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A RACK-MOUNTED PRECISION WAVEGUIDE-BELOW-CUTOFF ATTENUATOR WITH AN ABSOLUTE ELECTRONIC READOUT

Clarence C. Cook

National Bureau of Standards

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A coaxial precision waveguide-below-cutoff attenuator is described which utilizes an absolute (unambiguous) electronic digital readout of displacement in inches in addition to the usual gear-driven mechanical counter/dial readout in decibels. The attenuator is rack-mountable and has the input and output rf connectors in a fixed position. The attenuation rate for 55, 50, and 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.

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A RACK-MOUNTED PRECISION WAVEGUIDE-BELOW-CUTOFF ATTENUATOR WITH AN ABSOLUTE ELECTRONIC READOUT

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Certain commercical equipment and materials are identified on the drawings in order to adequately specify the fabrication 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.

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ABSTRACT

A coaxial precision waveguide-below-cutoff attenuator is described which utilizes an absolute (unambiguous) electronic digital readout of displacement in inches in addition to the usual gear-driven mechanical counter/dial readout in decibels. The attenuator is rack-mountable and has the input and output rf connectors in a fixed position. The attenuation rate for 55, 50, and 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. INTRODUCTION

This paper briefly describes the construction and operation of a waveguide-below-cutoff attenuator designed to operate at a primary frequency of 50 MHz with possible future operation at 55 or 30 MHz. This attenuator (fig. 1) has some unique features: 1) it is rack-mountable; 2) it has fixed input and output rf connectors at the back of the attenuator assembly; and 3) it has an absolute (unambiguous) electronic digital readout of the linear displacement in inches, in addition to a more common mechanical readout in decibels.

2. THEORY OF OPERATION

The waveguide-below-cutoff attenuator, [1, 2]* 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

* Numbers in brackets refer to the references given at the end of this paper.

References [1,2] 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.

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 1.8418378 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

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

$$A = \frac{15.99232}{a}\left[1 - \frac{\delta}{2a} - \frac{1}{2}\left(\frac{f}{f_c}\right)^2\right], \qquad (2)$$

where

A is in dB/inch, and

a is now in inches

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, which has the second lowest rate of attenuation. Fortunately, a simple mode filter consisting of several grounded metal strips perpendicular to the TE_{11} electric field will attenuate the TM_{01} mode by at least 60 dB while decreasing the desired mode by less than 0.5 dB.

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. 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-inches thickness was applied to the inner surface to minimize surface tarnishing.

The exciting unit [3] consists of a five-turn coil, an 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 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. In addition this increases the bandwidth of the attenuator, which is of particular interest to the users of this attenuator.

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, 0.025 inch wide, equally spaced perpendicular to the diameter of the ring. 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 0.036 inches from the end of the exciting coil.

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 is mounted to one end of a precision lead screw. A captive nut moves the screw along the guide.* The screw is keyed to prevent rotation of the receiving unit. Rapid movement of the receiving unit (piston) is provided by driving the nut with an electric motor. Also connected to the nut through suitable gears are a mechanical counter and an engraved circular dial. These give a mechanical readout of the receiving unit location. In addition, a knob on the dial provides the control for fine positioning of the attenuator manually after the approximate position is reached with the motor drive. An optical sensor and associated electronics provide an accurate digital display of the piston

* 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."

position independently of the mechanical readout. An auxiliary BCD output is available from the sensor, also. Semi-rigid 3-mm coaxial cable is run through a hole along the axis of the lead screw to bring the rf signal out of the attenuator. This is connected to one end of a solenoidal coil of similar cable. The other end of the coiled cable connects to the type N output connector on the back panel. The coil of cable is used to minimize effects of cable motion which is unavoidable when the receiving unit moves.

A cross arm is fastened securely to the back end of the lead screw. To keep this arm from twisting during operation of the attenuator, the outer ends are guided by low-friction linear roller bearings mounted on precision circular guide rods. The push rod of the displacement sensor is fastened to one side of the cross arm and the movable end of the coiled cable is fastened to the other side. These details can be seen by referring to figures 2 and 3.

The complete attenuator consists of two rack-mounted packages. The attenuator assembly contains the basic attenuator, drive motor, mechanical readout and associated gearing, all rf cables and connections, 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 required by the displacement sensor and readout.

4. ATTENUATOR OPERATION

4.1 Preliminary Setup and Check

To place the attenuator into operation, connect the two 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 each assembly to an ac power source and turn on the readout unit. A six-digit display should be obtained with the least significant (far-right) digit always even. The display is now indicating the position of the piston of the attenuator. This display is in inches and has a resolution of 20 microinches. Rotating the attenuator manual control knob should cause a change in the display.

4.2 Displacement Readouts and Attenuation Value

As mentioned previously, two independent readouts of the attenuator piston displacement are provided.

The mechanical readout consists of a 5-digit mechanical counter and a circular dial. The counter reads in dB in 0.1 dB increments (a decimal point is assumed to precede the far-right digit) while the dial indicates 0 to 0.1 dB in 0.001 dB increments for each one-half revolution of the dial. The attenuation value in dB is obtained by adding the counter reading and the <u>last two digits</u> of the dial reading with the exception noted below. Since the right "tenths" digit of the counter does not change at exactly .000 or .100 dial settings, and one revolution of the dial corresponds to two counts on the counter, a certain rule must be followed here. If the left digit of the dial is "0" and the right digit of the counter is odd, subtract one count from this counter reading. Likewise, if the left digit of the dial is "1" and the right digit of the counter is even, subtract one count from this counter reading. For example, if the counter reading is 31.2 and the dial reading is .065, the attenuation value is 31.265 dB, whereas readings of 31.3 and .095, respectively, correspond to a value of 31.295 and not 31.395 (in this case, the counter has changed from 31.2 to 31.3 prior to the dial reaching .100). Likewise, counter and dial readings of 11.1 and .132 correspond to an attenuation value of 11.132, whereas readings of 11.2 and .198 correspond to a value of 11.198.

The electronic readout provides a direct digital readout of the piston displacement in inches with the least increment being 20 microinches. Multiplication of this reading by 20 converts to decibels since the nominal attenuation rate of this attenuator is 20 dB/inch. Thus, the resolution of this display is 0.0004 dB. Datum switches on the readout unit permits 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 the attenuation. Of course, this may be positive or negative. If the electronic readout is used, the difference in the two readings is in inches and must be converted to decibels. Here, if the datum switches are used to zero the display in the initial position, the final display will give the net change directly in inches.

5. OPERATIONAL CONSIDERATIONS

5.1 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 guide 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 mechanical readout has been set to zero at a nominal insertion loss of 30 dB at 50 MHz. The datum switches were set so that the electronic readout was approximately zero at this setting, also; however, these switches may be readjusted as desired.

5.2 Operation

The attenuator is operated by moving the motor switch to the left to decrease attenuation or to the right to increase it. Limit switches turn the motor off if it runs below 0 or above about 53 dB, respectively. When the approximate value of attenuation is reached, the motor is turned off and the final adjustment made by using the manual control.

CAUTION: Never reverse the motor direction without coming to a complete stop first. When using the mechanical readout, always approach a given attenuator setting in the same direction to minimize effects of backlash in the nut and gears.

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.

6. ERROR ANALYSIS

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

$$A = \frac{15.99232}{a}\left[1 - \frac{1}{2a\sqrt{\pi\mu f\sigma}} - \frac{1}{2}\left(\frac{2\pi af}{p_{11}c}\right)^{2}\right] \qquad (3)$$

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 0.0093 dB/inch and that for finite cutoff frequency is about 0.0016 dB/inch. The only significant uncertainty in these corrections is that resulting from the uncertainty in the conductivity determination.

6.1 Waveguide Diameter

The inside diameter of the attenuator guide was measured by an air gauge at an ambient temperature of 68°F. Measurements were sampled every half inch along the center three inches of the guide. Three readings were taken at each point, equally spaced around the circumference. The average diameter was found to be 1.598347 inches with longitudinal variations in the average diameter of ± 13 microinches. The maximum variation around the circumference at any point was ± 9 microinches. The measurements are believed accurate to ± 20 microinches. Therefore, the diameter of the guide can be given as 1.598347 ± 33×10^{6} inches. The uncertainty in diameter causes an uncertainty in the attenuation rate of ± 0.0004 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:

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

6.2 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 55 MHz is estimated to be 5% lower than the dc value. This gives a value of 1.30×10^7 mho/meter. The uncertainty in this value may be as much as 10%. This gives an uncertainty in the attenuation rate of ± 0.0005 dB/inch.

6.3 Attenuation Rate

From the above, the total uncertainty in the attenuation rate is less than ± 0.001 dB/inch at 55 MHz. This is essentially the same at 50 and 30 MHz as well. The attenuation rate based on a diameter of 1.598347 inches and rf conductivity of 1.30×10^7 mho/meter is given in table I.

Table I

Attenuation Rate of Piston Attenuator at Ambient Temperature of 68 degrees F

Frequency of Operation MHz	Attenuation Rate dB/Inch
55	20.00018
50	20.00000
30	19.99803

6.4 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 variation in the lead of the lead screw over a one-inch span was 0.00012 inches. This causes an uncertainty in attenuation of 0.0024 dB/inch.

The uncertainty in the electronic readout is probably less than 50 microinches over its entire range. This gives an uncertainty of 0.001 dB over the range of 50 dB.

6.5 Miscellaneous Sources of Error

By use of a mode filter and approximately 30 dB minimum insertion loss, the effect of other modes 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 lead screw. However, space limitations necessitated mounting the sensor parallel to the attenuator guide with the axis of the push rod being offset about five and one-fourth inches from the axis of the lead screw. Any twisting or cocking of the cross arm 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 nut and lead screw 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 50 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.

6.6 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 11.6 parts per million (ppm)/°F. Thus, for each degree F increase in ambient temperature from 68°F, the attenuation rate given in table I must be reduced by 11.6 ppm or 0.000232 dB/inch. Thus, for an ambient temperature of 72°F, the attenuation rate would be decreased by a total of 0.000928 dB/inch. The attenuation rate at 72°F is given in table II.

Table II

Attenuation Rate of Piston Attenuator at Ambient Temperature of 72 degrees F.

Frequency of Operation MHz	Attenuation Rate DB/Inch
55	19.99925
50	19.99907
30	19.99710

The coefficient of thermal expansion of the lead screw is about 8 ppm/°F, which means that the lead of the screw changes by this amount. Thus, an indicated attenuation change on the mechanical readout should be decreased by only the difference between the guide and lead screw expansion coefficients, or 3.6 ppm/°F. The lead screw expansion compensates for much of the guide expansion in this case.

The electronic readout derives its two most significant digits from the geared digitizers so thermal expansion of the diffraction grating would have little effect on the over-all reading. Therefore, when the electronic readout is used to determine attenuation, the rate must be reduced by the full 11.6 ppm/°F for temperature increases.

6.7 Summary of Errors

To summarize, the attenuation rate is as given in table I to an uncertainty of ± 0.001 dB/inch. The uncertainty in measuring displacement is ± 0.001 dB/inch for the electronic readout and ± 0.0024 dB/inch for the mechanical readout. Thus, the total uncertainty in producing a 20 dB attenuation change at an ambient temperature of 68° F is as follows:

Electronic Readout . . . . . ± 0.0019 dB
Mechanical Readout . . . . . ± 0.0033 dB.

