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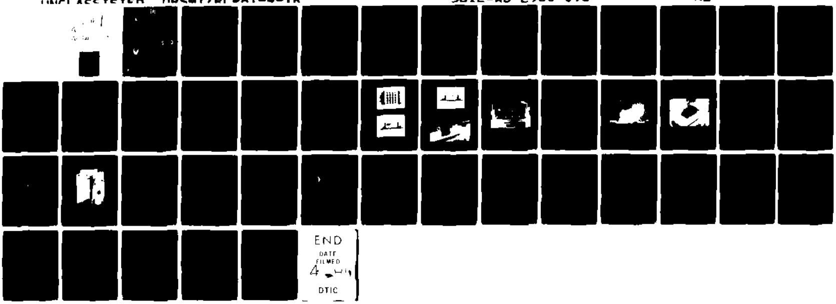

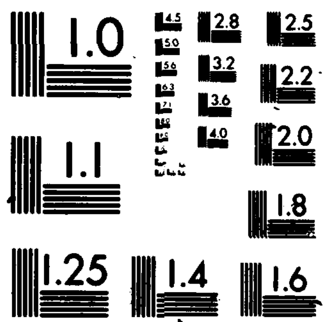

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TECHNICAL REPORT RL-81-4

A POLYVINYLIDENE FLUORIDE DIFFERENTIAL MEMBRANE PRESSURE ACOUSTICAL ARRAY TRANSDUCER

John A. Schaeffel, Jr.
Ground Equipment and Missile Structures Directorate
US Army Missile Laboratory

30 September 1980

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898

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Transducer Array

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This work describes the fabrication of a PVDF array transducer for use in NDT and Experimental Mechanics Applications. The array and its control electronics are described in the report. Specific performance data is also given.

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I. INTRODUCTION

The need for low cost, high output power, broad-band frequency response, variable focal length acoustical transducers is readily established in NDT and Experimental Mechanics applications. A single element transducer was developed [1] in 1979 to meet some of these requirements. The transducer was fabricated from Polyvinylidene Fluoride (PVDF) and featured the following:

- Low Cost
- Variable frequency response
- Variable focal length

The transducer had very low output power but showed great promise for being fabricated into arrays. This report documents the initial effort to package the differential membrane pressure acoustical transducer developed in 1979 into an integrated array.

The present device has the same basic operating characteristics as the previous single element device except that 16 transducers are presently packaged into a single array. It is conceived that large arrays may one day be packaged into units for applications in NDT and Experimental Mechanics.

II. ARRAY TRANSDUCER CONCEPT

Figure 1 illustrates the basic concept of the differential pressure acoustical PVDF membrane transducer. A PVDF membrane with surface deposited electrical conductors is sandwiched between two electrodes. The membrane and acoustical cavity walls form an acoustical cavity into which a gas or liquid is pumped through a pressure control port. By controlling the differential pressure between the acoustical cavity medium and the external acoustical cavity medium, the membrane is made to deflect in approximately a spherical shape as shown.

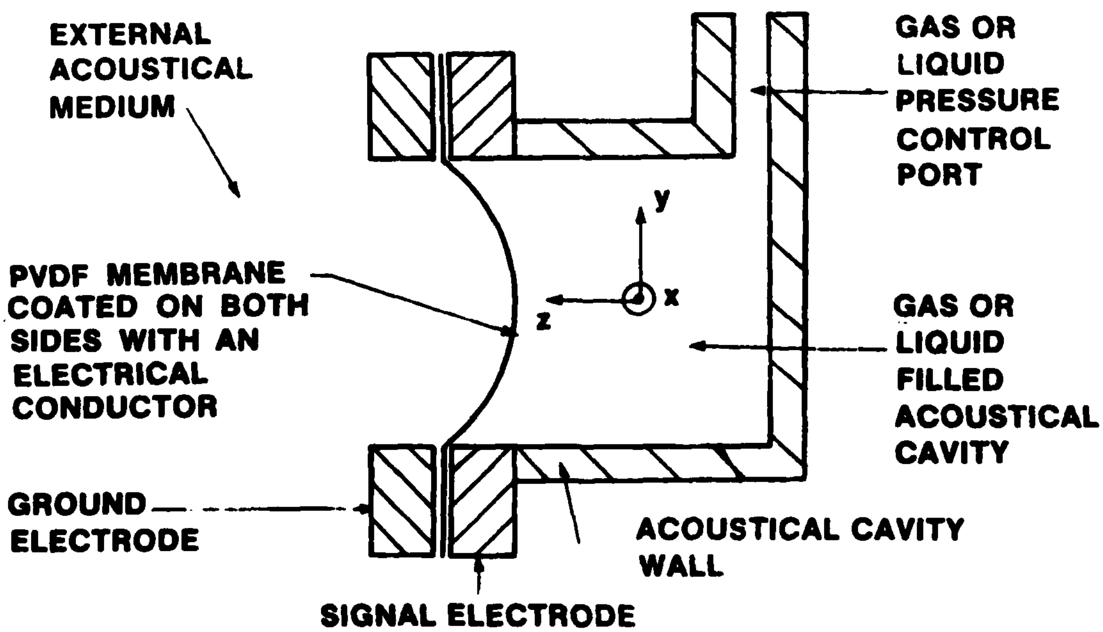

Figure 1. Cross sectional view of PVDF ultrasonic transducer design concept.

If a signal is applied to the two electrodes, the membrane will tend to contract or expand with the polarity of the applied voltage. The expansion is a length-expansion characterized by the piezoelectric constants d_{31} and d_{32} [2] and is tangential to the surface of the membrane. The ultimate result of applying the differential membrane pressure is to introduce a component of motion of the membrane in the z direction as shown in Figure 1.

When driven at ultrasonic frequencies (1-10 MHz), the result is the transmission of an acoustical wave into the external acoustical medium. Assuming that the wave is transmitted normal to the surface of the membrane then the beam will have a focal point determined by the membrane radius. By varying the differential membrane pressure, the focal point position in space is also varied.

When a mechanical stress is applied to an area of piezoelectric material a polarization per unit area P_i (or dipole moment per unit volume) is generated [3], where:

$$P_i = d_{ij} \sigma_j \tag{1}$$

$i = 1,2,3$ and $j = 1,2,3,4,5,6$

$P_i \equiv$ ploarization per unit area

$d_{ij} \equiv$ piezoelectric moduli (matrix representation)

$\sigma_j \equiv$ applied stress (matrix representation)

Equation (1) refers to the direct piezoelectric effect.

The converse piezoelectric effect occurs when an electric field is applied to a piezoelectric material and it becomes strained by an amount directly proportional to the electric field strength. For this case:

$$\epsilon_j = d_{ij} E_i \tag{2}$$

$\epsilon_j \equiv$matrix representation of strain

$E_i \equiv$electric field strength.

As illustrated in Equations (1) and (2) the piezoelectric moduli are measures of the conversion efficiency from an electrical signal to a mechanical strain in the material and vice versa.

Figure 2 shows a cross sectional view of a PVDF circular membrane deflected under a differential pressure (P) to form a focused transducer as shown in Figure 1. If the ultrasound is emitted normal to the surface of the membrane, the focal point of the transducer will be located at

$$r = \frac{a^2 + w^2}{2w} \tag{3}$$

where,

$r \equiv$ membrane transducer focal radius

$a \equiv$ membrane radius

$w \equiv$ membrane deflection.

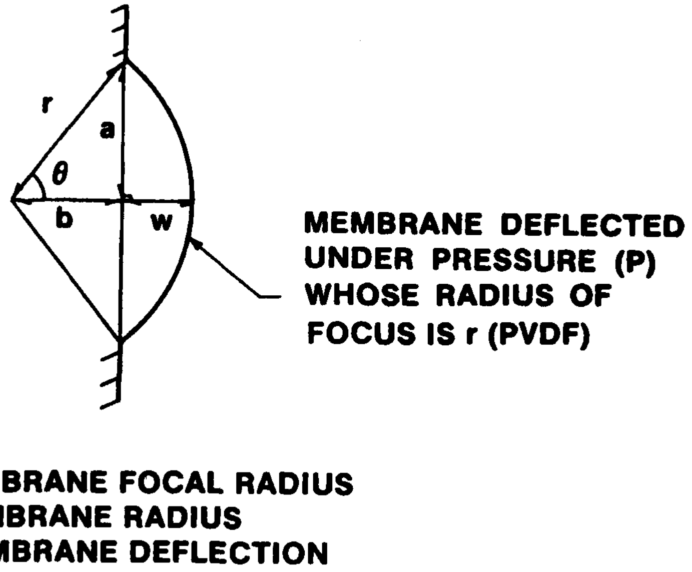

Figure 2. Circular membrane of radius (a) deflected under a differential pressure (P).

Equation 3 assumes a spherical shaped membrane deflection.

For the membrane under uniform pressure load P, the Hencky deflection equation is [4].

$$w = .662\ a\ \sqrt[3]{\frac{Pa}{Et}} \qquad (4)$$

where:

$w \equiv$ membrane deflection under differential pressure load

$a \equiv$ membrane radius

$t \equiv$ membrane thickness

$P \equiv$ differential membrane pressure

$E \equiv$ membrane modulus of elasticity

These equations assume the absence of a radial tensile force under no differential pressure load. Equations 3 and 4 were used to predict the focal length of .25 inch, .50 inch and .75 inch diameter PVDF transducers under a differential membrane pressure of 0 to 120 cm H_2O. The modulus of elasticity used in the computations was 8.438×10^6 cm H_2O. Figure 3 illustrates the results.

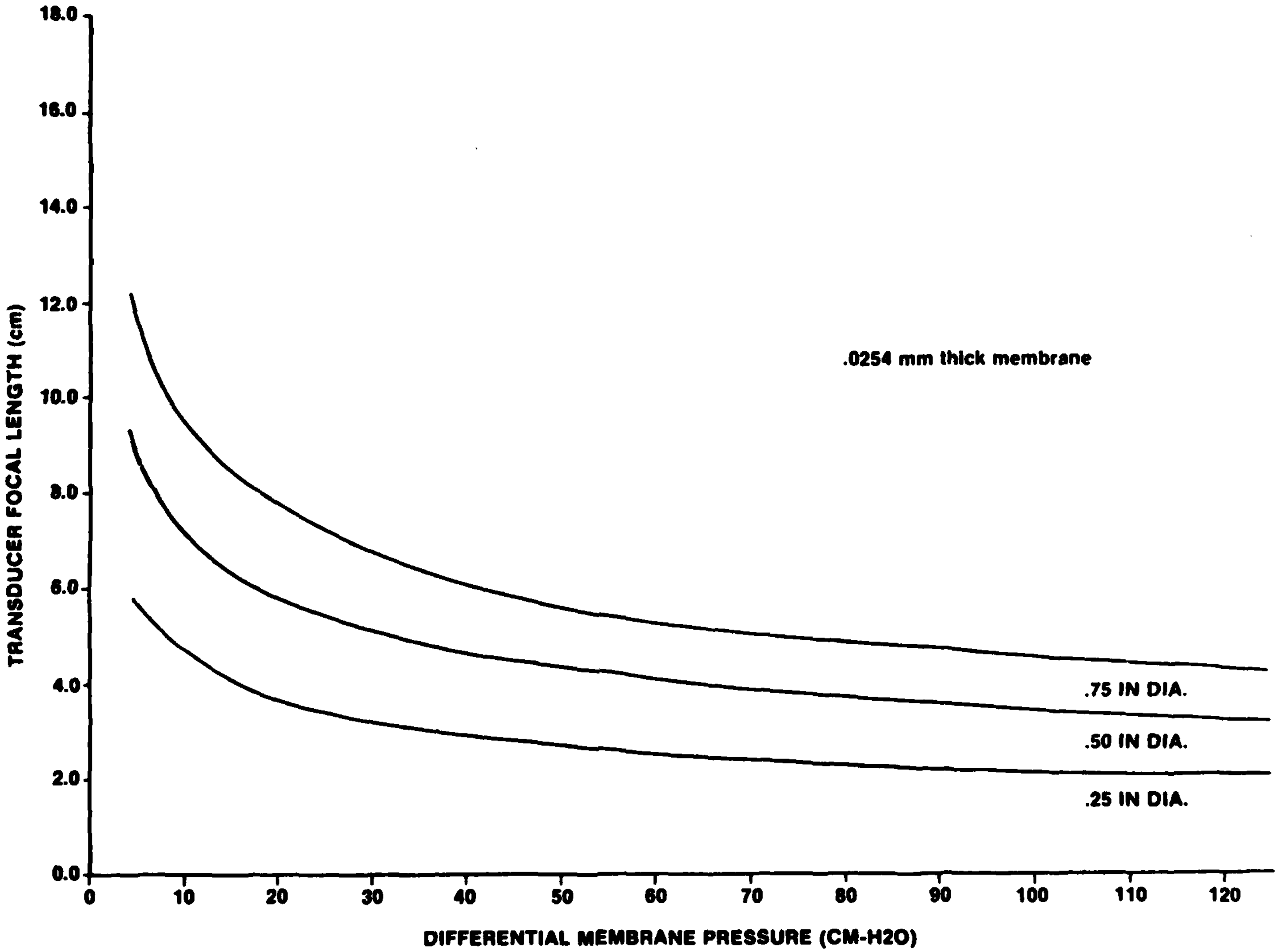

Figure 3. Transducer focal length versus differential membrane pressure.

