE
251	
PROJECT	SCALE
AI-7/153 D	
SHEET	TOTAL SHEETS
1	1

Figure 27(h).

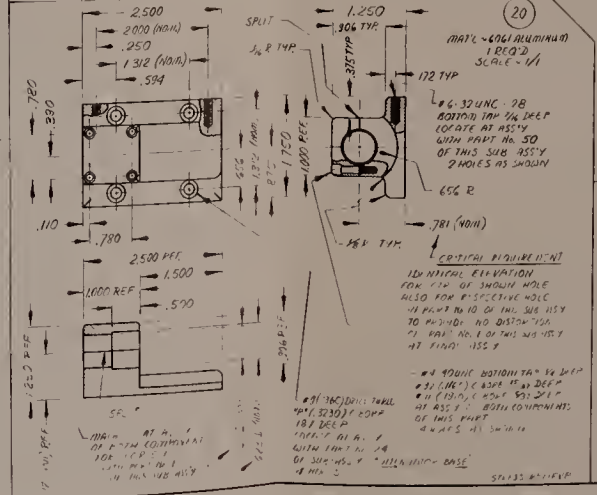
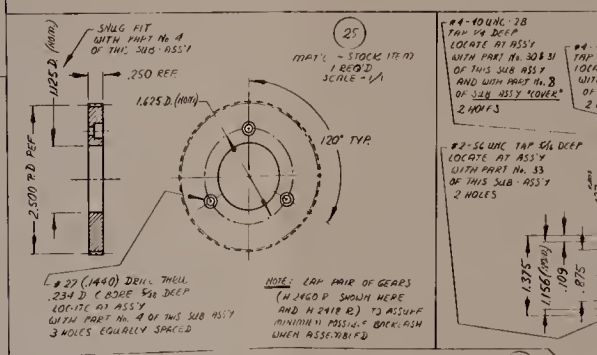
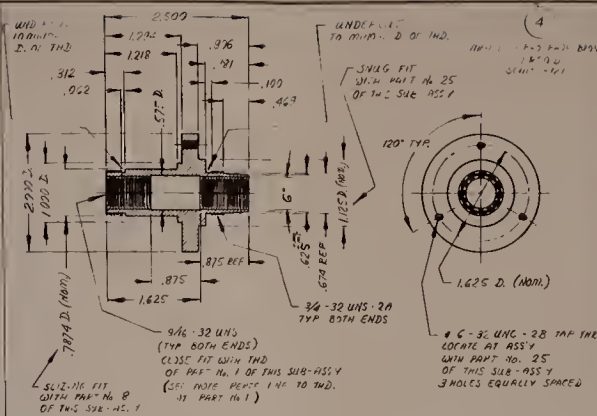
REVISIONS	
NO.	DESCRIPTION



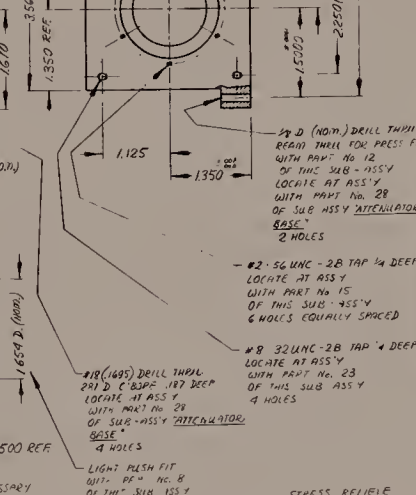
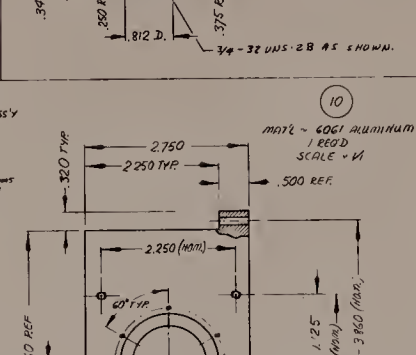
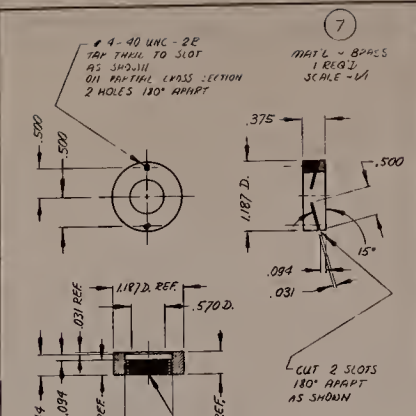
NATIONAL BUREAU OF STANDARDS	
NO.	DESCRIPTION



