NBSIR 76-833

A PRECISION 30 MHz WAVEGUIDE-BELOW-CUTOFF ATTENUATOR WITH AN ABSOLUTE ELECTRONIC READOUT

NBS MODEL XII

Robert T. Adair

Electromagnetics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80303

January 1976

Prepared for :
U.S. Army Metrology and Calibration Center
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

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A PRECISION 30 MHz WAVEGUIDE-BELOW-CUTOFF ATTENUATOR
WITH AN ABSOLUTE ELECTRONIC READOUT
NBS MODEL XII

Robert T. Adair

A coaxial precision waveguide-below-cutoff attenuator is described which utilizes an absolute (unambiguous) electronic digital readout of displacement in decibels instead of the usual gear-driven mechanical counter/dial readout in decibels. The attenuator has a fixed-position rf input connector and a movable rf output connector. The attenuation rate for 30 MHz operation is given along with a discussion of sources of errors. In addition, information is included to aid the user in making adjustments on the attenuator should it be damaged or disassembled for any reason.

KEY WORDS: Absolute (unambiguous) readout; piston; precision attenuator; sensor; waveguide-below cutoff.

1. GENERAL INFORMATION

1.1. Introduction

This document contains a description, specifications, operating procedures, theory of operation, and a parts list for the NBS Model XII, 30 MHz Attenuator. The Model XII, designed and constructed by the National Bureau of Standards, Boulder, Colorado, is a waveguide-below-cutoff attenuator designed as a very precise standard for calibrating various types of laboratory attenuators and attenuation measuring systems in a semi-automated fashion. This attenuator (fig. 1, 2, and 3) has some unique features: 1) It has a two-speed manual drive mechanism using a harmonic drive with a rack and pinion gear; and 2) It has an absolute (unambiguous) electronic digital readout of the linear displacement in decibels.

1.2. Specifications

Table 1.

Electrical:	
Frequency of Operation	30 MHz
Input and Output Impedances (VSWR F 1.02)	50 + j0 ohms
Minimum Insertion Loss (at 0 dB indicated)	30 dB nominal
Attenuation Range	100 dB
Resettability	± 0.001 dB
Phase Shift of Attenuator	< 0.1 degree/10 dB
Calibration Accuracy (Fig. 11)	± (0.004 dB/10 dB)
RF Input Power Capability	250 mW max. (Higher Power may cause damage or drift due to heating effects.)
AC Power Requirement	115 VAC, 60 Hz, 0.125 Ampere

Mechanical:		
Connectors	Precision 14 mm	
	Attenuator	Electronic Readout
Dimensions		
Width	76.2 cm	50.0 cm
Depth	25.4 cm	47.0 cm (including knobs)
Height	38.1 cm	20.3 cm
Mass	68.3 Kg	35.0 Kg

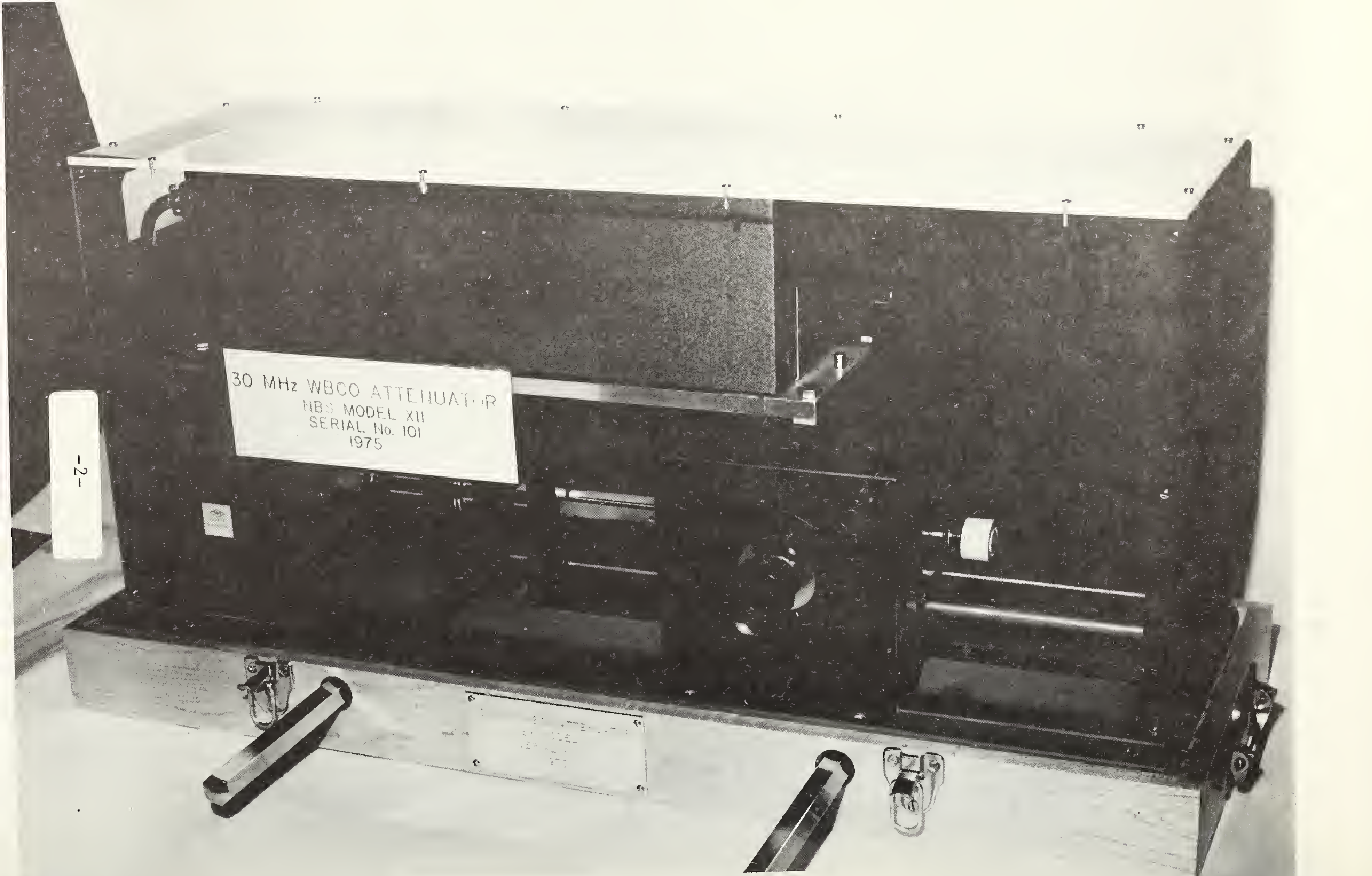

Figure 1. NBS Model XII, 30 MHz attenuator.

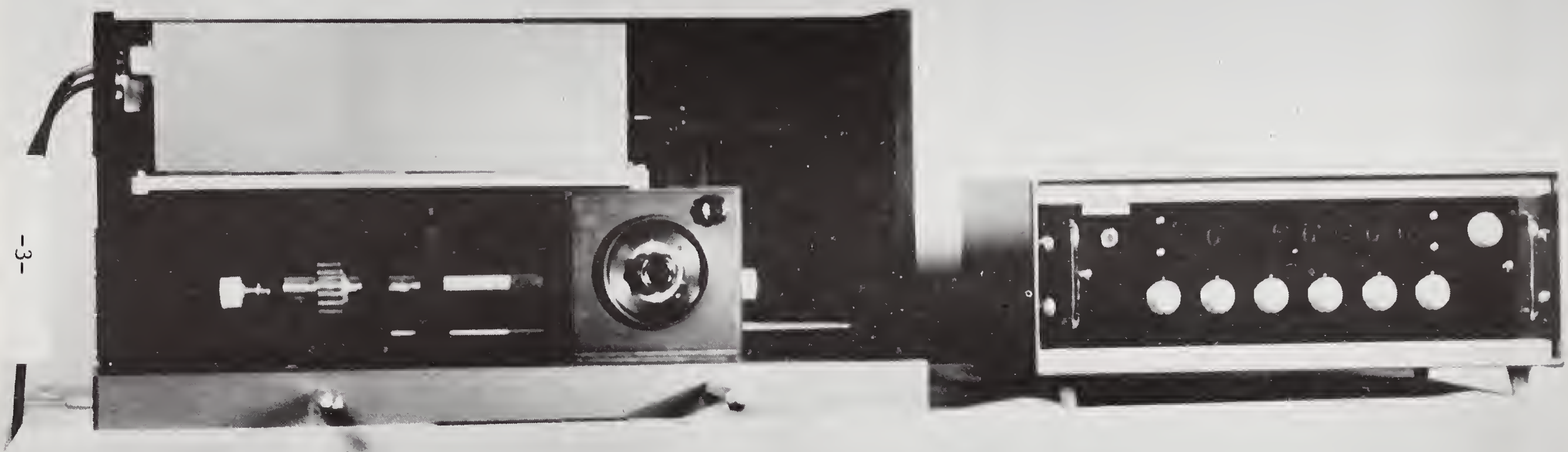

Figure 2. NBS Model XII attenuator with electronic readout.

Figure 3. NBS Model XII attenuator with protective housing removed.

1.3. Description of Attenuator

The basic piston attenuator consists of four principal parts: the circular waveguide or main body of the attenuator, the exciting unit, the receiving unit, and the mode filter (see figs. 4 and 5). The waveguide is a brass cylinder whose inside diameter is accurately machined to a known uniform value. During the fabrication process, this guide was stress-relieved several times to minimize any tendency for dimensional creep and to keep the rf conductivity of the wall as near as possible to that of the bulk material. A rhodium flash of a few micro cm (≈ micro in) thickness was applied to the inner surface to minimize surface tarnishing.

The exciting unit [1]* consists of an eight-turn coil, impedance matching network, and an rf input connector--all mounted in a metal housing which is screwed onto the input end of the guide. The coil, when current is applied to it, establishes the TE_{11} mode field in the guide, the electric field lines being parallel to the wires of the coil. The matching network transforms the low inductive reactance of the coil to a resistive 50 ohms. It consists of four miniature glass piston capacitors. These are used in two parallel combinations to double the effective capacitive range of each. One combination is mounted in shunt with the coil and the other combination is mounted in series with the rf input. The shunt capacitors are adjusted to give an impedance of 50 + jX ohms due to partial resonance of the coil-capacitance circuit. The series capacitors are adjusted to a value of -jX. This gives an input impedance of 50 + j0 ohms. Interaction between the capacitors causes the adjustment of the matching network in an actual attenuator to be much more complicated than in the ideal case, however. The coil and matching network result in a moderately high-Q circuit which is operated very close to parallel resonance. Thus the input impedance is quite sensitive to changes in coil inductance, matching network capacitances, coil losses, and operating frequency. To significantly decrease these effects, the coil in this attenuator has been shunted by a 2K-ohm rf resistor to effectively lower the Q to a reasonable value (see fig. 6).

The receiving unit consists of the following: a shunted coil and matching network similar to the ones in the exciting unit; metal contact fingers to provide ground contact to the guide wall and prevent signal leakage past this unit, a notched teflon guide to keep the receiving unit centered in the guide as the unit moves longitudinally, and an rf output connector. The receiving coil is parallel to the exciting coil and extracts a small portion of the field as it moves along the guide. This extracted field is proportional to the field strength; thus, the ratio of the extracted fields for two receiving unit locations in the guide is determined by the linear displacement between these points and the attenuation rate of the guide.

The mode filter consists of a metal ring and 15 metal strips, 0.063 cm (0.025 inch) wide, equally spaced perpendicular to the diameter of the ring (see fig. 5). The filter is mounted in the guide between the exciting and receiving coils with the strips perpendicular to the coil elements. It is located approximately 0.091 cm (0.036 inches) from the end of the exciting coil.

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* The numbers in brackets refer to the references given at the end of this document.

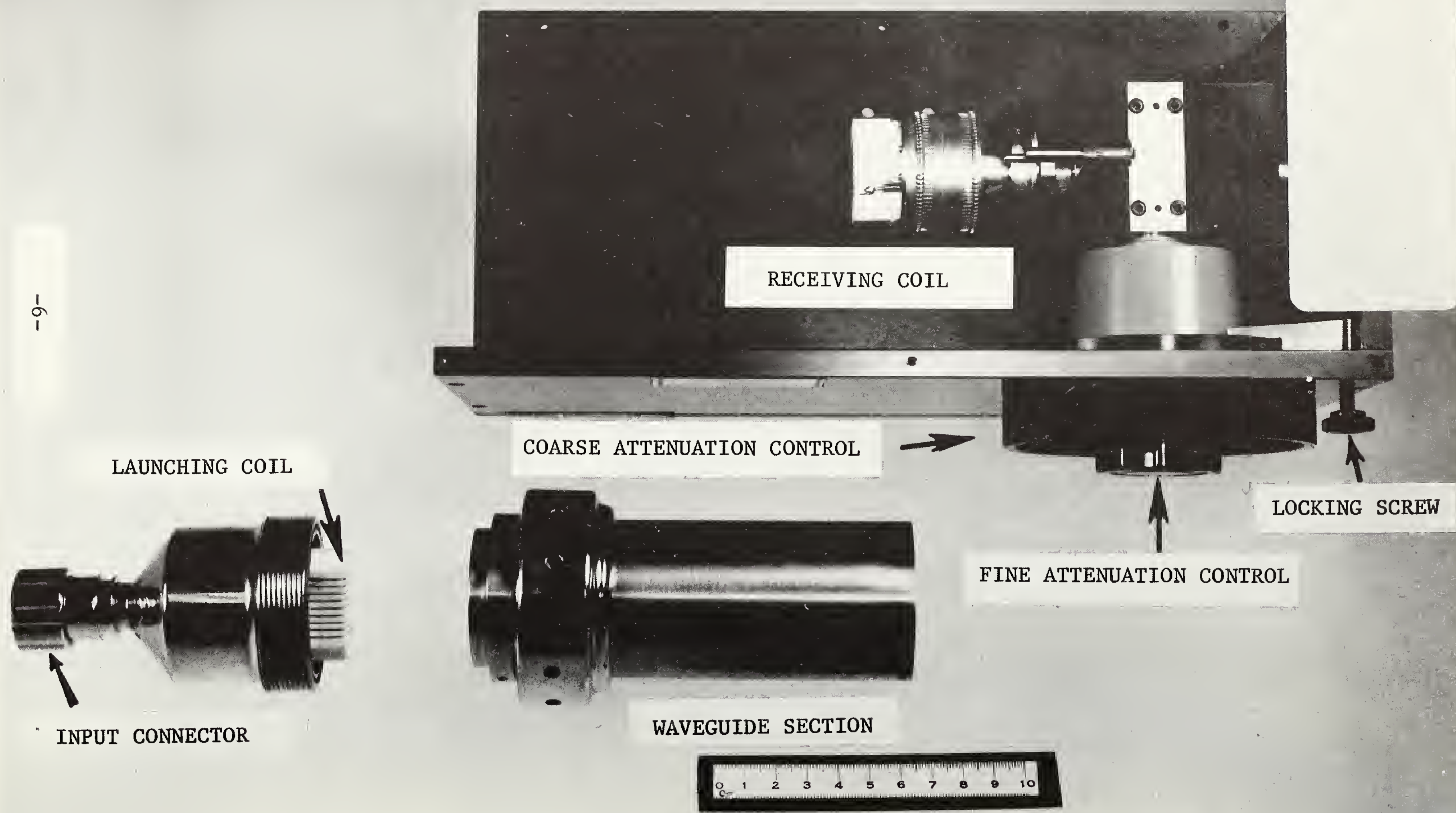
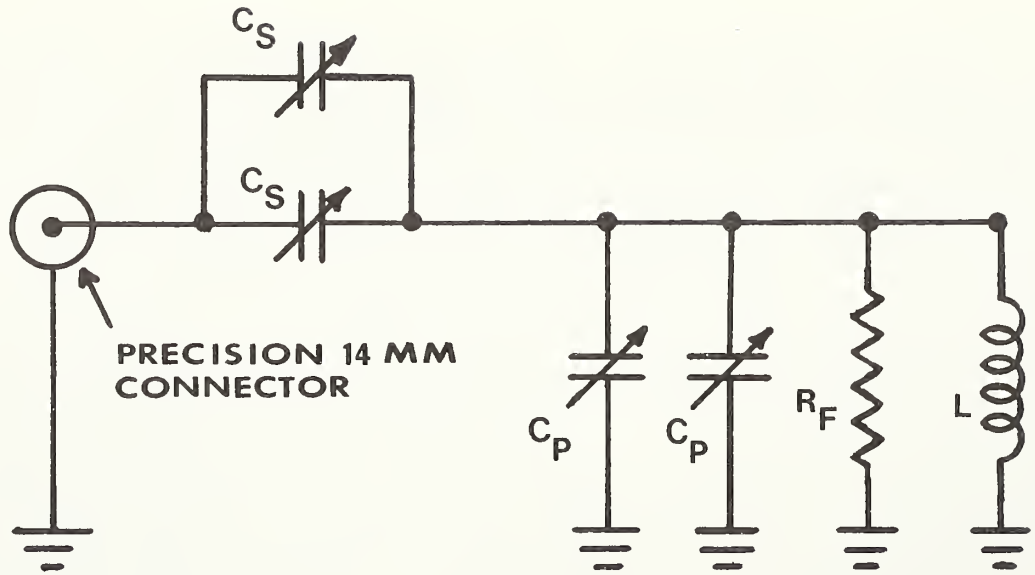


Figure 4. Pictorial view of signal launching and receiving assemblies.