7. SUMMARY

An accurate waveguide-below-cutoff (piston) attenuator has been described. The attenuator is adjusted to operate at a frequency of 50 MHz but the guide diameter was calculated to give an attenuation rate of 20 dB/inch at 55 MHz. The actual attenuation rate for the final guide diameter has been given for 55, 50, and 30 MHz. 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 68°F, the attenuation rate for 55 and 50 MHz may be considered to be exactly 20 dB/inch.

It is the author's opinion that this attenuator could be operated at 55 MHz without readjusting the impedance matching networks and get no adverse effects other than having large reflections in the system and mismatch losses of up to about 6 dB.

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 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 [1] and [2].

8. ACKNOWLEDGMENTS

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9. REFERENCES

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2. Robert W. Beatty, Microwave Attenuation Measurements and Standards, NBS Monograph 97, April 1967.

3. Clarence C. Cook and C. McKay Allred, An Excitation System for Piston Attenuators, IEEE Transactions on Instrumentation and Measurement, Vol. IM-20, No. 1, February 1971, 10-16.

10. PARTS LIST

This list includes only the critical parts necessary for the fabrication of this attenuator. These are identified by the corresponding part numbers in Figures 4(a) through 4(s). Non-critical stock items, such as machine screws, are not given here.

1. Attenuator base
2. Sliding cross arm
3. Microswitch base
4. Connector mount
5. Microswitch cover
6. Slide shaft (front)
7. Slide shaft (rear)
8. Shaft support block (6 required)
9. Microswitch mount (2 required)
10. Base, shaft support block (5 required)
11. Base, shaft support block
12. Mode filter
13. Input connector
14. Capacitor mount, exciter
15. Input connector mount
16. Exciter housing

17,18. Insulating mount, series capacitor (exciter)

19. Coil mount, exciter
20. Coil spacer, exciter (2 required)
21. Coil form, exciter
22. Circular waveguide
23. Locking nut, exciter
24. Coil form, receiver
25. Cover
26. Capacitor housing
27. Piston guide
28. Capacitor mount, receiver

29,30. Insulating mount, series capacitor, receiver

31. Lead screw
32. Coaxial cable
33. Retainer nut
34. Wiper (2 required)
35. Drive Nut

36,37. Helix gear pair
38. Anti-backlash nut
39. Drive shaft
40. Drive shaft spacer

41. Drive shaft bushing
42. Dial
43. Knob bushing
44,45. Bevel gear pair

46. Manual control knob
47. Waveguide support
48. Bearing housing
49. Helix gear housing
50. Bearing retainer

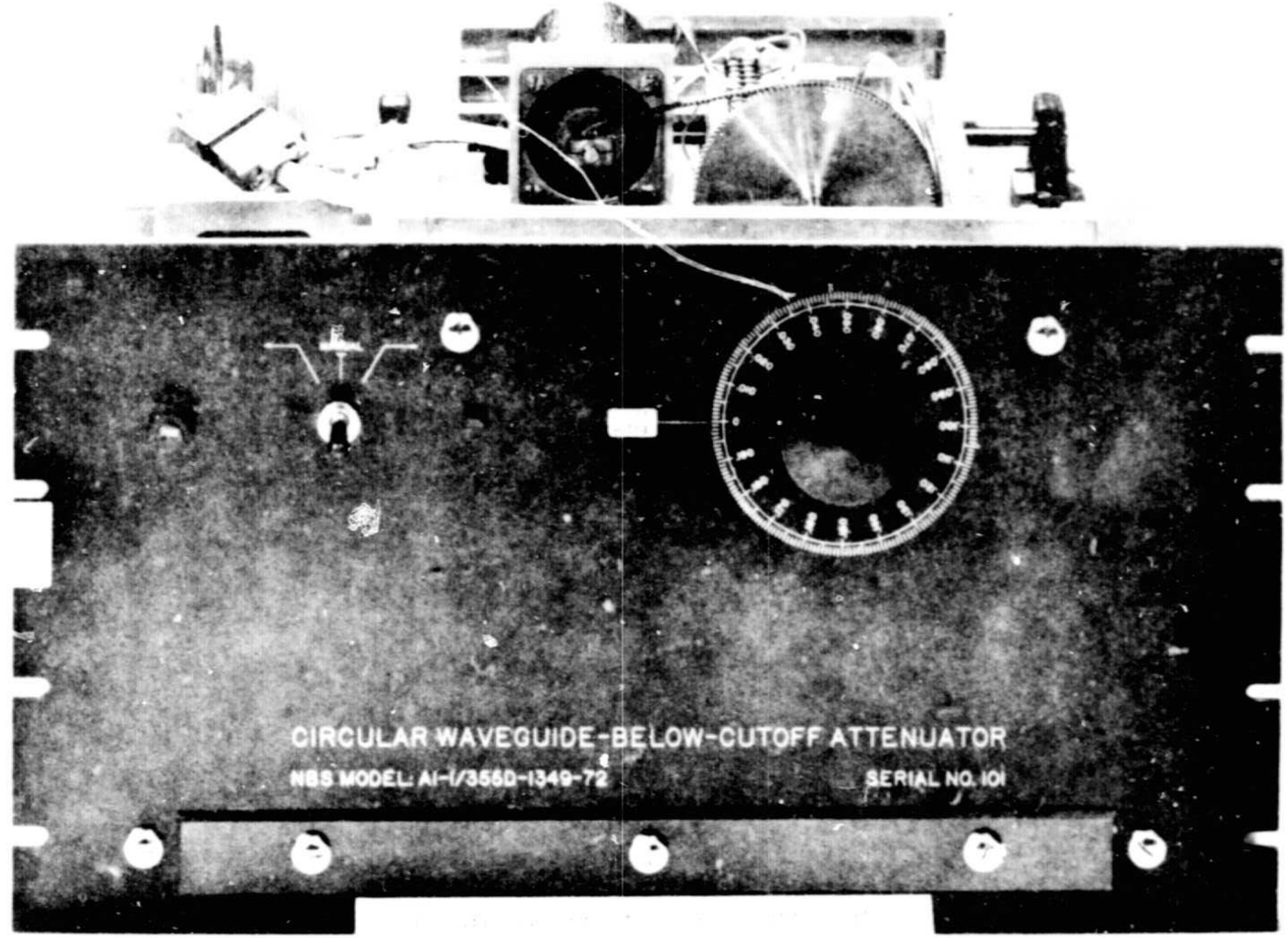
51. Preload ring (2 required)
52. Bearing spacer
53. Counter mount plate
54. Counter drive shaft support
55. Helix gear key

56. Bevel gear key
57. Counter
58. Counter drive shaft
59. Drive motor
60. Front panel mounting spacer (2 required)

61. Coiled semi-rigid coaxial cable
62. Input and output connector mount
63. Coaxial coil support
64. Coaxial coil end mount
65. Mount, shaft support block (5 required)

66. Mount, shaft support block
67. Front panel
68. Attenuator chassis
69. Chassis rear panel
70. Chassis corner mount

71. Chassis top panel
72. Attenuator base cushion (8 required)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NBS MODEL: AI-1/3550-1349-72
SERIAL NO. 101