If the transducer is operated as a diverging acoustic radiator, the angle of divergence θ will be given as

$$\Theta = \text{Arcsin}\left\{\frac{2wa}{a^2 + w^2}\right\} \quad (5)$$

Equations 3 and 5 assume normal transmission from the surface of the membrane into the external acoustical medium which is not exactly true. For instance, a plane circular surface radiator of ultrasound will have a beam divergence given as [5],

$$\gamma = 68.8\ \lambda/D \quad (6)$$

where

$\gamma \equiv$ angle of divergence in degrees

$\lambda \equiv$ ultrasonic wave length

$D \equiv$ diameter of circular radiator.

Equation 6 assumes small λ/D.

Another important parameter is the length of the near field [5]. For circular flat radiators of ultrasound

$$N = \frac{(D^2 - \lambda^2)}{4\lambda} \quad (7)$$

where,

$D \equiv$ diameter of ultrasonic radiator

$\lambda \equiv$ wavelength of ultrasonic wave

$N \equiv$ nearfield length

Figure 4 illustrates the variation of N with frequency for a 1500 m/sec wave velocity in water and a .5 inch diameter transducer. For uniform test results all calibration tests should be performed at ranges greater than N.

The basic concept for the PVDF array is illustrated in Figure 5. A membrane of KYNAR® PVDF piezoelectric film (obtained from the Pennwalt Corporation) had electrode material of nickel-chrome deposited on both sides of a film which measured 127 mm x 127 mm x 27 μm thick. Portions of both sides of the membrane were selectively etched in acid to leave four electrode strips (on each side). When an RF signal is applied to a front and rear electrode, where these electrodes cross-over, the E-field becomes intense. This action activates the PVDF material in the cross-over region and a transducer is formed. Figure 5 illustrates 16 such transducers on a single PVDF membrane. The next step is to place the membrane in a cavity similar to Figure 1 to generate ultrasound. In reality, sixteen individual cavities were used to contain ultrasound.

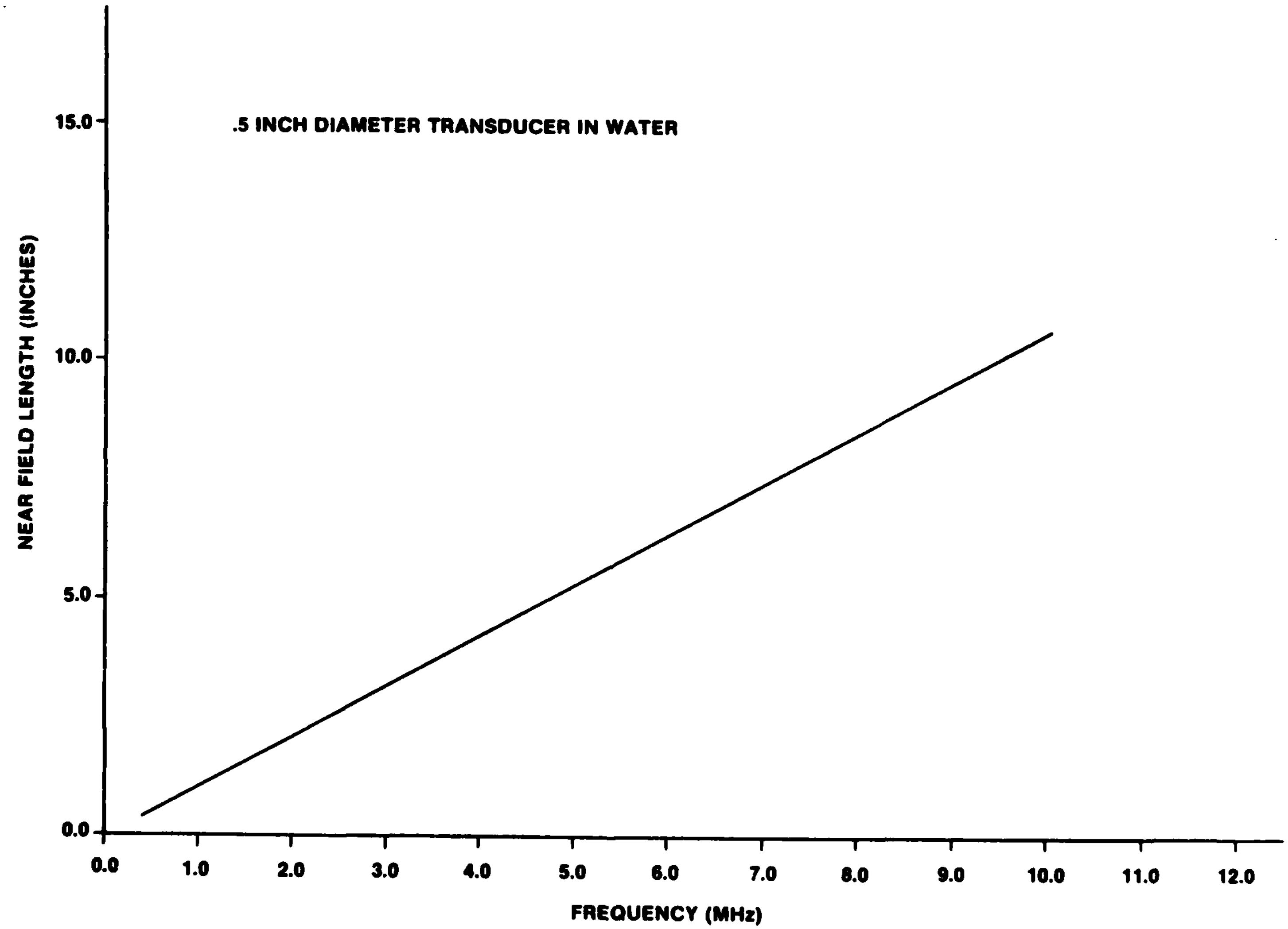

Figure 4. Near field length versus frequency for a .5 inch diameter transducer in water.

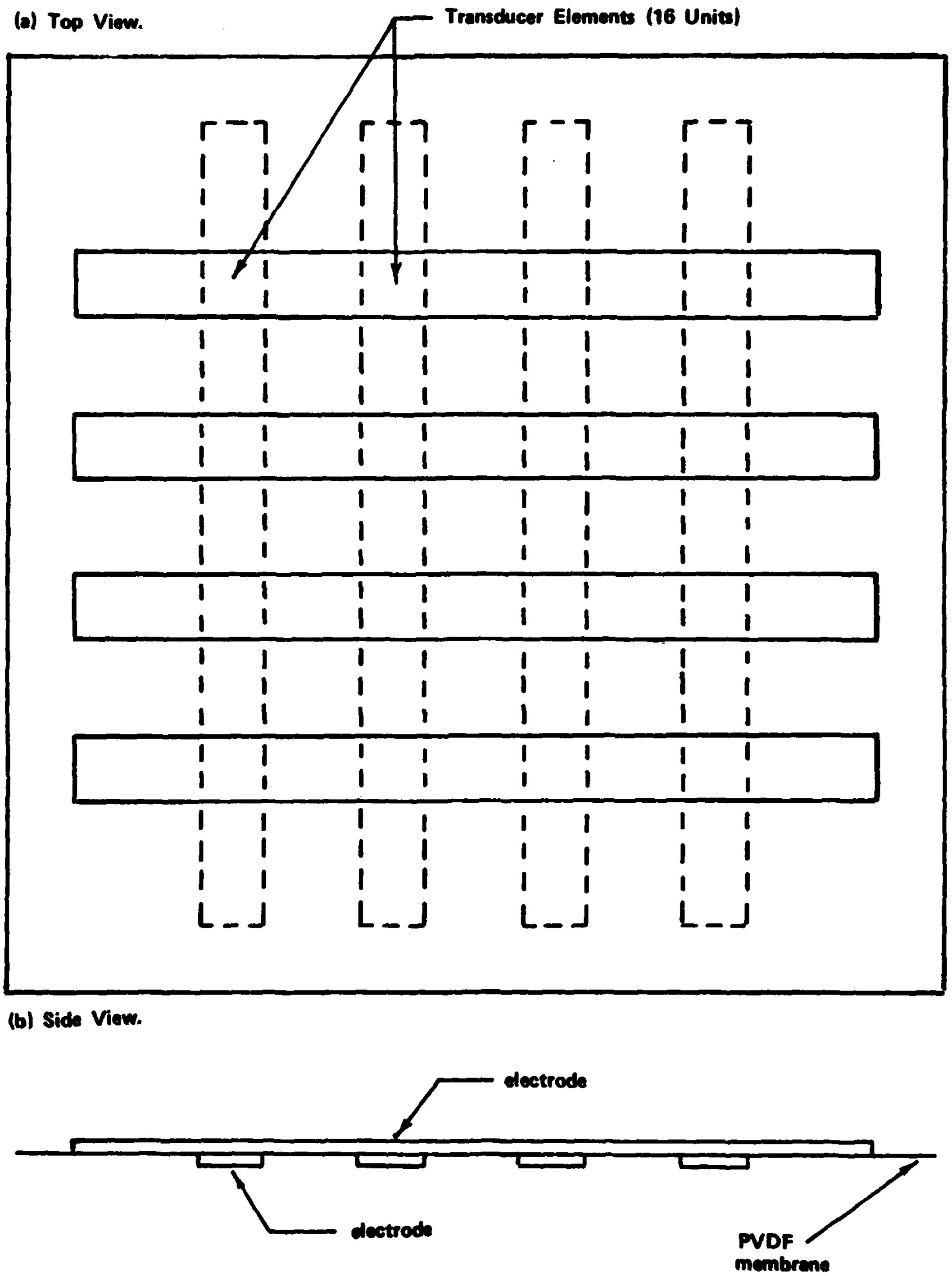

Figure 5. Schematic of PVDF Membrane.

III. ARRAY FABRICATION AND TESTING

In order to hold the PVDF membrane and obtain suitable electrode contacts, front and rear electrode holders were constructed as in Figure 6. The membrane was sandwiched between these holders. A gas supply chamber for supplying gas pressure to deflect the membrane was attached to the rear electrode holder. This chamber is illustrated in Figure 7.

Etching of the membrane was performed according to the following procedure:

1. Paint all regions not to be etched with a moderately thick coat of Pacific 8010-00-584-3150 Lacquer, Nitrocellulose, Type I, TT-L-50G and Amend III, Flat White, No. 37875 paint. Contract GS-10S-40992, flash point -56.6°C (-70°F.).

2. Etch the unpainted Ni-Cr metal with a 25 percent solution of 38.6 percent concentrated Hcl.

3. Rinse membrane in H_2O to remove residual Hcl.

4. Soak membrane in Hexane for 30 seconds and peel away the paint from the unetched Ni-Cr PvF2 membrane material.

The mask used in the etching procedure is illustrated in Figures 8 and 9.

Following the etching process, discontinuities in the Nickel-Chrome electrodes were removed by applying ten thin coats of powdered silver in Amyl Acetate over each electrode. Assembly of the transducer was performed by punching all the necessary assembly holes (16 in all) into the membrane. Flathead counter-sunk screws for electrode contacts were then placed in the electrode holders and covered with liquid solder for good electrical contact. The membrane was sandwiched into the holders and the gas supply assembly was bolted to the transducer as a complete packaged unit. Figures 10 through 12 illustrate the transducer assembled and mounted in a holder frame.

The control electronics for the transducer were designed and fabricated by Sperry Support Services in Huntsville, Alabama under contract to the government. Figures 13 and 14 illustrate the system with the transducer attached. The RF switch system block diagram is illustrated in Figure 15 for the control electronics. The system features a Wavetek, Model 143 signal generator for generating RF signals (either continuous or pulsed). The signals are amplified by an ENI Model A150 signal RF amplifier and selectively switched to the array by a selector switch assembly shown in Figure 16. Figure 17 illustrates the array connected to the electronics.