Figure 5. Pictorial view of mode filter.



C_S AND C_P ARE PISTON CAPACITORS (1 - 16 $\mu\mu$F)

R_F IS AN RF METAL FILM RESISTOR : 2 KΩ, 1%, 2 WATT

L IS NOMINALLY 1 μH CONSISTING OF APPROX-IMATELY 8 TURNS OF MANGANIN WIRE

Figure 6. Schematic diagram of signal launching and receiving networks.

The basic attenuator has been described. To use this device, a manner of moving the receiving unit and a precise indication of the amount of this movement must be provided. The receiving unit (signal output end of attenuator) is mounted to one end of a precision 14 mm coaxial line. The rack and pinion gear moves the receiving unit along the guide. Rapid movement of the receiving unit (piston) is accomplished by rotating the "COARSE ATTENUATION CONTROL". There is no mechanical readout of the receiving unit location. The "FINE ATTENUATION CONTROL" provides for fine positioning of the attenuator manually after the approximate position is reached with the COARSE ATTENUATION CONTROL. An optical sensor and associated electronics provide an accurate digital display of the piston position. An auxiliary BCD (positive TTL) output is available from the sensor readout package.

An end plate is fastened securely to the output end of the 14 mm line which is positioned by the rack and pinion gear. To keep this plate from twisting during operation of the attenuator, the bottom end is guided by low-friction linear roller bearings mounted on precision circular guide rods. The push rod of the displacement sensor is fastened to the top of the end plate. These details can be seen by referring to figures 9 and 10.

The complete attenuator consists of two separate packages. The attenuator assembly contains the basic attenuator, manual drive mechanism, and the electronic sensor. The readout assembly contains the digital display of the attenuator displacement, BCD output connector, datum shift switches, and all necessary electronics and interconnecting cables required by the displacement sensor and readout.

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* The corresponding motion of the receiving unit inside the guide can be compared to the motion of a piston in a cylinder. Thus, this unit is frequently referred to as the "piston". In fact, this is the origin of the name "piston attenuator".

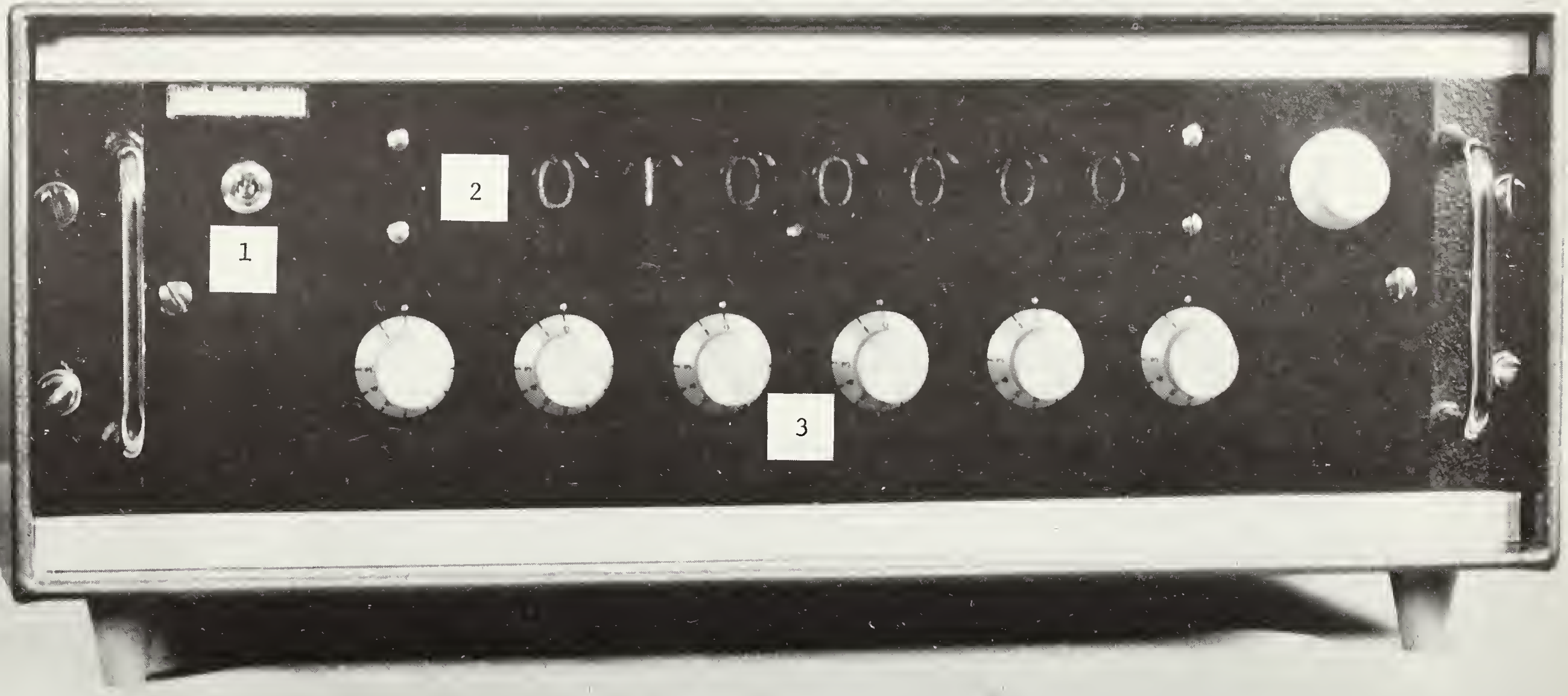

Figure 7. Electronic readout unit showing datum change switches.

Figure 8. Electronic readout unit showing rear panel details.

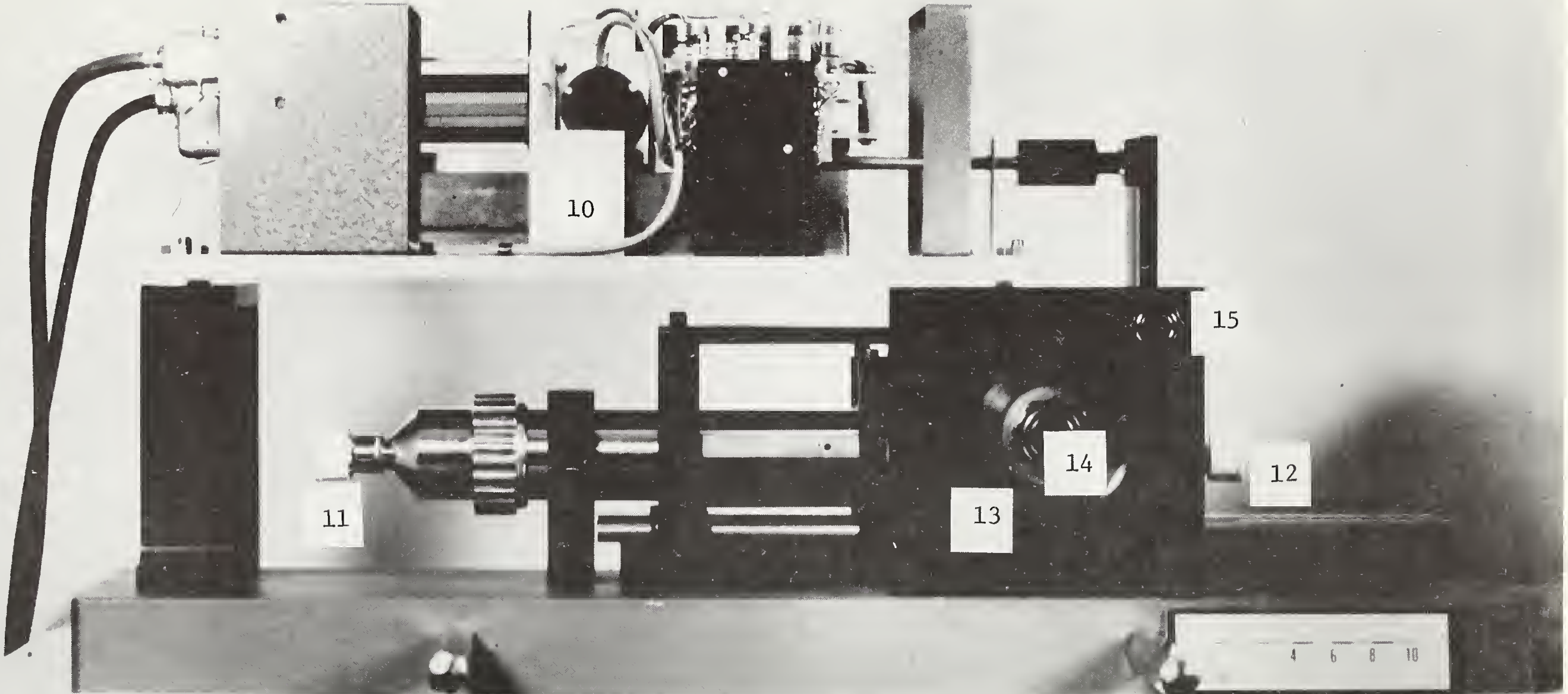

Figure 9. NBS Model XII attenuator with sensor cover removed.

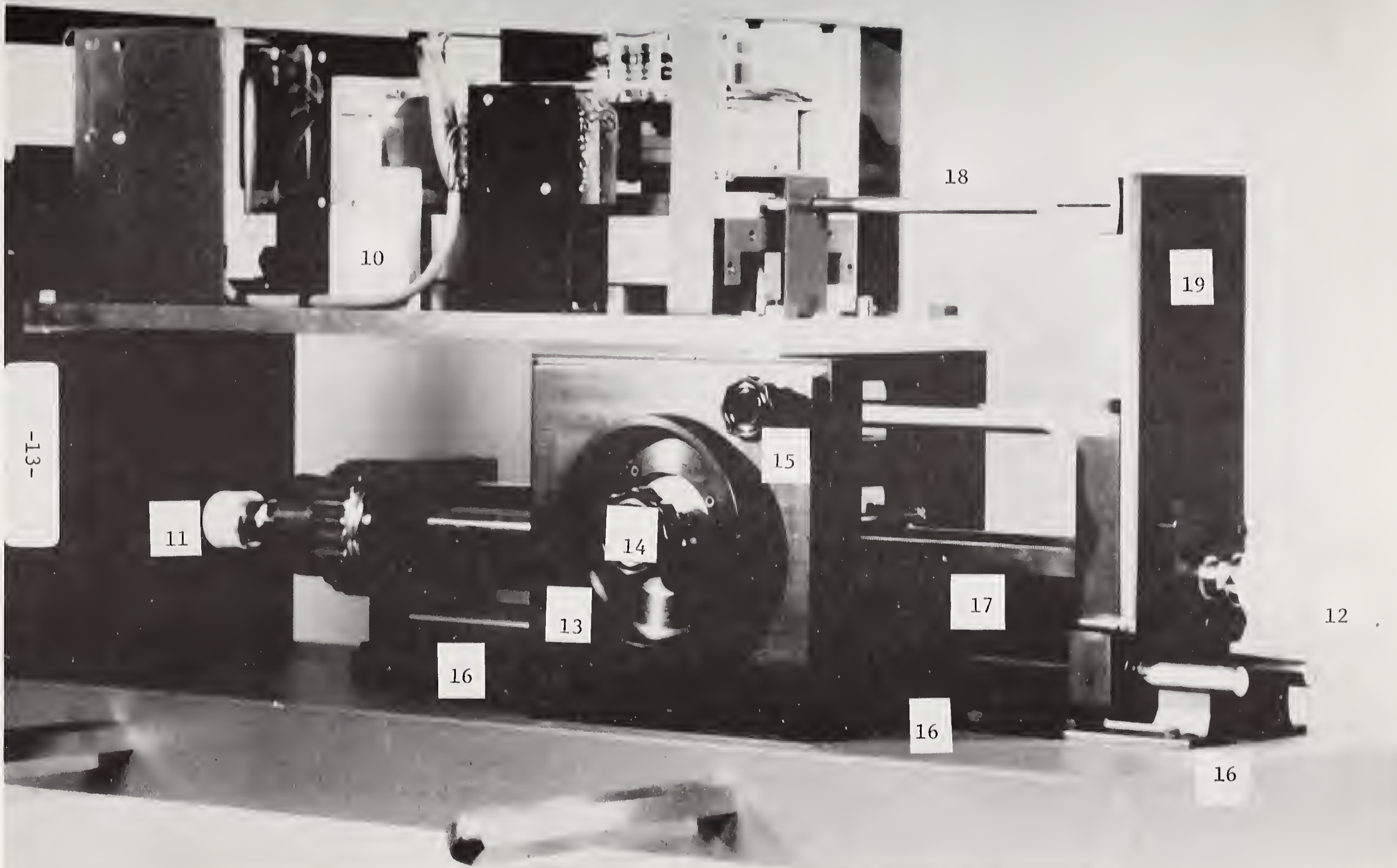

Figure 10. Close-up view of NBS Model XII showing details.

1.4 Controls and Indicators

The Model XII controls and indicators are described in table 2 below and are identified in figures 7, 7, 9 and 10 by index. numbers.