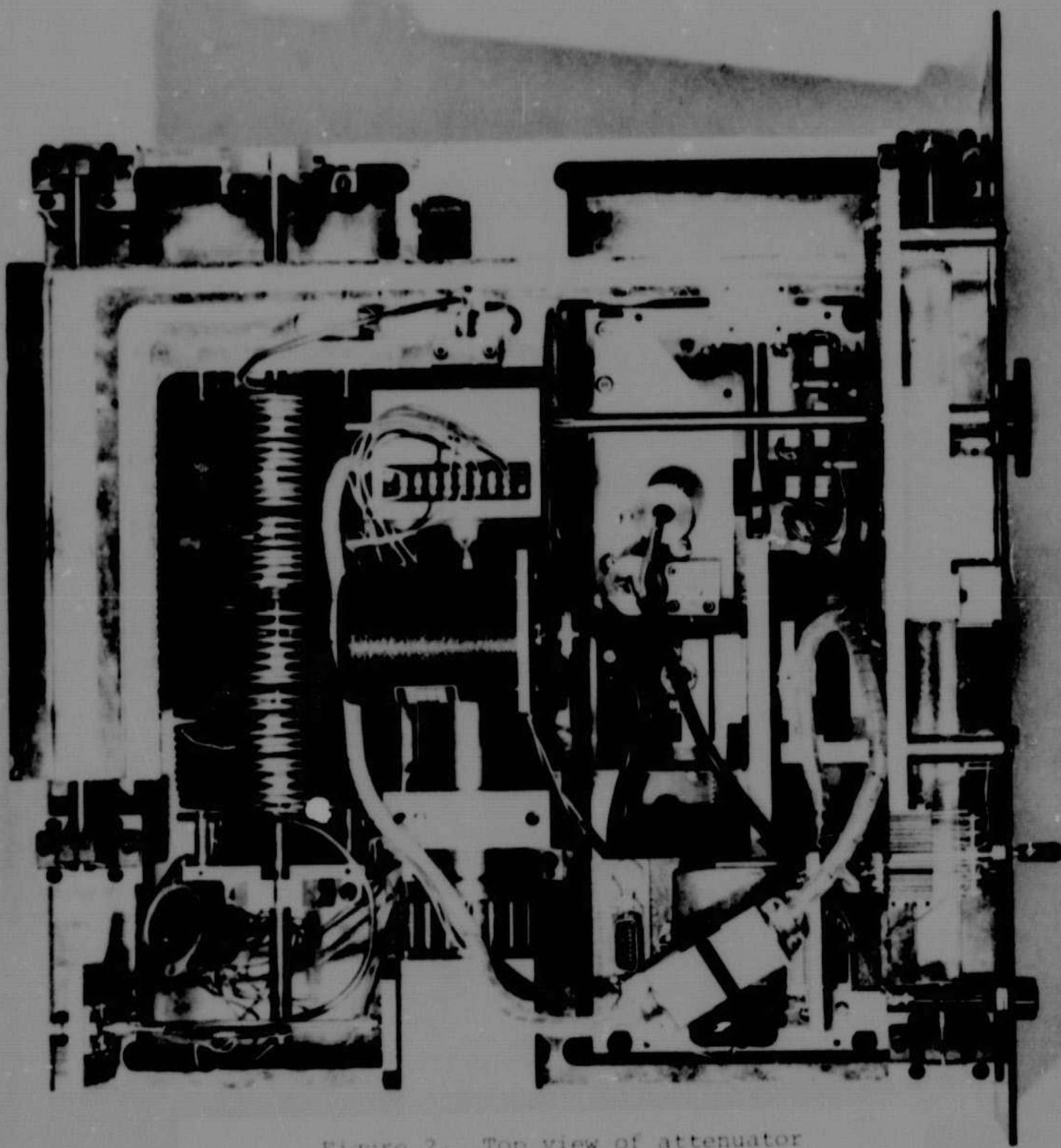


Figure 2. Top view of attenuator

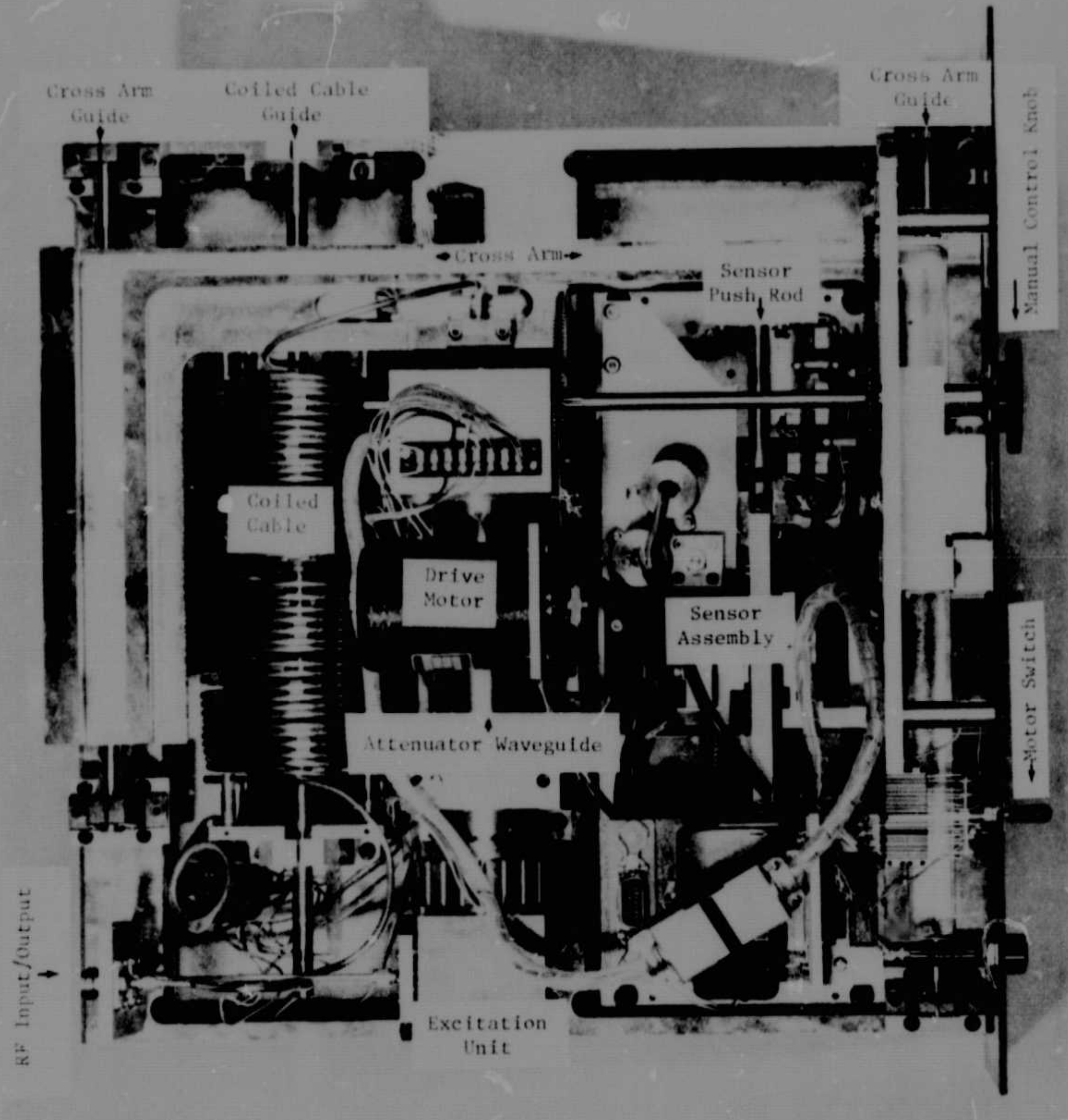


Figure 3. Top view of attenuator with various parts labeled

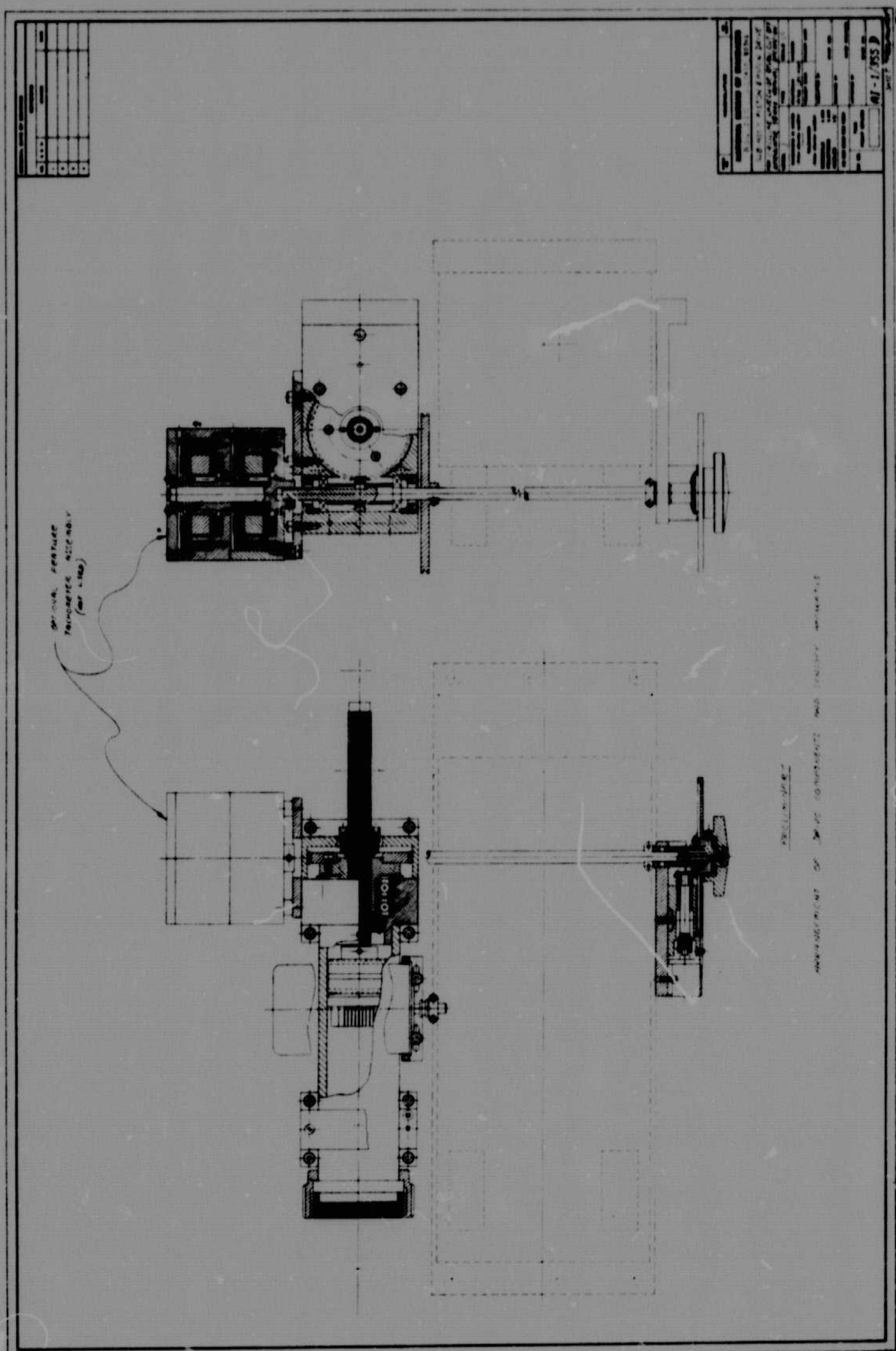
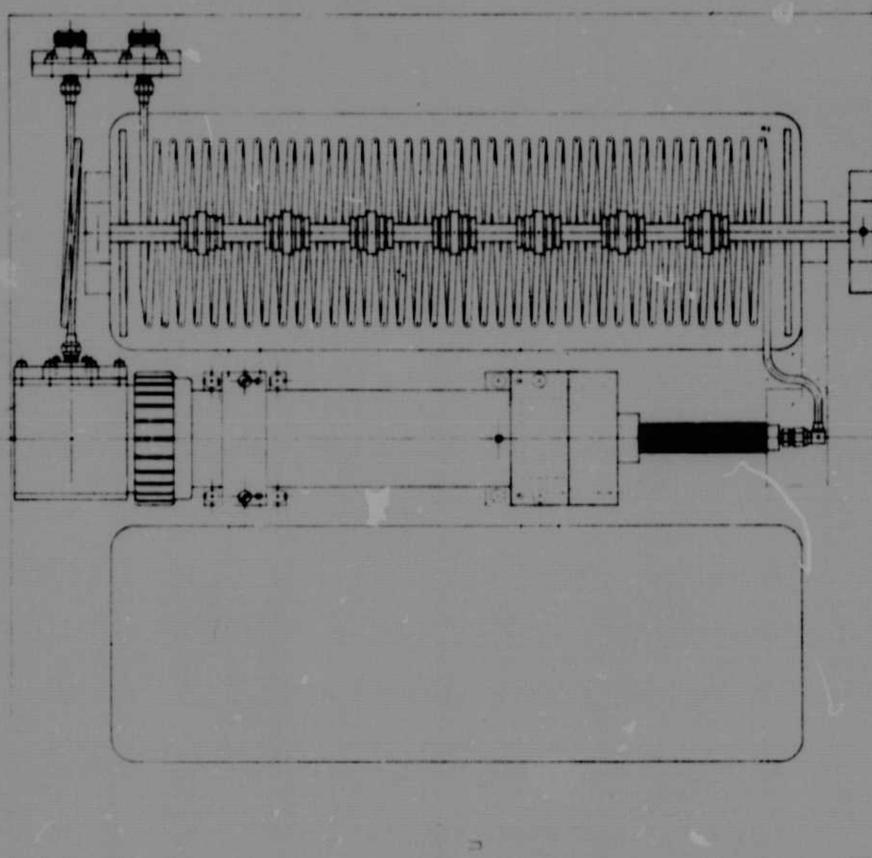


Figure 4(a)



ATTACHMENT TO PRELIMINARY SHOWING PROPOSED COIL SUSPENSION

Figure 4(b)