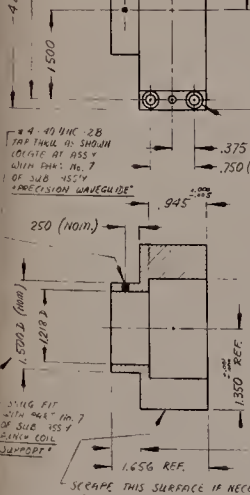
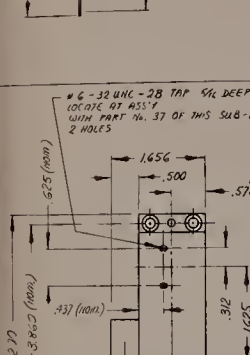
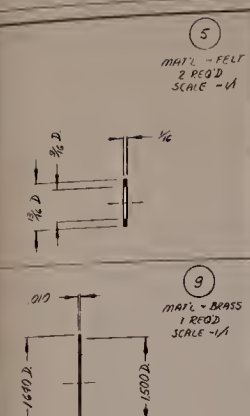
NATIONAL BUREAU OF STANDARDS	
NO.	DESCRIPTION



NATIONAL BUREAU OF STANDARDS	
NO.	DESCRIPTION



NATIONAL BUREAU OF STANDARDS	
NO.	DESCRIPTION



NATIONAL BUREAU OF STANDARDS	
NO.	DESCRIPTION

Figure 27(i).