Table 2

Description of Controls and Indicators

Item No	Item	Description
1.	ON/OFF SWITCH	The switch which controls the power applied to the position indicating circuit (transducer) and the electronic readout.
2.	ATTENUATION VALUE READOUT	This reading is the actual attenuator setting in decibels when all Datum Change Switches are in the zero position. It indicates an arbitrary reading when the Datum Change Switches are not all in the zero position. This readout also provides a visual indication when AC power is applied to the readout circuit.
3.	DATUM CHANGE SWITCHES	Provide means of setting attenuator readout to a desired indication other than the actual attenuator setting.
4.	LEAD/LAG SWITCH	Must be in the "ON" position for normal operation of the readout. The "OFF" position is used during factory set-up of the unit.
5.	RECODE SWITCHES	Preset at factory for correct tracking of readout from one digit to the next. Must be in the correct position as indicated on the unit.
6.	SENSOR INPUTS TO READOUT	Provides means of getting information from the position sensor into the readout circuitry.
7.	FUSE	Protects position indicating circuit.
8.	AC POWER INPUT	Provides connection for the 115 volt, 60 Hz power cable.
9.	BCD OUTPUT JACK	Provides rear panel output of digital readout value in BCD format.
10.	LINEAR DISPLACEMENT SENSOR ASSEMBLY	Provides true unambiguous indication of attenuator position information for the readout circuitry to process and indicate.
11.	INPUT CONNECTOR	A precision 14 mm connector which provides the connection for a coaxial cable to the input of this attenuator. The input impedance is nominally 50.0 ohms.
12.	OUTPUT CONNECTOR	A precision 14 mm Connector which provides the connection for a coaxial cable to the output of this attenuator. The output impedance is nominally 50.0 ohms.

Table 2 (contd.)

Item No	Item	Description
13.	COARSE ATTENUATION CONTROL	Provides coarse setting of the receiving coil. The locking screw must be loose to adjust this control.
14.	FINE ATTENUATION CONTROL	Provides fine setting of the receiving coil to obtain the desired attenuation exactly. The locking screw must be tightened before operating this control.
15.	LOCKING SCREW	Locks coarse attenuation control but allows the fine attenuation control to operate.
16.	GUIDE RODS	Precision circular guide rods with low friction linear bearings to provide accurate alignment of piston during movement along its entire travel.
17.	RACK AND PINION GEAR	Provides accurate linear means of positioning attenuator piston.
18.	PUSH ROD	Displacement sensor push rod which operates the coarse digit resolvers and the glass grating for the high resolution digits in the sensor assembly.
19.	END PLATE	Provides rigid connection between the attenuator piston and the sensor drive rod to accurately indicate attenuator setting.

2. THEORY OF OPERATION

2.1. General

This section contains the basic theory of operation for the Model XII, Precision 30 MHz Attenuator including the electronic readout.

2.2. Waveguide-Below-Cutoff Attenuator Theory

The waveguide-below-cutoff attenuator [2, 3]*, commonly called a piston attenuator, is a section of waveguide operated at a frequency far below the cutoff frequency of the waveguide. Thus, the field strength in the guide decreases exponentially along the longitudinal axis of the guide. Many modes can exist in a waveguide. The rate of decay of these modes below cutoff increases as the cutoff frequency increases. The mode having the lowest decay rate and lowest cutoff frequency is called the dominant mode and is the mode used in most piston attenuators. For practical considerations, the circular waveguide is the most common shape used. The attenuator described here operates in the dominant mode in circular waveguide, namely, the TE_{11} mode. The attenuation rate of the ideal piston attenuator is given by $\frac{p_{nm}}{a}$, where a is the radius of the guide and p_{nm} is a constant determined by the waveguide configuration and the mode of operation. For the circular TE_{11} mode, p_{11} equals 1.84118378 and is the first root of the first derivative of the first-order Bessel function of the first kind. For a practical circular-waveguide piston attenuator, the attenuation rate is affected slightly by the finite conductivity of the guide wall and the ratio of cutoff frequency to operating frequency. The actual rate is closely approximated by the following equation:

$$A = \frac{p_{11}}{a}\sqrt{1 - \frac{\delta}{a} - \left(\frac{f}{f_c}\right)^2} \quad , \qquad (1)$$

where

A is the attenuation rate

δ is the skin depth of the guide $= \frac{1}{\sqrt{\pi \mu f \sigma}}$

f_c is the cutoff frequency $= \frac{p_{11} c}{2\pi a}$

μ is the permeability of the guide

σ is the conductivity of the guide

c is the velocity of propagation in free space

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* References [2, 3] contain extensive bibliographies on all phases of attenuation measurements as well as waveguide-below-cutoff and other common types of attenuators Therefore, the number of references used in this paper is kept to a minimum.

and MKS units are assumed throughout. This equation can be approximated as follows:

$$A = \frac{6.29619}{a} \left[1 - \frac{\delta}{2a} - \frac{1}{2} \left(\frac{f}{f_c} \right)^2 \right], \qquad (2)$$

where

A is in dB/cm and

a is now in centimeters

Of all the factors involved in the second-order corrections, only the conductivity (σ) is not known to sufficient accuracy to leave no uncertainty in these corrections.

Extra modes must not exist in a piston attenuator if high accuracy is desired. For the TE_{11} mode attenuator, the most bothersome mode is the TM_{01} mode by at least 60 dB while decreasing the desired mode by less than 0.5 dB.

2.3. Displacement Readout and Attenuation Value

As mentioned previously, only an electronic readout of the attenuator piston displacement is provided. The linear displacement transducer has a basic resolution of 127 microcentimeters (50 microinches). The unit utilizes a double density scale (which doubles the readout indication). The decimal point in the readout unit was shifted one place to the right. Thus the readout indicates precisely 7.8740 x displacement in cm (20 times the displacement in inches).

This readout provides a direct digital indication of the piston displacement in decibels (with the least increment being 0.001 dB) since the nominal attenuation rate of this attenuator is 7.8740 dB/cm (20.000 dB/inch). Datum change switches on the readout unit permit the display to be zeroed or set to any desired value at any attenuator setting.

As with any attenuator a known change in attenuation can be made only by taking the difference between two settings of the attenuator. Thus, the final setting of the attenuator minus the initial setting gives the net change in attenuation. Of course, this may be positive or negative. Since the electronic readout reads in decibels, the difference in the two readings is in decibels. Thus, if the datum switches are used to zero the display in the initial position, the final display will give the net change directly in decibels.

3. OPERATING PROCEDURE

3.1. General

This section contains information on preparation for use, identification and description of controls and indicators, and a step by step operating procedure.

3.2. Initial Alignment

These alignments are made during assembly of the attenuator and ordinarily are not attempted by the user. However, should circumstances warrant repair or adjustment by the user, the following information may be useful.

The exciting and receiving units are mounted such that the wire elements of the two units are in the same vertical plane as seen looking down the guide. Since the relative coupling is proportional to the cosine of the angle between these coils, visual alignment is adequate for this purpose. Rotation of the receiving unit during attenuator operation must not be allowed, however. Similarly, visual alignment of the mode filter to put the filter elements perpendicular to the exciting elements is satisfactory.

Four small holes in the excitation unit housing permit adjustment of the capacitors to match the input impedance of the attenuator to 50 ohms. The use of a vector impedance meter to monitor the input impedance simplifies the procedure. The series and shunt capacitors alternate around the adjustment hole circle. As the adjustment screws of the series capacitors are part of the input circuit, these must be tuned by making an adjustment and removing the screwdriver from contact before reading the impedance. The excitation unit should be in place on the waveguide before tuning as the mode filter and attenuator barrel affect the impedance. To avoid heating effects, the rf power to this unit should not exceed 250 milliwatts. Adjustment of the receiving unit is done in a similar manner. Unfortunately, the tuning capacitors cannot be reached without disassembling this end of the attenuator.

A certain minimum value of insertion loss must be maintained in a piston attenuator in order to prevent interaction between exciting and receiving units, keep undesired modes at an insignificant level, and prevent excessive coupling of the TE_{11} field to the receiving unit. Otherwise, high precision cannot be attained. This minimum insertion loss has been determined to be approximately 30 dB. Therefore, the attenuator has been set at a nominal insertion loss of 30 dB. The datum switches were all set at zero so that the electronic readout was exactly zero at this setting.

3.3. Initial Setup Procedure

To prepare the Model XII for use, remove the transducer stops and the connector cover plates.

To place the attenuator into operation, connect the multiconductor cables to the readout assembly and attenuator assembly by mating the marked multi-pin plugs to the corresponding sockets. Make the necessary connections to the rf input and output. Connect the readout assembly to an ac power source and turn on the readout unit. A seven-digit display should be obtained with the least significant (far-right) digit always zero or five. The display is now indicating the position of the piston in decibels. Rotating the attenuator manual control knobs should cause a change in the display. CAUTION: DO NOT lift the Model XII by anything other than the lifting rods which screw into the attenuator base.

3.4. Basic Operation

The attenuator is operated by moving the COARSE ATTENUATION CONTROL counter clockwise to decrease attenuation or clockwise to increase it. Mechanical stops prevent the attenuator from traveling below 0 or above about 110 dB. When the approximate value of attenuation is reached, the COARSE CONTROL is locked in position with the thumb screw provided and the final adjustment made by using the FINE ATTENUATION CONTROL. Operation and maintenance of the electronic displacement readout and sensor are explained by a comprehensive manual provided by the manufacturer and will not be covered any further here.

3.5. Detailed Operating Procedure

CAUTION

The Model XII is a precision instrument and must be handled with care. To preclude physical damage, never lift the instrument by the input or output connectors when the connector covers are removed or force the internal mechanisms into the mechanical stops. Always follow the procedure outlined below when operating the Model XII.

To establish a 0 dB reference level with the Model XII connected in a system proceed as follows:

a. Set all the datum change switches to zero.

b. Loosen the LOCKING SCREW.

c. Carefully rotate the COARSE ATTENUATION CONTROL clockwise until the electronic readout is nearly 0.

d. Tighten the LOCKING SCREW finger-tight.

e. Adjust the FINE ATTENUATION CONTROL until the electronic readout indication is 000.0000.

This completes the procedure for setting the Model XII to the 0 dB position.

Since the 0 dB reference level has been established, the attenuator can be set in any desired position as follows:

a. Loosen the LOCKING SCREW.

b. Carefully rotate the COARSE ATTENUATION CONTROL counter-clockwise until a setting near the desired value is reached.

c. Tighten the LOCKING SCREW finger-tight.

The precise value of attenuation presented to the measurement system by the Model XII is listed in the Report of Calibration furnished by NBS (or the calibration facility where it was last calibrated.) A sample calibration report appears on the following pages.

FORM NBS 443
(REV 7 65)

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
INSTITUTE FOR BASIC STANDARDS
BOULDER, COLORADO 80302

REPORT OF CALIBRATION

Variable Waveguide Below-Cutoff Attenuator

Coaxial Connectors

National Bureau of Standards
Model XII, Serial No. 101

Submitted by:

National Bureau of Standards
Division 276.03

The measurements on this attenuator were performed under ambient conditions of approximately 23°C and 40 percent relative humidity. The power presented to the attenuator during the calibration was less than 150 milliwatts. The attenuator was terminated at each end in approximately 50 + j0 ohms. The calibration frequency of 30 MHz was accurate to one part in 10^5. The change in insertion loss when the piston is moved from a 000.0000 reference setting on the sensor readout is indicated in the attached table.

The insertion loss of the attenuator with the sensor readout set at 000.0000 is 29.6 decibels.

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Figure 11

Sample Report of Calibration

Variable Waveguide-Below-Cutoff Attenuator
Coaxial Connectors
National Bureau of Standards
Model XII, Serial No. 101

Sensor Readout	Change in Insertion Loss Decibels	Limits of Systematic Error Decibels	Maximum Uncertainty Decibels
001.0000	0.998	0.006	0.008
002.0000	1.996	0.006	0.008
003.0000	2.994	0.007	0.009
004.0000	3.993	0.007	0.009
005.0000	4.993	0.008	0.010
006.0000	5.993	0.008	0.010
007.0000	6.992	0.009	0.011
008.0000	7.991	0.009	0.011
009.0000	8.991	0.010	0.012
010.0000	9.991	0.010	0.012
011.0000	10.991	0.011	0.013
012.0000	11.990	0.011	0.013
013.0000	12.991	0.012	0.014
014.0000	13.991	0.012	0.014
015.0000	14.990	0.013	0.015
016.0000	15.990	0.013	0.015
017.0000	16.990	0.014	0.016
018.0000	17.990	0.014	0.016
019.0000	18.990	0.015	0.017
020.0000	19.990	0.015	0.017
025.0000	24.989	0.018	0.020
030.0000	29.991	0.020	0.022
035.0000	34.993	0.023	0.025
040.0000	39.992	0.025	0.027
045.0000	44.990	0.028	0.030
050.0000	49.991	0.030	0.032
055.0000	54.996	0.033	0.035
060.0000	60.001	0.035	0.037
070.0000	70.010	0.040	0.042
080.0000	80.019	0.045	0.047

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Figure 11. (Contd.)

Variable Waveguide-Below-Cutoff Attenuator
Coaxial Connectors
National Bureau of Standards
Model XII, Serial No. 101

Three measurements were made at each attenuator setting to find the mean value of "Change in Insertion Loss" and to estimate the standard deviation (S.D.) of this mean. A combined estimate of S.D. (RMS value of all the S.D.'s above) has been assigned to each mean. The maximum uncertainty is the sum of the limit of systematic error and the random error where the latter is defined as three times the estimate of S.D. of the mean.

This calibration data is valid only if the datum switches on the sensor readout unit are all set to 0 and the two recode switches on the back of the readout unit are set to 3 and 6, respectively, as marked. The lead/lag switch must be in the on position.

For the Director,
Institute for Basic Standards

David H. Russell
Program Chief
Microwave Metrology Services
Electromagnetics Division

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Figure 11 (Contd.)

4. ERROR ANALYSIS

For convenience, the equation for the attenuation rate is rewritten here in slightly different form.

$$A = \frac{6.29619}{a}\left[1 - \frac{1}{2a\sqrt{\pi\mu f\sigma}} - \frac{1}{2}\left(\frac{2\pi af}{p_{11}c}\right)^2\right] \quad (3)$$

It is readily seen that the guide radius is by far the most critical factor in determining the attenuation rate and that the uncertainty in this dimension will cause the largest uncertainty in the attenuation rate. The total correction due to finite conductivity is about 0.0049 dB/cm (0.0124 dB/inch) and that for finite cutoff frequency is about 0.0002 dB/cm (0.0005 dB/inch). The only significant uncertainty in these corrections is that resulting from the uncertainty in the conductivity determination [4].

4.1. Waveguide Diameter

The inside diameter of the attenuator guide was measured by an air guage at an ambient temperature of 20° C (68° F). Measurements were sampled every 1.27 cm (half inch) along the center 12.7 cm (five inches) of the guide. Three readings were taken at each point, equally spaced around the circumference. The average diameter was found to be 4.059248 cm (1.598129 inches) with longitudinal variations in the average diameter of ± 127 micro cm (± 50 micro in). The maximum variation around the circumference at any point was ± 23 micro cm (± 9 micro in). The measurements are believed accurate to ± 50.8 micro cm (± 20 micro in). Therefore, the diameter of the guide can be given as $4.059248 \pm 178 \times 10^{-6}$ cm ($1.598129 \pm 70 \times 10^{-6}$ inches). The uncertainty in diameter causes an uncertainty in the attenuation rate of ± 0.0004 dB/cm (± 0.0009 dB/inch).

