NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROGRAM

VLA ELECTRONICS MEMORANDUM NO. 170

GAS TIGHT WAVEGUIDE WINDOWS FOR THE VLA WAVEGUIDE SYSTEM

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1.0 INTRODUCTION

The circular TE_{01} mode waveguide used in the VLA signal distribution and communication system is subject to environmental effects not experienced in other areas of the system. Due to the direct burial technique employed in the installation of the 60 mm diameter main trunk waveguide and the consequent deep manholes at each antenna station for coupler placement, the main guide is susceptible to water seepage and corrosion which can seriously impair the transmission performance. To overcome these possible problems the waveguide system is pressurized to 2 psi above normal atmospheric pressue with dry nitrogen in order to create a positive pressure against fluid penetration. To contain the gas and yet permit low loss, low reflection signal transmission with minimal spurious mode generation in the overmoded circular (20 mm diameter) antenna waveguide, high performance, gas tight waveguide windows are required. This report describes the design, construction and performance of the windows presently used in the VLA waveguide network.

2.0 THEORETICAL ANALYSIS

The windows used to seal the VLA waveguide are mechanically simple in concept, comprising two thin sheets of dielectric material clamped in a metal holder and spaced approximately 1/4 of a guide wavelength apart. The performance of such a structure can be analyzed in the following manner. Consider an air/dielectric interface in circular waveguide as shown in Figure 1.

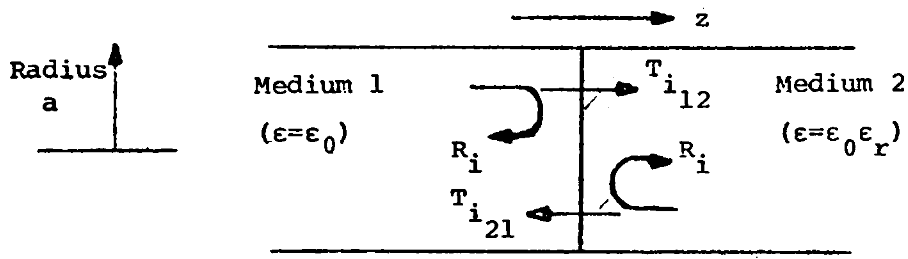


FIGURE 1

Consider an incident TE_{01} mode; the only possible higher order modes which should be considered are the TE_{on} modes (by symmetry considerations). Let $\underline{e}_i$, $\underline{h}_i$ represent the electric and magnetic fields of the i^{th} mode in Region 1, and $\underline{e}_i'$, $\underline{h}_i'$ the electric and magnetic fields of the same mode in Region 2. Then, if R_i, $T_{i_{12}}$ represent the non-normalized reflection and transmission coefficients for the i^{th} mode, by continuity

$$\underline{e}_i + \sum_{n=1}^{\infty} R_n \underline{e}_n = \sum_{n=1}^{\infty} T_{n_{12}} \underline{e}_n'$$

$$\underline{h}_i - \sum_{n=1}^{\infty} R_n \underline{h}_n = \sum_{n=1}^{\infty} T_{n_{12}} \underline{h}_n'$$

Defining

$$(\underline{e}_i, \underline{h}_j) = \iint_S (\underline{e}_i \times \underline{h}_j^*) \cdot i_z ds$$

there result

$$(\underline{e}_i,\underline{h}_i') + \sum_{n=1}^{\infty} R_n(\underline{e}_n,\underline{h}_i') = \sum_{n=1}^{\infty} T_{n_{12}} \quad (\underline{e}_n',\underline{h}_i')$$

$$(\underline{e}_i',\underline{h}_i) - \sum_{n=1}^{\infty} R_n(\underline{e}_i',\underline{h}_n) = \sum_{n=1}^{\infty} T_{n_{12}} \quad (\underline{e}_i',\underline{h}_n')$$

For the TE_{on} modes

$$\begin{aligned}(\underline{e}_i,\underline{h}_j) &= 0 \qquad \forall \quad i \neq j \\ &= \frac{\pi\omega\mu a^2 B_{oi}^{\ 2}}{k_{oi}^{\ 2}} \beta_{oi} \, J_o^{\ 2}(k_{oi}a) \qquad \text{if } i = j\end{aligned}$$

where B_{oi} is a normalization constant

β_{oi} is the waveguide propagation constant for the i^{th} mode in Region 1. (β_{oi} in Region 2).

k_{oi} is the i^{th} root of $J_o'(\chi)=0$.

Similarly

$$\begin{aligned}(\underline{e}_i,\underline{h}_j') &= 0 \qquad \forall \quad i \neq j \\ &= \frac{\pi\omega\mu a^2 B_{oi}^{\ 2}}{k_{oi}^{\ 2}} \beta_{oi}' \cdot J_o^{\ 2}(k_{oi}a) \quad \text{if } i = j\end{aligned}$$

$$\begin{aligned}(\underline{e}_i',\underline{h}_j) &= 0 \qquad \forall \quad i \neq j \\ &= \frac{\pi\omega\mu a^2 B_{oi}^{\ 2}}{k_{oi}^{\ 2}} \beta_{oi} \cdot J_o^{\ 2}(k_{oi}a) \qquad \text{if } i = j\end{aligned}$$

Thus the continuity equations reduce to

$$1 + R_1 = T_{1_{12}} \qquad \frac{\beta_{01}}{\beta_{01}'}(1 - R_1) = T_{1_{12}} \tag{i}$$

$$R_i\beta_{oi}' = T_{i_{12}} \qquad - R_i\beta_{oi} = T_{i_{12}} \tag{ii}$$

where B_{oi} was chosen so that $(\underline{e}_i,\underline{h}_j) = \delta_{ij}$

From equations (ii), it follows

$$T_{i_{12}} = R_i = 0$$

Hence

$$R_1 = \frac{\beta_{01} - \beta_{01}'}{\beta_{01} + \beta_{01}'} = R$$

and the unnormalized transmission coefficient

$$T_{1_{12}} = \frac{2\beta_{01}}{\beta_{01} + \beta_{01}'}$$

Note that, theoretically, no spurious higher order modes should be excited at the interface.

Similarly,

$$R_1' = \frac{\beta_{01}' - \beta_{01}}{\beta_{01}' + \beta_{01}} = -R$$

$$T_{1_{12}} = \frac{2\beta_{01}'}{\beta_{01}' + \beta_{01}}$$

The normalized transmission coefficients are given by

$$T = \left(\frac{T_{1_{12}} \, T_{1_{12}}^*}{\left(\frac{\beta_{01}}{\beta_{01}'} \right)} \right)^{\frac{1}{2}} = \frac{2\sqrt{\beta_{01}\beta_{01}'}}{(\beta_{01} + \beta_{01}')}$$

Let a_1, b_1 be the amplitudes of the forward and reverse traveling waves in Region 1; a_2, b_2 be the amplitudes in Region 2. Thus

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{T_{1_{12}}} \begin{bmatrix} 1 & -R_1' \\ R_1 & \dfrac{T_{1_{12}} T_{1_{12}} - R_1 R'}{T_{1_{12}}} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} = \frac{1}{T_{1_{12}}} \begin{bmatrix} 1 & R \\ R & 1 \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}$$

For a dielectric sheet of thickness t, the transmission matrix is

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{T_{1_{12}} \, T_{1_{21}}} \begin{bmatrix} e^{j\beta'_{01}t} & Re^{-j\beta'_{01}t} \\ Re^{j\beta'_{01}t} & e^{-j\beta'_{01}t} \end{bmatrix} \begin{bmatrix} 1 & -R \\ -R & 1 \end{bmatrix} \begin{bmatrix} a_3 \\ 0 \end{bmatrix}$$

where a_3 is the amplitude of the wave transmitted beyond the sheet. Then the reflection coefficient at the sheet in Region 1 is

$$S_{11} = \frac{R[e^{j\beta'_{01}t} - e^{-j\beta'_{01}t}]}{e^{j\beta'_{01}t} - R^2 e^{-j\beta'_{01}t}}$$

and the transmission coefficient is

$$S_{12} = \frac{(1-R^2) \; e^{-j\beta'_{01}t}}{1-R^2 \; e^{-2j\beta'_{01}t}}$$

Similarly, for the double waveguide window, where the separation between the corresponding surfaces of the sheets is ℓ, the total reflection coefficient is given by (to third order in R)