Table 1 contains a summary of the electronics functions. The system is capable of generating continuous or pulsed RF signals. In the pulsed RF mode, 0.1-50 μs pulses with a 1 to 10,000 Hz repetition rate trigger the RF wave burst mode of the Wavetek RF generator which can generate either 1-20 MHz continuous or pulsed RF signals. The selector switch assembly can be used to apply the RF signal to all, one, any combination of row or any combination of column transducers. The method in which the signal can be applied to the transducer assembly is illustrated in Table 1.

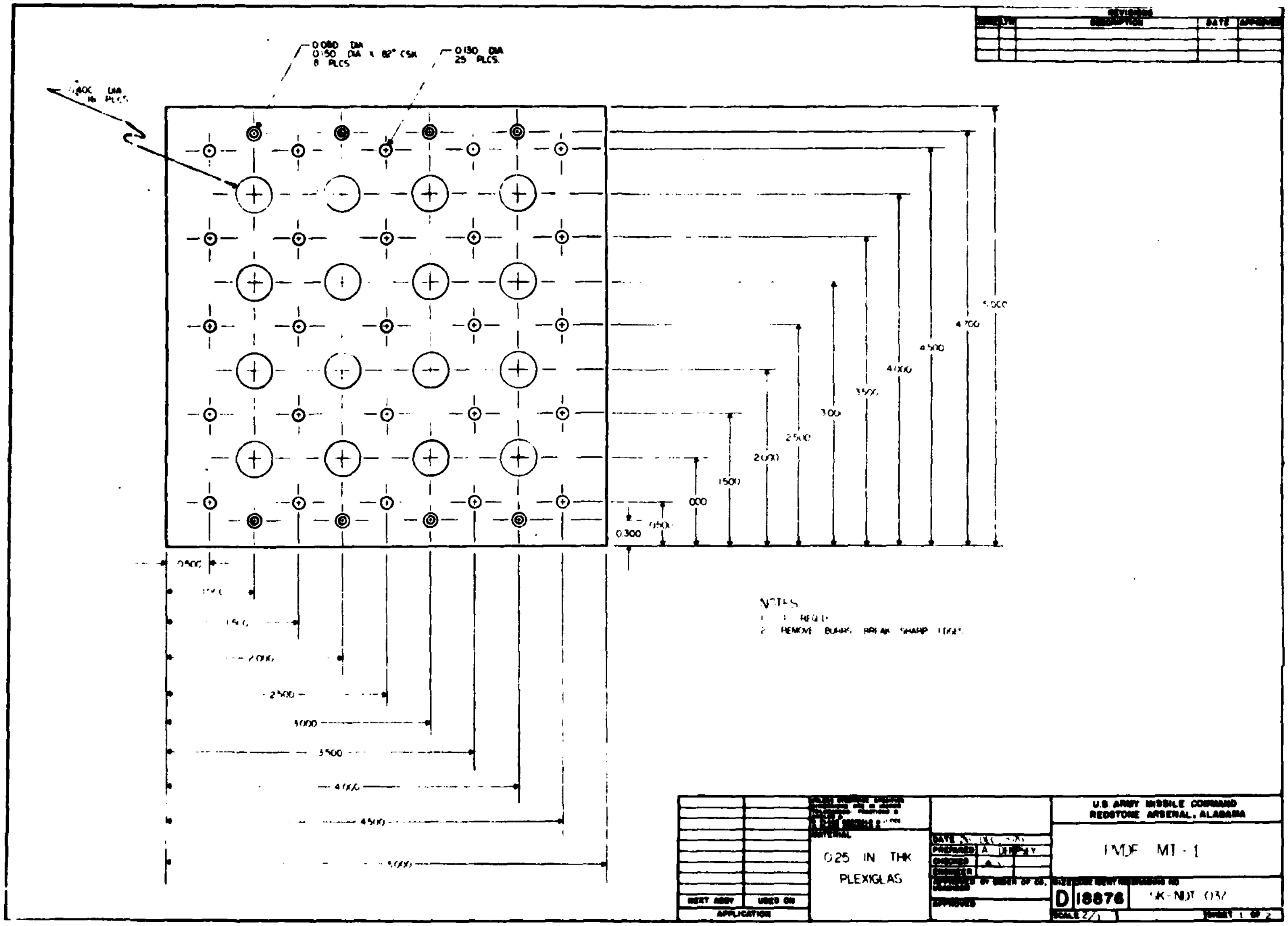

Figure 6. Front and Rear Electrode Holders for the PVDF Array Transducer.

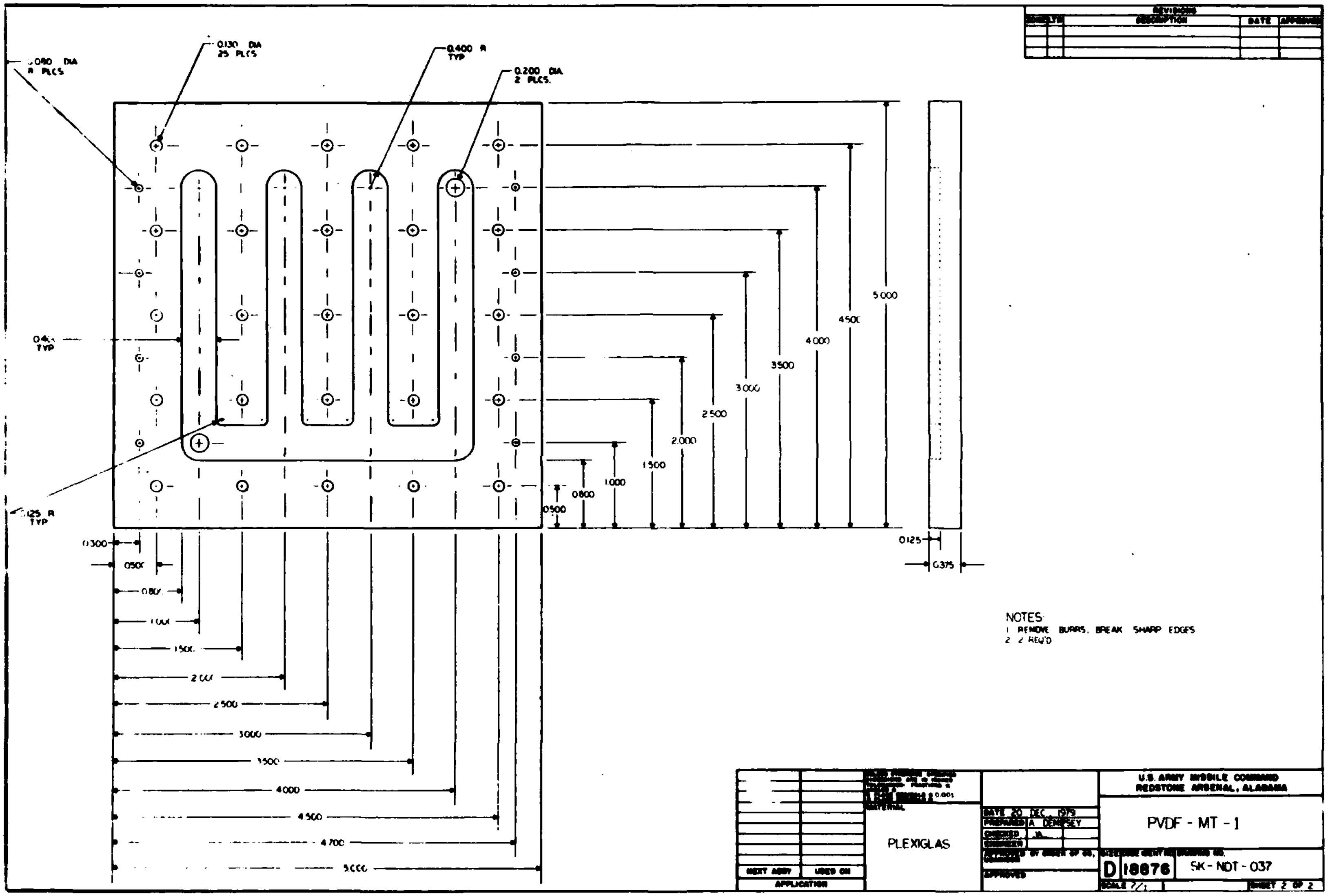

Figure 7. Gas Supply Chamber for the PVDF Array Transducer.

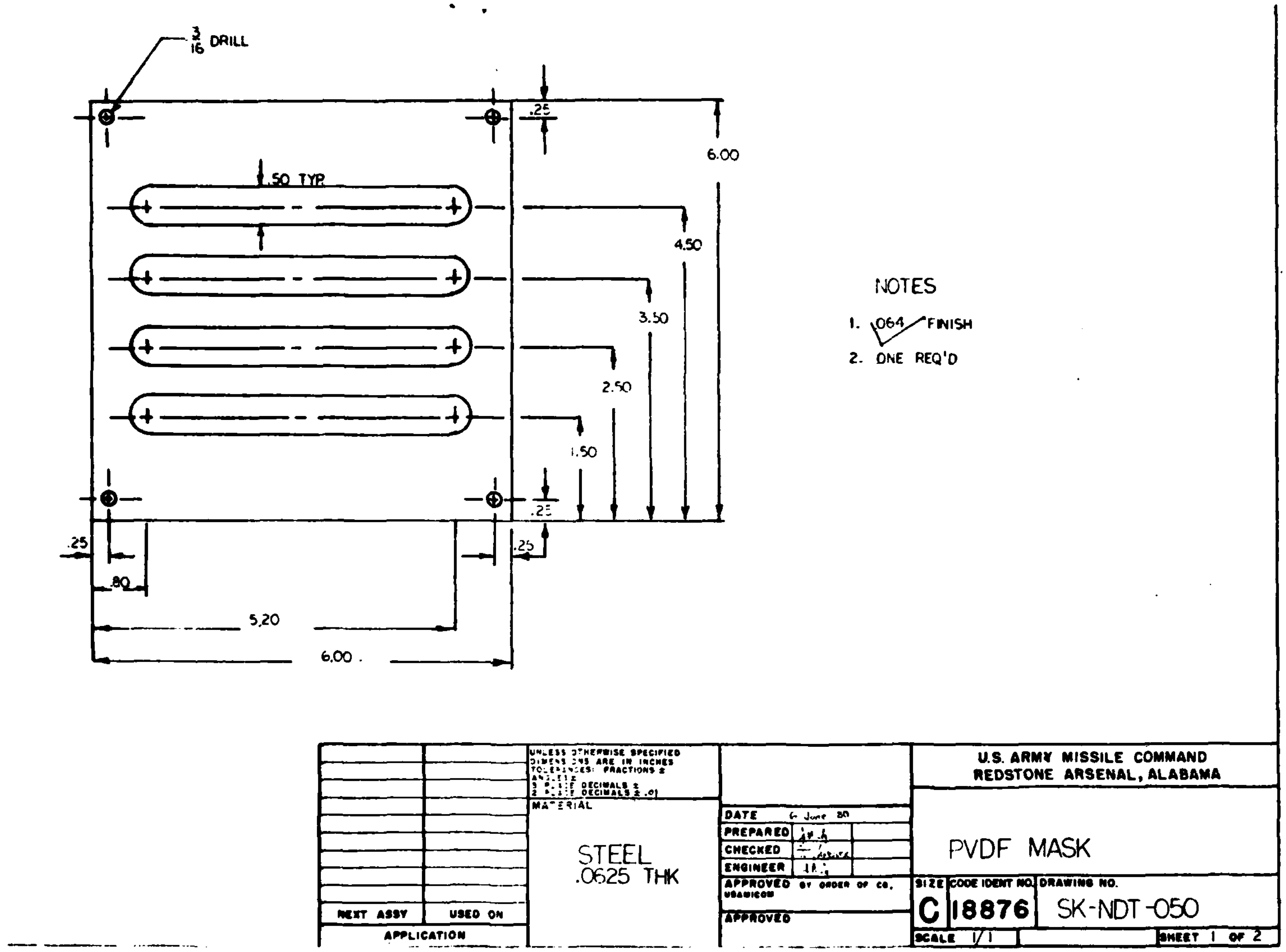

Figure 8. Front Mask for Etching the PVDF Membrane.