Although equation (3) shows that the radius, a, is involved in both correction terms, these are second-order terms and are affected very little by small variations in the radius. This fact is very useful in calculating the attenuation rate of a piston attenuator. Assume that one has used equation (3) to determine the attenuation rate, A_1, corresponding to an approximate radius, a_1. Then the radius, a_2, required to give the desired rate of A_2 is quickly determined by the following relations:

$$A_2 = A_1\frac{a_1}{a_2} \text{ or } a_2 = a_1\frac{A_1}{A_2}$$

4.2 Waveguide Conductivity

The bulk conductivity of the brass waveguide was measured at dc. Based on the findings of several researchers in the field, the effective rf conductivity at 30 MHz is estimated to be 5% lower than the dc value. This gives a value of 1.325×10^7 mho/meter. The uncertainty in this value may be as much as 10%. This gives an uncertainty in the attenuation rate of ± 0.0003 dB/cm (± 0.0007 dB/inch).

4.3. Attenuation Rate

From the above, the total uncertainty in the attenuation rate is less than ± 0.0006 dB/cm (± 0.0016 dB/inch). The attenuation rate based on a diameter of 4.059248 cm (1.598129 inches) and rf conductivity of 1.325×10^7 mho/meter is 7.87436 dB/cm (20.00087 dB/inch) at 20°C (68°F).

4.4. Displacement Readout

The uncertainty in measuring the displacement of the piston from its initial to its final value is almost always the source of the greatest uncertainty in piston attenuators. Only by the use of ultraprecise length measuring systems such as laser-interferometers or the system used on this attenuator can this source of error be reduced to a reasonable value.

The uncertainty in the electronic readout is probably less than 127 microcentimeters (50 microinches) over its entire range. This gives an uncertainty of ± 0.001 dB over a range of 50 dB.

4.5. Miscellaneous Sources of Error

By use of a mode filter and approximately 30 dB minimum insertion loss, the effect of other modes of signal propagation is believed to be negligible at the attenuator zero setting. With increasing attenuation, the effect of spurious modes is reduced still further. The ratio of TM_{01} to TE_{11} mode strength is reduced by a factor of 2 for each 20 dB increase in attenuation.

Optimum layout of the displacement sensor for the electronic readout is in line with the piston. However, space limitations necessitated mounting the sensor above the attenuator guide with the axis of the push rod being directly above the axis of the attenuator. Any twisting or cocking of the end plate between the two positions of the piston during an attenuation measurement would produce an erroneous reading. It is believed that this effect is negligible if the roller bearings and guides and the sensor bearings are clean and running freely as when the attenuator left NBS. However, should any of the bearings become contaminated by dust or dirt causing erratic movement, errors would occur. Such a condition probably could be detected by an inability to repeat an attenuation value, tendency of the electronic readout to creep after the piston motion has ceased, or tendency to get changes in readings when the attenuator is jarred slightly. A small change in the readout upon being jarred may be normal, e.g., the relaxing of the forces built up between the rack and pinion gears due to motion of the piston in one direction.

Leakage from the attenuator is believed to be negligible for all values of attenuation from 0 to 100 dB.

The input and output impedances are adjusted to 50 ohms resistive to avoid reflections when the attenuator is inserted in a 50-ohm system. The match is not essential to proper operation of the device and moderate mismatches would only increase the initial insertion loss due to mismatch losses. However, high standing waves in the interconnecting rf cables would increase the possibility of leakage from these cables.

4.6. Temperature Effects

Temperature changes have a very definite effect upon the attenuation rate; namely, the percentage change in attenuation rate is the negative of the percentage change in guide radius. The coefficient of thermal expansion of the brass attenuator guide is about 20.9 parts per million (ppm)/°C (11.6 ppm/°F). Thus, for each degree C (F) increase in ambient temperature from 20° C (68°F), the attenuation rate given in paragraph 4.3 must be reduced by 0.00006 dB/cm (0.000145 dB/inch). Thus, for an ambient temperature of 22.2°C (72°F), the attenuation rate would be decreased by a total of 0.00023 dB/cm (0.00058 dB/inch). The attenuation rate at 22.2°C (72°F) is 7.87411 dB/cm (20.00023 dB/inch). This was the design temperature for the attenuator.

The electronic readout derives its three most significant digits from the geared digitizers so thermal expansion of the diffraction grating would have little effect on the overall reading. Therefore, the electronic readout does not contribute significantly to the errors due to temperature changes but the attenuation rate must be reduced by the full 20.9 ppm/°C (11.6 ppm/°F) for temperature increases due to the attenuator guide changing diameter.

4.7. Summary of Errors

To summarize, the attenuation rate is as given in paragraph 4.3 to an uncertainty of 0.0006 dB/cm (± 0.0016 dB/inch). The uncertainty in measuring displacement is ± 0.0004 dB/cm (± 0.001 dB/inch) for the electronic readout. Thus, the total uncertainty in producing a 20 dB attenuation change at room temperature is ± 0.0026 dB. This should not be considered as the only source of errors when making a measurement with this device in a measurement system. The accuracy of the NBS calibration on this device (fig. 11) does include the above mentioned sources of error.

5. PRECAUTIONARY MEASURES

A summary of precautions to observe when handling and operating the NBS Model XII attenuator follows:

1. Do not lift the device by its coaxial connectors, or anything else other than the base or the special lifting rods.
2. Do not force the position sensor against its stops.
3. Lock the "COARSE ATTENUATION CONTROL" in position when transporting this attenuator around the laboratory.
4. Keep the coaxial connector protector caps and a dust cover on the device when it is not in use.
5. Never lubricate the inside of the barrel (waveguide section).
6. The lead/lag switch on the rear panel of the readout unit must be in the ON position and the recode switches must be in the 3 and 6 positions for the units to operate properly.
7. The datum change switches must all be in the zero position for the NBS calibration to be valid.

6. SUMMARY

An accurate waveguide-below-cutoff (piston) attenuator has been described. The attenuator is designed to operate at a frequency of 30 MHz and the guide diameter was calculated to give an attenuation rate of 7.874 dB/cm (20 dB/inch) at an ambient temperature of 22.2°C (72°F). Sources of error in the attenuation rate and displacement readouts have been evaluated. The effects of ambient temperature changes have been analyzed and sufficient data given to enable the user to make accurate corrections for these effects.

The results show that at 22.2°C (72° F), the attenuation rate may be considered to be exactly 7.8740 dB/cm (20 dB/inch).

This discussion has covered the operation of a piston attenuator and sources of errors associated with it. In order to use this attenuator, it must be inserted into a system containing a minimum of an rf signal source, an rf detector, a device under test, and appropriate interconnecting cables. This introduces additional sources of errors, such as rf source instability (amplitude or frequency), detector instability and noise, rf leakage, and movement of flexible coaxial cables during measurement. Discussion of the measurement system is beyond the scope of this paper but is covered in references [2] and [3].

7. CONCLUSIONS

The NBS Model XII 30 MHz attenuator is a very precise attenuation transfer standard. Although this instrument is a relatively rugged, transportable standard, it must be handled carefully and treated with respect. Specifically, the ATTENUATION CONTROL knobs must not be turned so far that the attenuator hits the travel stops forcefully. This could damage the attenuator drive mechanism or change the initial insertion loss setting which would destroy all previous calibration data. This procedure must be strictly followed to obtain repeatable and correct calibration results [5].

The inside surface of the barrel (waveguide section) on this attenuator should never be lubricated prior to assembly of the device. Lubricants tend to leave residues which hamper the operation of the attenuator. The barrel and piston of a waveguide-below-cutoff attenuator should be cleaned with alcohol and allowed to dry prior to assembly.

This attenuator should be recalibrated by NBS a minimum of once every twelve to eighteen months.

8. ACKNOWLEDGMENTS

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The author would like to acknowledge the assistance of the following persons: Victor Lecinski for a superior job of mechanical design and layout, especially in locating the electronic displacement sensor assembly before the unit was received; and Clarence C. Cook for his invaluable help during the design and documentation stages of this project. A significant portion of the material contained in this document was obtained from reference [4] with the author's permission.

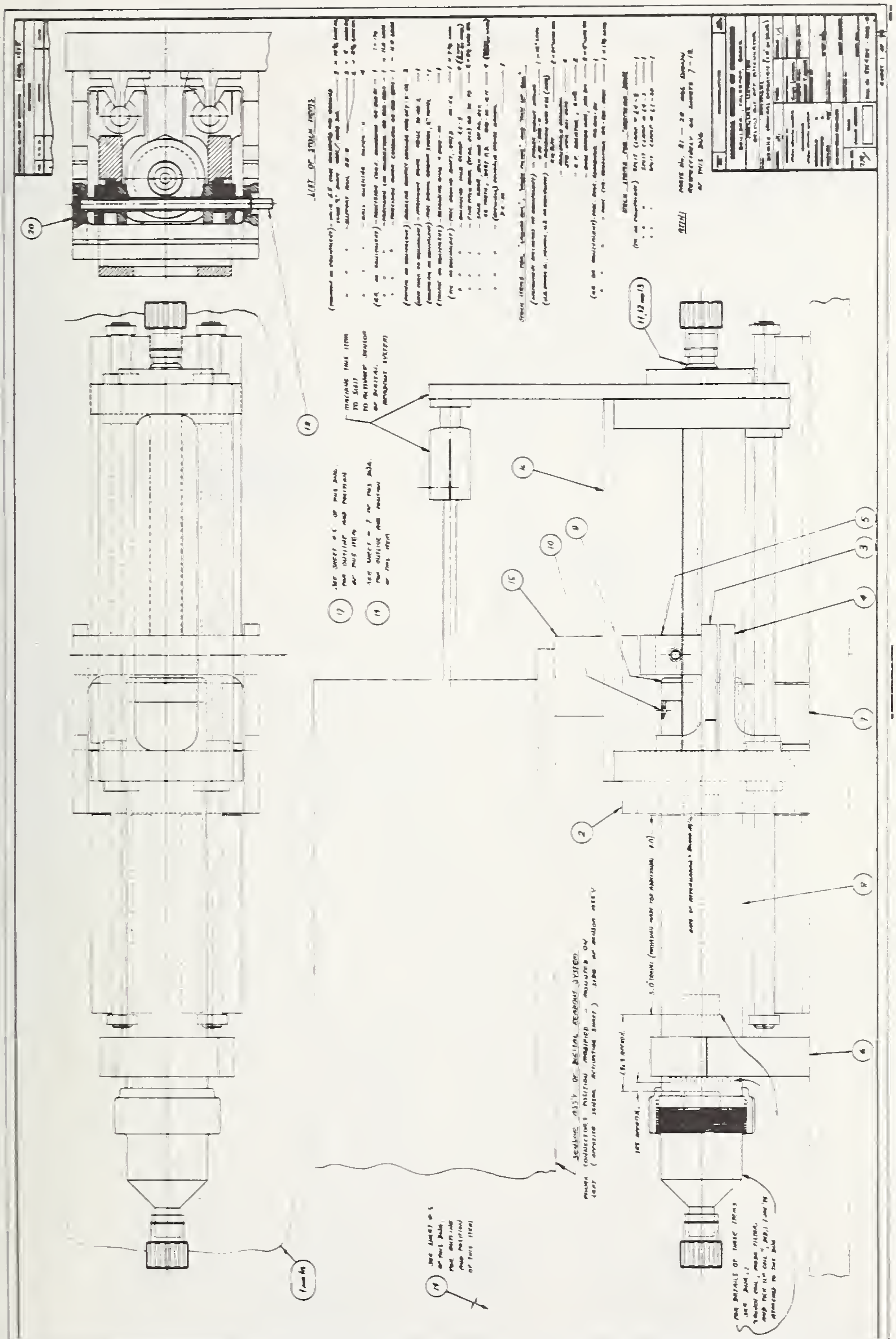
9. REFERENCES

1. Clarence C. Cook and C. McKay Allred, An Excitation System for Piston Attenuators, IEEE Transactions on Instrumentation and Measurement, Vol. IM-20, No. 1, Feb. 1971, 10-16.
2. D. Russell and W. Larson, RF Attenuation, Proceedings of the IEEE, Vol. 55, No. 6, June 1967, 942-959.
3. Robert W. Beatty, Microwave Attenuation Measurements and Standards, NBS Monograph 97, April 1967.
4. Clarence C. Cook, A Rack-Mounted Precision Waveguide-Below-Cutoff Attenuator with an Absolute Electronic Readout, NBSIR 74-394, November 1974.
5. Robert T. Adair, Precision 30 MHz, 10 dB, Waveguide Below Cutoff Step Attenuator NBS Model SA/1, NBS Unpublished Report.

10. APPENDIX I

Construction drawings of attenuator.

A detailed, itemized list of parts is not included in this document since its primary purpose is to aid in the operation and maintenance of the attenuator. The critical parts necessary for the fabrication of this attenuator are listed on the specific construction drawings. These parts are identified by corresponding part numbers in figures 12(a) through 12(q). Non-critical common stock items, such as machine screws, are not listed here.