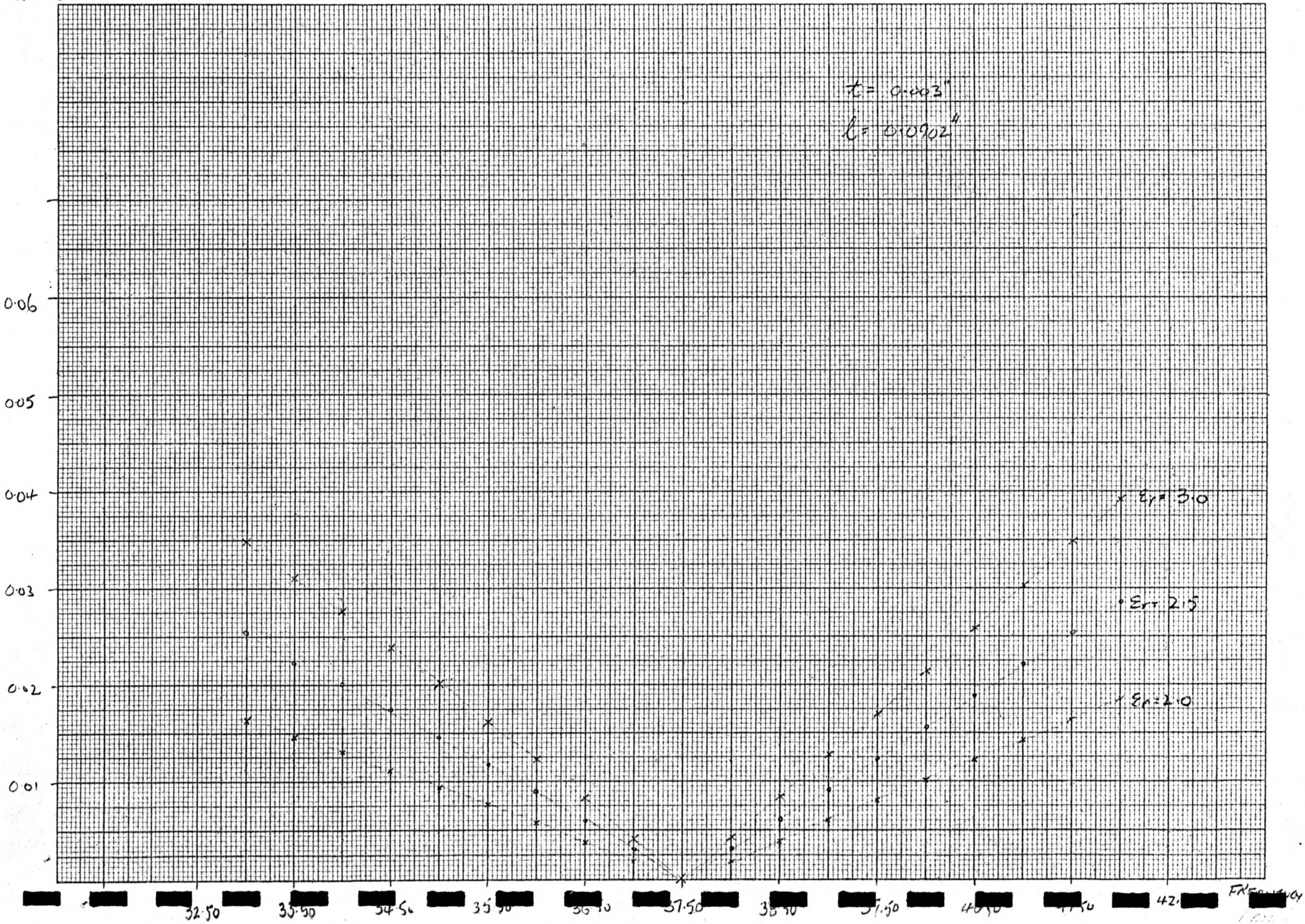
$$S_{11} = \frac{R\{(1-e^{-2j\beta'_{01}t})[(1-R^2\cos(2\beta'_{01}t)(1+e^{2j\beta_{01}\ell})-4R^2\sin^2(\beta'_{01}t)(1+e^{-2j\beta_{01}\ell})]\}}{1 - 2R^2\cos(2\beta'_{01}t) - 8R^2\sin^2(\beta'_{01}t)\cos(2\beta_{01}\ell)}$$

$$+ \frac{\{R^2(1 - e^{2j\beta'_{01}t})(1 + e^{-2j\beta_{01}\ell})\}}{1 - 2R^2\cos(2\beta'_{01}t) - 8R^2\sin^2(\beta'_{01}t)\cos(2\beta_{01}\ell)}$$

and the transmission coefficient by

$$S_{12} = \frac{(1-\beta)e^{-j\beta_{01}\ell}}{1 - \beta e^{-2j\beta_{01}\ell}}$$

FIGURE 2



[redacted]

FIGURE 3

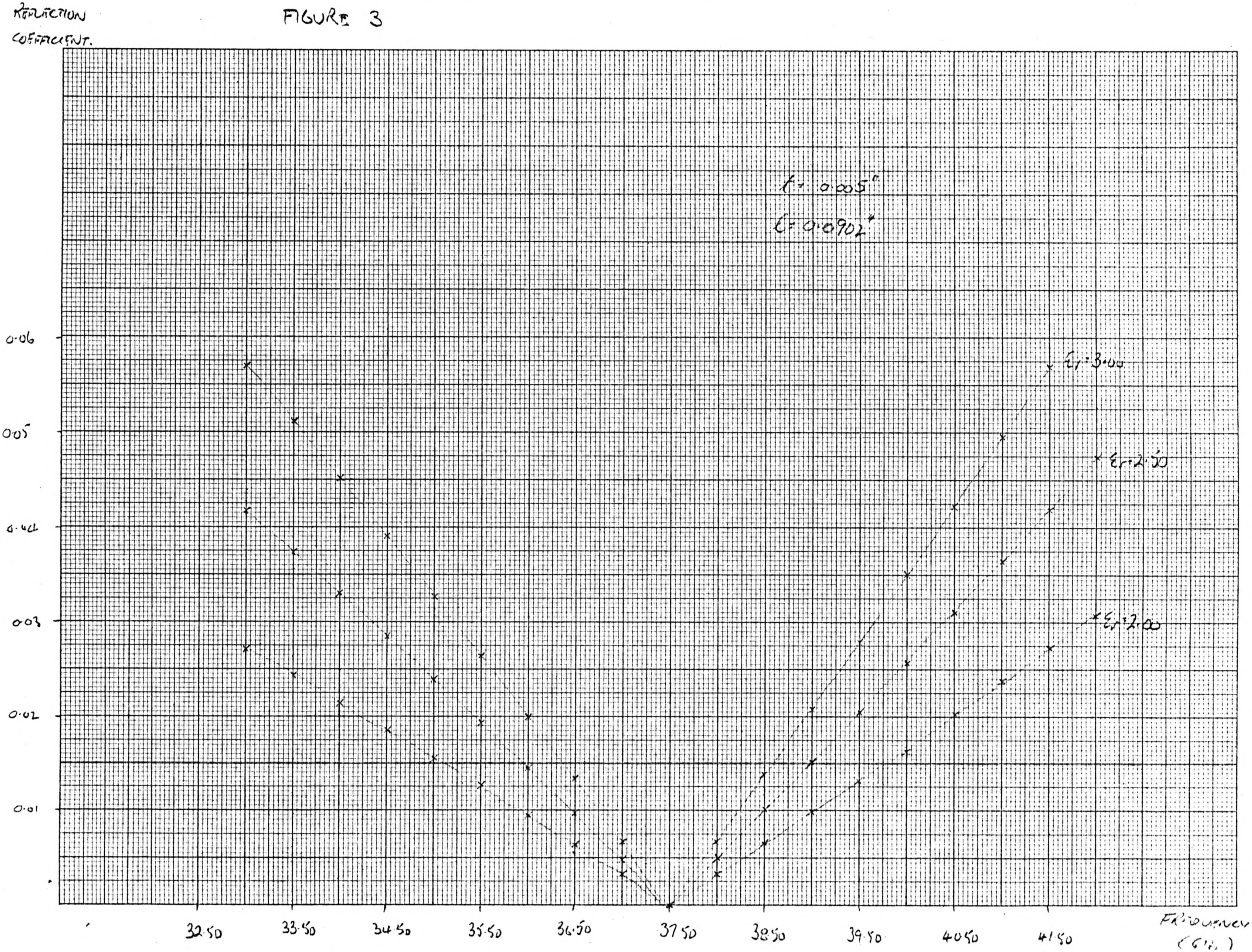
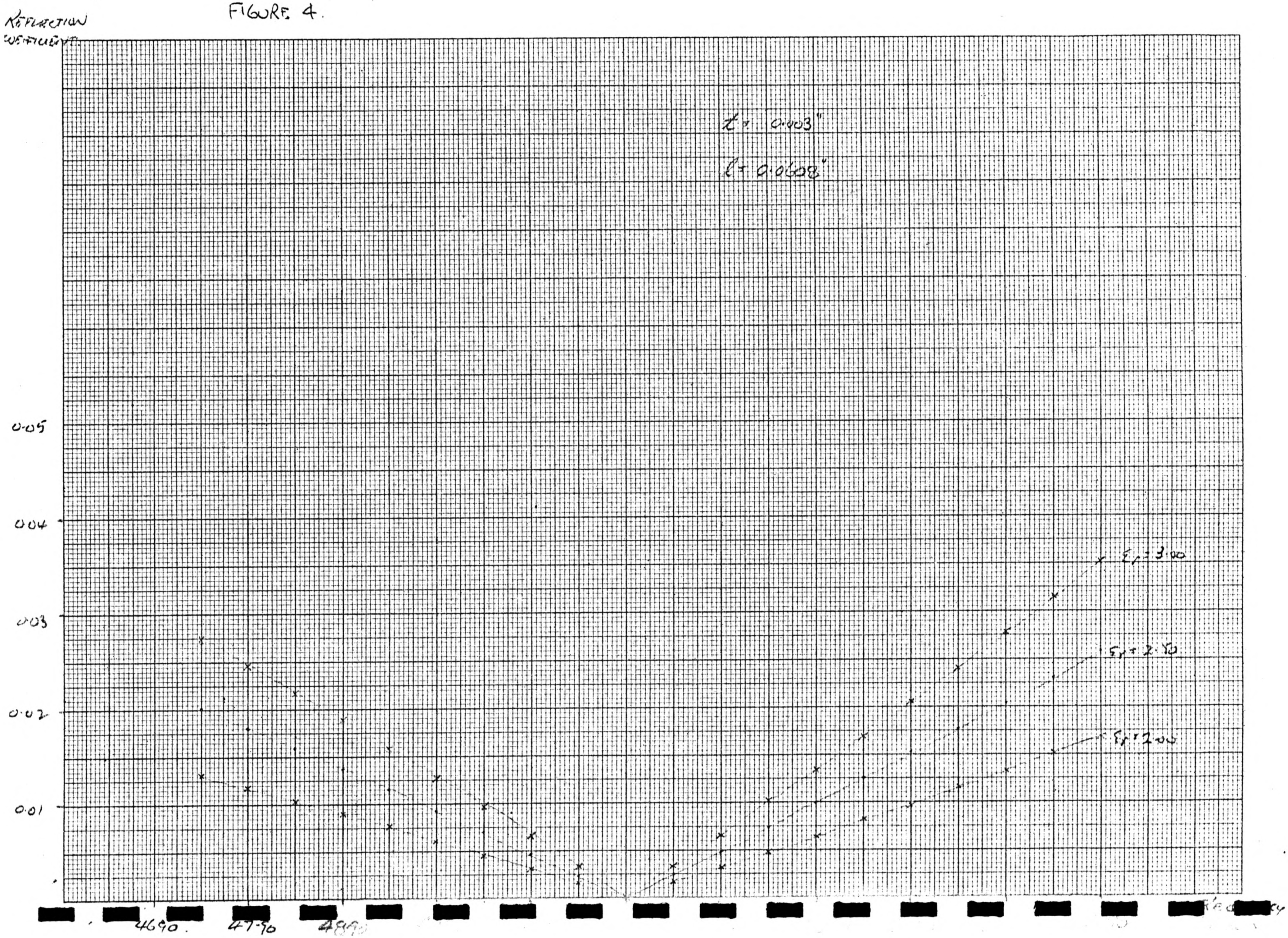

REFLECTION
COEFFICIENT.
t = 0.005"
ℓ = 0.0902"
0.06
0.05
0.04
0.03
0.02
0.01
εr = 3.00
εr = 2.50
εr = 2.00
32.50
33.50
34.50
35.50
36.50
37.50
38.50
39.50
40.50
41.50
FREQUENCY
(GHz)

FIGURE 4.