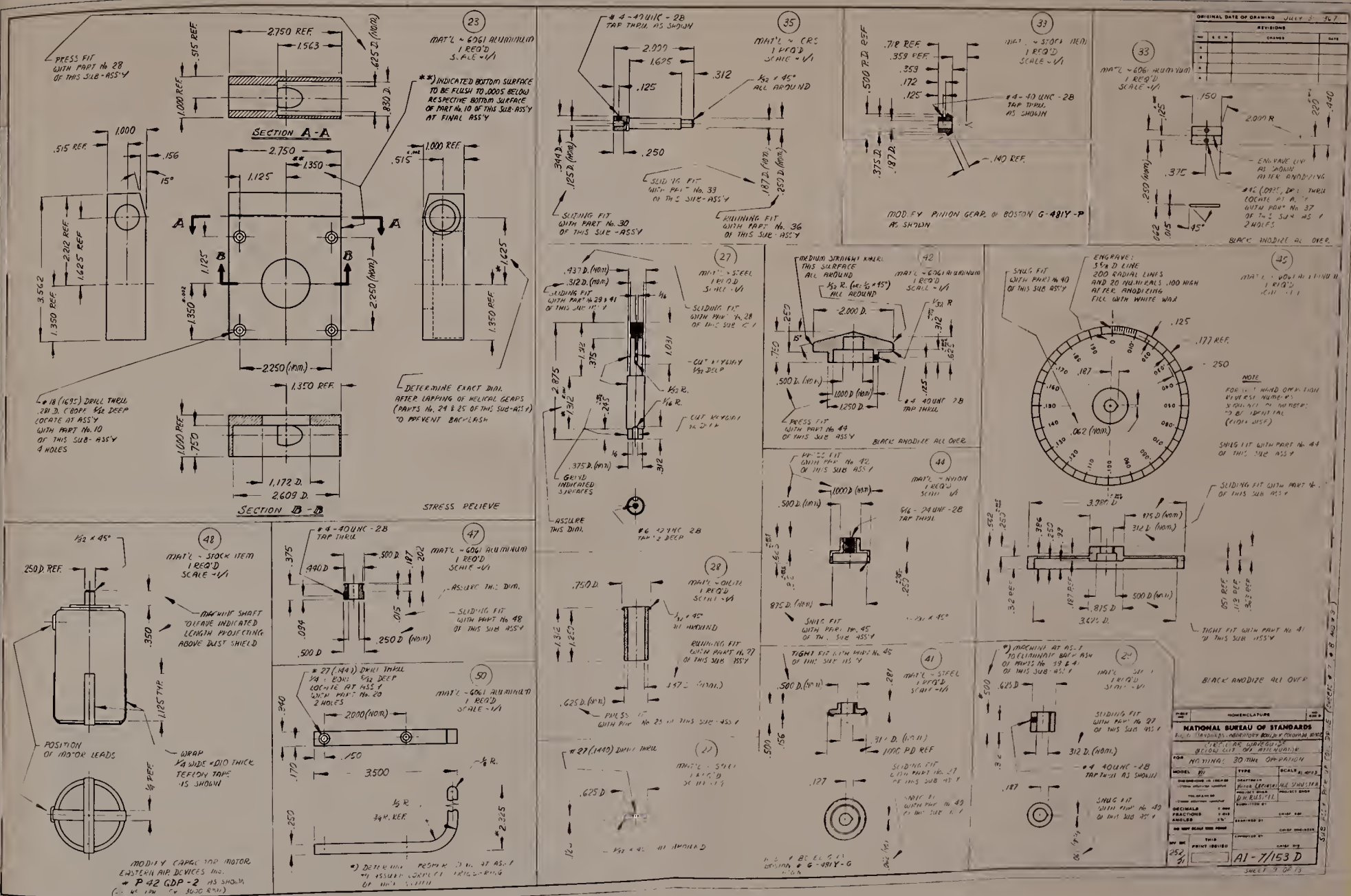
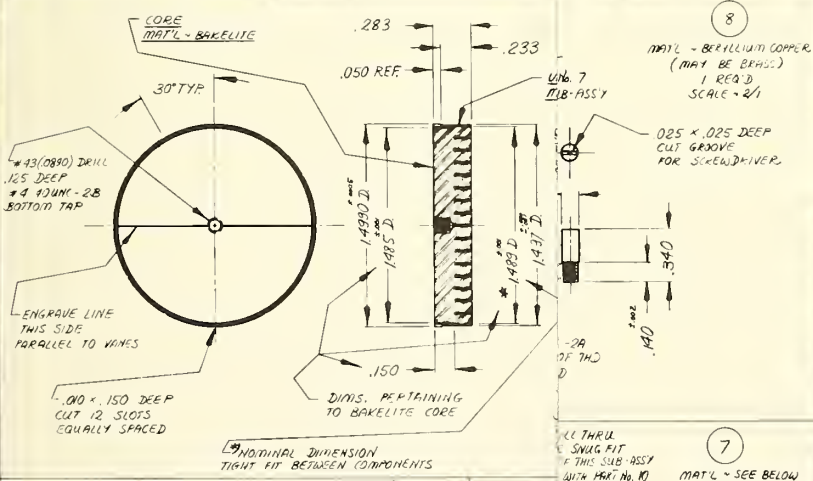
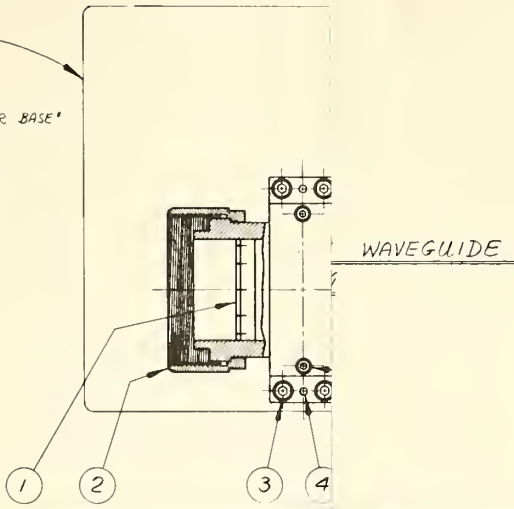


Figure 27(i).

ORIGINAL DATE OF DRAWING JULY 3, 1947		
REVISIONS		
NO.	E. C. N.	CHANGE
1		
2		
3		
4		

OUTLINE
SUB-ASSY: ATTENUATOR BASE



NO.	DESCRIPTION	QTY.
8	SCREW MATERIAL - BERYLLIUM COPPER OR BRASS	1
1	WAVEGUIDE MATERIAL - COPPER OR BRASS	1
6	SUPPORT WITH COVER MATERIAL - COBALT ALUMINUM	1
5	BRASS SCREW # 6 - 32 UNC. FILLISTER HEAD, 1 3/8 LONG	2
4	ALIGNMENT PIN MATERIAL - 1/200 D STEEL DRILL ROD	2
3	BRASS SCREW # 8 - 32 UNC. FILLISTER HEAD, 3/4 LONG	4
2	NUT MATERIAL - BRASS	1
1	MODE FILTER MATERIAL - BRASS & BAKELITE	1