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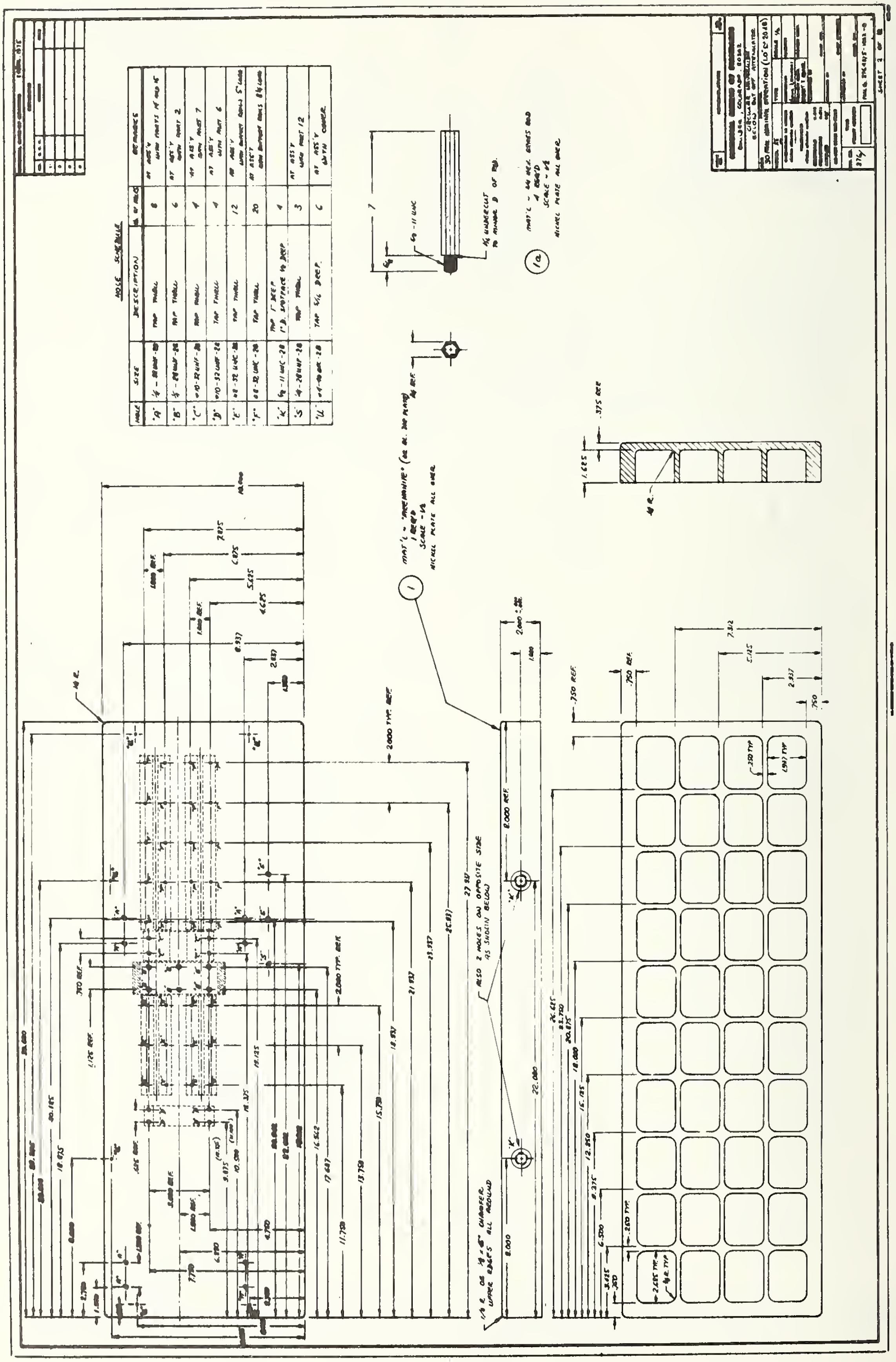

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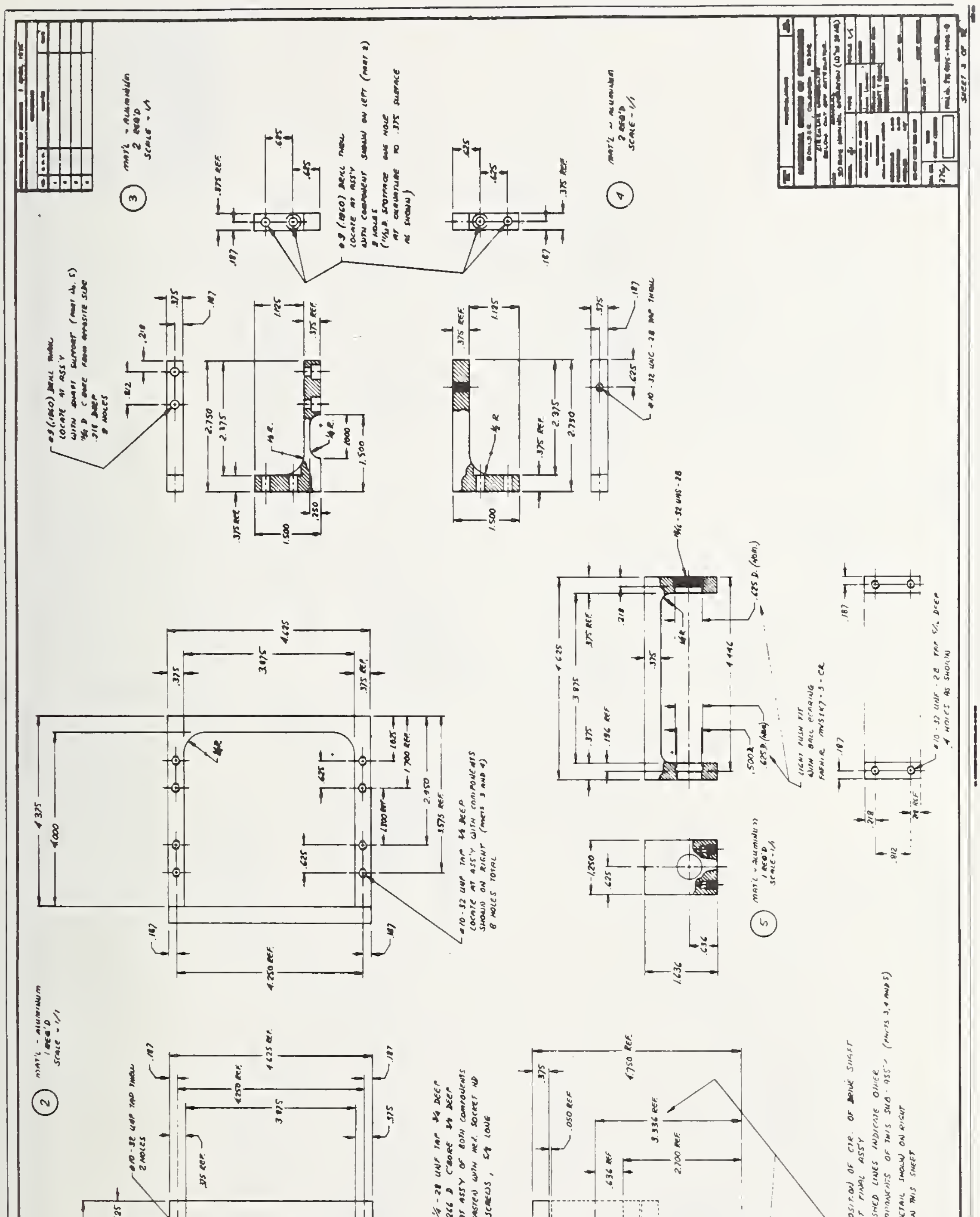

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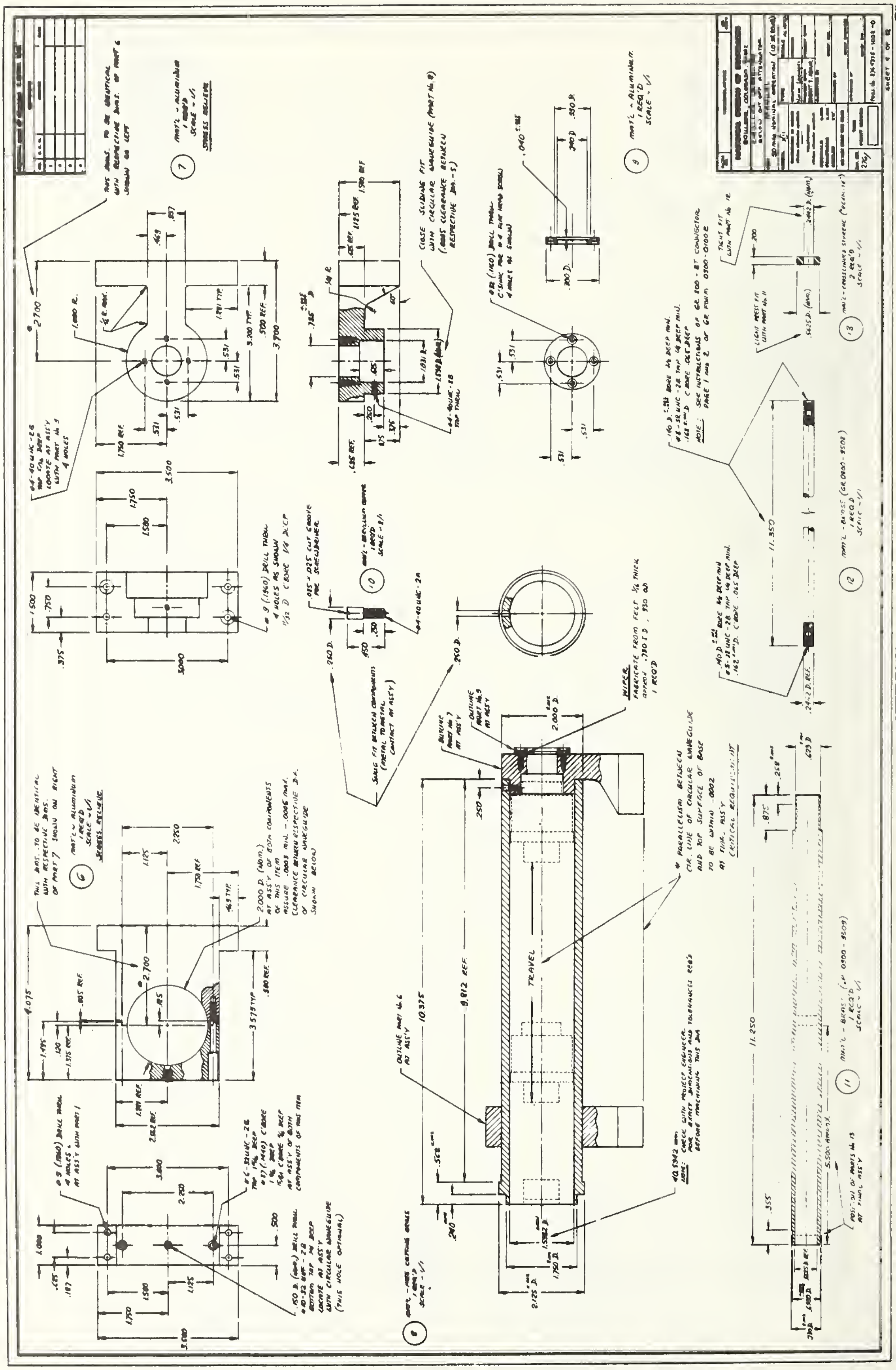

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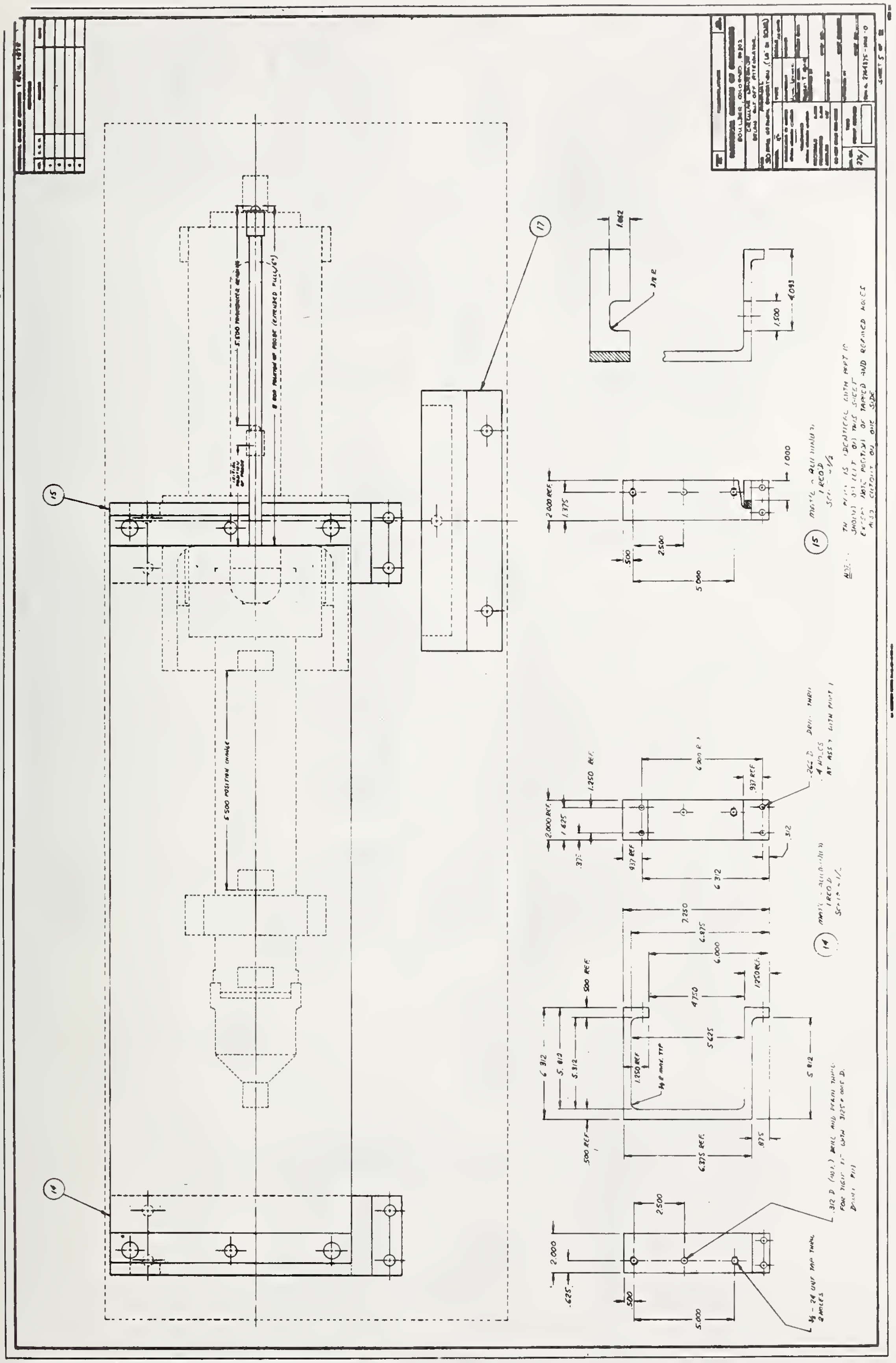

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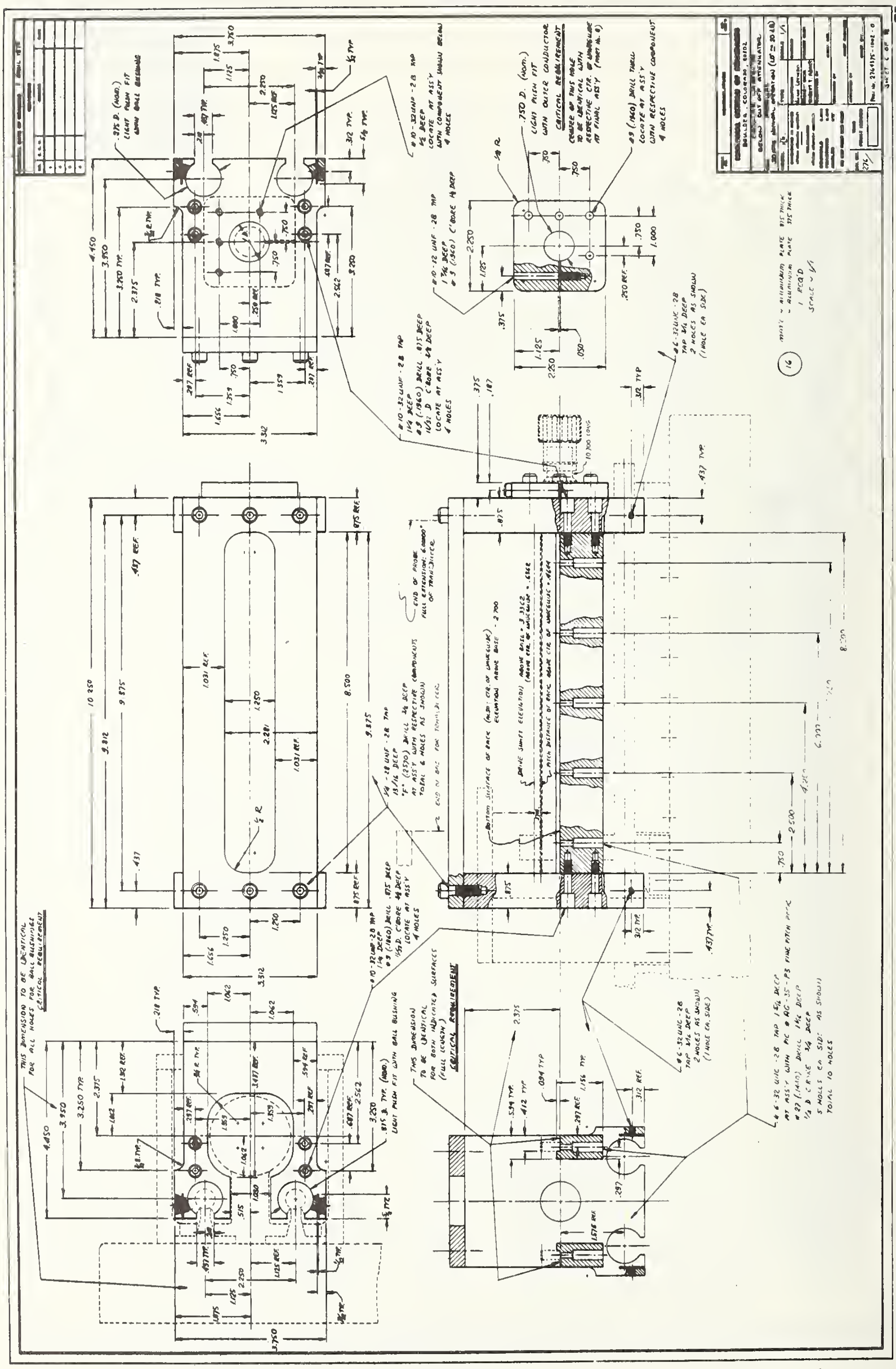