REFLECTION COEFFICIENT
0.05
0.04
0.03
0.02
0.01
t = 0.003"
l = 0.0608"
εr = 3.00
εr = 2.50
εr = 2.00
[redacted]
4690
4790

where

$$\beta = \frac{4R^2 \sin^2(\beta'_{01}t)}{2R^2 - e^{2j\beta'_{01}t}}$$

The theoretical return loss as a function of frequency in waveguide channels 5 and 11 is plotted in Figures 2, 3 and 4 for a range of window material dielectric constants and thicknesses. It is clear that reducing the thickness of the dielectric broadens the bandwidth of the response, as does a decrease in dielectric constant. Furthermore, the bandwidth of the return loss response can be expected to remain approximately a constant percentage of the center frequency of the window - about 6% of the center frequency for a return loss of greater than -40 dB for $\varepsilon_r = 3{\cdot}0$, $t = 0{\cdot}003"$ and about 12% of the center frequency for $\varepsilon_r = 2{\cdot}0$, $t = 0{\cdot}003"$. It is clear that, with judicious choice of dielectric constant and thickness, a window can be designed to operate with low reflection in a number of waveguide channels, especially at the higher frequencies.

3.0 SYSTEM CONSIDERATION

The tolerated degradation in return loss is determined by the effect on the transmission response of the waveguide distribution system. If there exists two sources of reflection in the 20 mm diameter antenna waveguide, one source being the mismatch at the coupler coupled port and the other being the combined, almost coplanar, modem mismatch and waveguide window reflection, then the ripple in the waveguide amplitude response due to these reflection sources will have a period of approximately 3·75 MHz and a peak-to-peak amplitude given by

$$A_{pp} = \frac{1 - \rho_c \rho_m e^{-2\alpha_{01}\ell_a}}{1 + \rho_m \rho_c e^{-2\alpha_{01}\ell_a}}$$

where ρ_c, ρ_m are the coupler and modem/window reflection coefficients, respectively. α_{01} is the TE_{01} mode attenuation coefficient in the 20 mm diameter antenna waveguide (~0·1 dB/meter). ℓ_a is the distance between reflection sources (~40 meters).

Typically, A_{pp} is required to be less than 1% of the overall average waveguide loss. Furthermore, ρ_c is found experimentally to be 0·1259, thus

$$\rho_m < 0{\cdot}1236$$

is required for a peak-to-peak ripple of less than 1%. In terms of return loss

$$R_m > 18 \text{ dB.}$$

The return loss of the modem by itself is of the order of 25 dB, so the window must not degrade the return loss by more than 7 dB. The worst case window return loss allowable (reflected signals in phase) is then 23·5 dB. The criterion for application of a given window in a certain waveguide channel will be that the return loss in that channel should be greater than 35 dB, resulting in a maximum peak-to-peak ripple of 0·75%.

4.0 MECHANICAL DESIGN

The window is designed to interface with the standard 20 mm waveguide flange used throughout the VLA system. As shown in Figure 5 through 8, it is comprised of three major sections - two clamping flanges and a spacer of accurately determined thickness. The flanges and spacer are held together, as shown in Figure 8, by counter-sink screws, clamping the mylar dielectric material (ϵ_r=2·6, t=0·003") in the recess provided. The structure is rendered gas tight by the two '0' ring seals between flanges and spacer. The optimum spacer thickness for a given waveguide channel is indicated in the table in Figure 5.

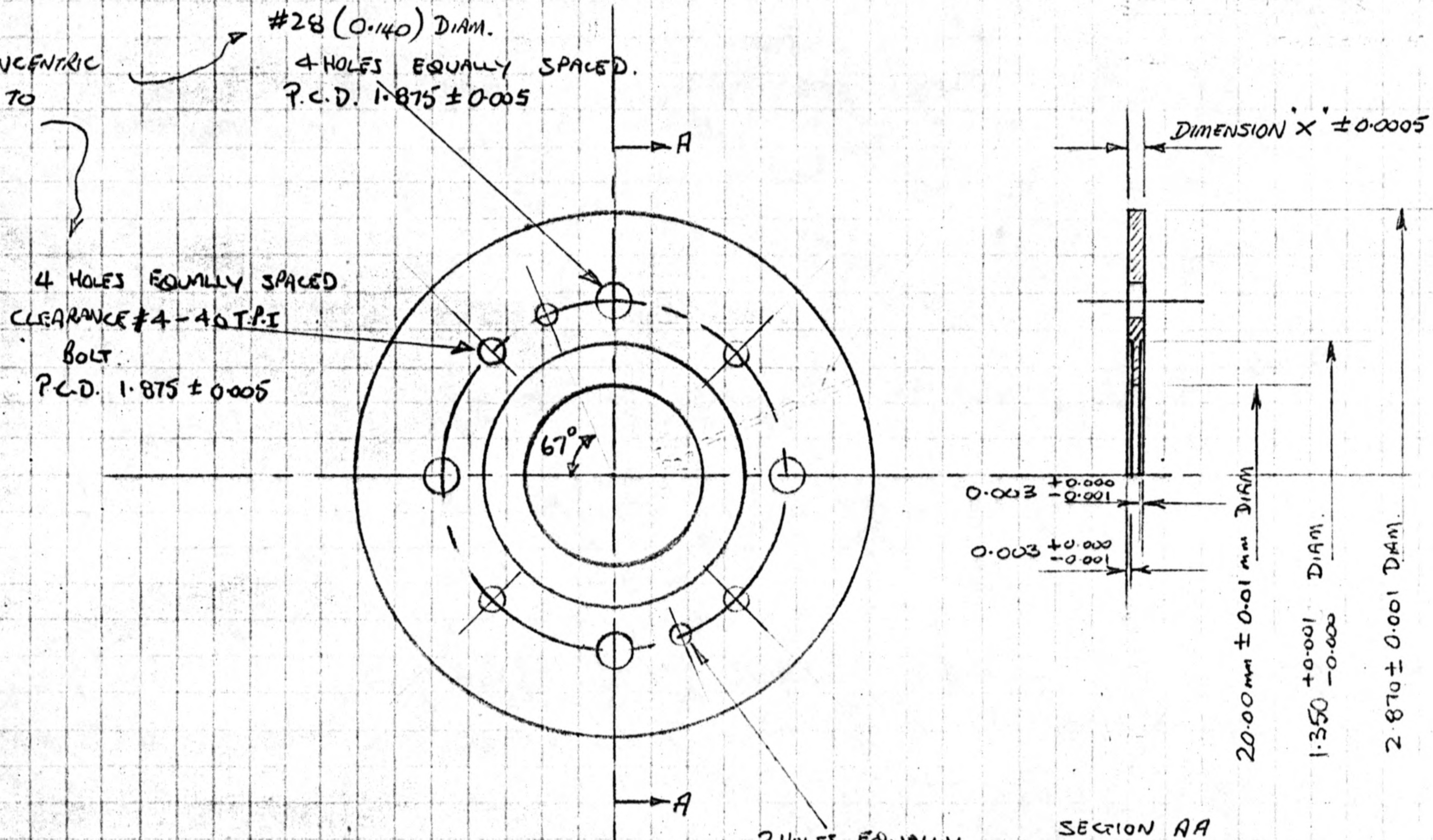
FIGURE 5

BOGUE MACHINE 265-7561.

20mm WAVEGUIDE GAS TIGHT WINDOW

a) SPACER.

PITCH CIRCLE FOR THESE HOLES TO BE CONCENTRIC WITH INNER SURFACE TO WITHIN ± 0.001



2 HOLES EQUALLY SPACED
0.102 +0.001 −0.000 DIAM
P.C.D. 1.875 ± 0.001
CONCENTRIC WITH INNER SURFACE TO ± 0.0005

SECTION AA

CHANNEL NO.	DIMENSION "X" (INCHES)
1	0.1177
2	0.1084
3	0.1005
4	0.0876
5	0.0823
6	0.0777
7	0.0697
8	0.0677
9	0.0633
10	0.0608
11	0.0570

NOT TO SCALE.

MATERIAL: BRASS

FINISH: NATURAL

ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED.