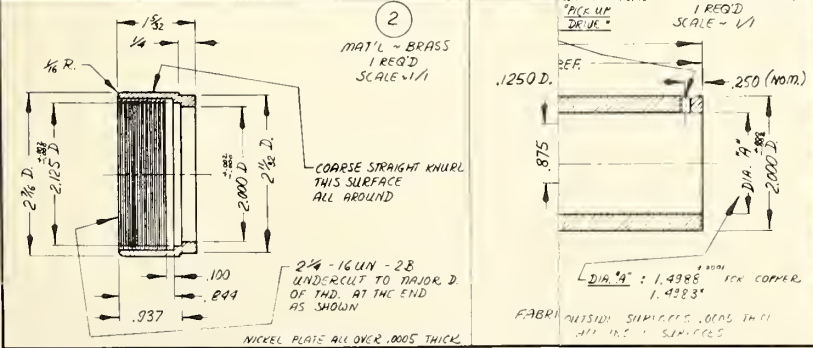
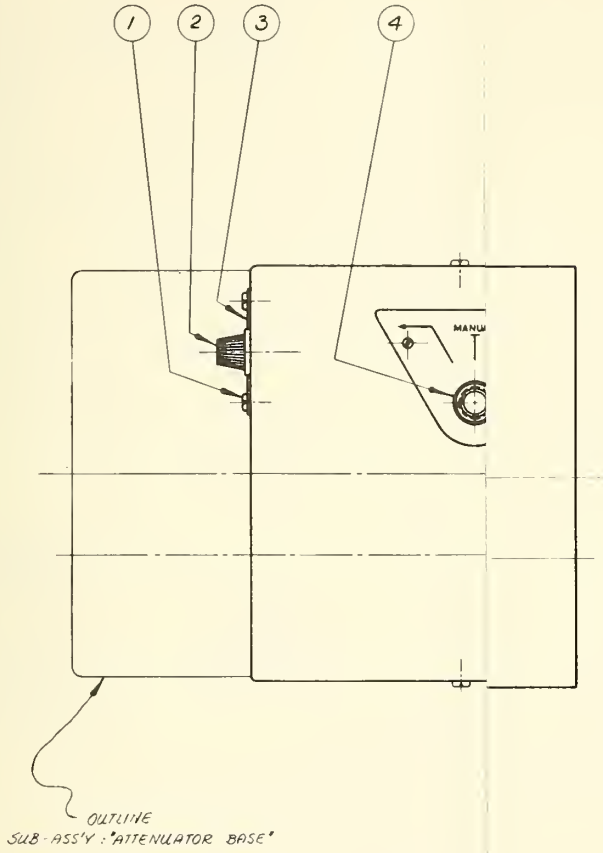


Figure 27(k).