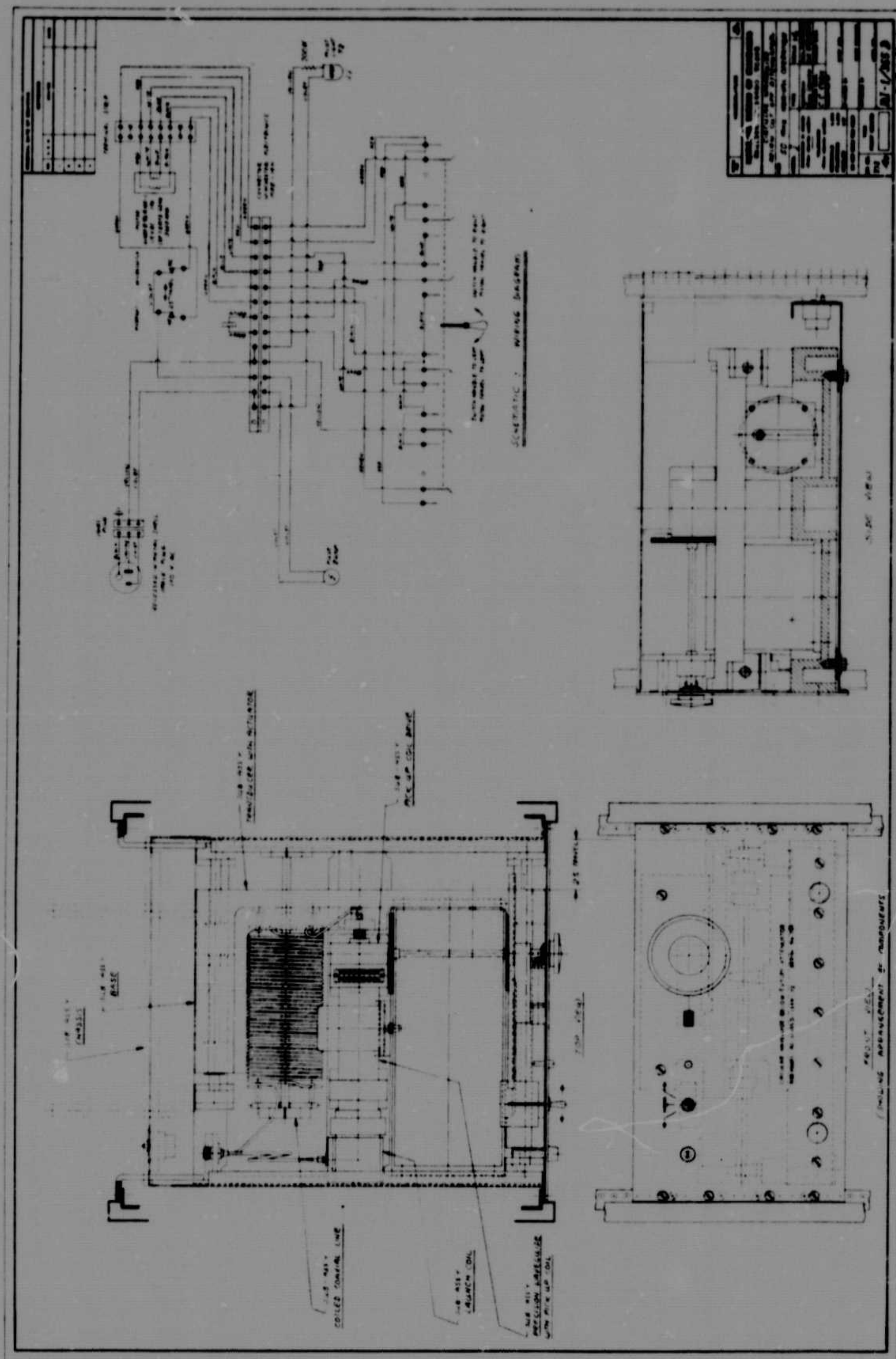


Figure 4(c)

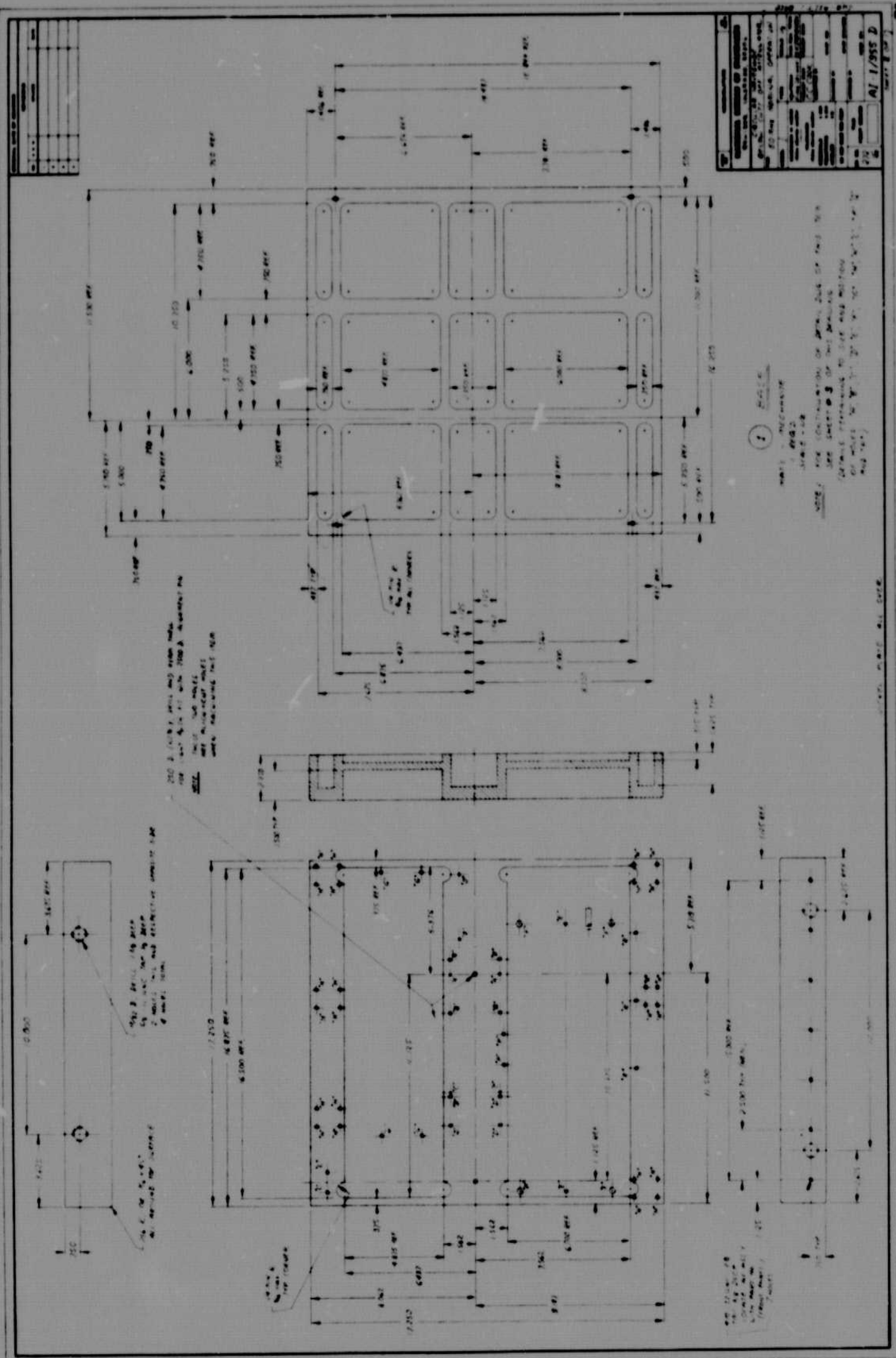


Figure 4(d)

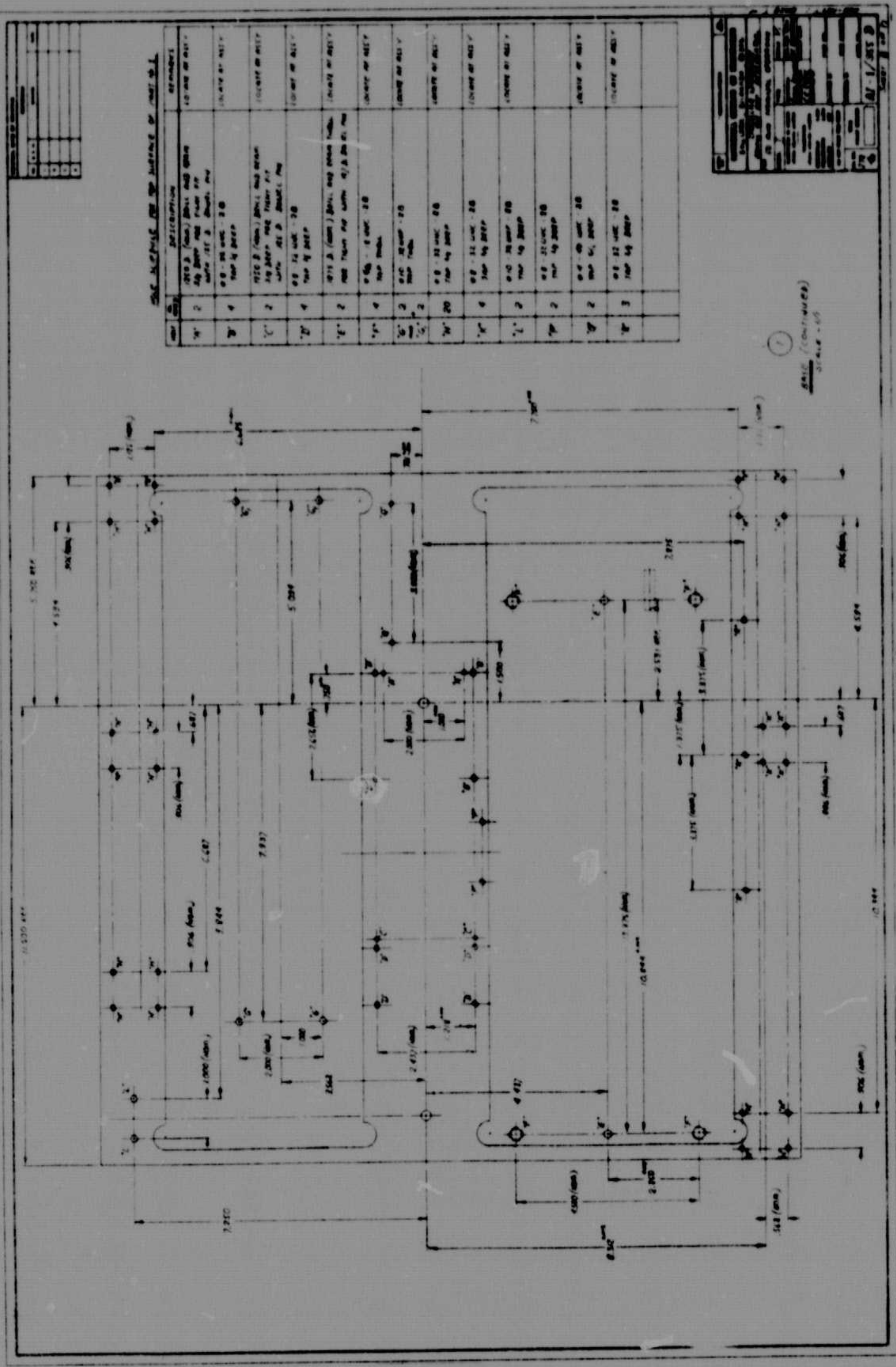


Figure 4(e)