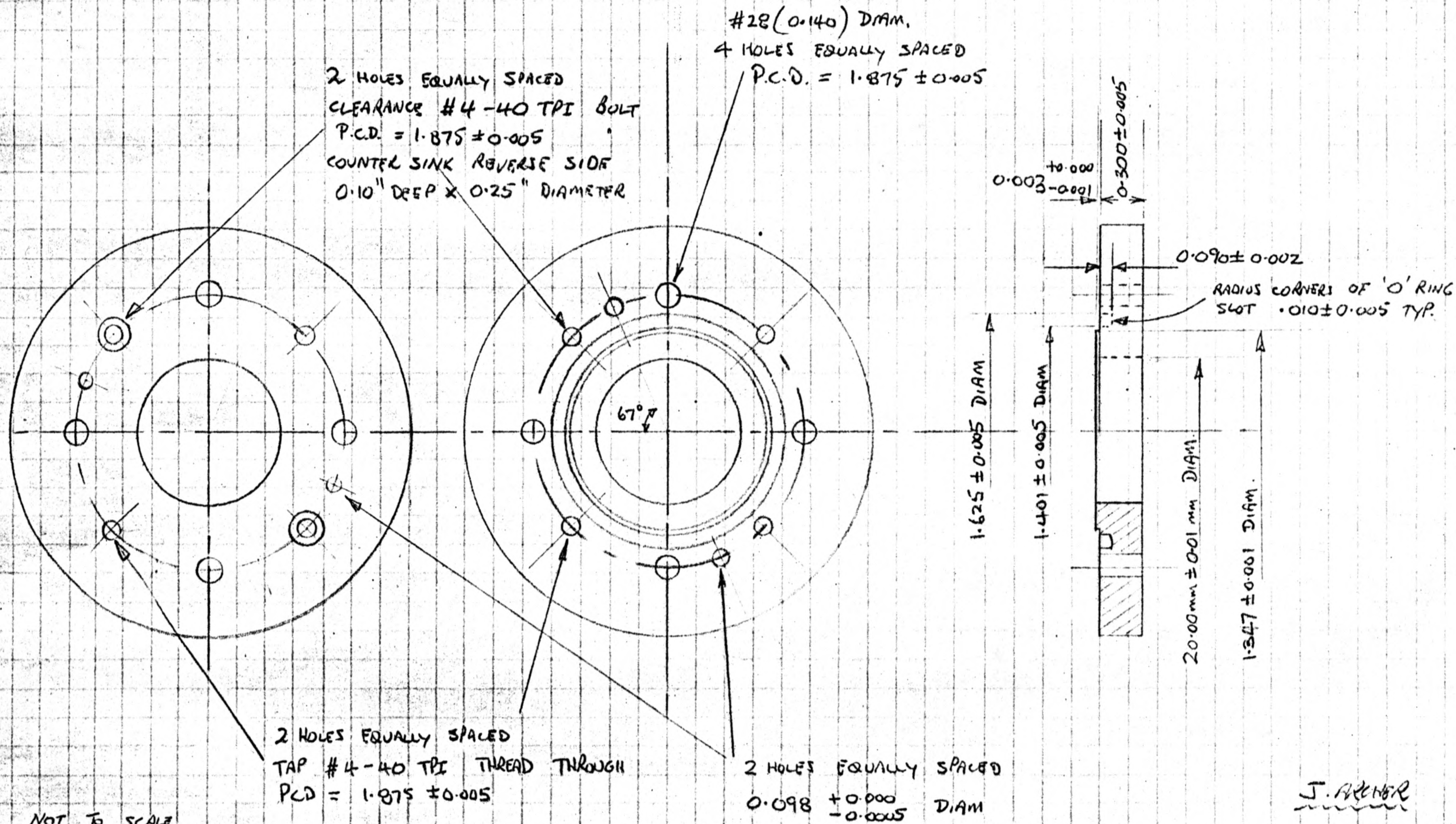
J. ARCHER

EXT 292.

FIGURE 6

20mm WAVEGUIDE GAS TIGHT WINDOW

b) FLANGE NO. 1 – LOCATING PIN



PRESS FIT FOR LOCATING PINS

PITCH CIRCLE DIAMETER 1.875 ±0.001

CONCENTRIC WITH INNER SURFACE TO ±0.0005

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EVT 292.

NOT TO SCALE

MATERIAL: BRASS

FINISH: NATURAL

ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

LOCATING PIN

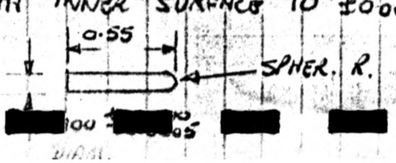
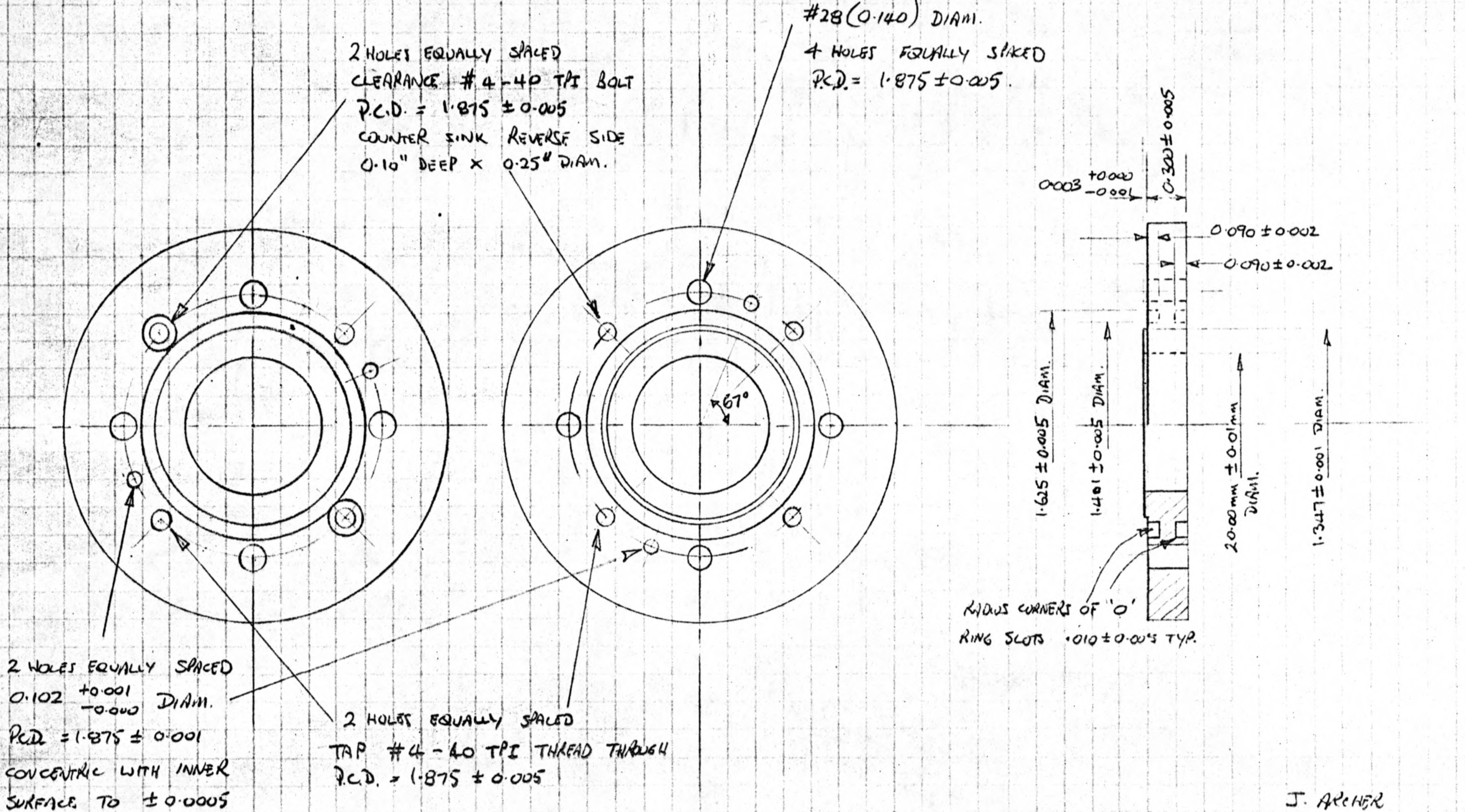


FIGURE 7

20 mm WAVEGUIDE GAS TIGHT WINDOW.

c) FLANGE No. 2



J. ARCHER

EVT 292.

MATERIAL: BRASS

NOT TO SCALE

FINISH: NATURAL.

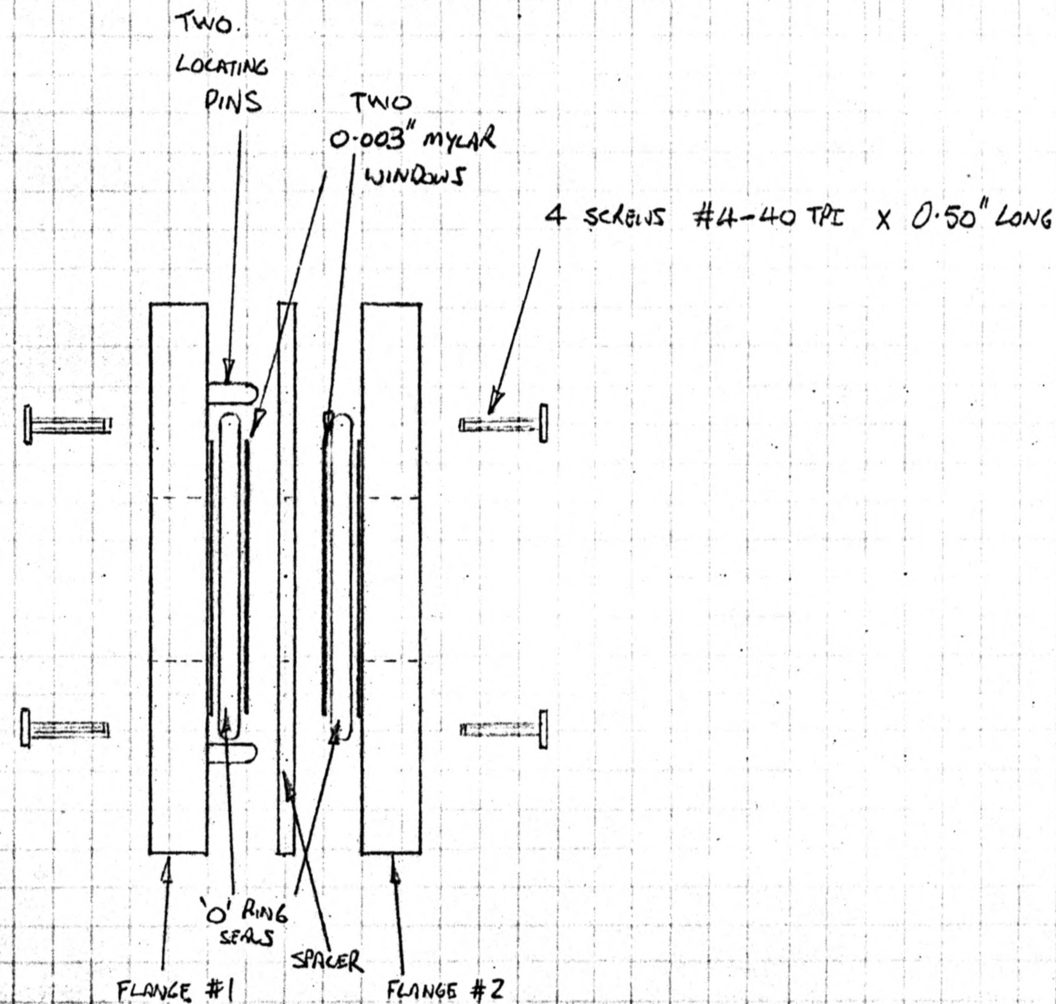
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED.

FIGURE 8

20mm WAVEGUIDE GAS TIGHT WINDOW.

d) ASSEMBLY DETAIL.