ORIGINAL DATE OF DRAWING July 31 1967			
REVISION			
NO	L. C. N.	CHANGES	DATE
1			
2			
3			
4			



LIST OF PARTS

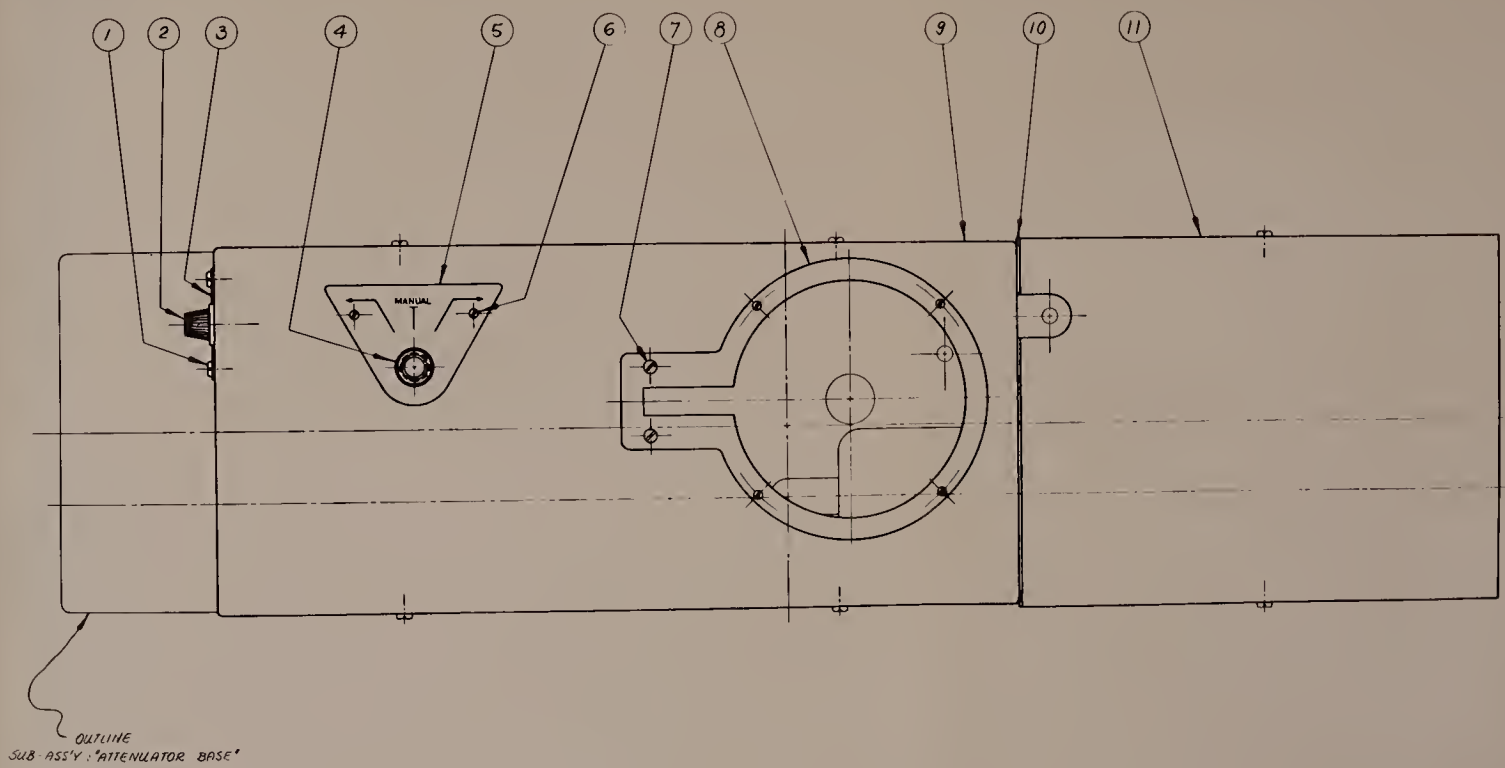
* STOCK 17E-705

11	COVER, TRANSPARENT SECTION MATERIAL - LUCITE 3/8 THICK	1
10	SPACER MATERIAL - FELT 1/8 THICK	1
9	COVER, MATERIAL - 52 S ALUMINUM 3/16 THICK	1
8	ESCUATCHION MATERIAL - 6061 ALUMINUM 1/8 THICK	1
* 7	BRASS SCREW, # 4 ROUND, BINDING HEAD, 3/8 LONG	2
* 6	BRASS SCREW, # 2 - 56 UNC ROUND HEAD, 3/8 LONG	6
5	INDICATOR PLATE MATERIAL - 6061 ALUMINUM	1
* 4	DIRECTIONAL SWITCH 2 SWITCHES SWITCHCRAFT # 3006 SW	1
* 3	PLUG, 2 POLE INSERT W/GROUND 125 V, 15 AMP	1
* 2	LITTLE FUSE 3AG, 3/16 A FUSE W/FUSE MOUNT TYPE 342001	1
* 1	BRASS SCREW, # 6 - 32 UNC BINDING HEAD, 3/4 LONG	2

FIG. NO.	NOMENCLATURE	NO. OF PARTS
NATIONAL BUREAU OF STANDARDS RADIO STANDARDS LABORATORY BOLTON, COLORADO, BOULDER CIRCULAR WAVEGUIDE BELOW CUT OFF ATTENUATOR FOR NOMINAL 30 MHz OPERATION		
MODEL #	TYPE	SCALE AS NOTED
DIMENSIONS IN INCHES 1) DIMENSIONS IN MILLIMETERS 2) DIMENSIONS IN CENTIMETERS	DRAFTSMAN NATOR LEVINSKI PROJECT ENGINEER D.H. RUSSELL	CHECKED BY A.L. SCHUSTER PROJECT ENGINEER
TOLERANCES 1) DIMENSIONS UNLESS OTHERWISE SPECIFIED	SUBMITTED BY	
DECIMALS ± .000	CHIEF ENGINEER	
FRACTIONS ± .010	EXAMINED BY	
ANGLES ± 1'	CHIEF ENGINEER	
DO NOT SCALE THIS FIGURE	APPROVED BY	
BY INC	THIS PRINT ISSUED	CHIEF D.E.
252	AI-7/153 D	

Figure 27(1).