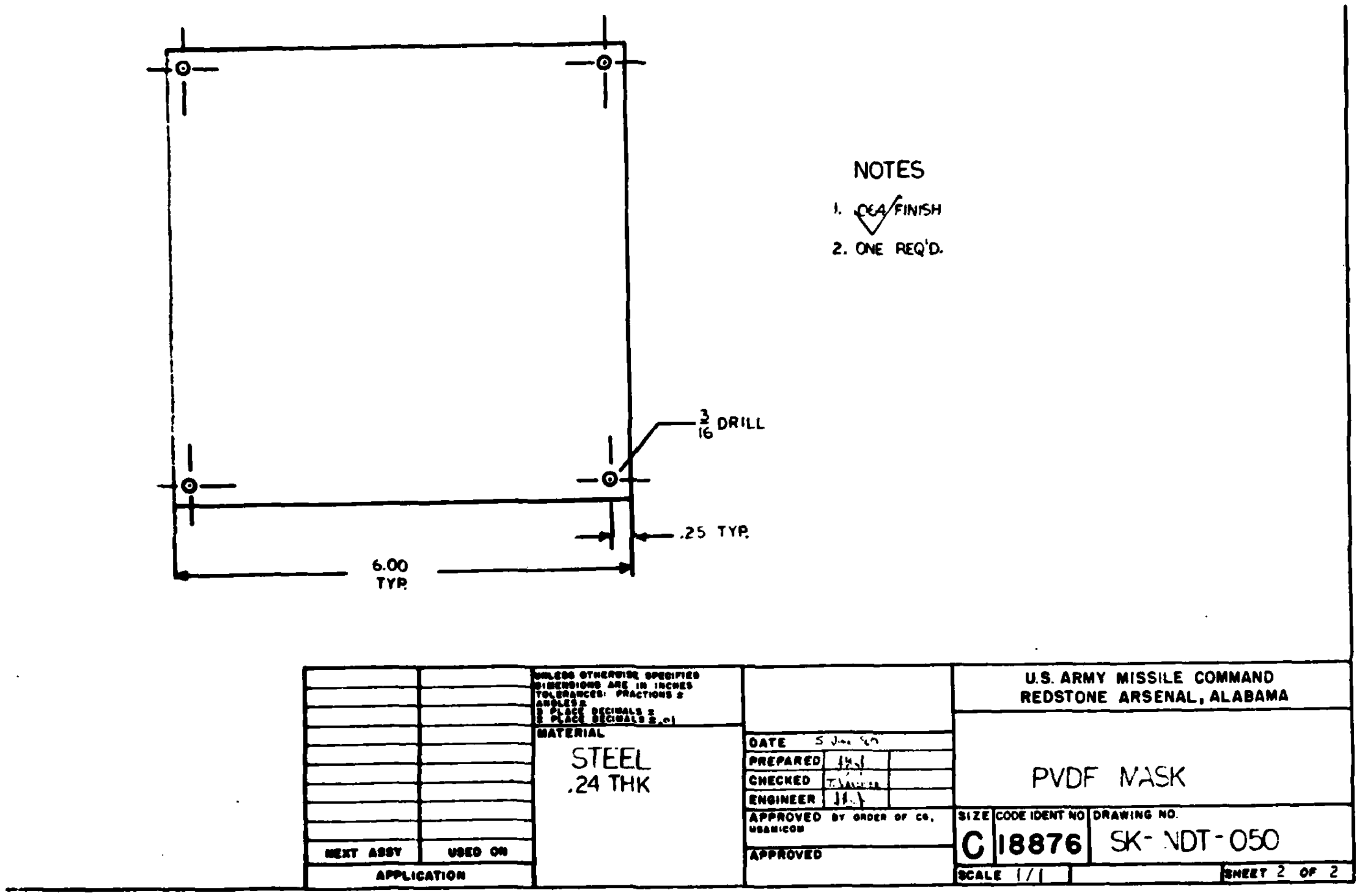

Figure 9. Back Pressure Plate for the Etching Mask.

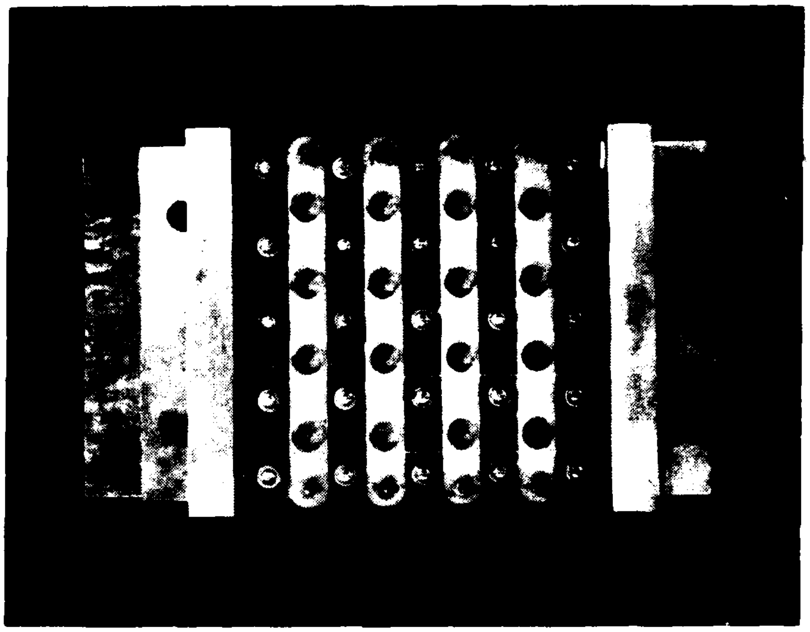

Figure 10. Top view of the assembled PVDF array transducer.

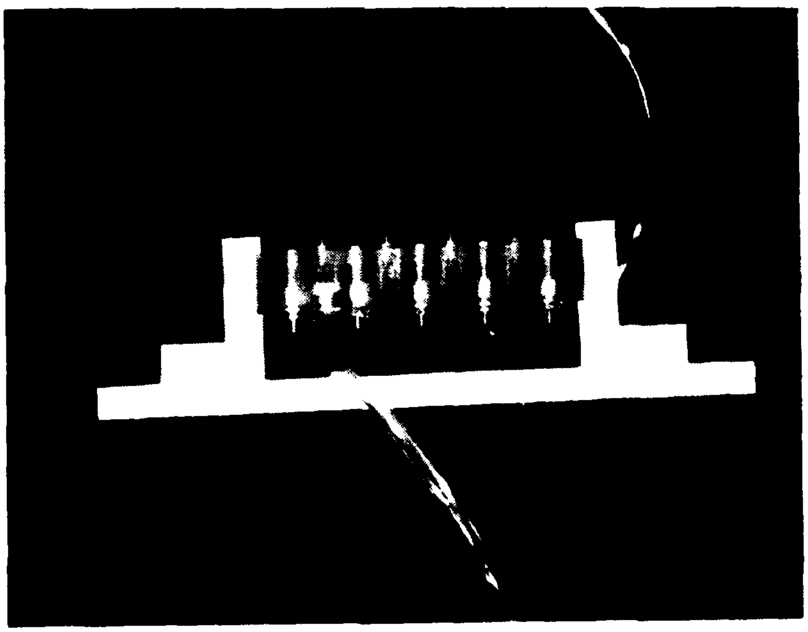

Figure 11. Gas fittings for the PVDF array transducer.

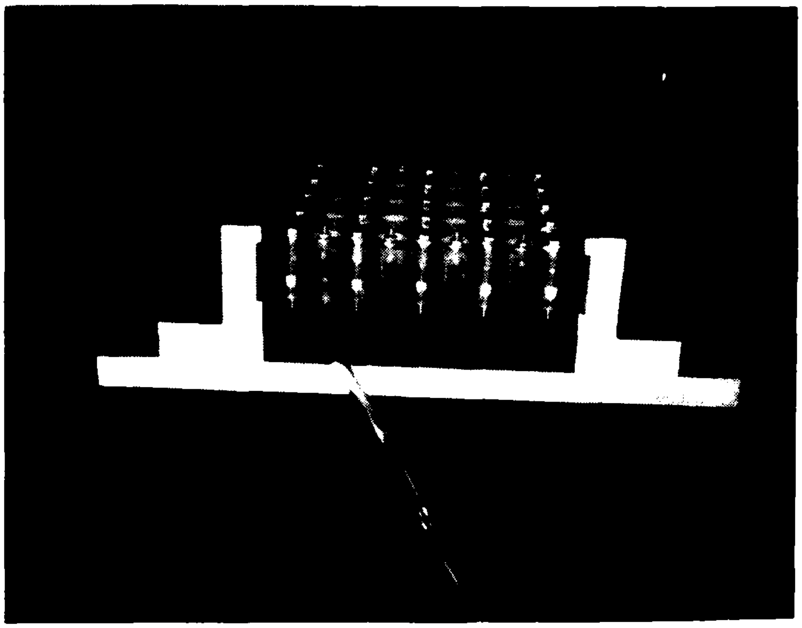

Figure 12. Assembled PVDF array transducer.

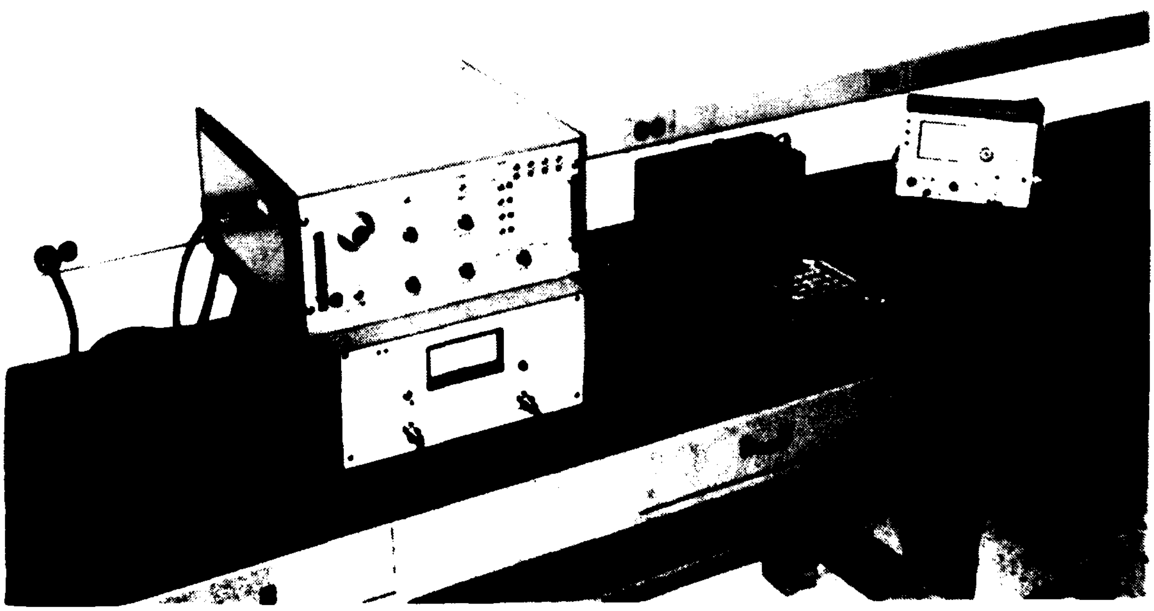

Figure 13. System control electronics.

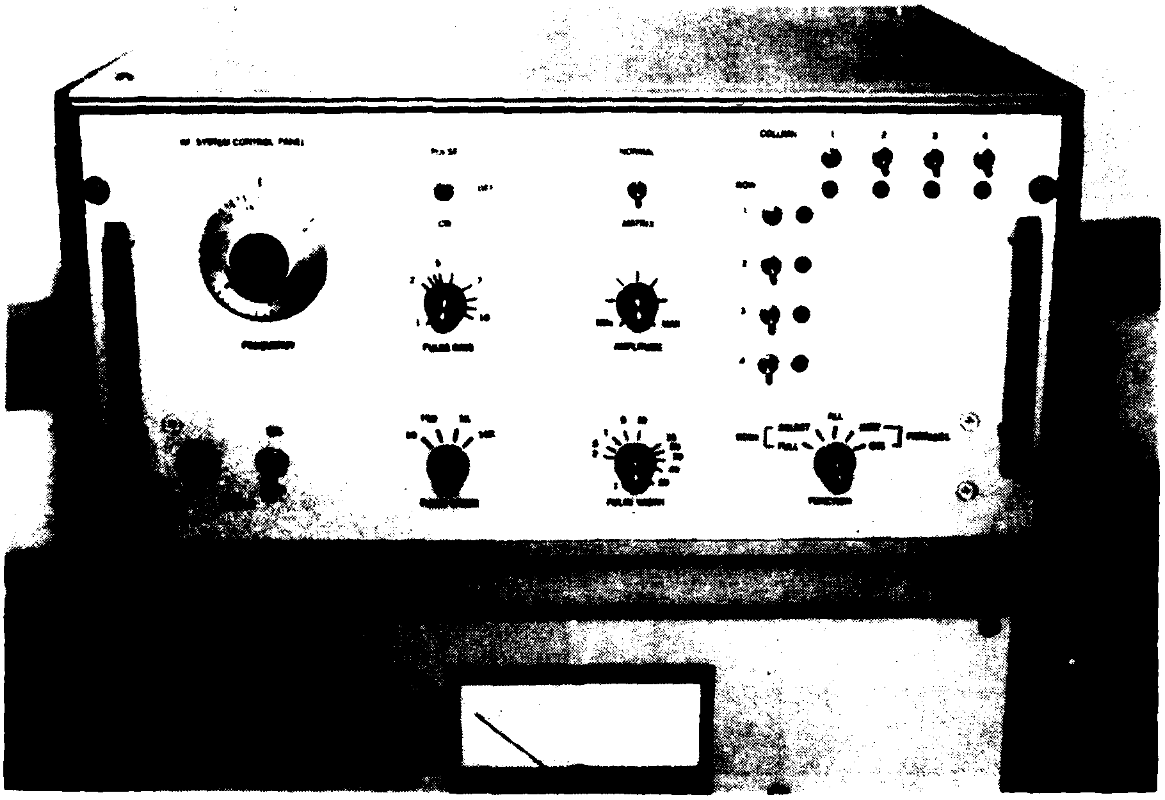

Figure 14. Transducer electronics control panel.