NOT TO SCALE



5.0 PERFORMANCE

After assembly, the return loss of each waveguide window for channels 1 through 9 was measured* using the test configuration indicated in Figure 9. The measured responses are shown in Figures 9 through 17. In each plot, the reference trace indicates the return loss of a standard waveguide termination inserted following the window. Hence, the return loss of the window is approximately given by the difference in loss between the traces with and without the window in position. It can be seen that the windows perform adequately for the design channel and that the higher frequency devices (channels 5 through 9) are capable of covering at least two waveguide bends.

The maximum withstandable pressure differential has been tested on two production windows, and in both cases no rupture was observed for pressures up to 60 psi. Clearly, there exists an adequate safety margin, since the envisaged operating pressure is no more than 20 psi.

In order to investigate the effect on electrical performance of distortion of the mylar window material at high pressure gradients, the return loss was measured before and after pressurization to 60 psi (for a channel 5 window). As can be seen from Figures 18-19 the observed performance degradation is sufficiently small to be of little significance under normal operating condition. The magnitude of the TE_{02} mode generated by the device, with a TE_{01} mode incident, was measured and was found to be at least 35 dB below the transmitted TE_{01} power level in any given channel.

*These measurements were made with the window unpressurized.

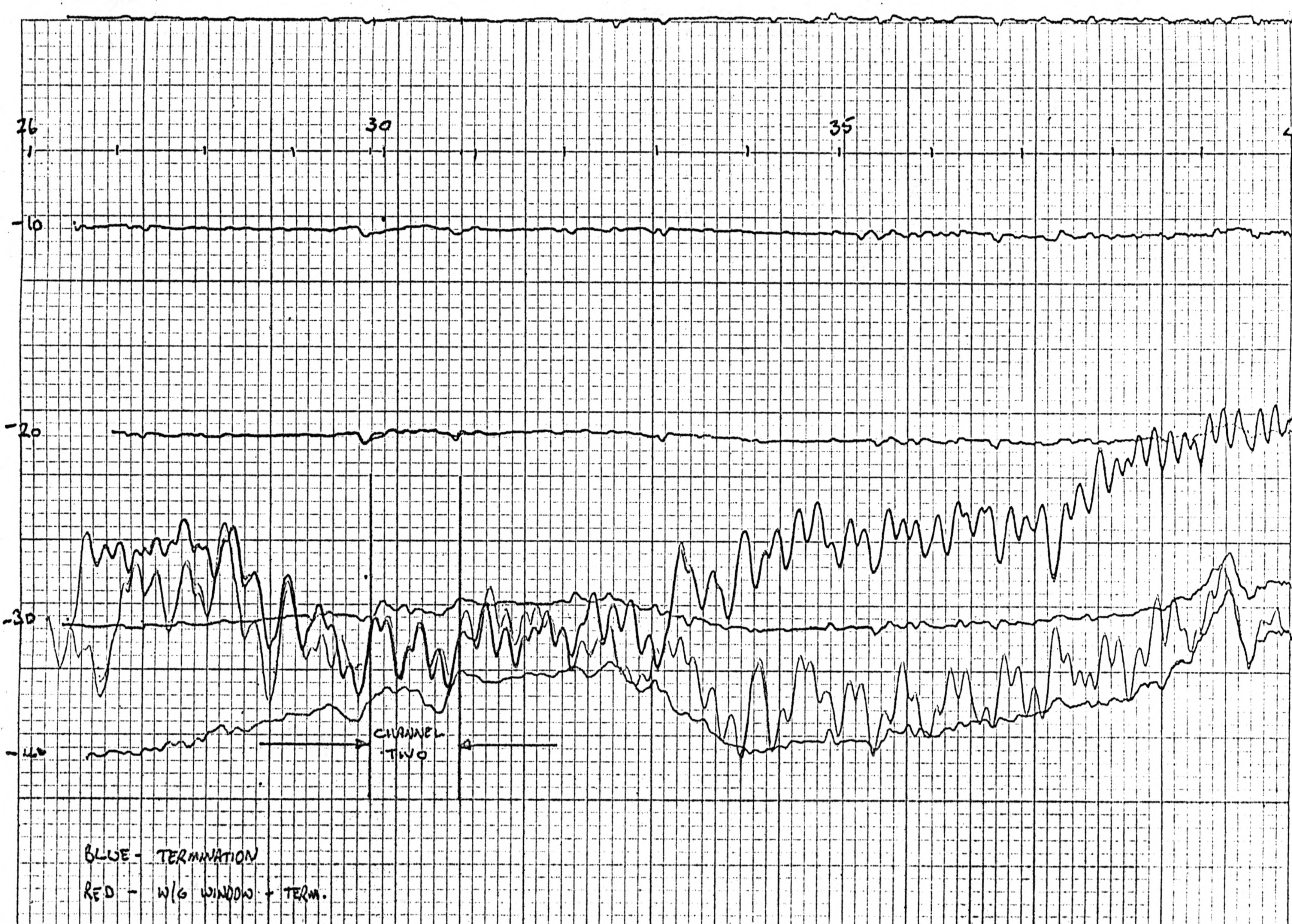
K+E 10 X 10 TO THE INCH • 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

46 0782

FIGURE 9 CHANNEL ONE (0.1177" SPACER) 5/2/78.

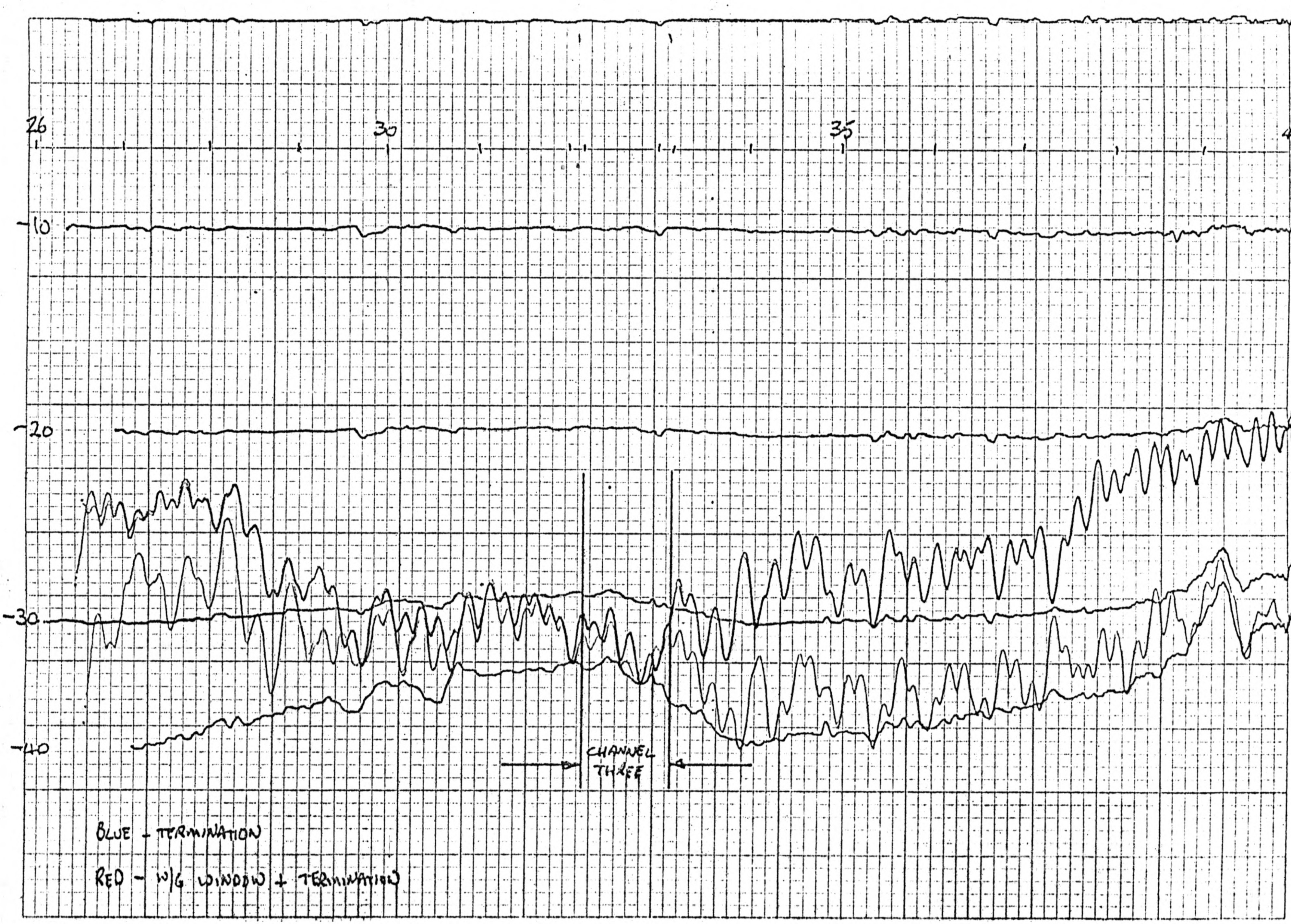
[redacted] TO T[redacted]CH • [redacted]NCHES [redacted] [redacted]782

FIGURE 10 CHANNEL TWO (0.1084" SPACER) 5/2/78



K+E 10 X 10 TO THE INCH • 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 0782

FIGURE 11 CHANNEL 3 (0.1005" SPACER) 5/2/78



[redacted] [redacted] TO [redacted] CH • [redacted] NCHE [redacted]
KEUFFEL & ESSER CO. MADE IN U.S.A. [redacted] 0782