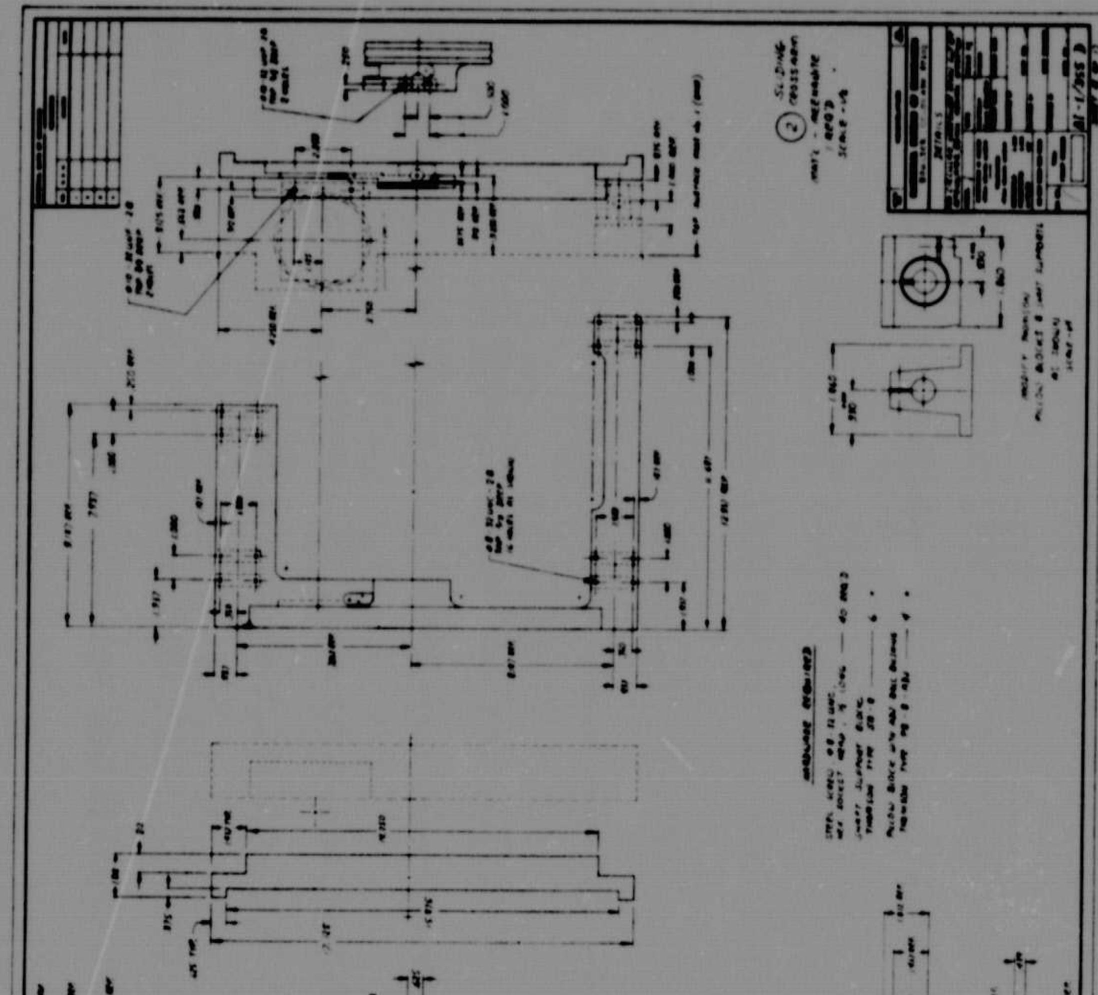


Figure 4(f)

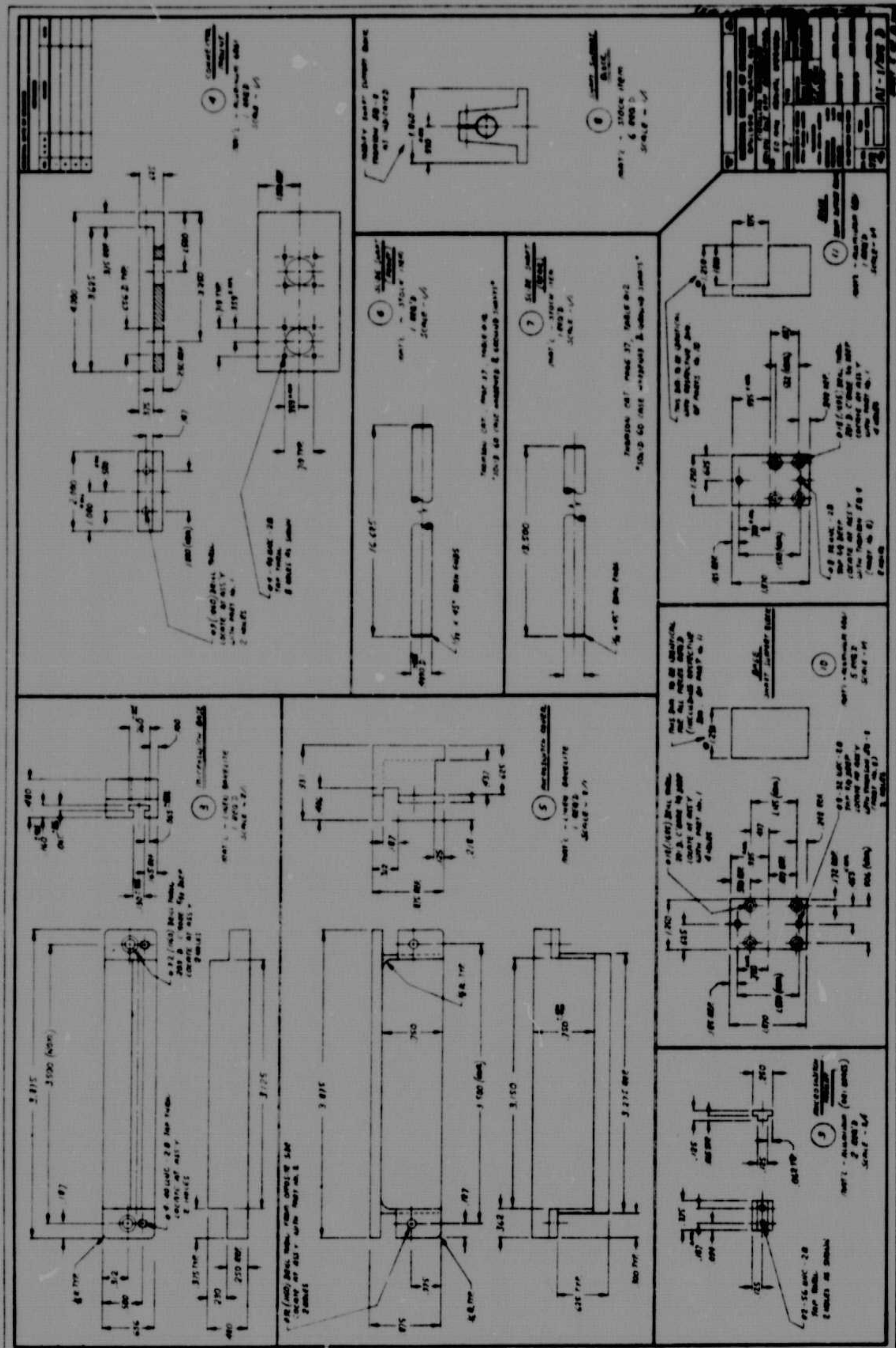


Figure 4(g)

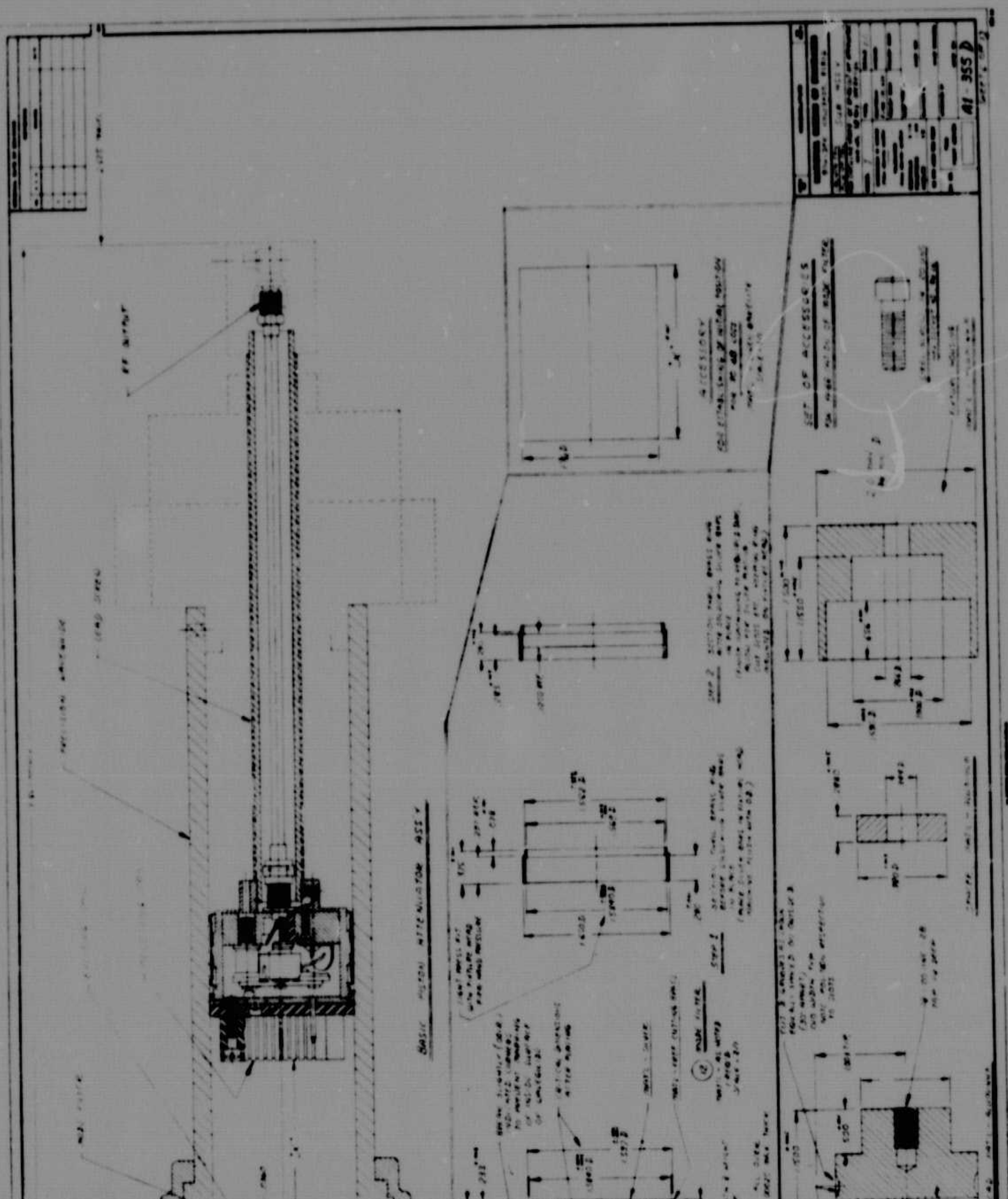


Figure 4(h)