ORIGINAL DATE OF DRAWING		
JULY 31 1947		
REVISIONS		
NO.	DESCRIPTION	DATE
1		
2		
3		
4		
5		



OUTLINE
SUB-ASS'Y: 'ATTENUATOR BASE'

SUB-ASS'Y: COVER
SCALE = 1/1

LIST OF PARTS
STOCK # QTY

11	COVER TRANSPARENT SECTION MATERIAL - LUCITE 3/4 INCH	1
10	SPACER MATERIAL - FEEC 1/4 INCH	1
9	COVER MATERIAL - 52 ALUMINUM BRASS ESCUTCHEON	1
8	MATERIAL - 6061 ALUMINUM 1/4 INCH DIMENSIONAL SWITCH	1
7	BRASS SCREW #4 1/2 INCH BINDING HEAD 1/4 INCH LONG	2
6	BRASS SCREW #2 1/2 INCH BUNDLED HEAD 1/4 INCH LONG	6
5	MATERIAL - 6061 ALUMINUM 1/4 INCH DIMENSIONAL SWITCH	1
4	BRASS SCREW #4 1/2 INCH BINDING HEAD 1/4 INCH LONG	1
3	PLUG, 2 POLY INSERT W/LEADS 12.5 AMP	1
2	LITTLE FUSE 3AG, 4EN FUSE W/PLATE MOUNT TYP. 3200V	1
1	BRASS SCREW #4 1/2 INCH BINDING HEAD 1/4 INCH LONG	2

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MODEL: 77
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SHEET: []

Figure 27(1).