FIGURE 12 CHANNEL 4 (0.0876" SPACER) 5/2/78

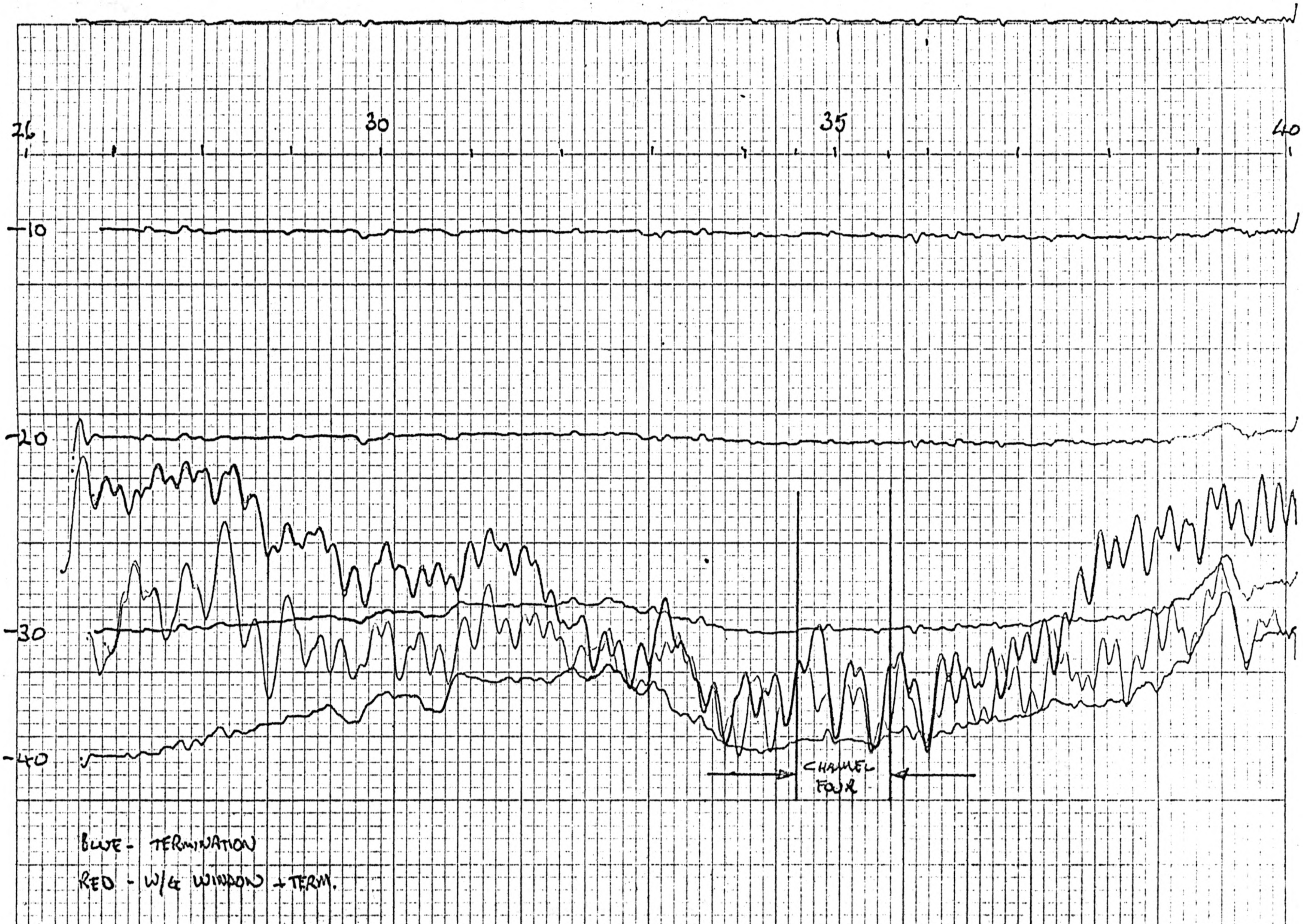


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FIGURE 13 CHANNEL 5 (0.0823" SPACER) 5/2/78

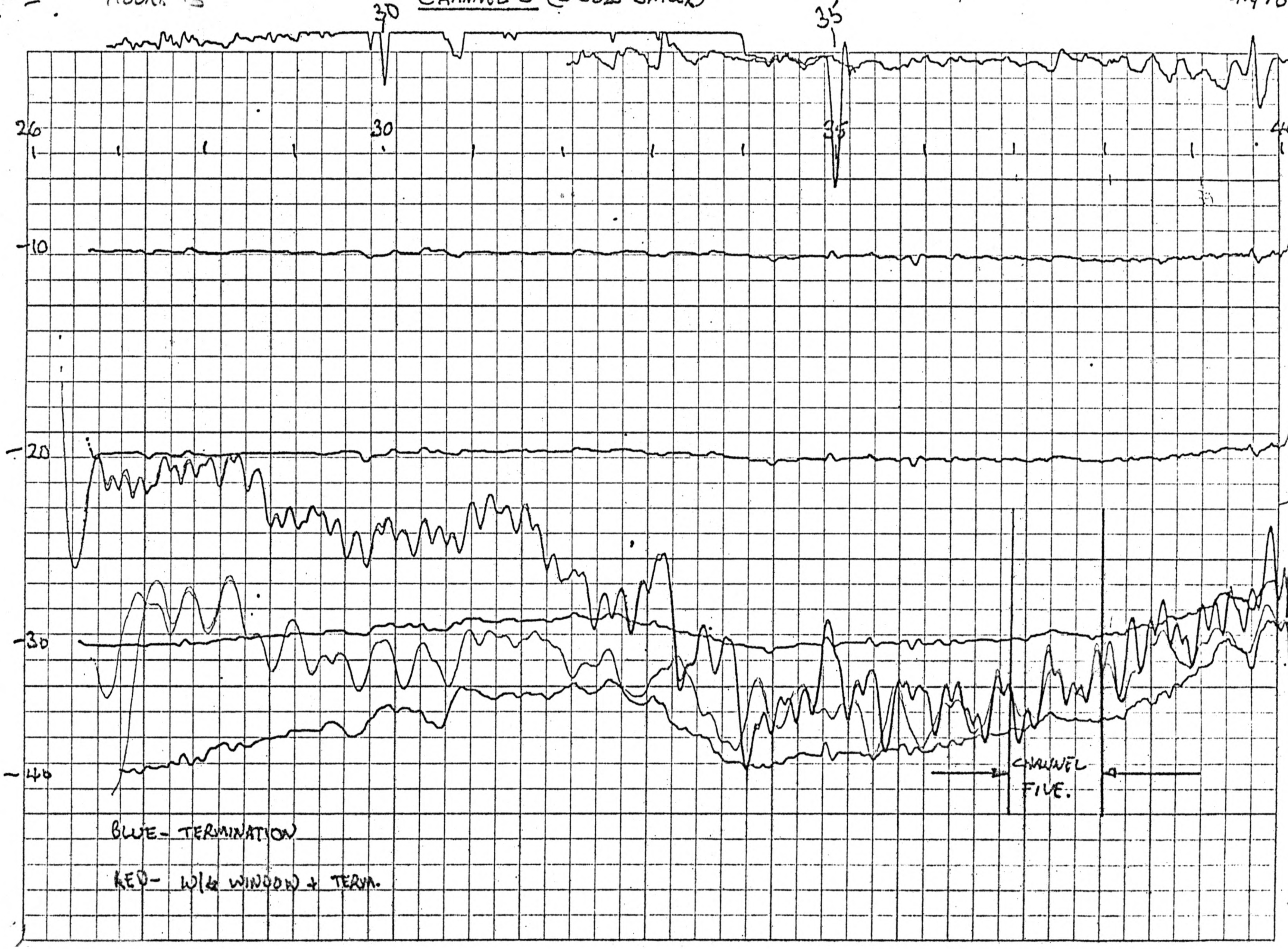

FIGURE 14-(a) CHANNEL 6 (i) (0.0777" SPACER) 5/2/78

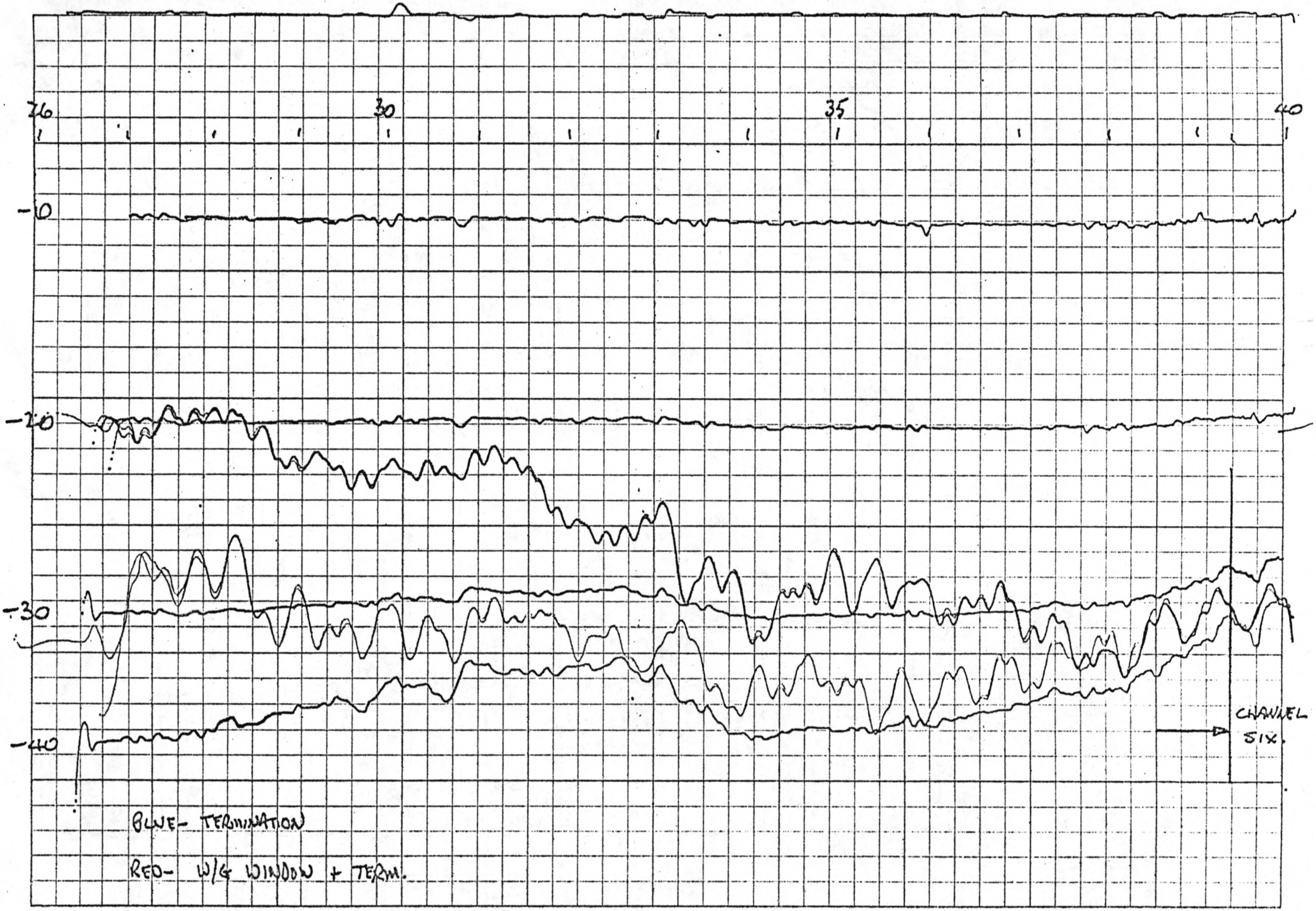

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FIGURE 14 (6) CHANNEL SIX (ii) (0.0777" SPACER) 5/2/78