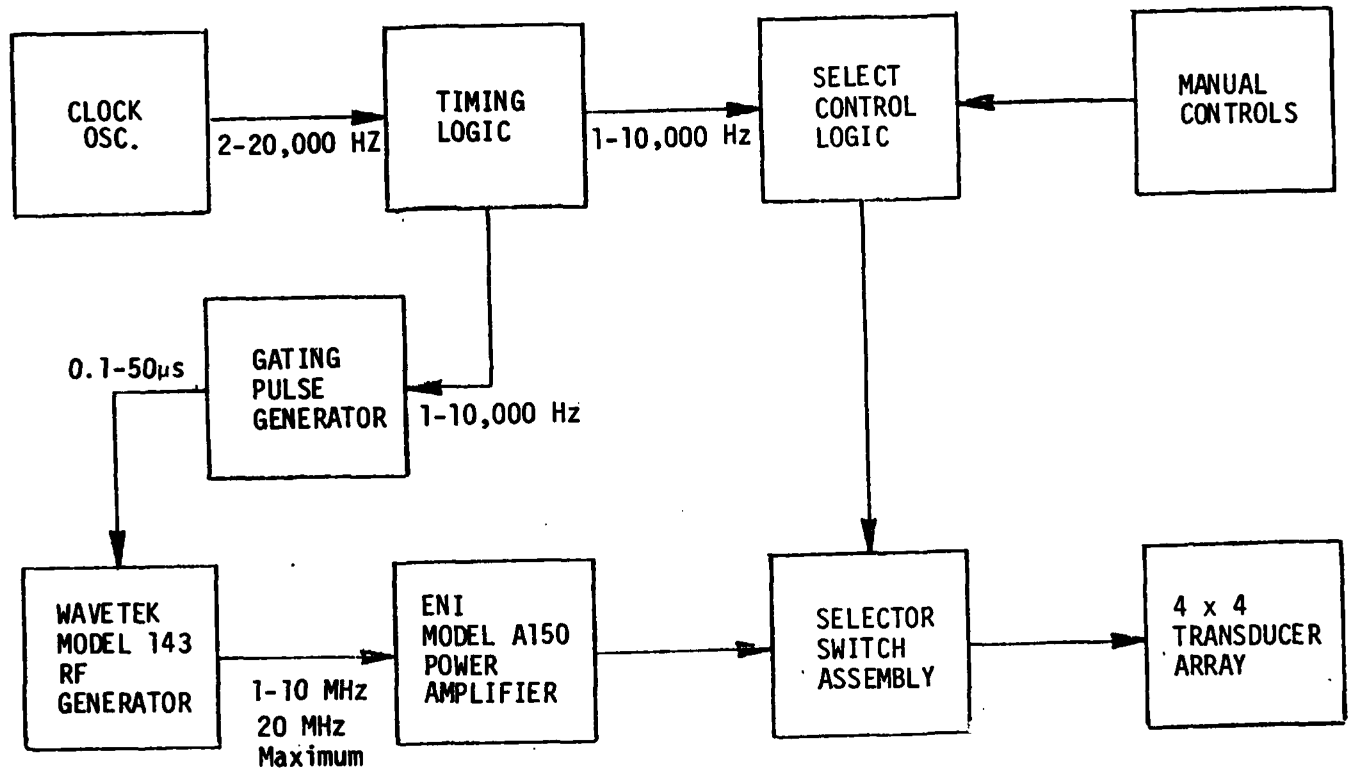

Figure 15. RF Switch System Block Diagram.

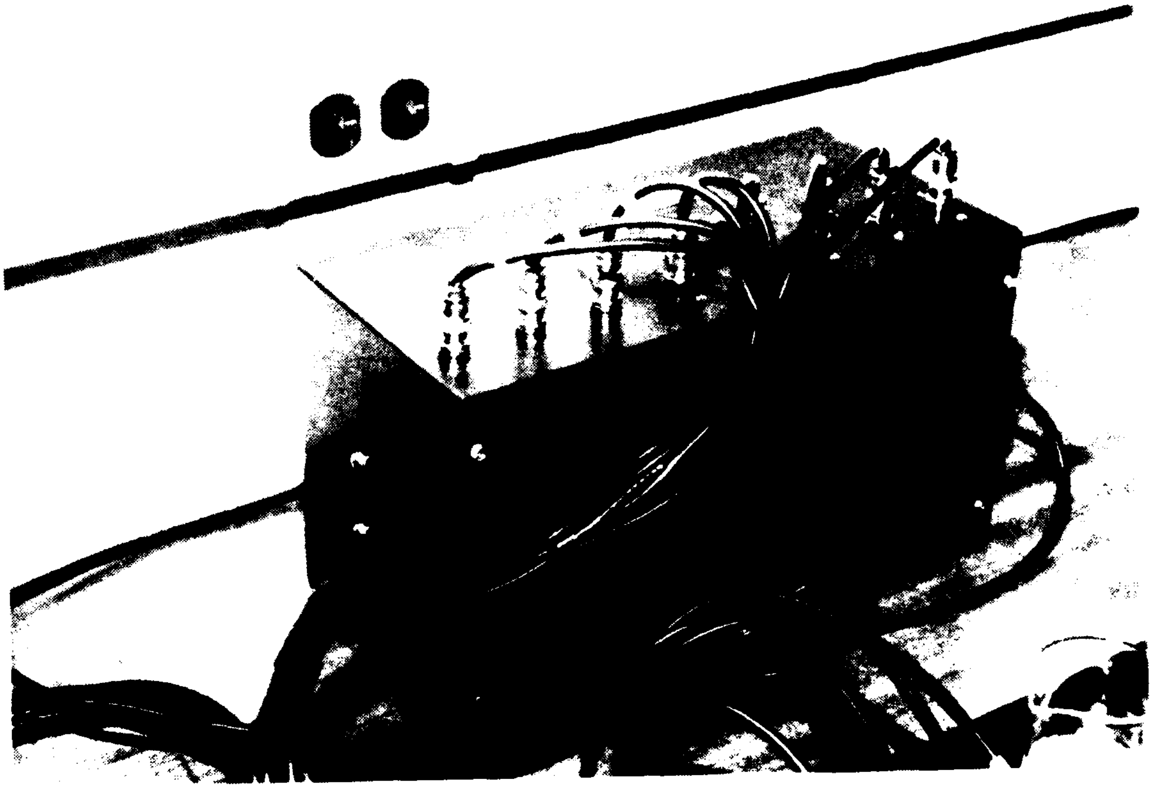

Figure 16. Selector switch assembly.

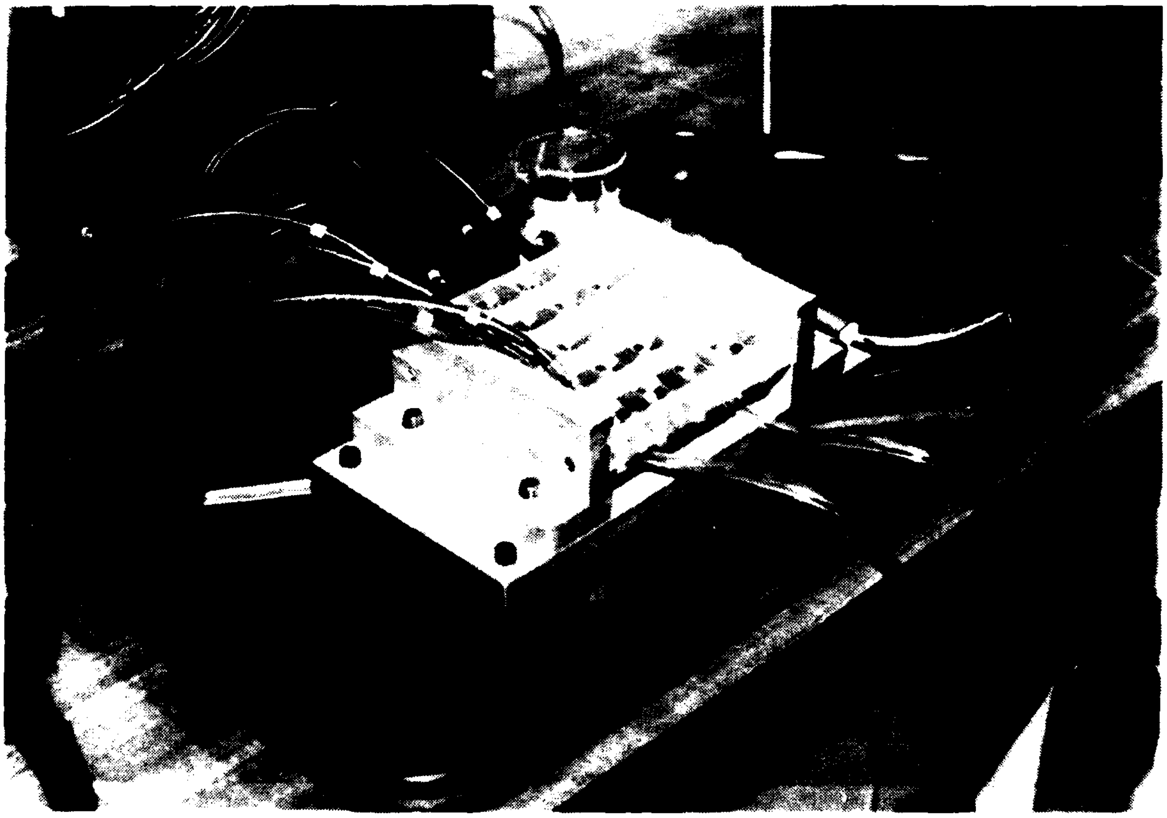

Figure 17. Array transducer connected to the electronics system.

Table 1. System electronic control functions

FUNCTIONS	NORMAL	MATRIX
FULL SCAN	Sequences through all of the rows and columns - one at a time	Sequences through all 15 crosspoints in order - one at a time
SELECT SCAN	Sequences through any rows and columns that are selected	Sequences through any of the cross-points that are selected
ALL	All rows are excited and all columns are grounded	All columns are excited and all rows are grounded
ROW PARALLEL	Selected rows are excited and all columns are grounded	Selected columns are excited and selected rows are grounded
COLUMN PARALLEL	Selected columns are excited and rows are grounded	Selected columns are excited and selected rows are grounded

To test the transducer in the laboratory, the gas system was attached as illustrated in Figure 18 and shown in Figure 19. A gas pressure regulator (Matheson 40-L) supplied pressure to one port of the array transducer. The differential pressure acting on the membrane was monitored through the other array gas pressure port using a mercury manometer. Fine control of the gas pressure was performed using a micrometer air-bleed valve.

Preliminary tests have been conducted on the transducer to better understand its operation. In the tests, the transducer was mounted face-up as shown in Figure 17. A .4375 in. dia. acoustical receiver transducer was connected to an oscilloscope. In each transducer, water was placed as an acoustical couplant material between the membrane and receiver transducer. All transducers were found satisfactory for operation. In row 1, the column 2 transducer had about 20 percent of its silver paint flaked off due to membrane crimping during assembly. The column 4 transducer had a scratch on the paint. The row 2, column 2 transducer suffered about a five percent paint loss. In all the tests 2.8 cm Hg differential membrane gas pressure was used.