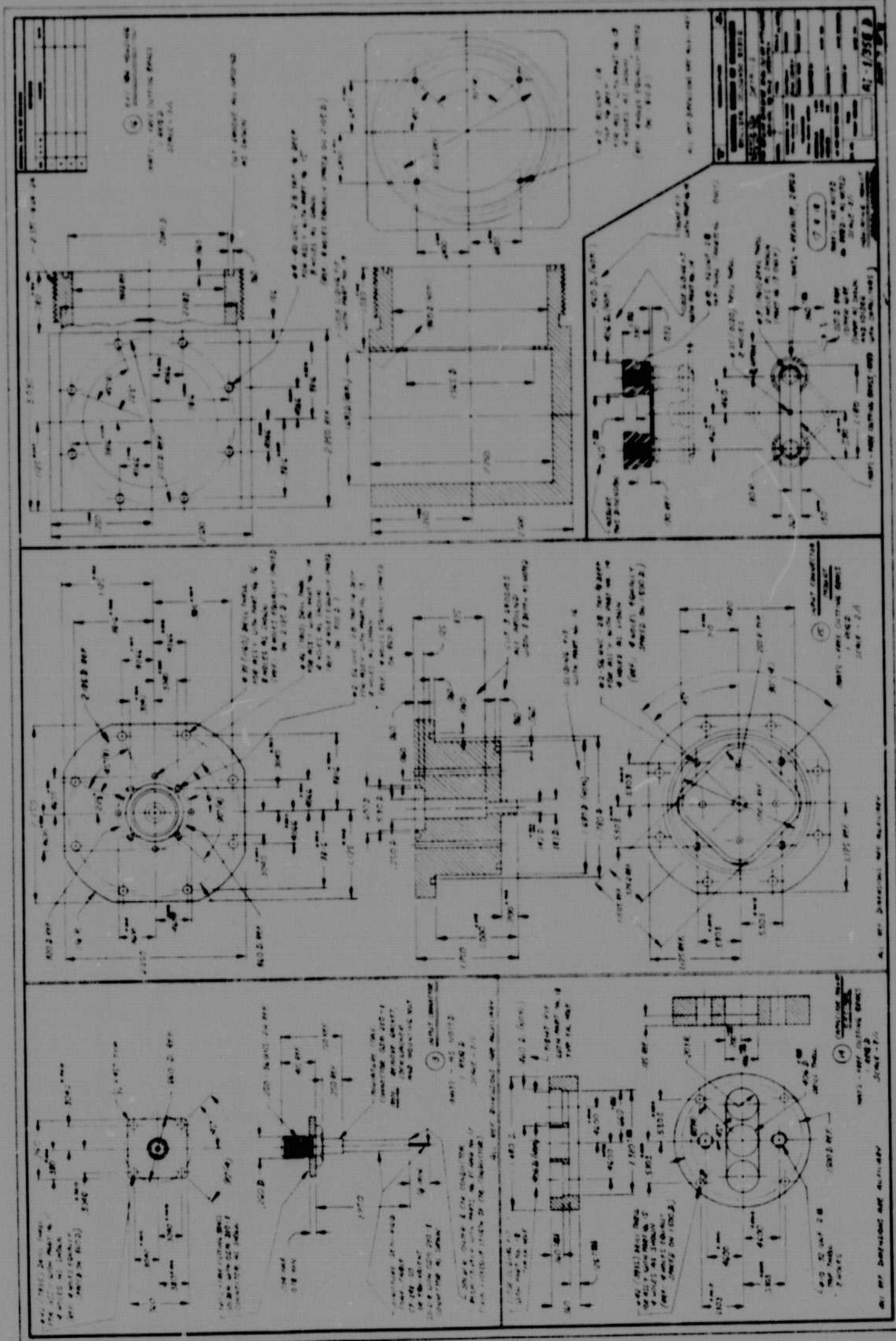


Figure 4(i)

Figure 4(j)

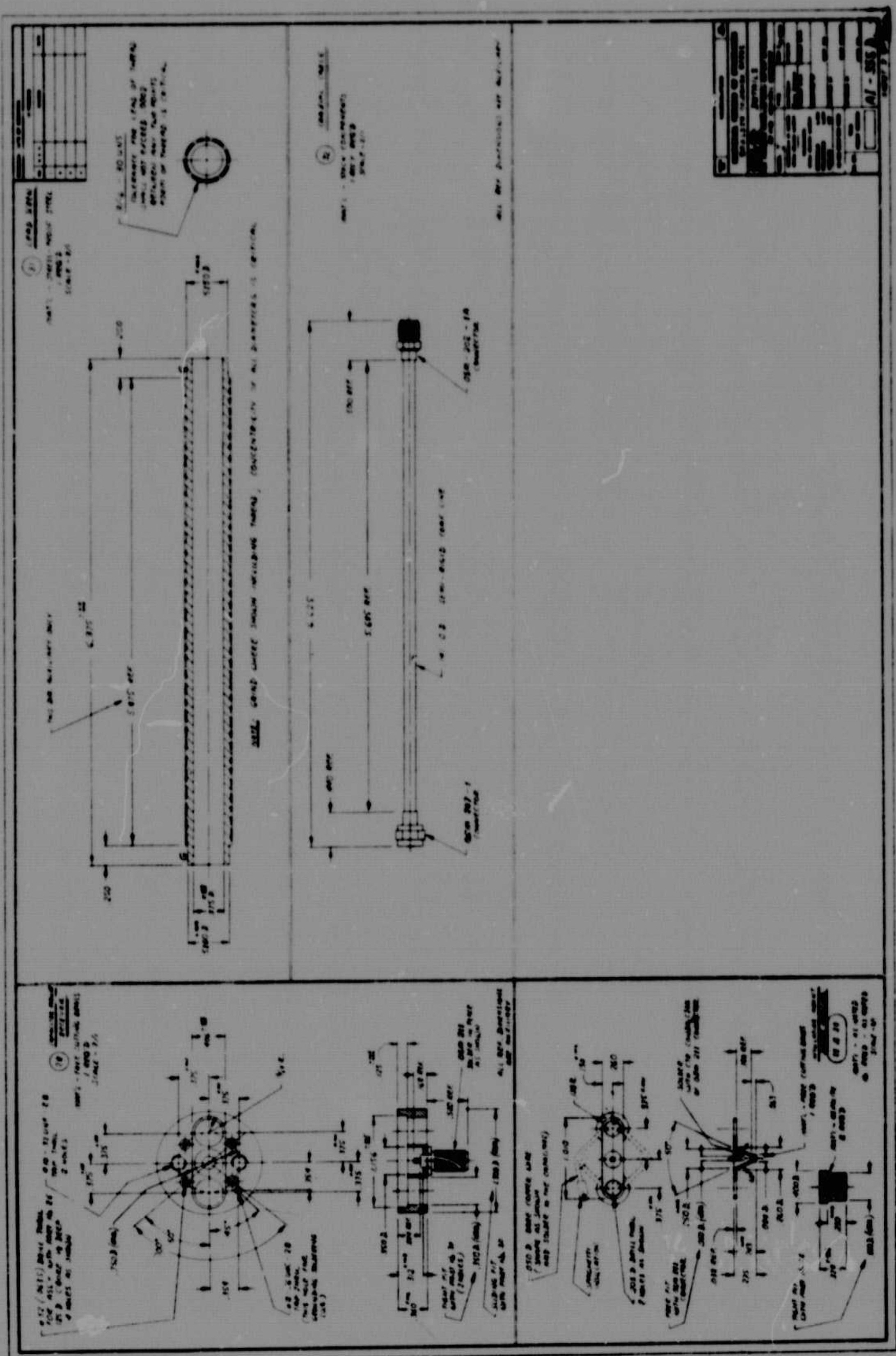


Figure 4(k)

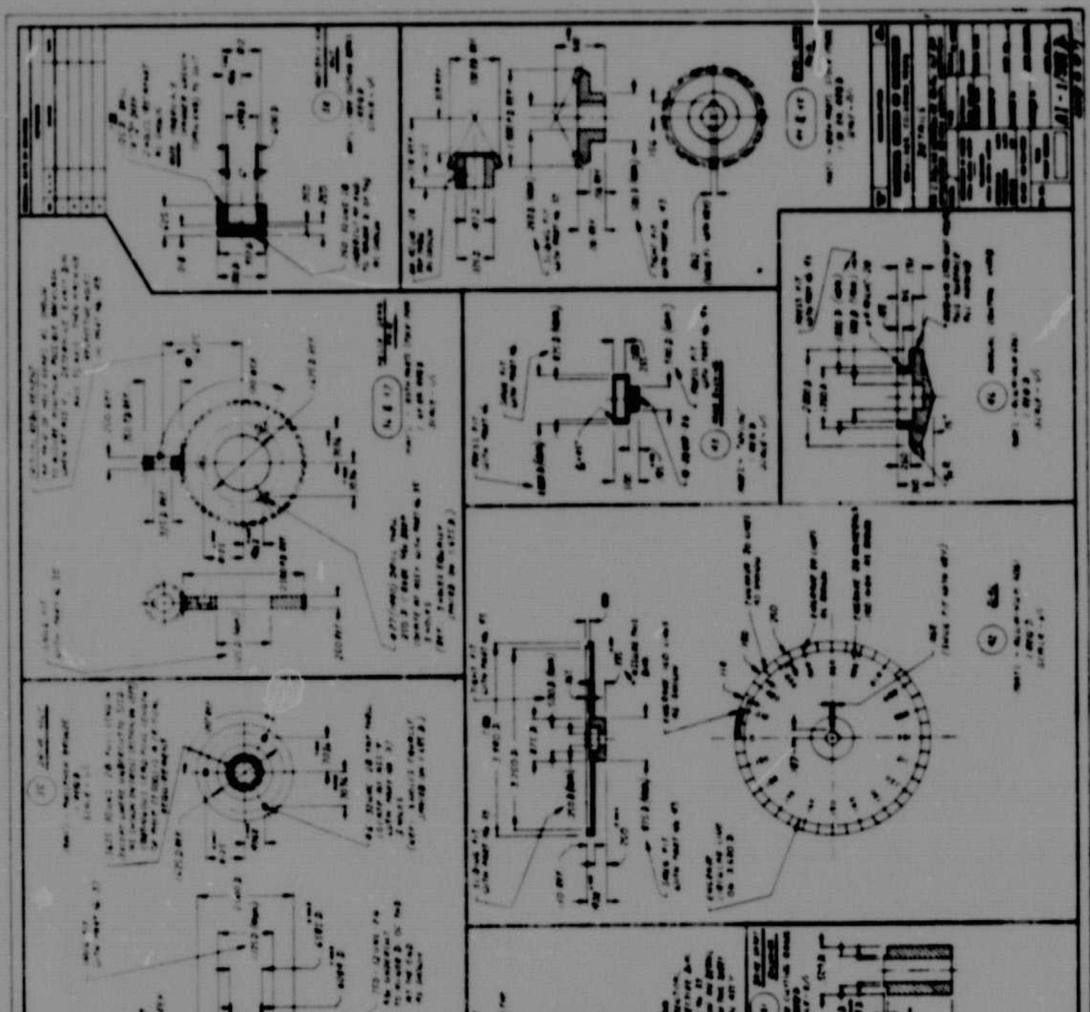


Figure 4(1)