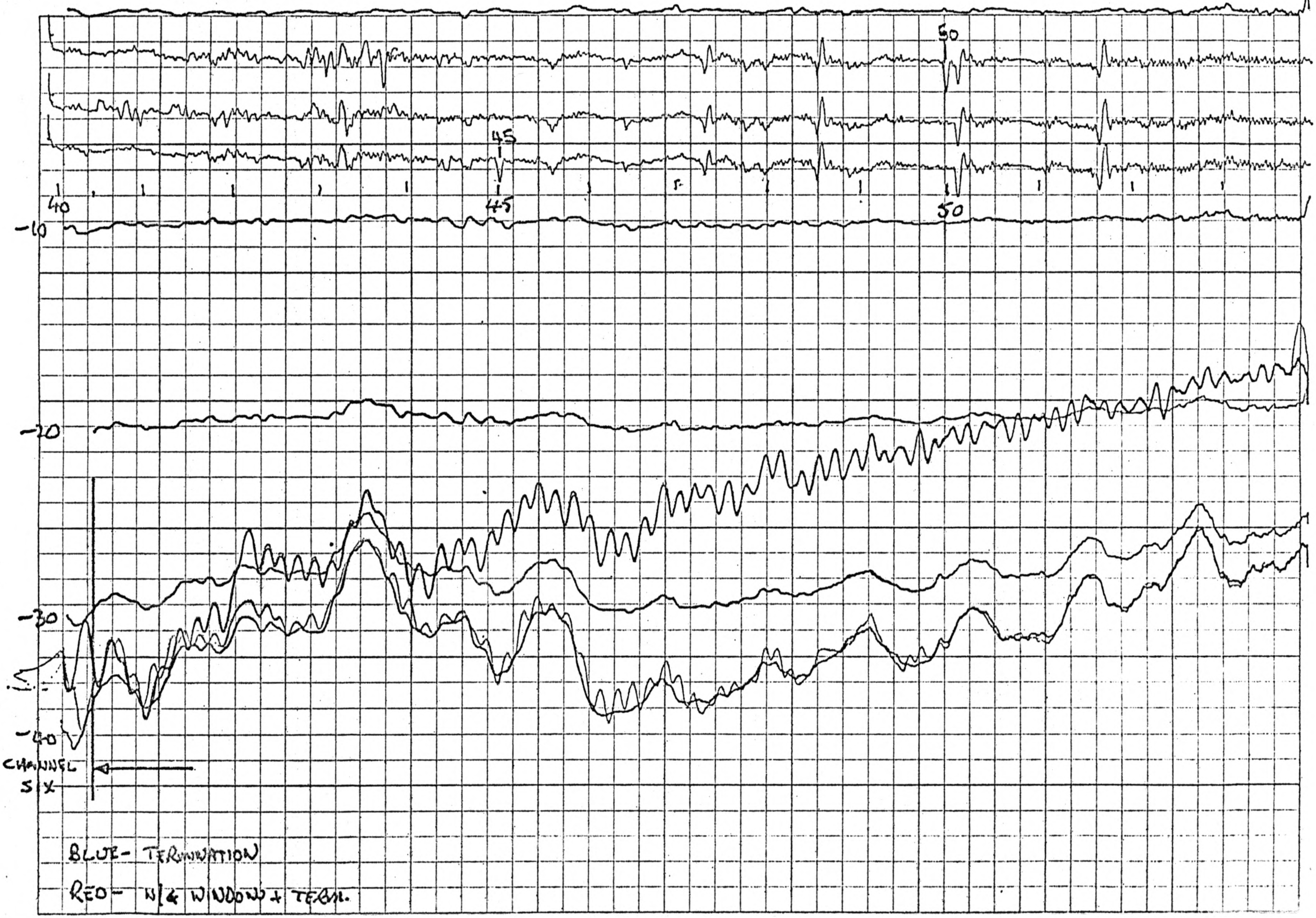

FIGURE 15

CHANNEL 7 (0.0697" SPACER)

5/2/78

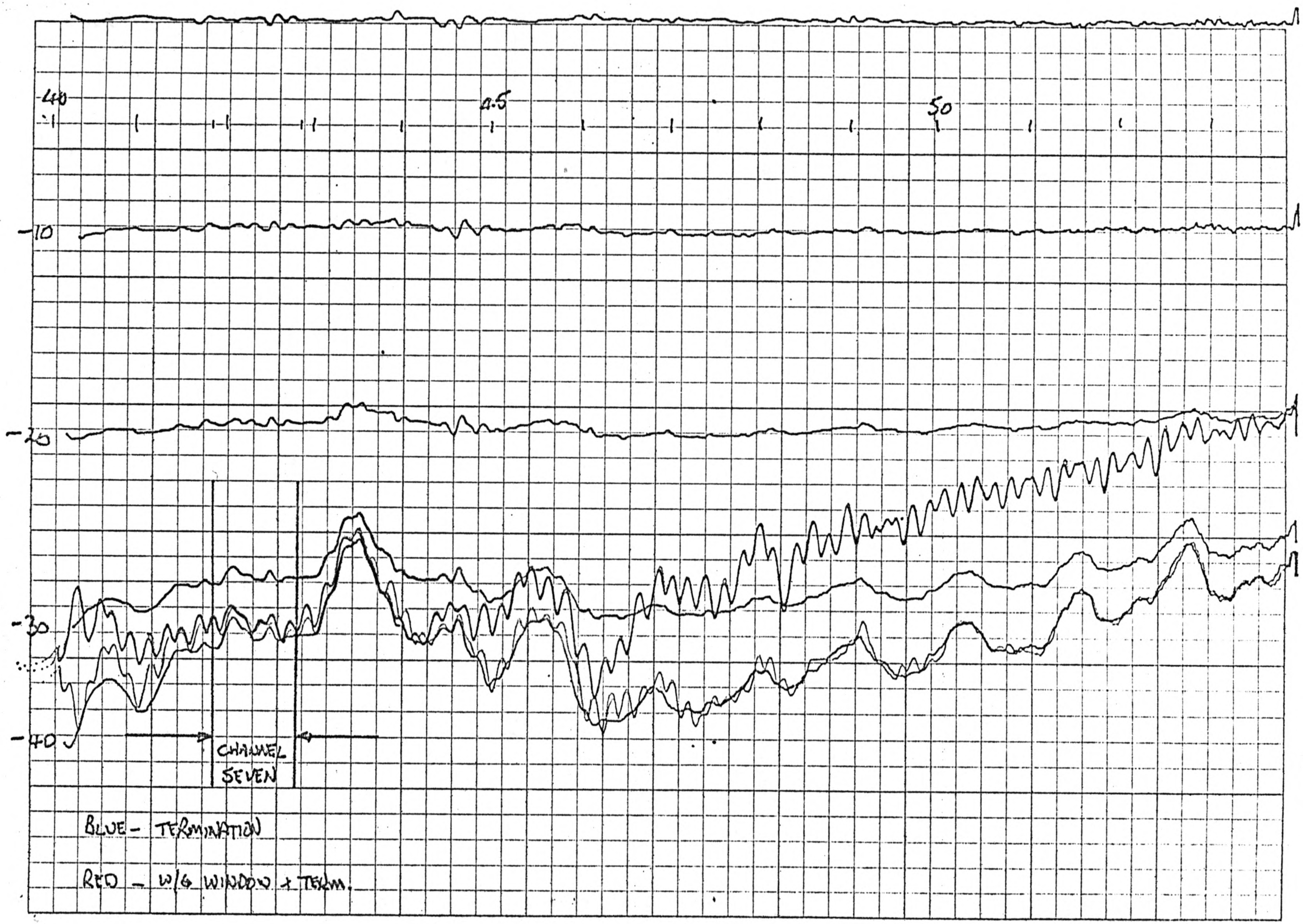

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FIGURE 16 CHANNEL EIGHT (0.0677" SPACER) 5/2/78