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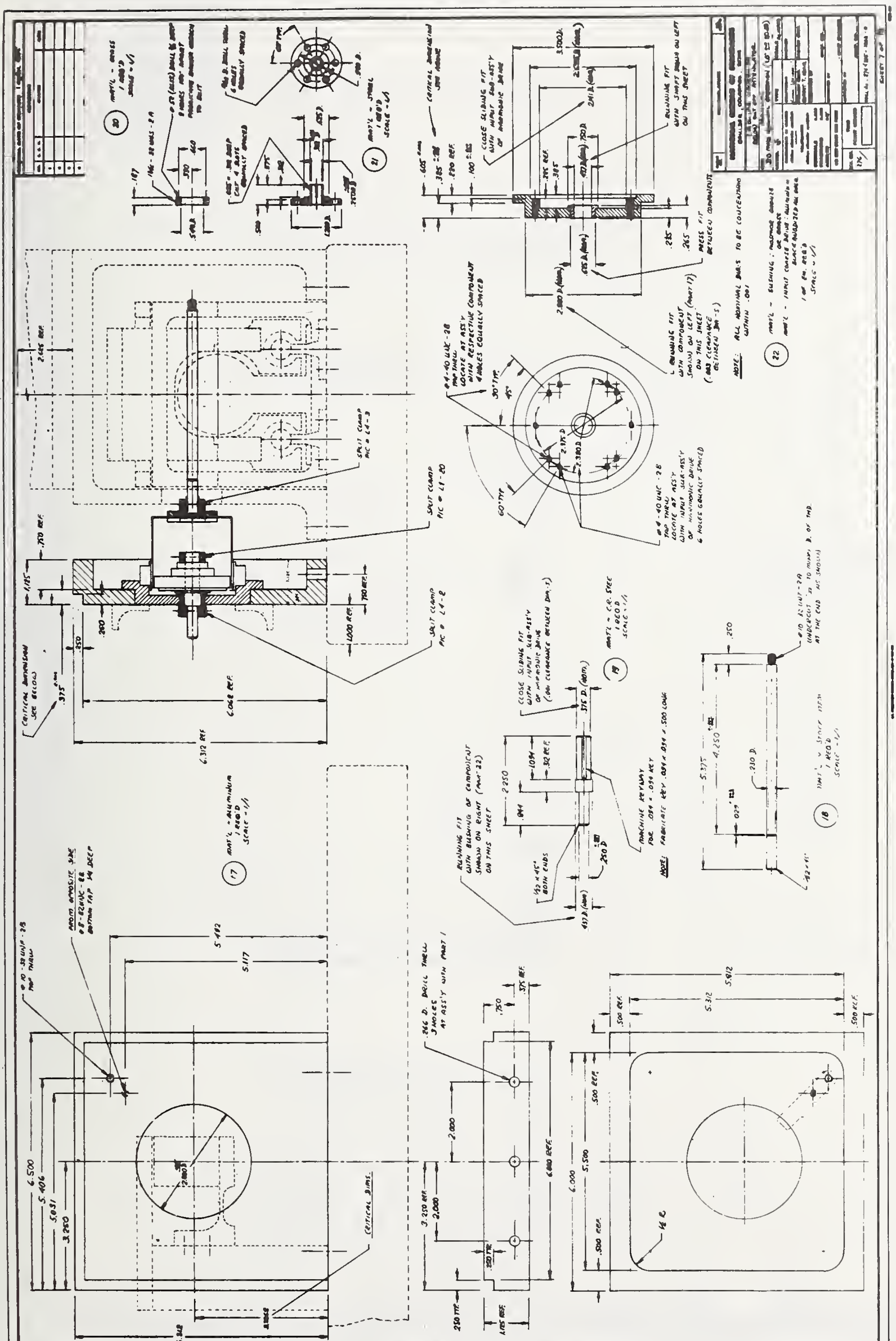

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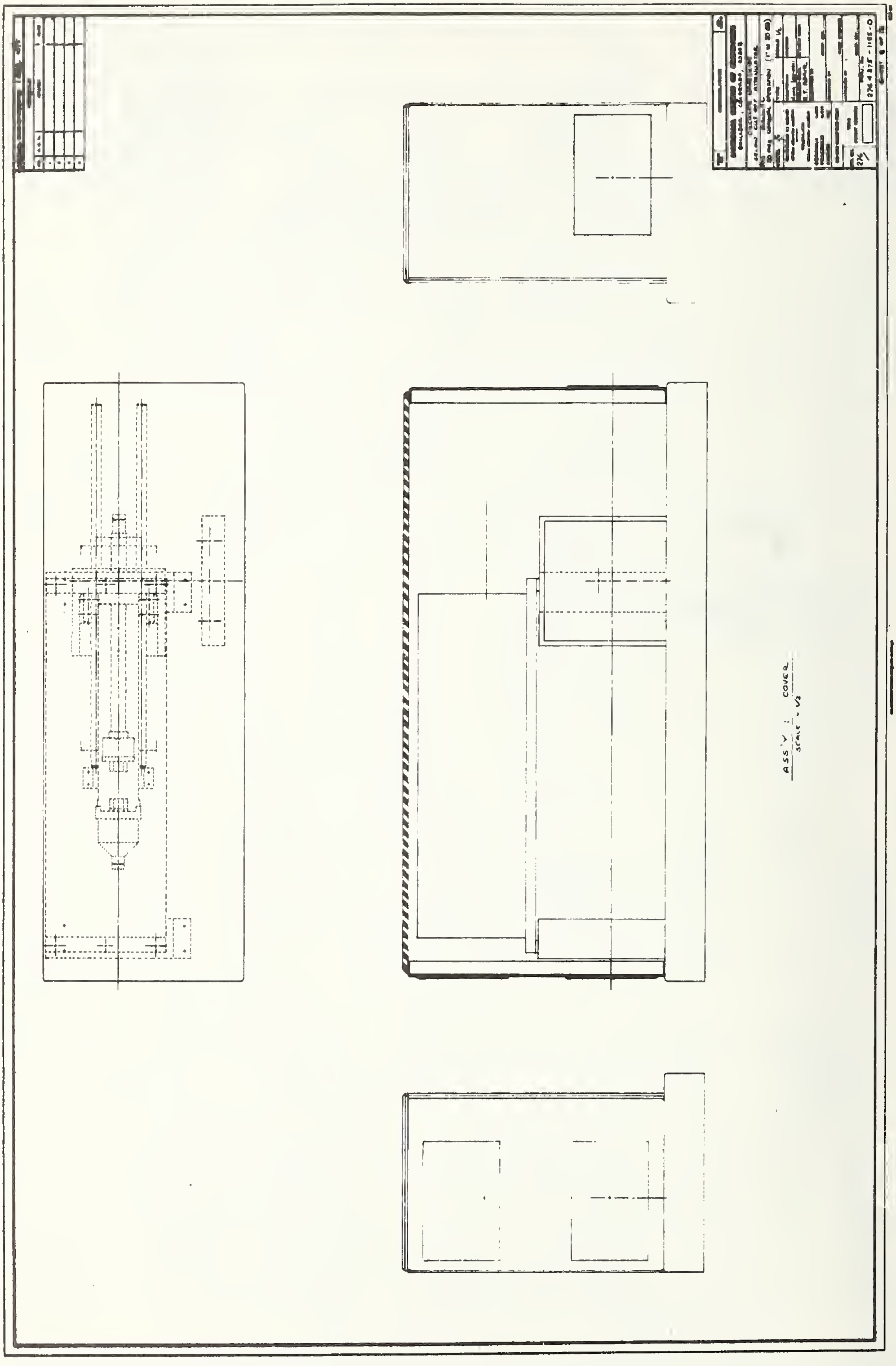

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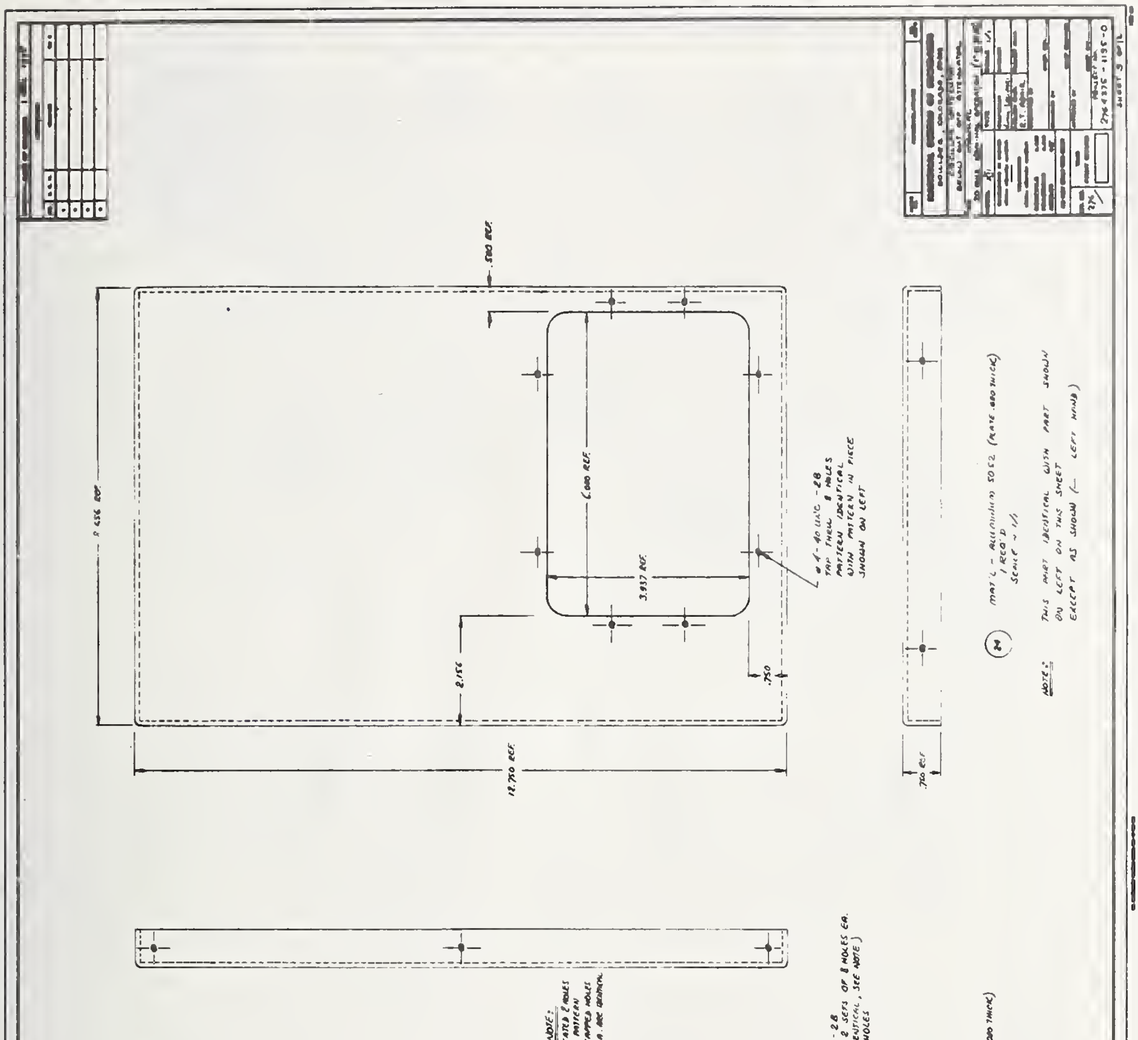
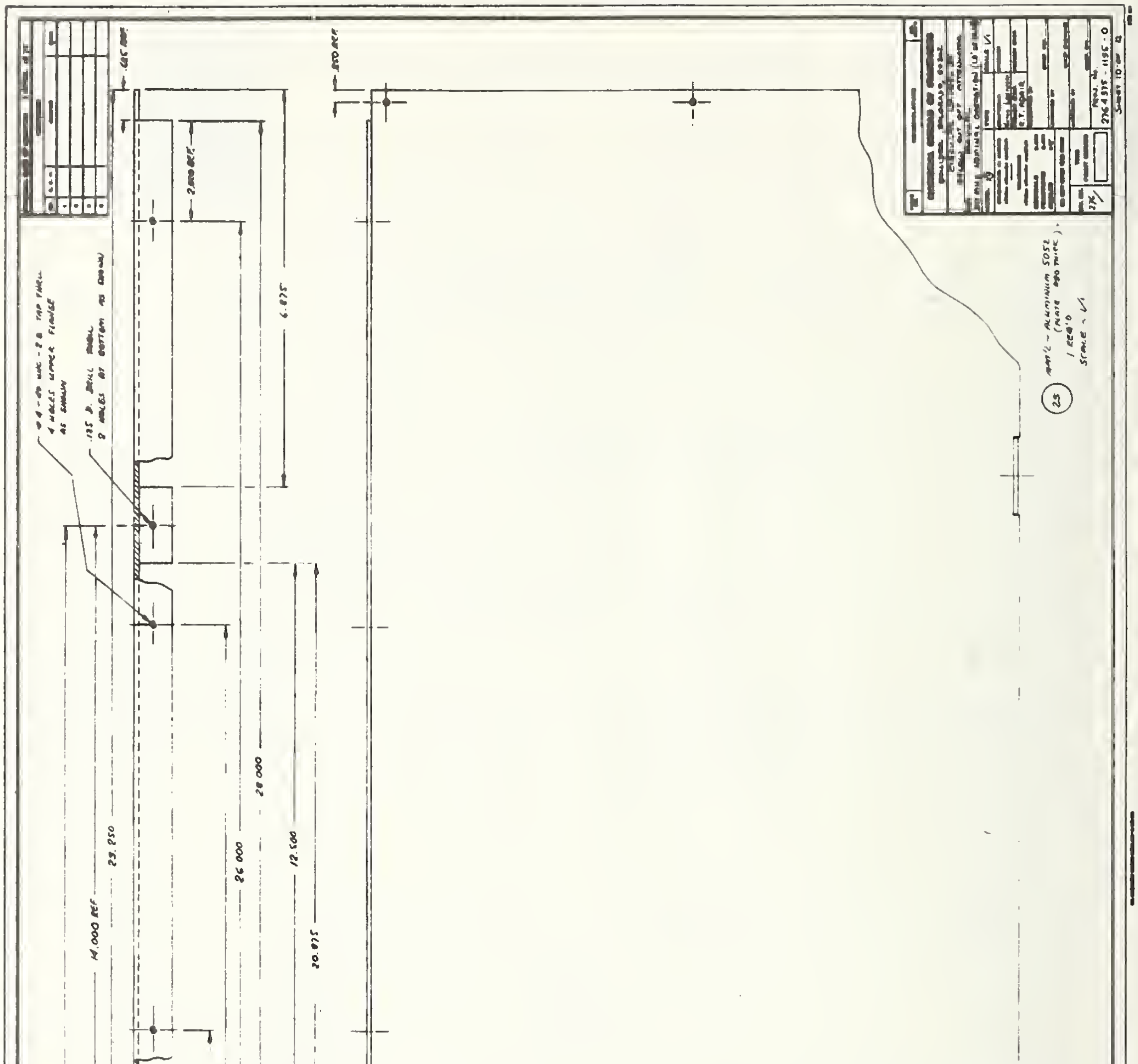