In test procedure-1 a continuous wave 20 MHz signal at 30 percent Amplitude was applied to all of the transducers. When the receiver transducer was placed over each transducer, a signal from 90 to 110 mv peak-to-peak could be received. The orientation of the receiver was very important. This test established initial uniformity of the transducer output signal. Table 2 indicates the results of the test. In test procedure-2, the frequency was lowered to 15.2 MHz and readings were again taken. The uniformity of the signal output is indicated in Table 3. In test procedure-3, the test was the same as in previous experiments except that all the transducers in row-1 were activated in the pulse mode. Although the row-1 transducers generated more output power overall, there was still a great deal of signal being generated from the other units. This RF coupling problem needs further investigation. Even when a single transducer was activated, significant RF bleed-over was encountered. To test whether or not this was RF coupling between the source electrode and the transducer, the parameters of test procedure-2 were repeated. In the first step, transducer 3-3 [row-3, column-3] was read at 128 mv peak-to-peak. When a .0045 inch thick piece of foil was placed in front of the receiver 12 mv peak-to-peak was read. Finally, the signal electrode output was placed on the foil and no change was observed in the transducer output. This indicates that RF antenna coupling to the receiver transducers may not be the problem. The major problem in using a transducer as a single element is its own internal capacitance. The high capacitance of the dielectric PVDF material results in significant internal coupling. Even when a signal and ground electrode on a transducer have been connected, output from the shorted transducer has been observed.

The final test of the array was to set up the system shown in Figure 20. Spatially filtered argon laser light is collimated on to the water covered surface of the array and collected onto a viewing screen. An aperture is placed at the focal point of the lense for higher-order filtering of the reflected light from the water surface. When a transducer element is activated, levitation of the water surface occurs resulting in a diffracted image on the viewing screen. When maximum continuous wave power was applied to all transducer elements simultaneously with an 8.4 cm Hg vacuum and 1.0 inch of water covering the array, the following was observed:

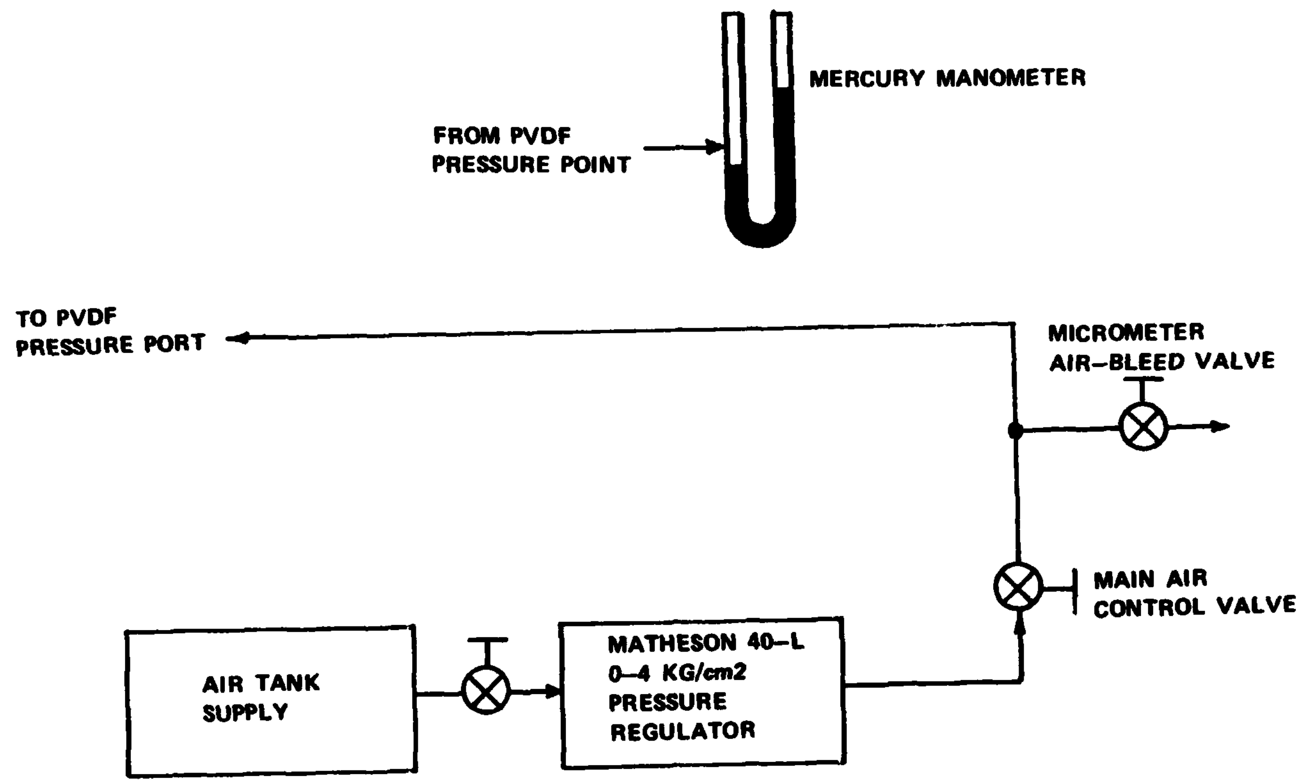

Figure 18. Mechanical Block Schematic of PVDF Transducer Gas Supply System.

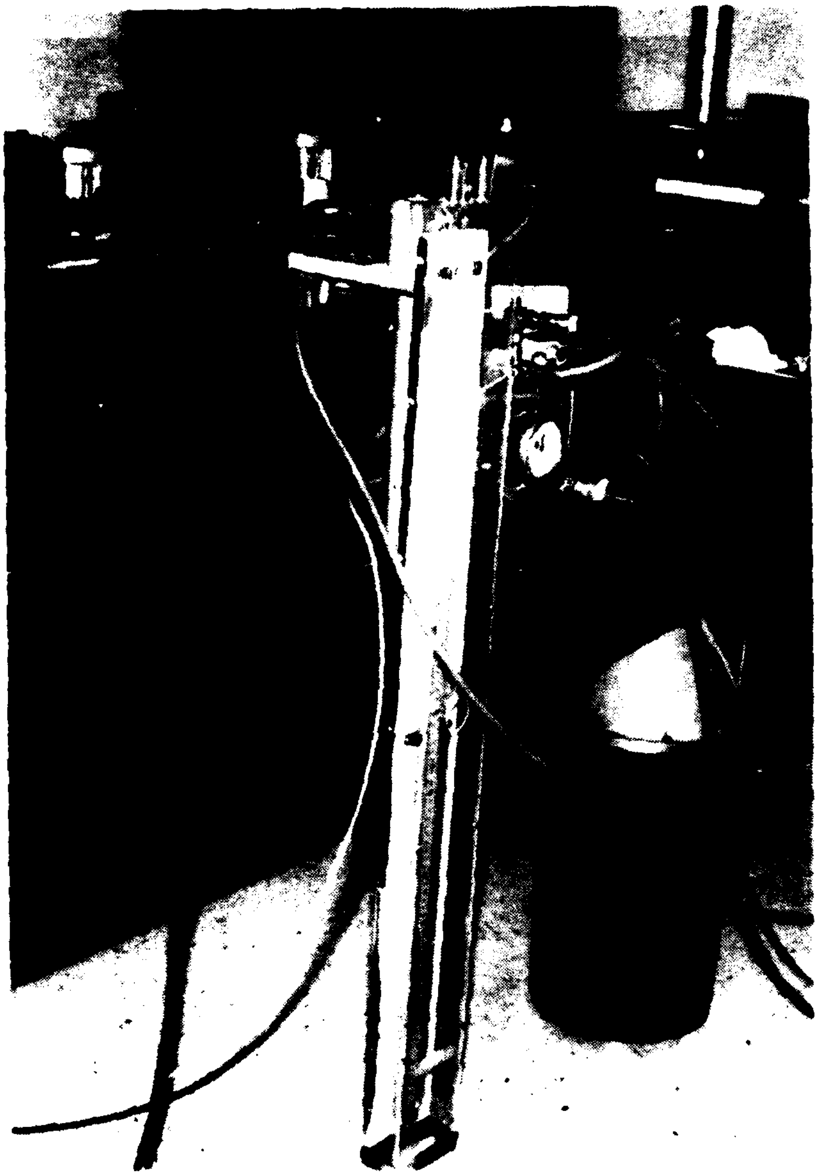

Figure 19. PVDF Transducer Gas Supply System.

Procedure - 1

Test Parameters:

Δ^P membrane = 2.8 cm Hg

20 MHz Operating Frequency

CW Mode

Transmit - ALL

10,000 pps

30% Amplitude

50 μs pulse width

Table 2. Procedure-1 Receiver Voltages

Column Electrodes

Row Electrodes	1	2	3	4
1	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%
2	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%
3	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%
4	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%	100 mv ± 10%

Signals are peak-to-peak voltages

<u>Procedure - 2</u>

Test Parameters:

Same as Procedure - 1 except that a 15.2 MHz Operating Frequency was used.

Table 3. Procedure-2 Receiver Voltages

Column Electrodes

Row Electrodes	1	2	3	4
1	140 mv	146 mv	146 mv	146 mv
2	148 mv	146 mv	140 mv	144 mv
3	150 mv	146 mv	146 mv	144 mv
4	150 mv	160 mv	144 mv	144 mv

Signals are peak-to-peak voltages

Procedure - 3

Test Parameters:

Same as Procedure - 2 except that the Row Mode and Pulse Mode were activated. Row-1 was activated.

Table 4. Procedure-3 Receiver Voltages

Column Electrodes

	1	2	3	4
1	70 mv	70 mv	64 mv	64 mv
2	62 mv	62 mv	64 mv	66 mv
3	60 mv	62 mv	62 mv	62 mv
4	60 mv	62 mv	64 mv	64 mv

Signals are peak-to-peak voltages

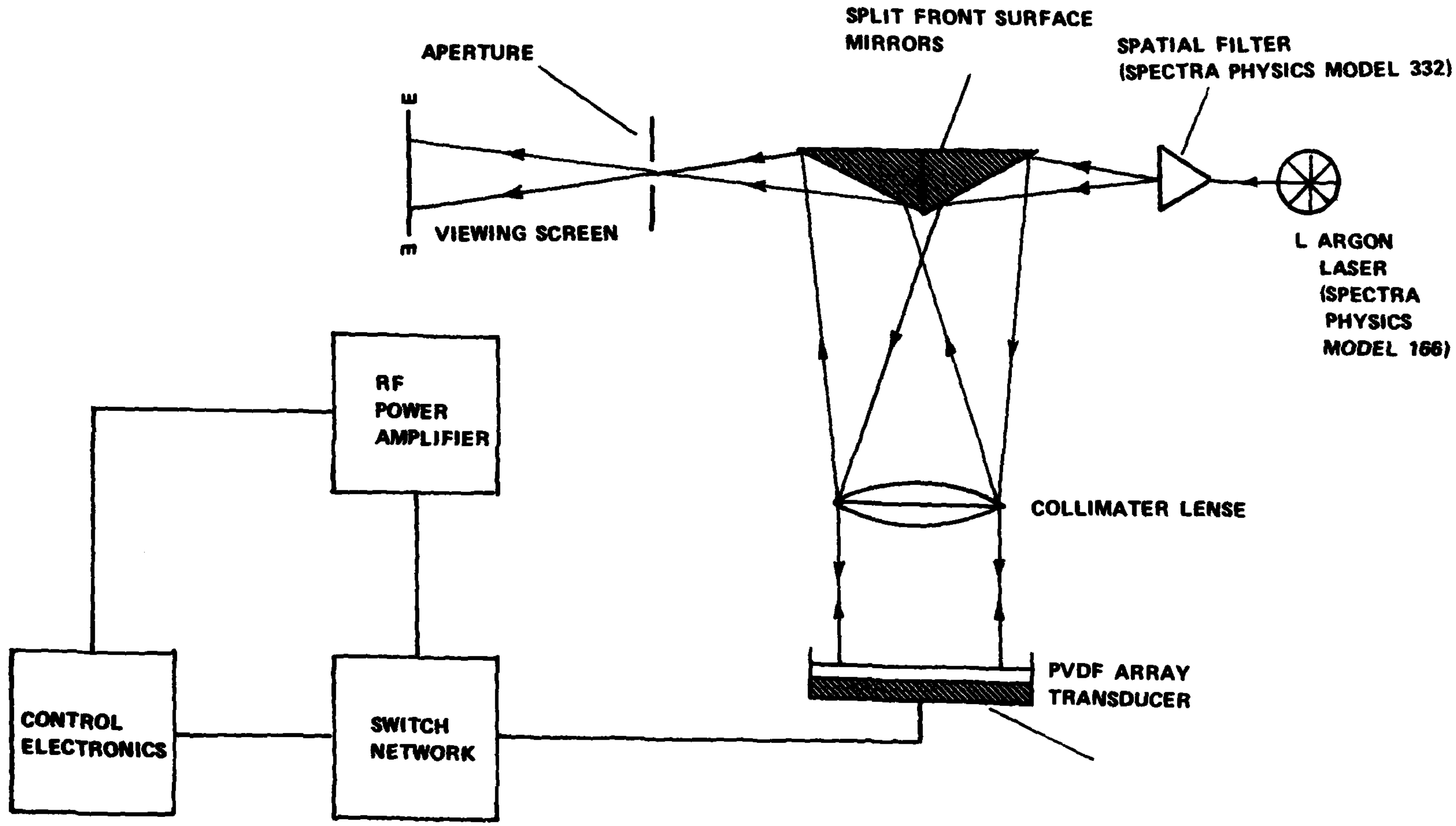

Figure 20. Real-time Array Performance Viewing System.