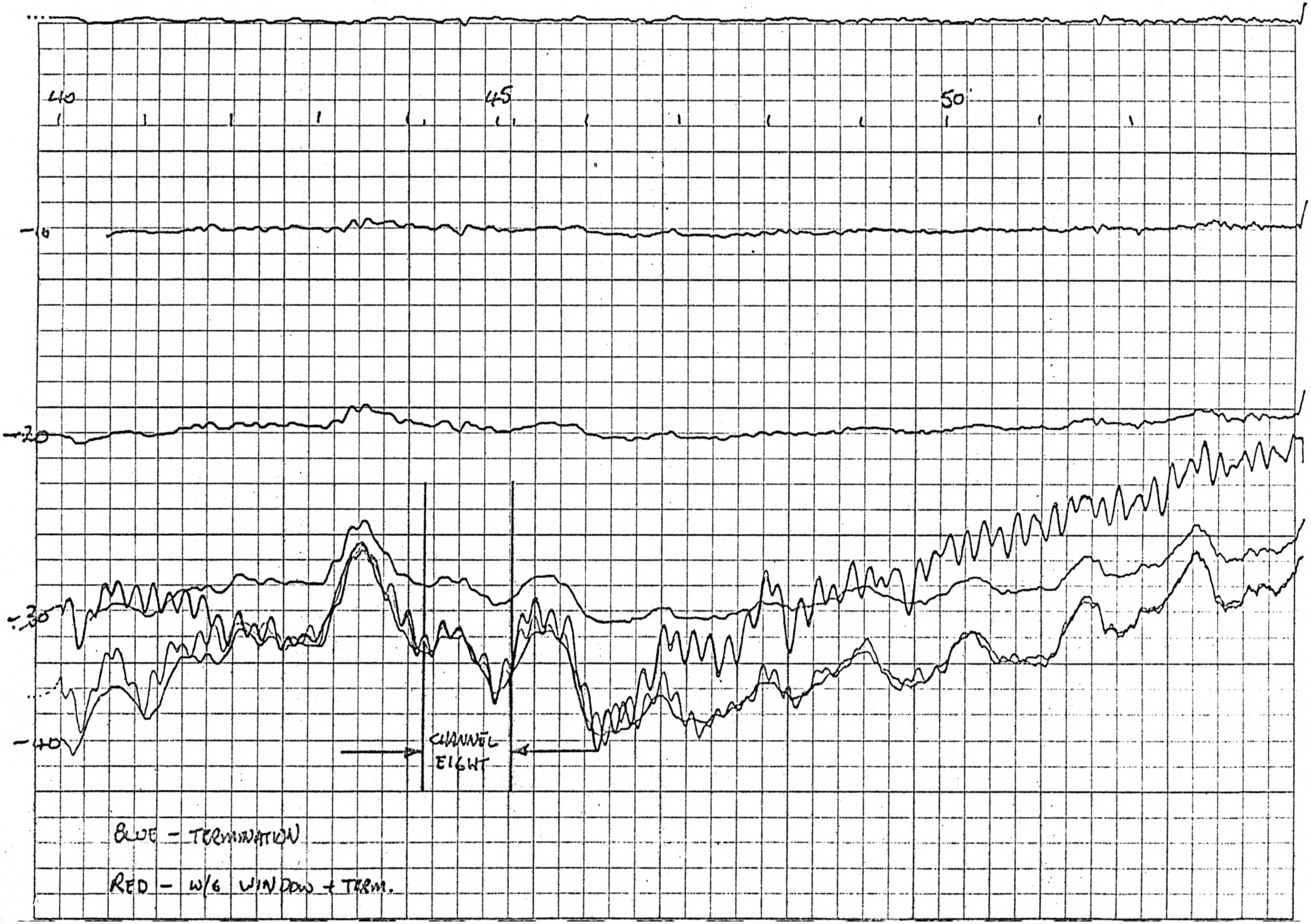

FIGURE 17 CHANNEL NINE (0.0633" SPACER) 5/2/78.

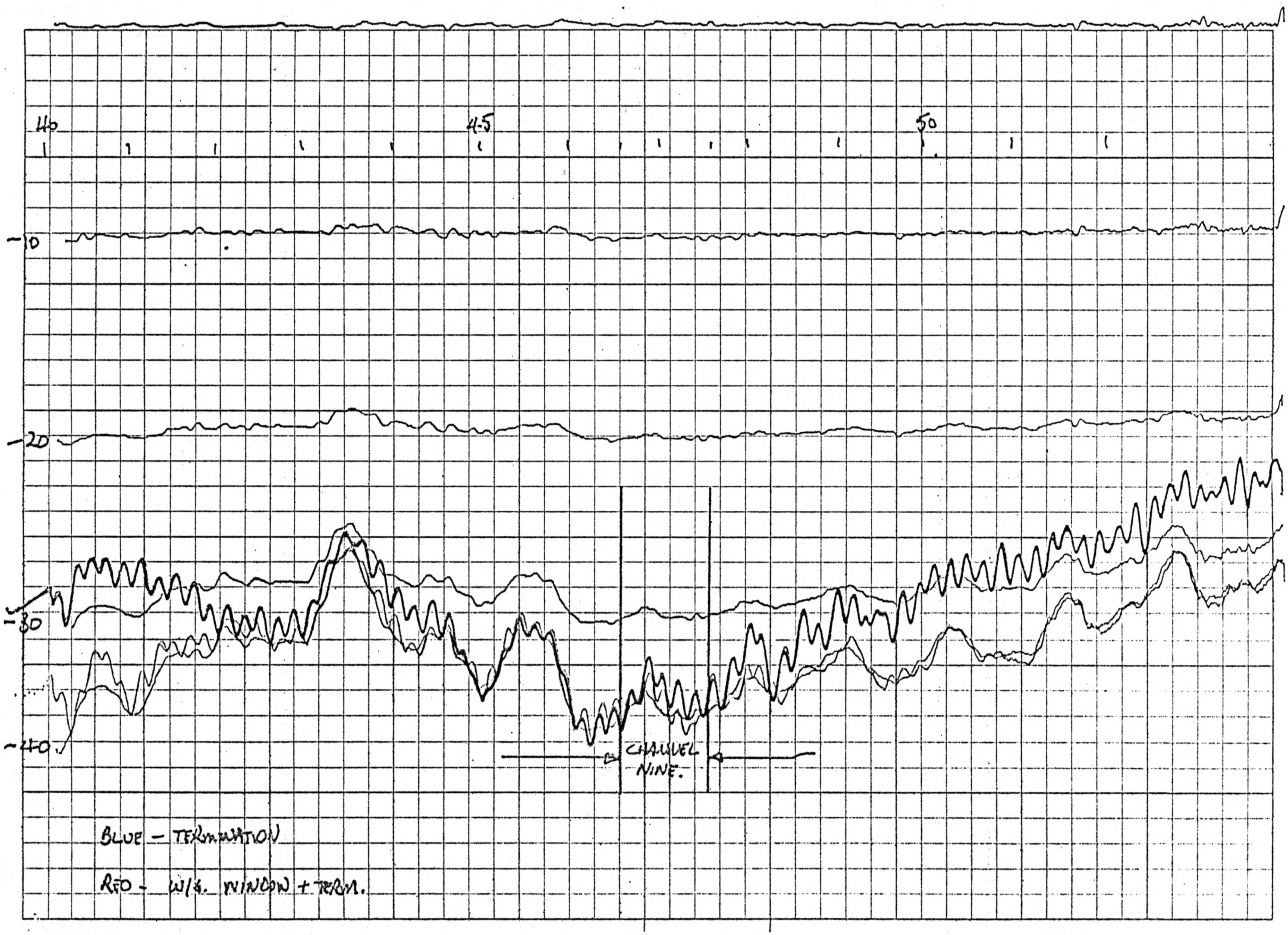

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FIGURE 18

3MIL MYLAR DOUBLE WINDOW. (BEFORE PRESSURIZATION) 1/16/78

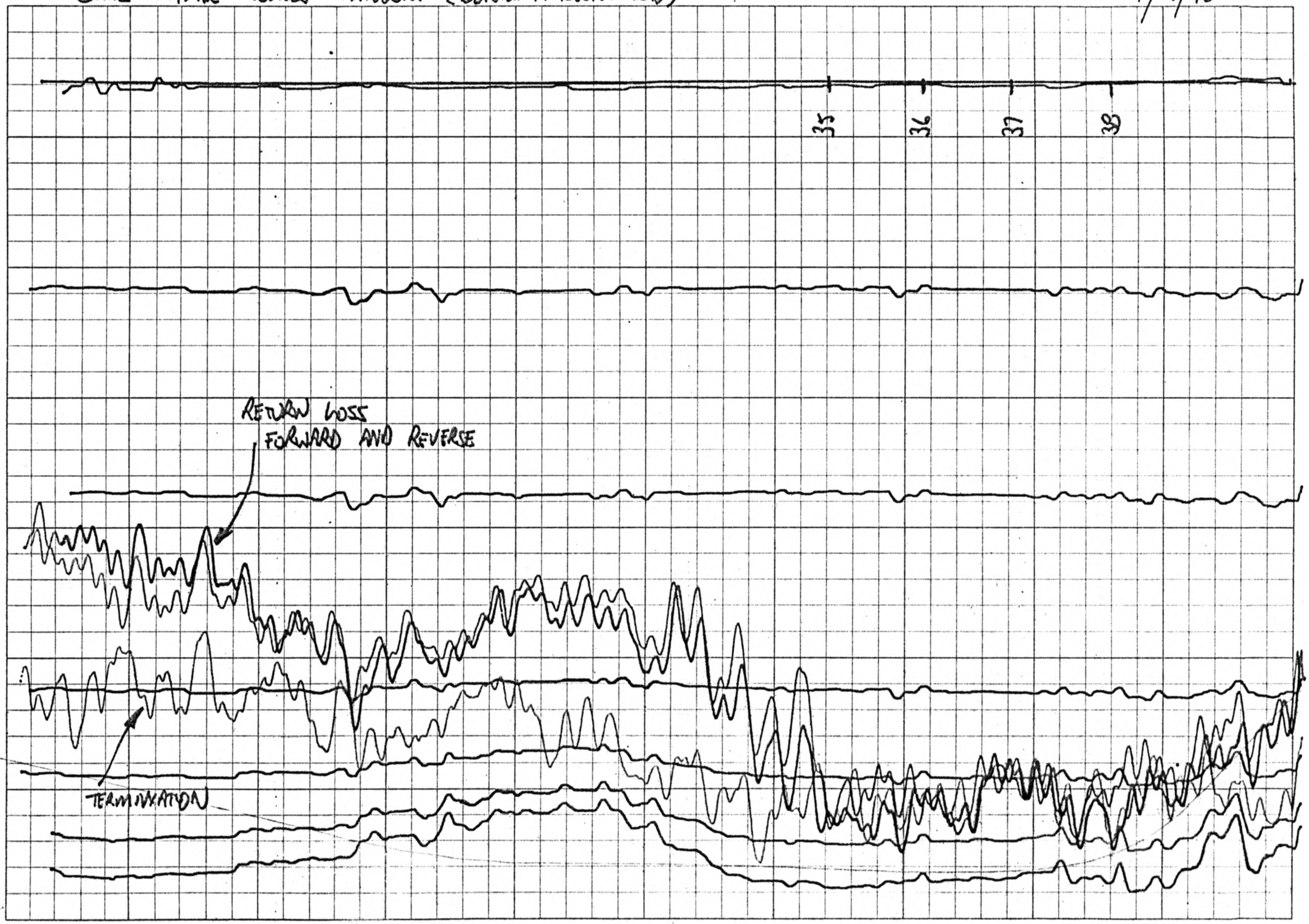

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FIGURE 19

3MIL MYLAR DOUBLE WINDOW (AFTER PRESSURIZATION TO 60 psi for 5 minutes) 1/16/78