Figure 12(i)



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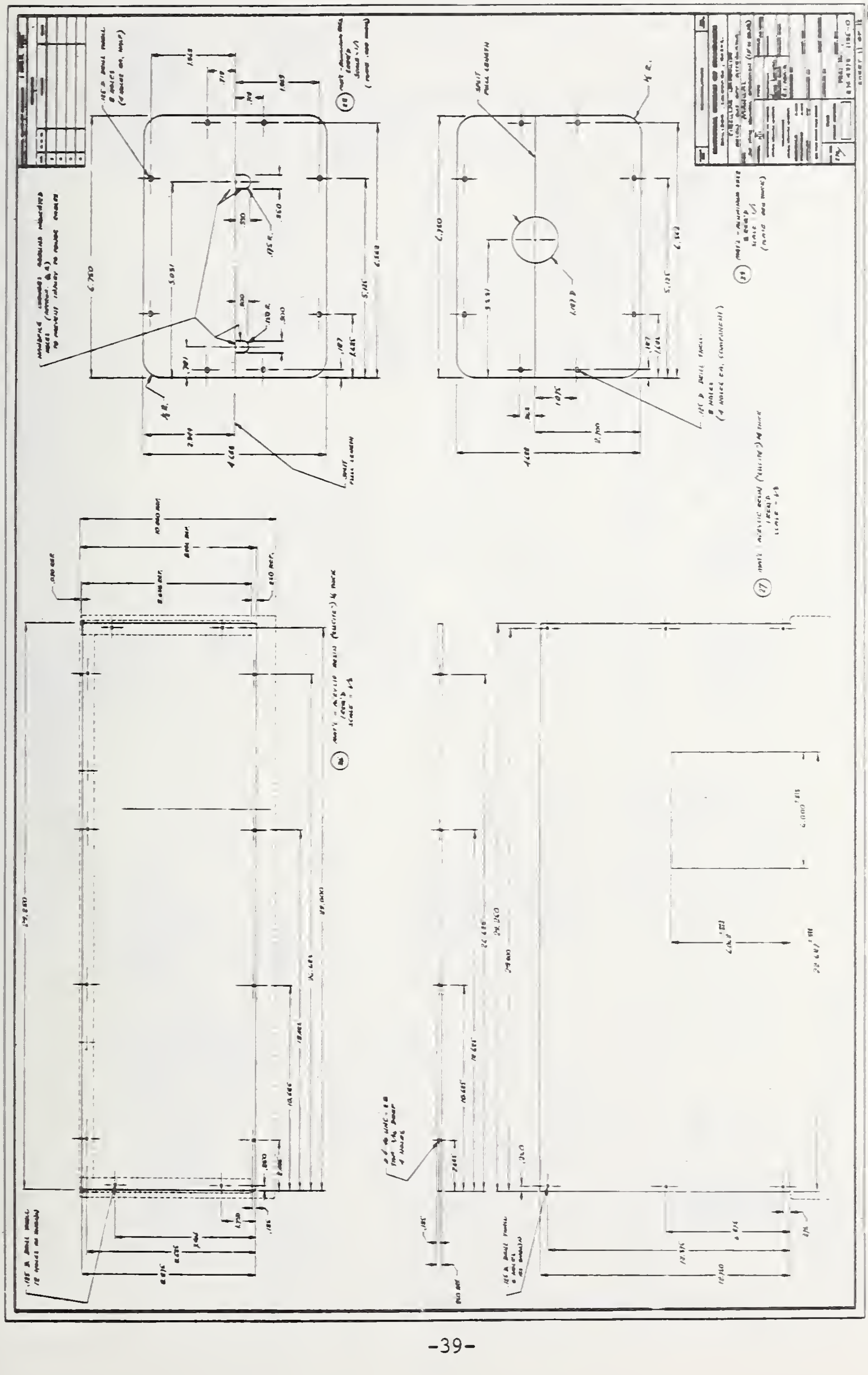

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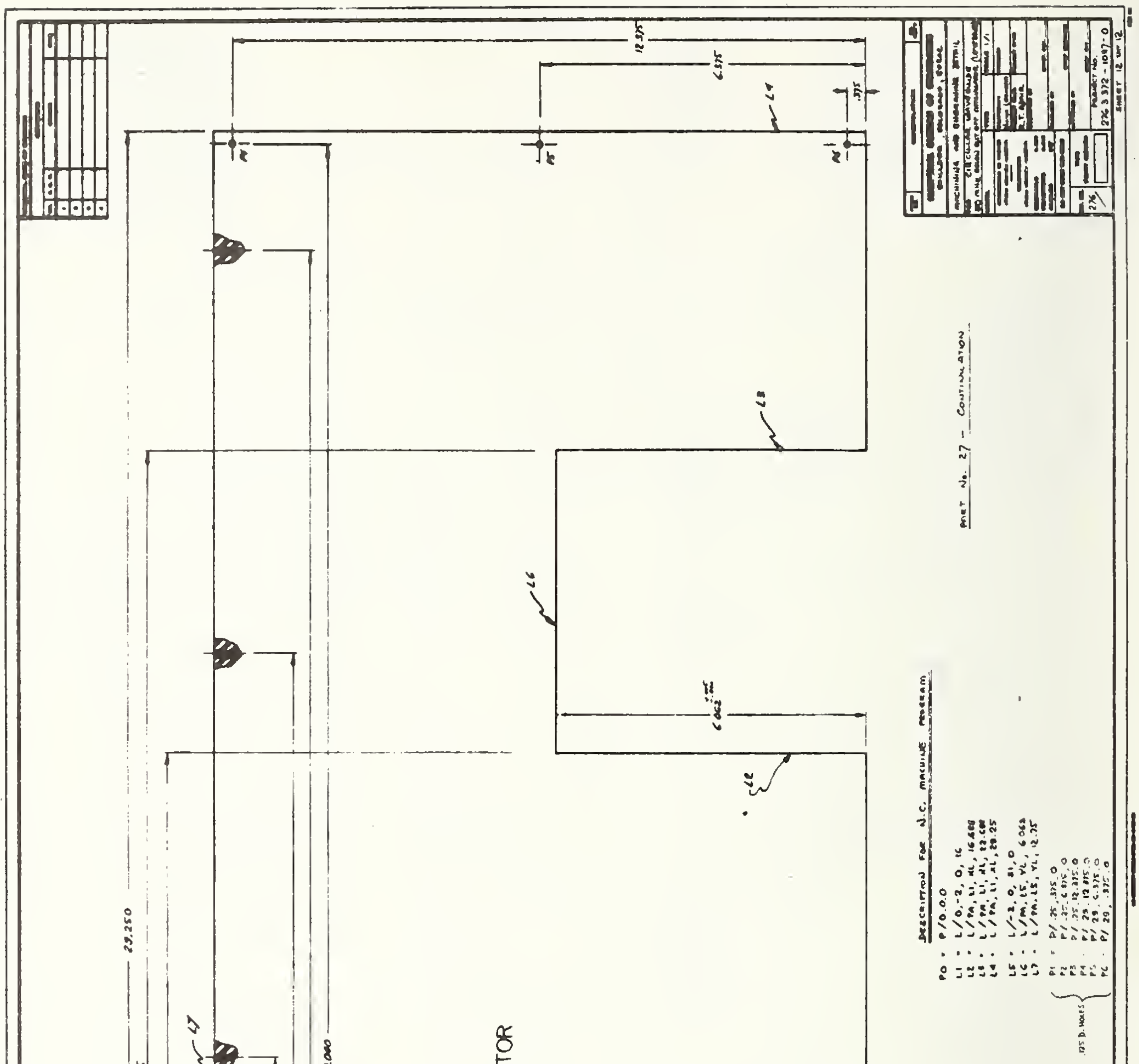

30 MHz WBCO ATTENUATOR
NBS MODEL XII
SERIAL NO. 101
1975
DESCRIPTION FOR N.C. MACHINE PROGRAM
SHEET No. 27 - CONTINUATION

Figure 12(1)

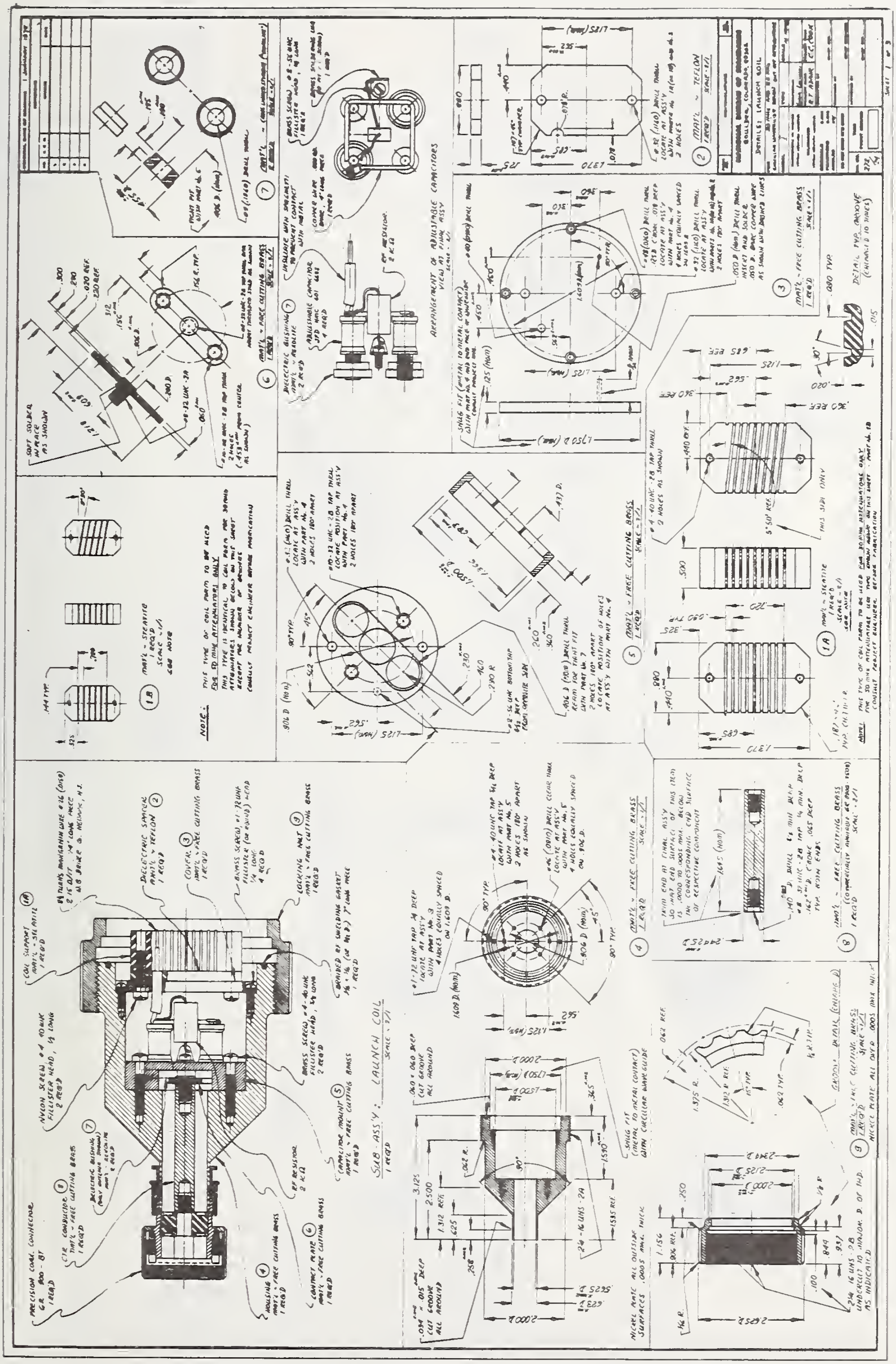


Figure 12(m)