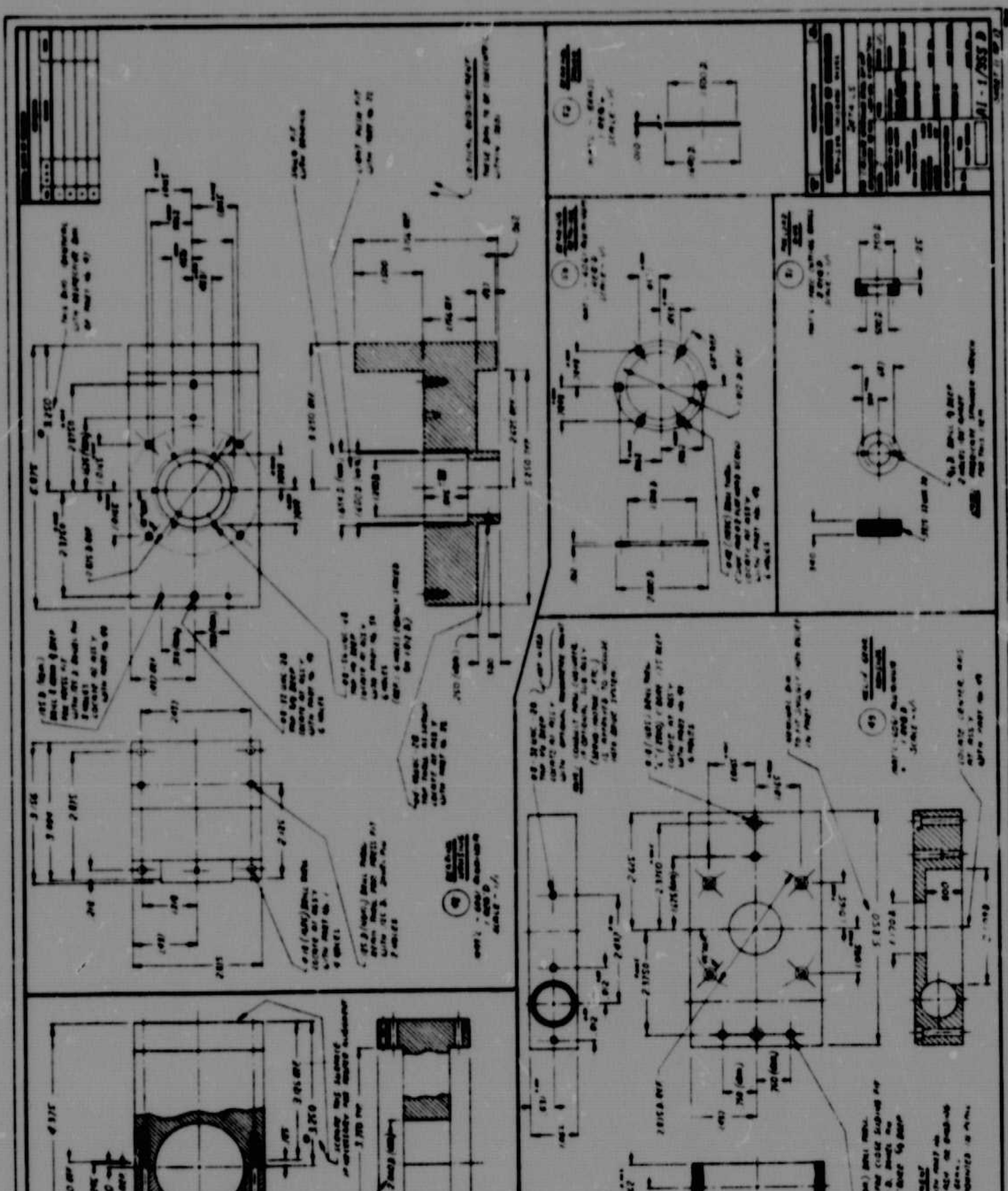


Figure 4(m)

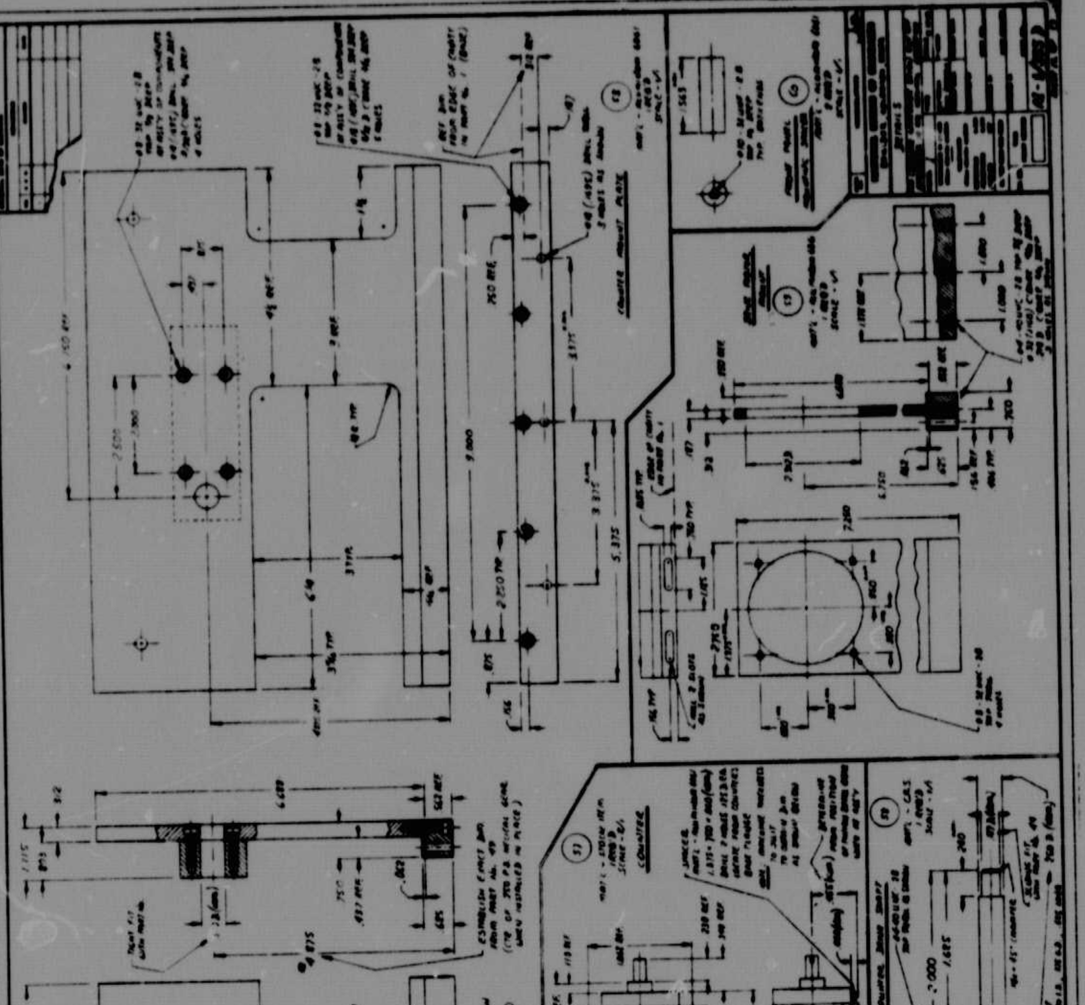


Figure 4(n)

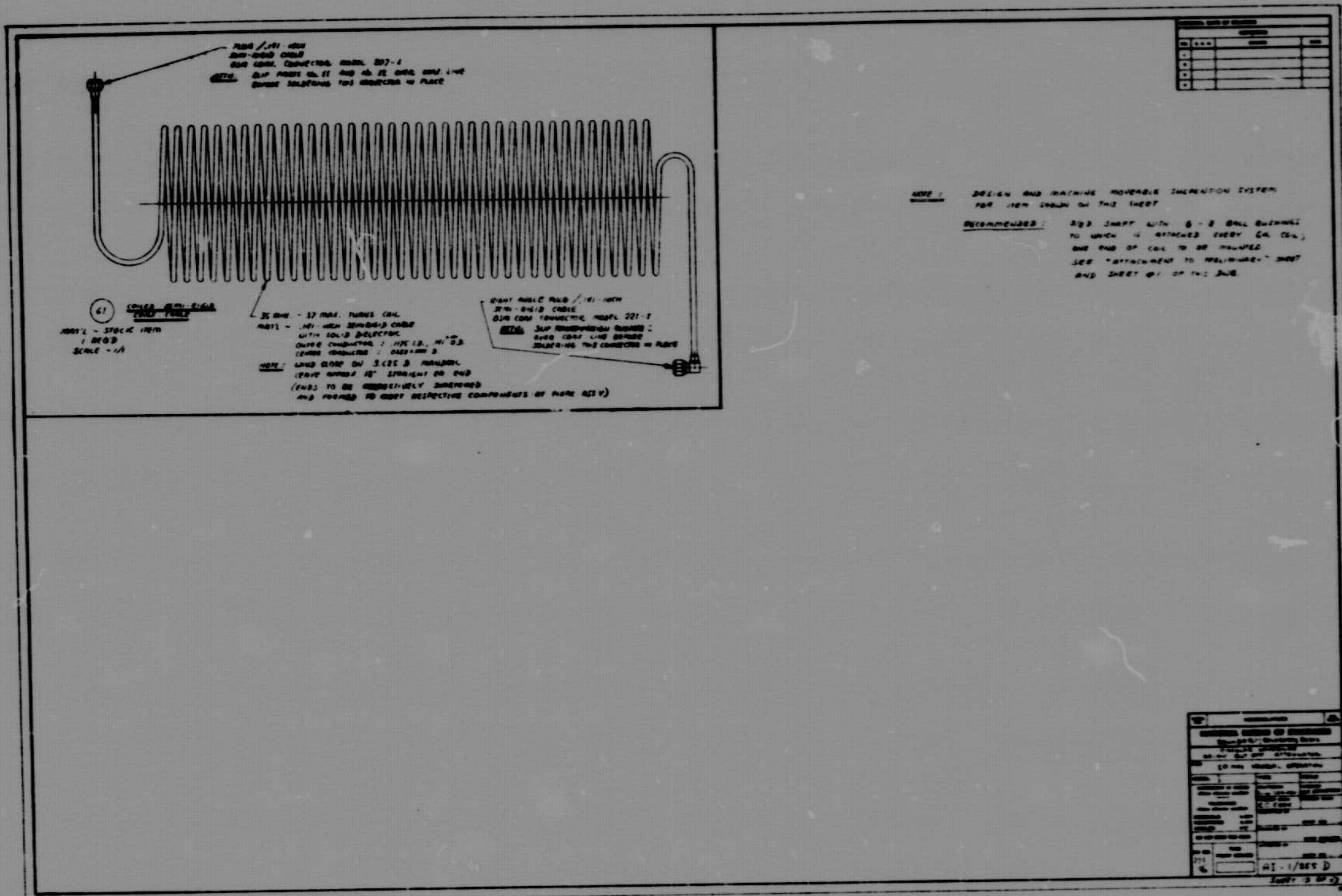

NOTE:
DESIGN AND MACHINE MOVEABLE SUSPENSION SYSTEM
FOR ITEM SHOWN ON THIS SHEET
RECOMMENDED:
ONE END OF COIL TO BE MOUNTED
SEMI-RIGID CABLE
WITH SOLID DIELECTRIC
MAT'L - STOCK ITEM
SCALE - 1/1
NOTE:

Figure 4(o)