(1) A .500 MHz to 13.500 MHz Response Frequency was observed.

(2) The maximum response occurred at 13.500 MHz.

(3) Transducer performance was improved with the applied vacuum.

When a single transducer was activated, RF cross-over to the other transducers was observed only at the higher frequencies. The transducer was not characterized by broad-band frequency response. The array tended to resonate at rather narrow select frequencies. In general, all the elements of the array responded in a similar manner. Also, transducers with crimped edges tended to perform much more poorly.

IV. CONCLUSIONS

The acoustical array transducer is relatively inexpensive to fabricate, has a good frequency response range and a variable focal length. Specific problems encountered with the present device include RF cross-over, low power output resulting in low efficiency and electrode problems. A suitable replacement needs to be found for the silver paint since it tends to dampen the generation of ultrasound and degrades with operating time and exposure to water. The present device shows promise for being integrated into large panels of transducers and possibly phased arrays. It shows potential for NDT and Experimental Mechanics Applications.

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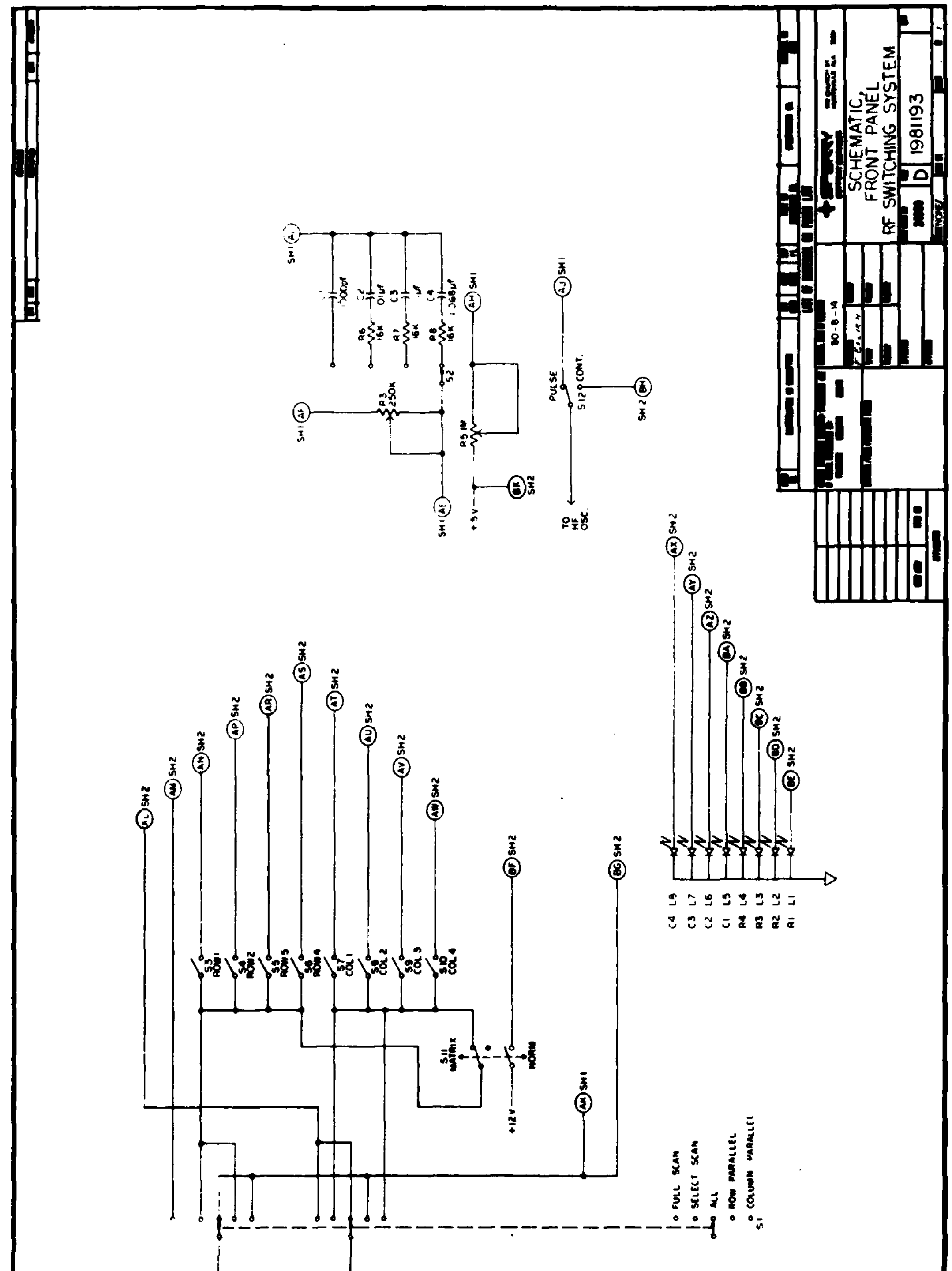
APPENDIX

This appendix contains drawings of the control electronics manufactured by Sperry Support Services to control the PVDF array transducer.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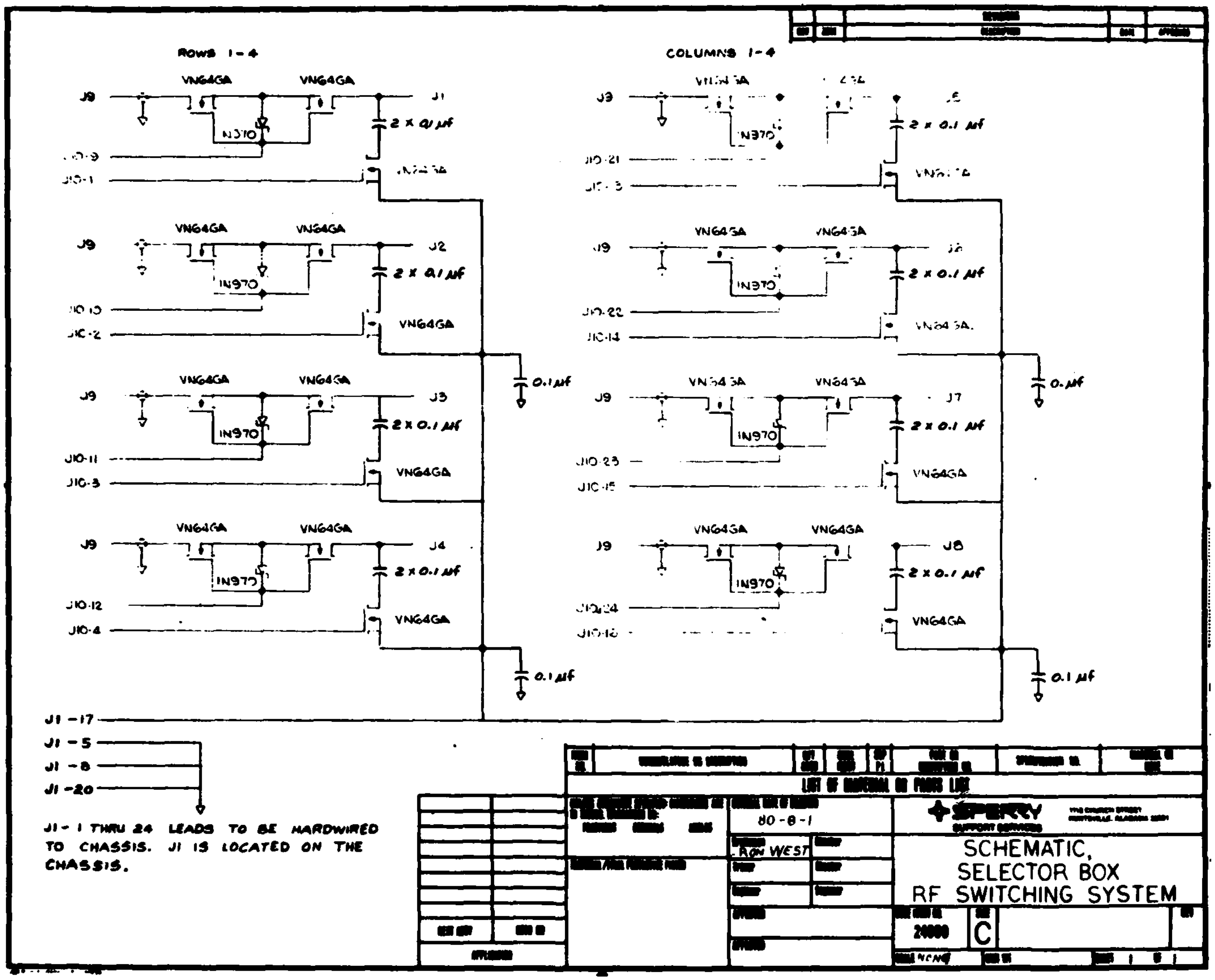
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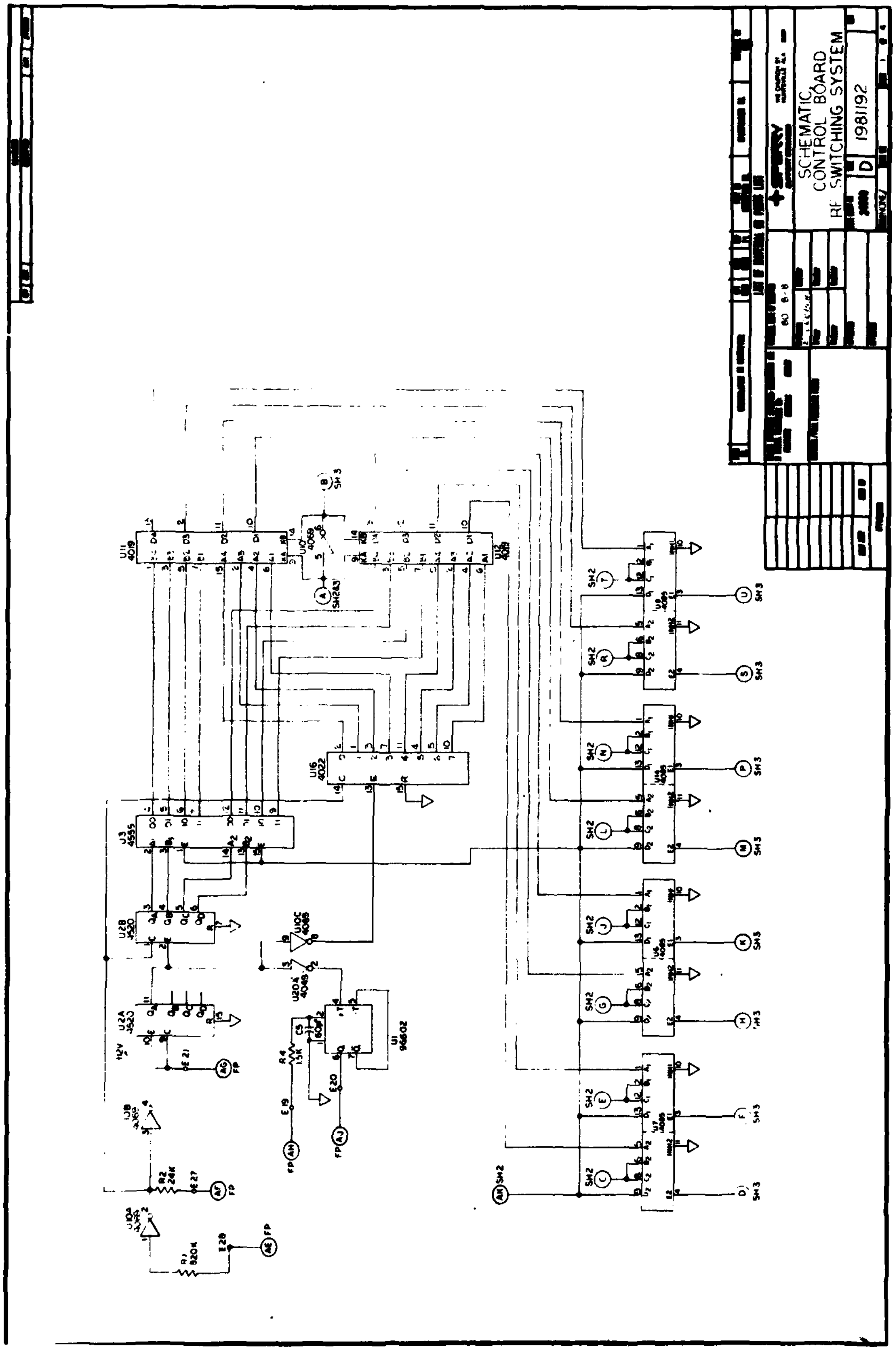
RF SWITCHING SYSTEM
C