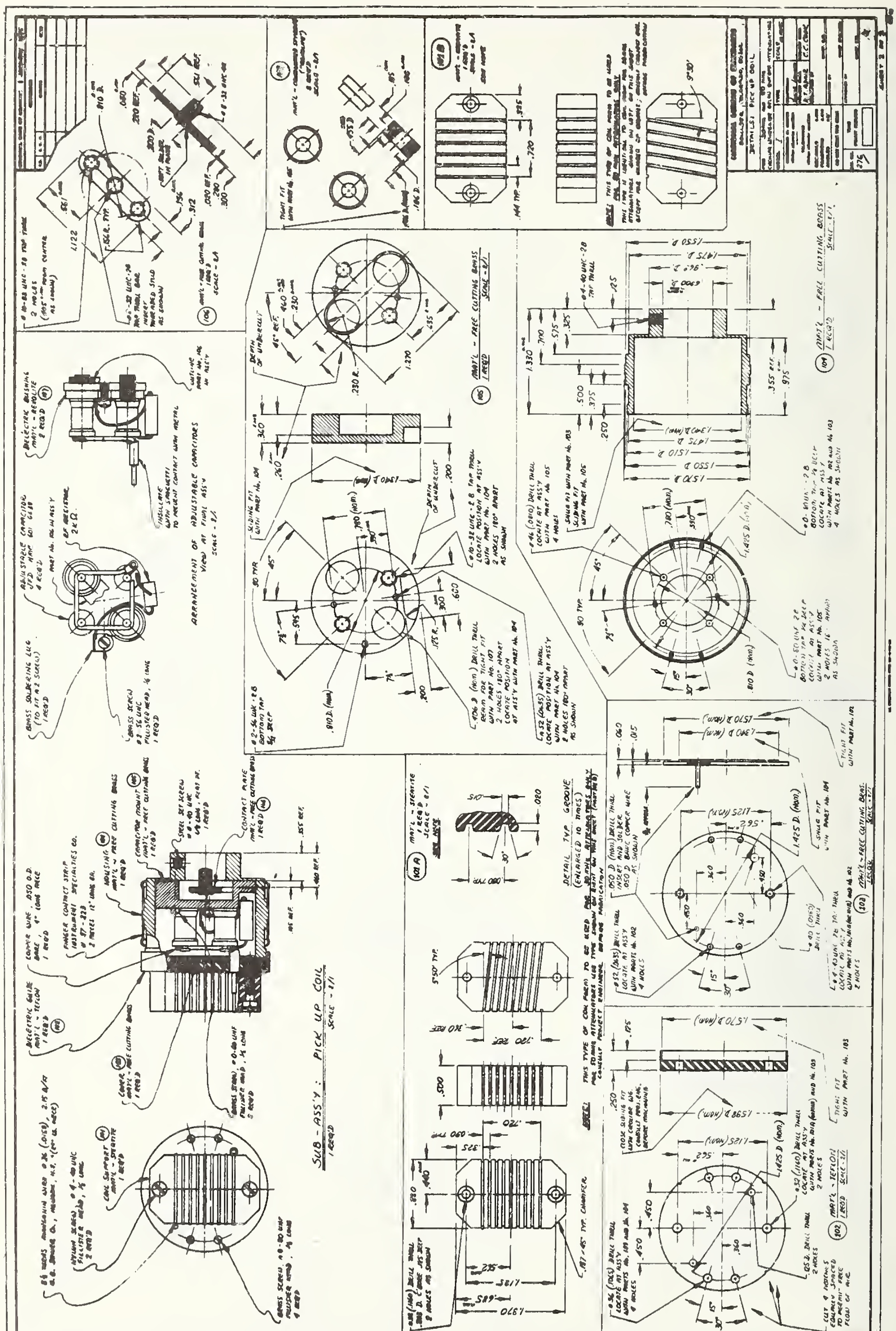
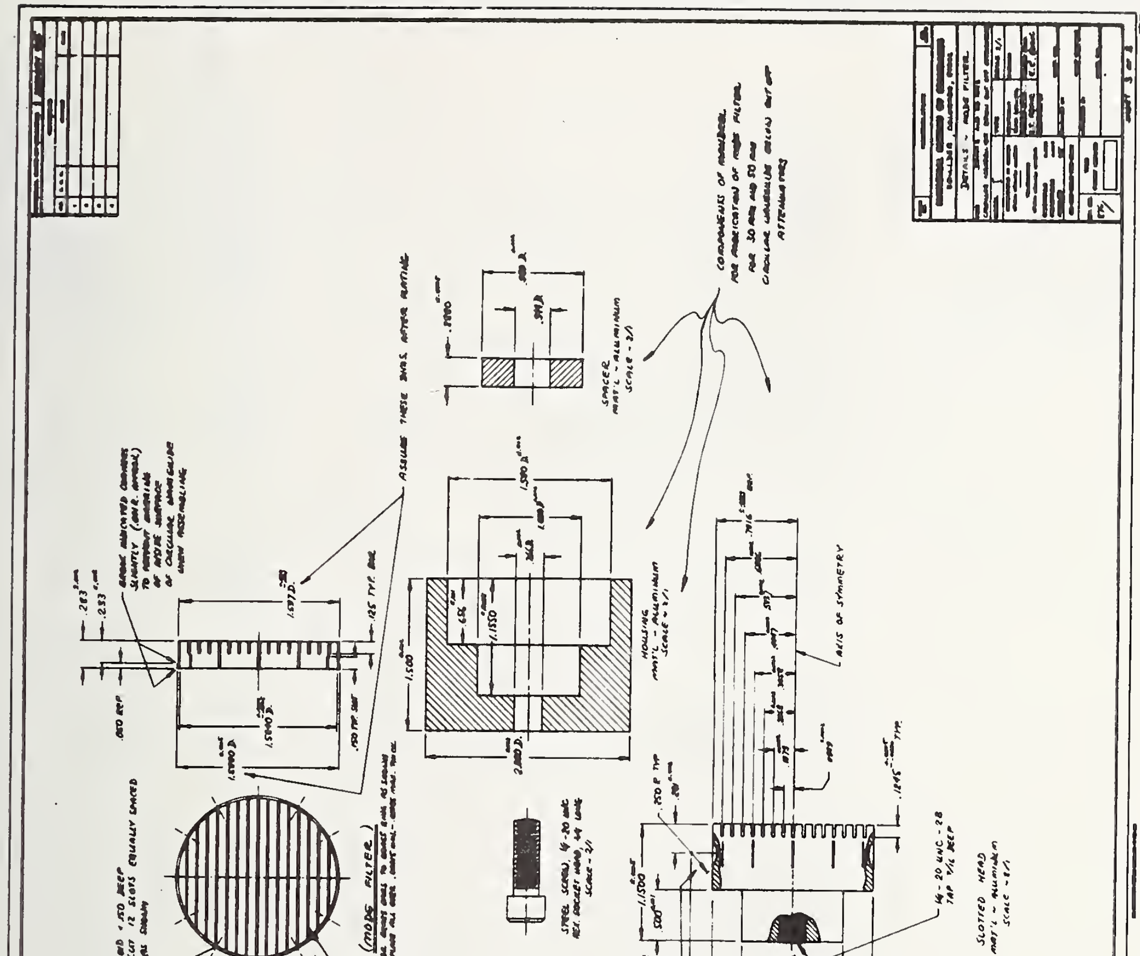


Figure 12(n)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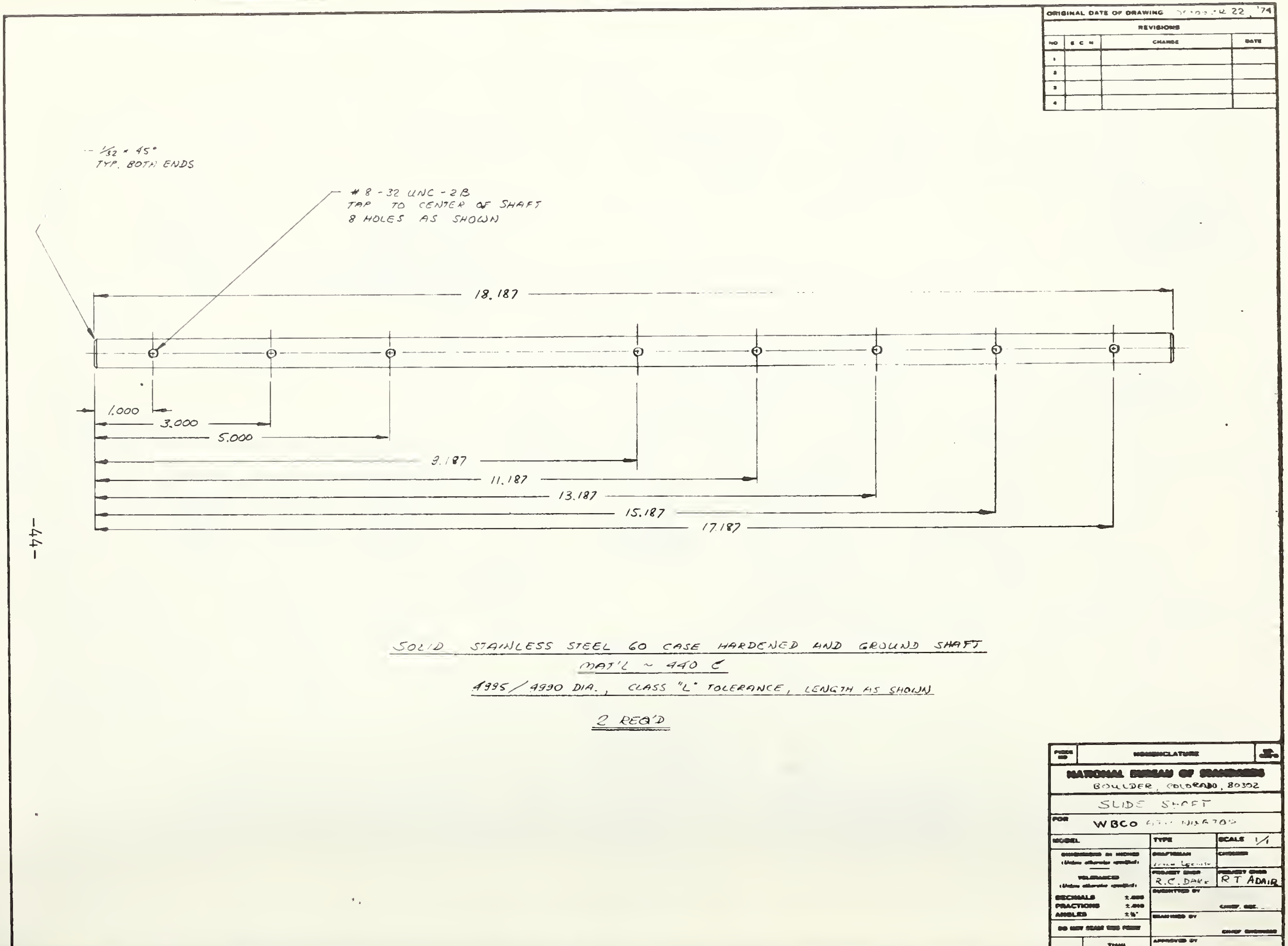
HOUSING
SPACER
SLOTTED HEAD
AXIS OF SYMMETRY
STEP 1
STEP 2

Figure 12(o)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MAT'L ~ 440 C
.4995/.4990 DIA., CLASS "L" TOLERANCE, LENGTH AS SHOWN
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BOULDER, COLORADO, 80302
SLIDE SHAFT
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WBCO
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PROJECT CHIEF
R.C. DAKE
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CHIEF, SEC.
EXAMINED BY
CHIEF ENGINEER
APPROVED BY
CHIEF, DIV.
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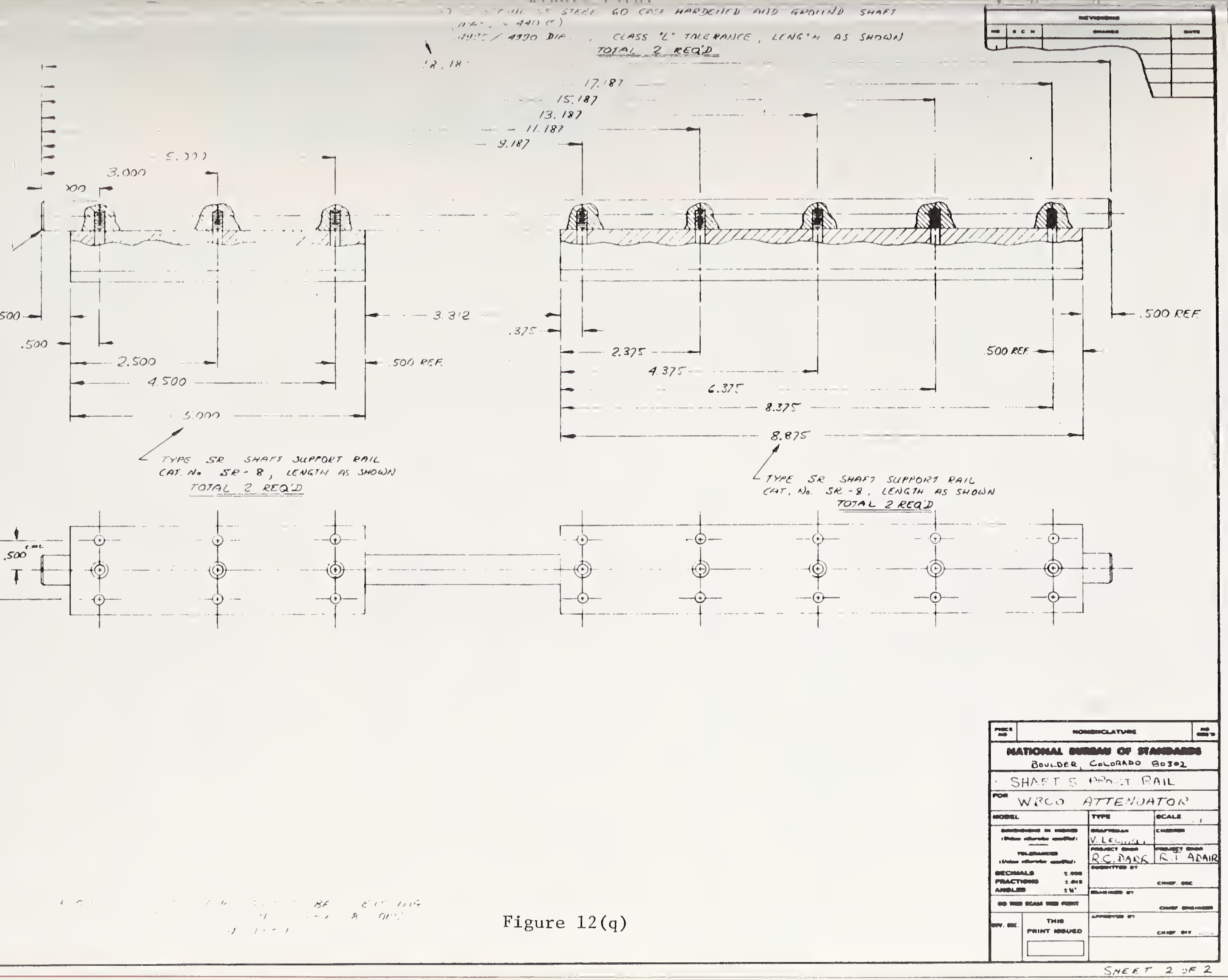
Figure 12(p)


STEEL 60 CASE HARDENED AND GROUND SHAFT
CLASS "L" TOLERANCE, LENGTH AS SHOWN
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17.187
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4.375
6.375
8.375
8.875
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.500 REF.
TYPE SR SHAFT SUPPORT RAIL
CAT. No. SR-8, LENGTH AS SHOWN
TOTAL 2 REQ'D
TYPE SR SHAFT SUPPORT RAIL
CAT. No. SR-8, LENGTH AS SHOWN
TOTAL 2 REQ'D
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NATIONAL BUREAU OF STANDARDS
BOULDER, COLORADO 80302
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ADAIR
DECIMALS
FRACTIONS
ANGLES
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SHEET 2 OF 2

Figure 12(q)

NBS-114A (REV. 7-73)

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7. AUTHOR(S) Robert T. Adair			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 2763375 11. Contract/Grant No. Order No. A1-4-41244-91-D1
12. Sponsoring Organization Name and Complete Address (Street, City, State, ZIP) U.S. Army Metrology and Calibration Center Redstone Arsenal Huntsville, Alabama 35809			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A coaxial precision waveguide-below-cutoff attenuator is described which utilizes an absolute (unambiguous) electronic digital readout of displacement in decibels instead of the usual gear-driven mechanical counter/dial readout in decibels. The attenuator has a fixed- position rf input connector and a movable rf output connector. The attenuation rate for 30 MHz operation is given along with a discussion of sources of errors. In addition, information is included to aid the user in making adjustments on the attenuator should it be damaged or disassembled for any reason.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Absolute (unambiguous) readout; piston; precision attenuator; sensor; waveguide-below-cutoff.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
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