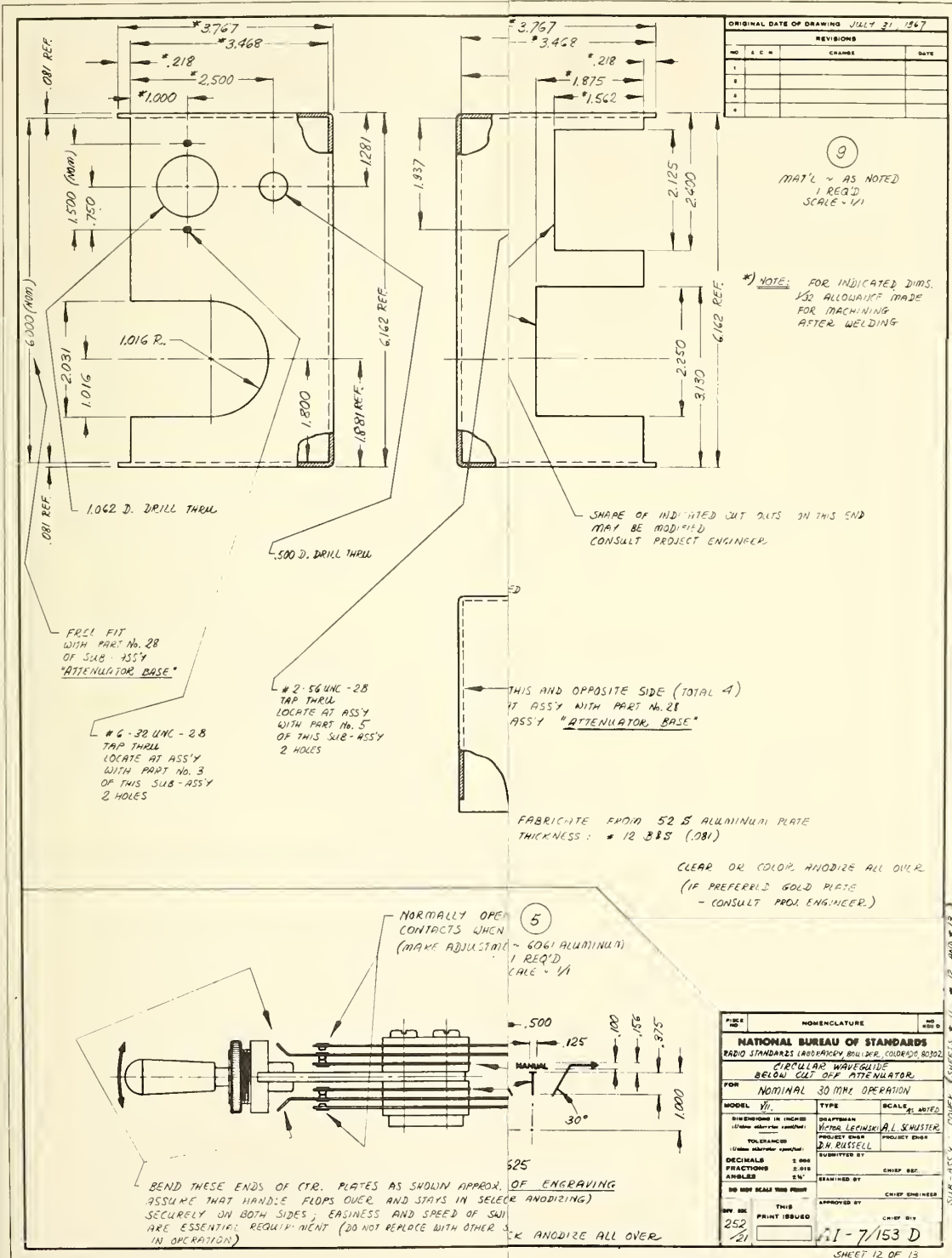


Figure 27(m).

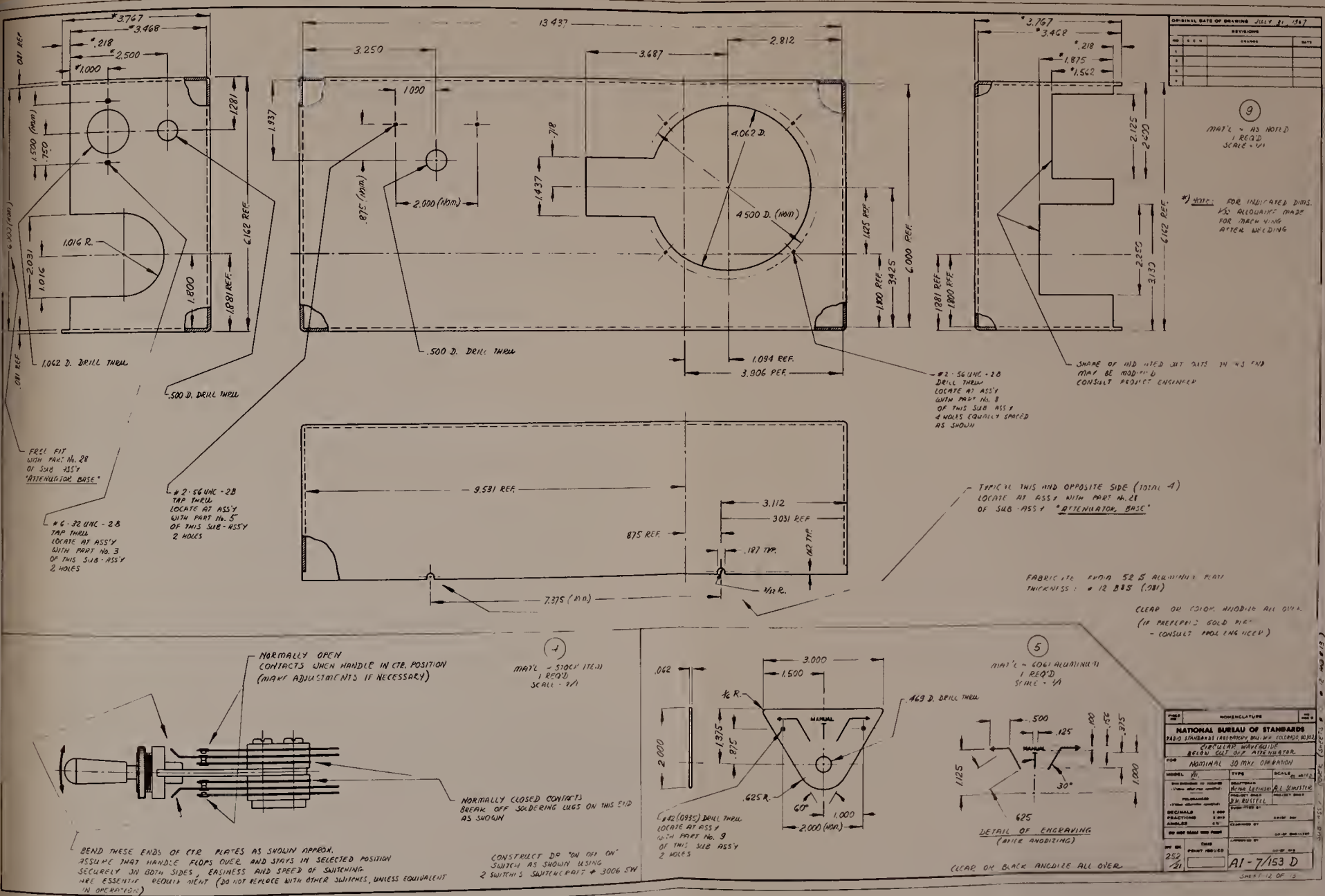


Figure 27(m).