SCHEMATIC
CONTROL BOARD
RF SWITCHING SYSTEM
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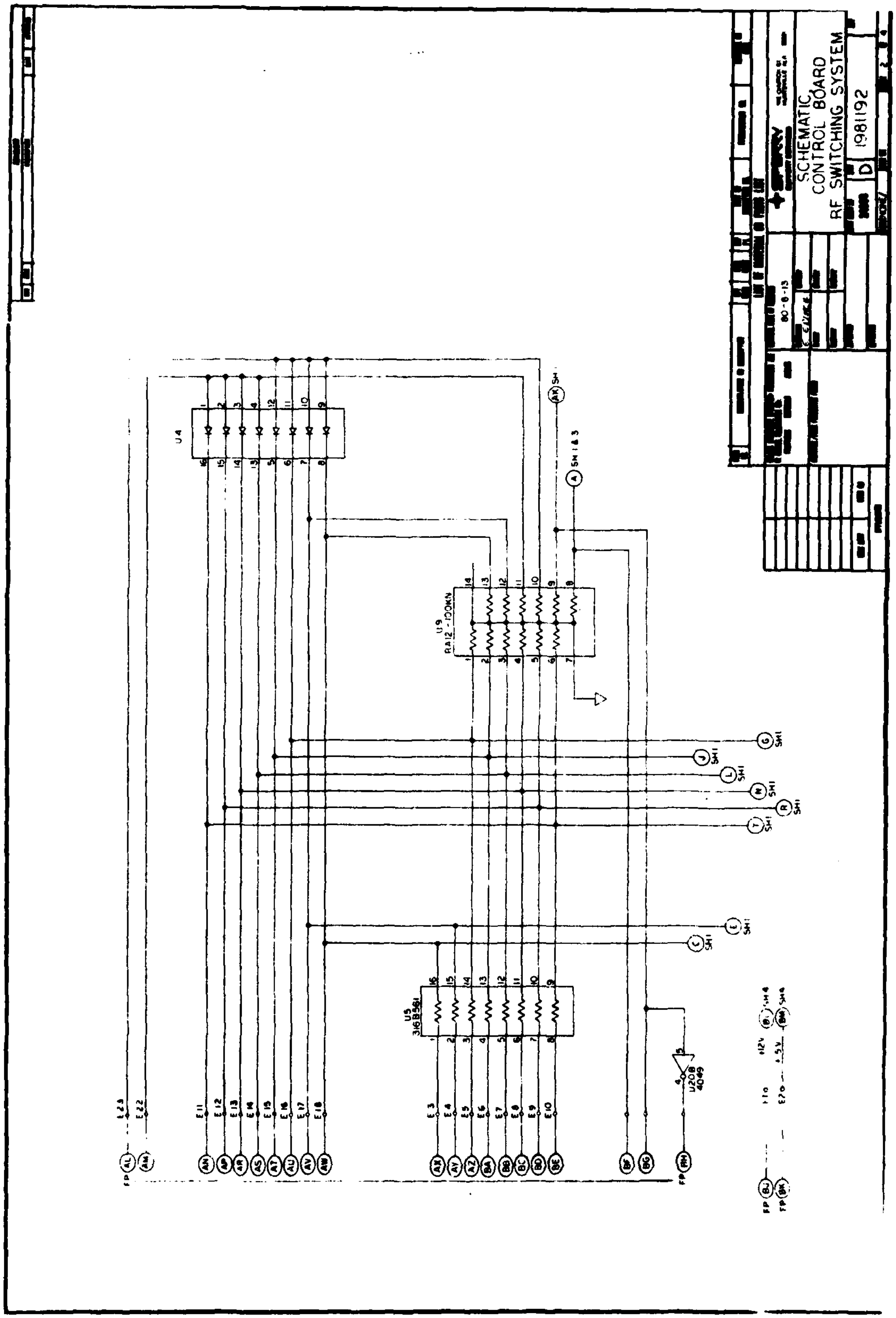
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U4
U9
RA12 - 100KN
U5
316B561
U20B
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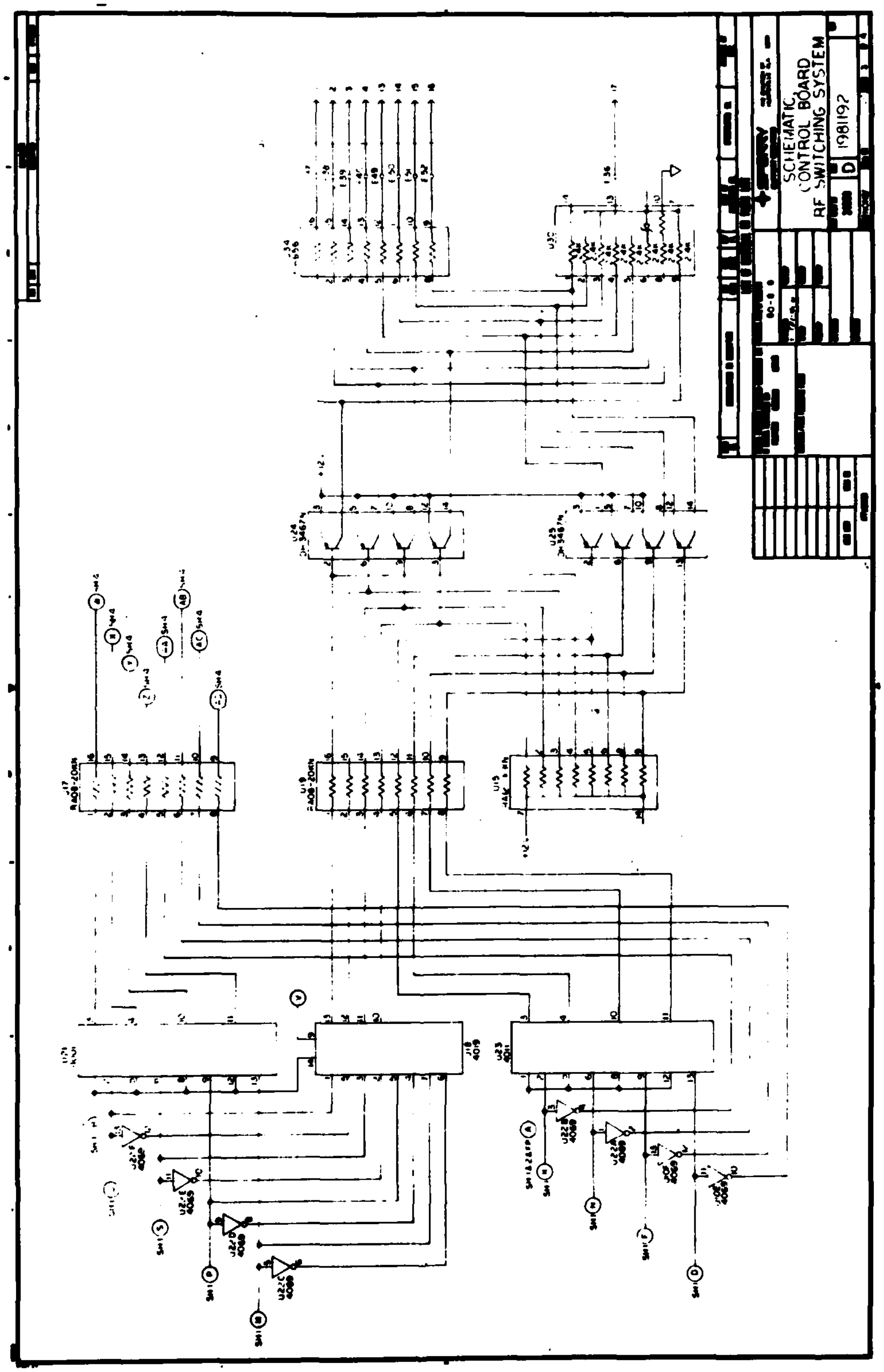
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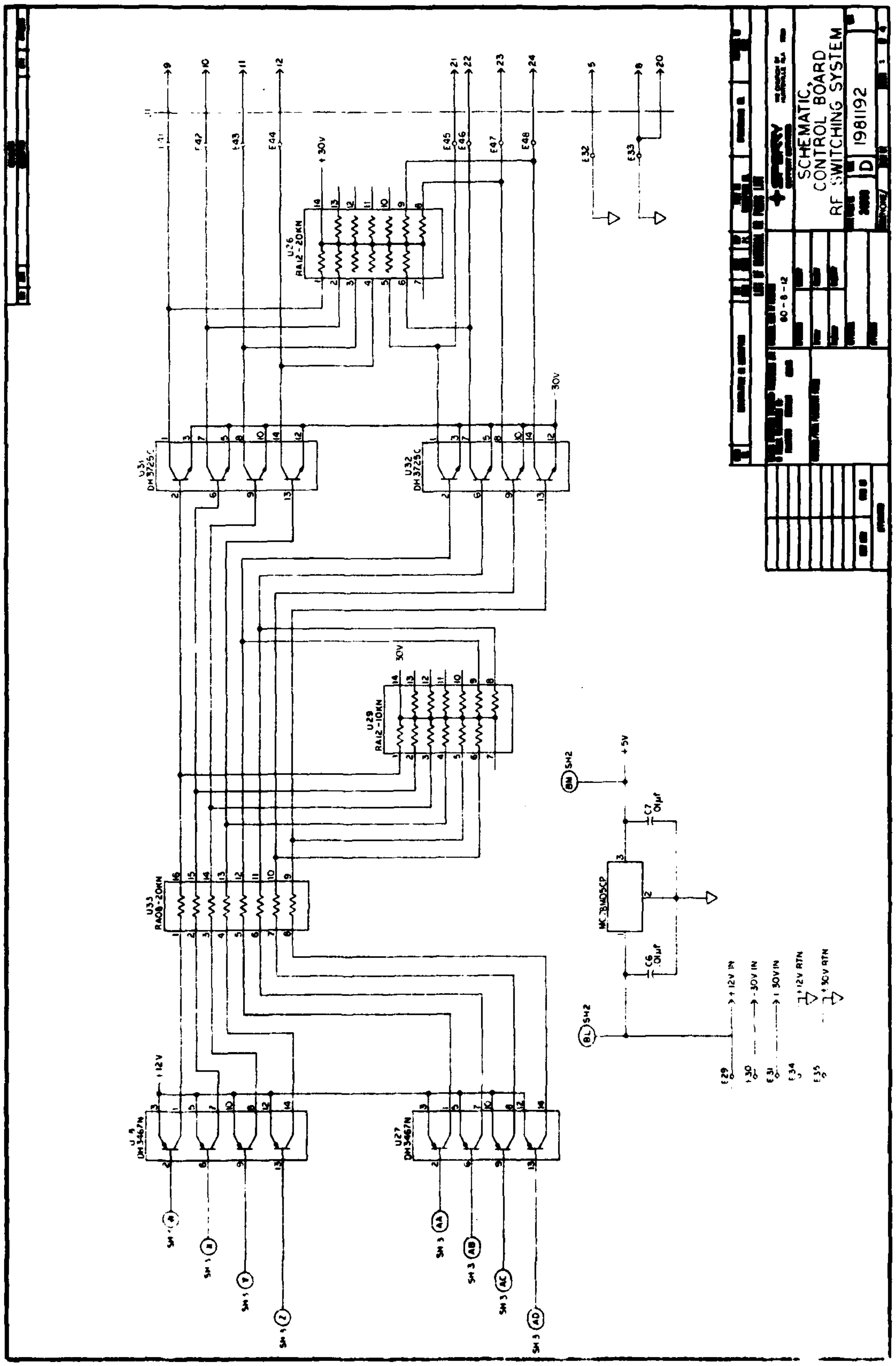

SCHEMATIC, CONTROL BOARD RF SWITCHING SYSTEM
D
1981192
U31 DH3725C
U32 DH3725C
U26 RA12-20KN
U28 RA12-10KN
U33 RA08-20KN
U8 DH3467N
U27 DH3467N
MC7805CP
C6 .01µF
C7 .01µF
+30V
30V
+5V
+12V
+12V IN
-30V IN
+30V IN
+12V RTN
+30V RTN

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