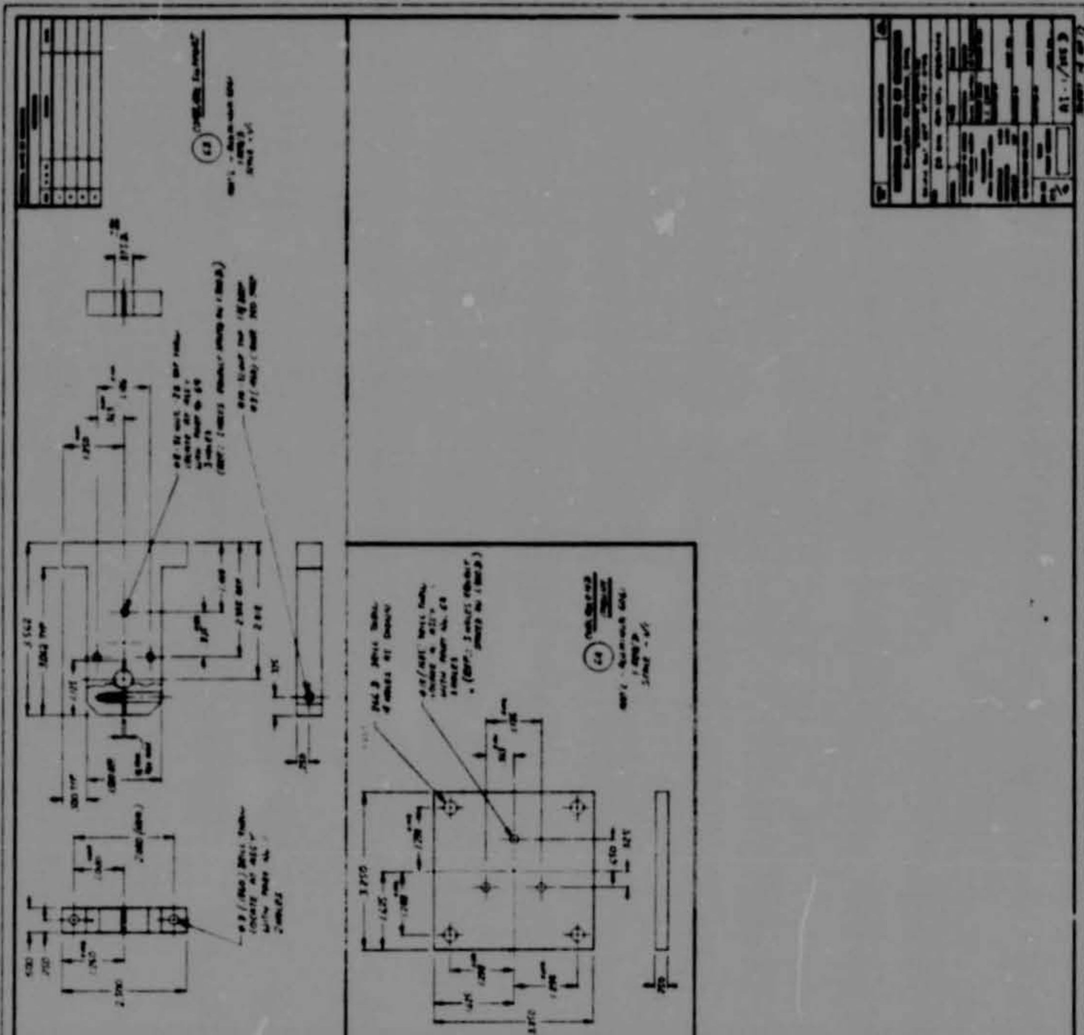


Figure 4(p)

Figure 4(q)

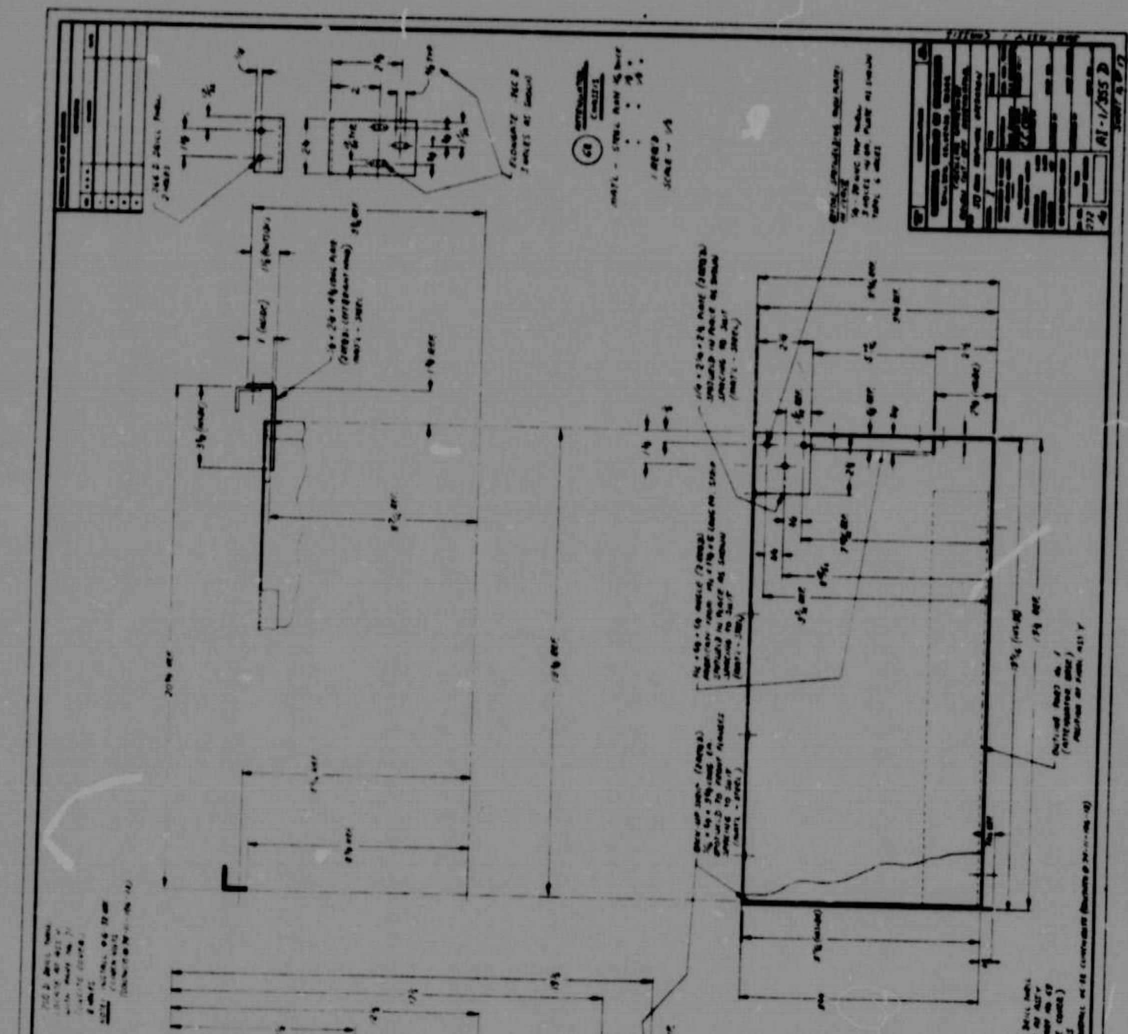


Figure 4(r)

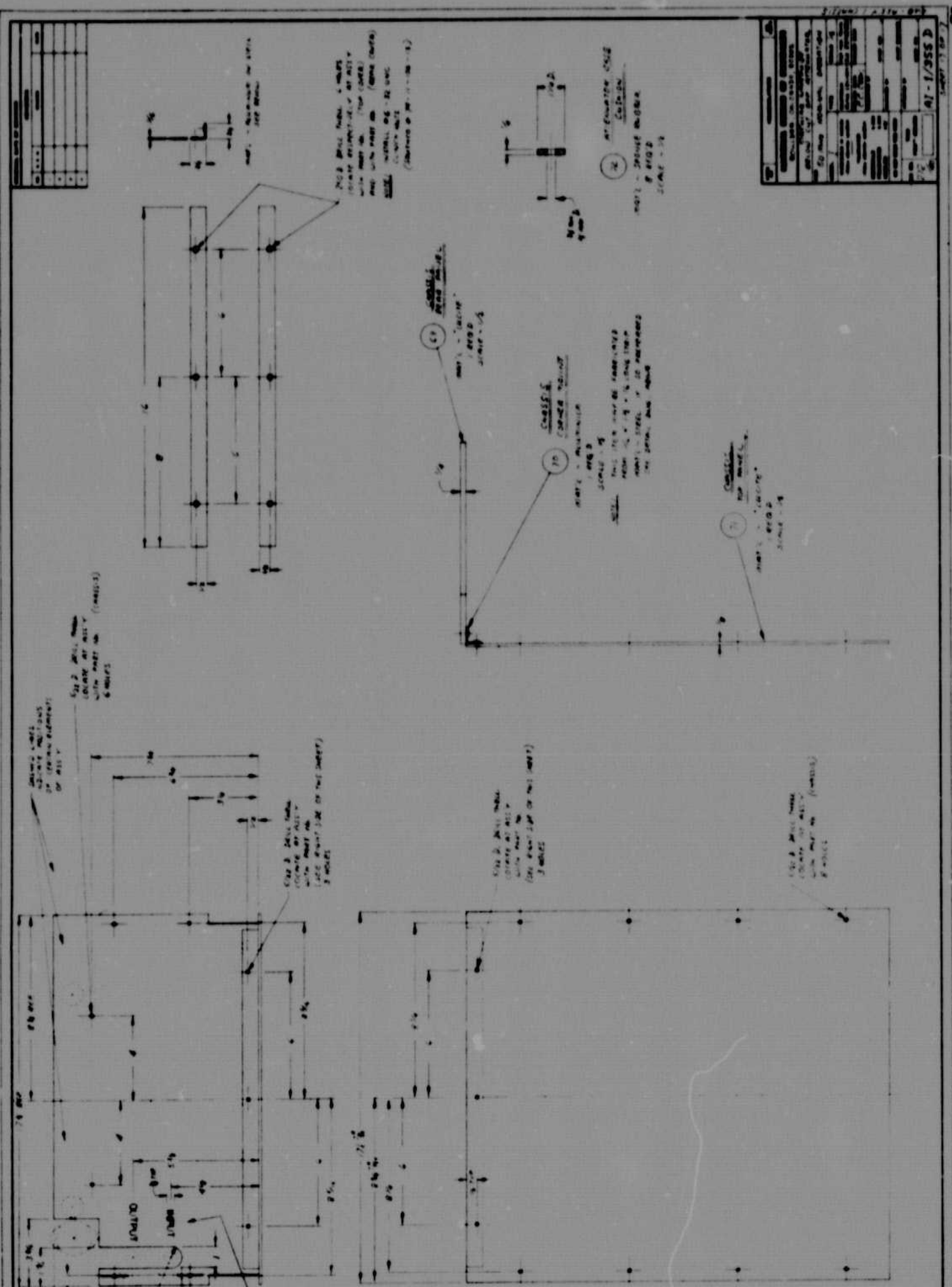


Figure 4(s)