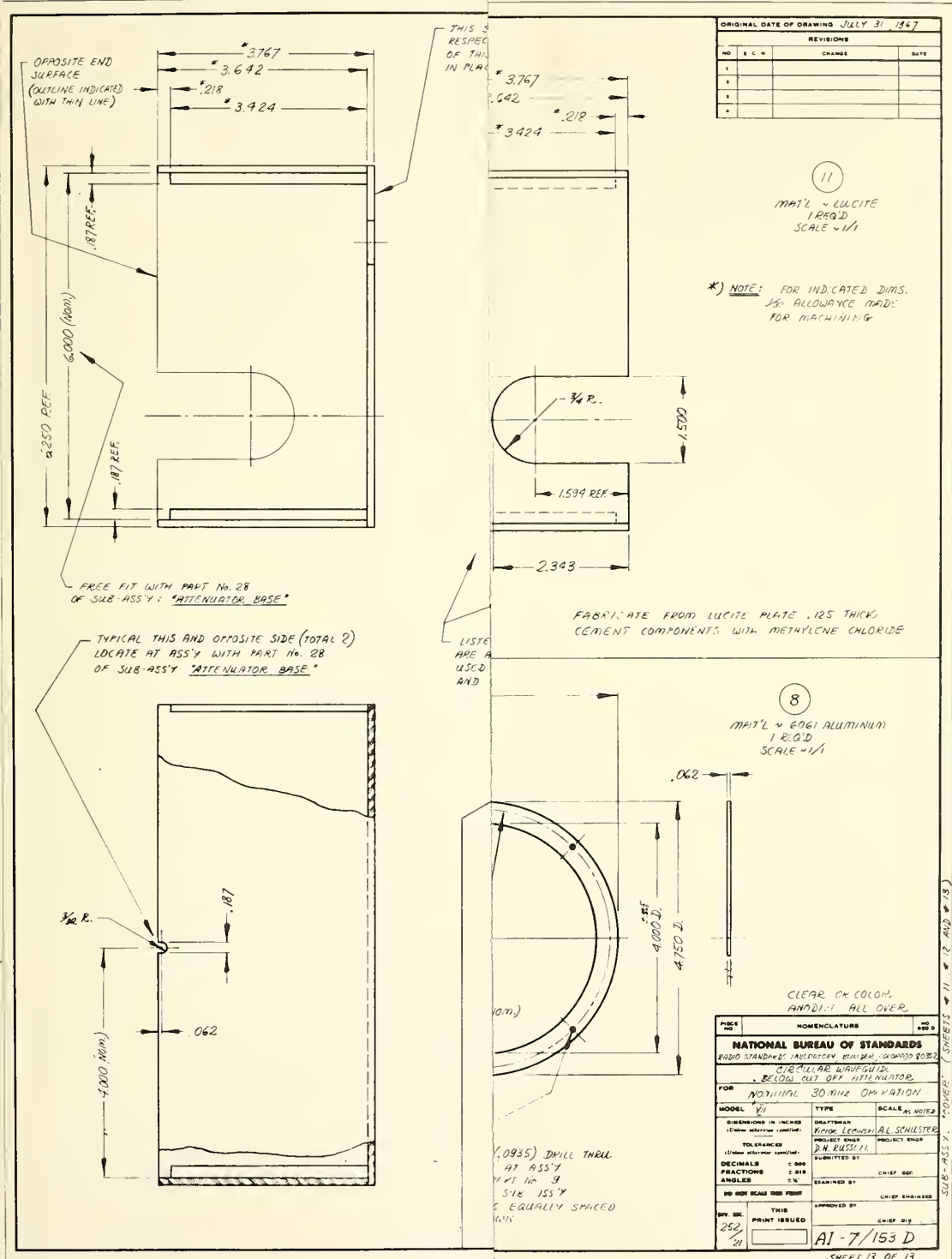


Figure 27(n).

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