(NASA CR-135238)

MEAN VELOCITY, TURBULENCE INTENSITY AND TURBULENCE CONVECTION VELOCITY MEASUREMENTS FOR A CONVERGENT NOZZLE IN A FREE JET WIND TUNNEL

COMPREHENSIVE DATA REPORT

PWA-5516

Prepared for
NASA Lewis Research Center
Under Contract NAS3-17866

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Project Manager, Orlando A. Gutierrez, VSTOL and Noise Division, NASA Lewis Research Center, Cleveland, Ohio

16 Abstract

The effect of flight on the mean flow and turbulence properties of a 0.056m circular jet were determined in a free jet wind tunnel. The nozzle exit velocity was 122 m/sec, and the wind tunnel velocity was set at 0, 12, 37, and 61 m/sec. Measurements of flow properties including mean velocity, turbulence intensity and spectra, and eddy convection velocity were carried out using two linearized hot wire anemometers.

This report contains the raw data as obtained from the Saicor Model SAI-42 Probability and Cross-Properties Analyzer and the Spectral Dynamics 301C Spectrum Analyzer and 302C Ensemble Averager. Graphical presentations of the data are also included.

The final technical report, NASA CR-2949, includes a description of the test facilities, test hardware, along with significant test results and conclusions.

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FOREWORD

This report is a compilation of the turbulence and mean flow measurements obtained during Task VIII of Contract NAS3-17866.

The companion final report, NASA CR-2949, includes a description of the facilities used, the hot wire measurements, the significant test results and conclusions.

TABLE OF CONTENTS

INTRODUCTION

The hot wire data measured during Task VIII of the program are presented in this volume in graphical form according to the requirements of the work plan. Hot wire measurements of local flow properties were made at each of the stations in Table 1. The hot wire measurements were divided into two categories according to whether a single probe or two probes were necessary to acquire the data. A single probe was used to measure mean velocity and turbulence intensity profiles, and its signal was analyzed to provide frequency spectra and autocorrelations for selected points in the shear layer. The signals from two probes were cross correlated for varying values of probe separation. The mean velocity, turbulence intensity, and turbulence spectra obtained from a single probe are contained in Sections A to C and the autocorrelations and two probe data are contained in Sections D to G. The specific contents of each section of this report are described below.

Section A

This section contains the mean velocity profiles plotted at constant tunnel velocity at the required axial locations.

Section B

This section contains the turbulence intensity profiles corresponding to the mean velocity profiles in Section A.

Section C

This section presents the turbulence spectra at the maximum turbulence region of the shear layer (i.e., the "center" of the jet shear layer).

Section D

This section contains the auto and cross correlations at each exial station (see Table 1) with the various probe separations for the "inner," "center," and "outer" region of the jet shear layer.

Section E

This section contains the selected filtered auto and cross correlations.

Section F

This section presents the normalized corss correlation coefficients plotted versus the probe separation.

TEST MATRIX

The convergent nozzle (2.23 in. dia.) was operated at a nominal exit velocity of 400 fps, while the tunnel velocity was set at 0, 40, 120 and 200 fps. The resulting values of the velocity ratio, m, defined as the wind tunnel velocity divided by the jet velocity, were 0, 0.1, 0.3 and 0.5. The various downstream measurement stations, normalized by the jet diameter, D, were selected for each velocity ratio as shown below:

TABLE 1

Downstream Measurement Stations

Velocity Ratio, $m = \frac{U_e}{U_j}$	Axial Measurement Stations, X/D		
0	3.0	5.0	-
0.1	3.0	5.5	7.7
0.3	3.0	6.8	9.5
0.5	3.0	7.7	12.1

DATA INDEX

The data presented in Sections A through F are arranged by the tunnel to jet velocity ratios, m. At the constant velocity ratio, data are presented in the ascending order of axial locations. For the two probe data, they are further arranged by the normalized radial locations, R/D, (i.e., the "inner," "center," and "outer" of the jet shear layer where R is measured from the jet centerline) and by the increasing probe separation.

The following index delineates the contents of the data compiled in this volume. The index is self-explanatory, listing the type of data, the tunnel to jet velocity ratios (m), axial locations (X/D), normalized radial locations (R/D), probe separations, and the page number.

C. Normalized Turbulence Spectra (Max. Turbulence Region)

m	X/D	Page
0	3.0	C1
o	5.0	C2
0.1	3.0	C3
0.1	5.5	C4
0.1	7.7	C5
0.3	3.0	C6
0.3	6.8	C7
0.3	9.5	C8
0.5	3.0	C9
0.5	7.7	C10
0.5	12.1	C11

D. Auto and Cross Correlations

m	X/D	R/D	Δ X (in.)	Page
0	3.0	0.363	0.6	D1
			3.0	D4
			5.4	D6
		0.507	0.6	D8
			3.0	D10
			5.4	D12
	3.0	0.665	0.6	D14
			3.0	D16
			5.4	D18
	5.0	0.304	1.0	D20
			6.0	D22
			11.0	D24
		0.462	1.0	D26
			6.0	D28
			11.0	D30
		0.665	1.0	D32
			6.0	D34
			11.0	D36
0.1	3.0	0.381	0.5	D38
			3.0	D40
			5.5	D42
		0.471	0.5	D44
			3.0	D46
			5.5	D48
		0.687	0.5	D50

m	X/D	R/D	ΔX (in.)	Page
			3.0	D52
			5.5	D54
	5.5	0.290	0.3	D56
			3.3	D58
			6.3	D60
0.1	5.5	0.484	0.3	D62
			3.3	D64
			6.3	D66
		0.700	0.3	D68
			3.3	D70
			6.3	D72
	7.7	-0.006	0.5	D74
			3.0	D76
			5.5	D78
		0.462	0.5	D80
			3.0	D82
			5.5	D84
		0.782	0.5	D86
			3.0	D88
			5.5	D90
0.3	3.0	0.410	0.3	D92
			1.8	D94
			3.3	D96
		0.518	0.3	D98
			1.8	D100
			3.3	D102
		0.608	0.3	D104
			1.8	D106
			3.3	D108
0.3	6.8	0.352	0.3	D110
			3.3	D112
			6.3	D114
		0.496	0.3	D116
			3.3	D118
			6.3	D120
		0.658	0.3	D122
			3.3	D124
			6.3	D126
	9.5	-0.045	0.4	D128
			4.4	D130
			8.4	D132
		0.450	0.4	D134

m	X/D	R/D	ΔX (in.)	Page
			4.4	D136
			8.4	D138
		0.518	0.4	D140
			4.4	D142
			8.4	D144
0.5	3.0	0.401	0.2	D146
			1.2	D148
			2.2	D150
		0.518	0.2	D152
			1.2	D154
			2.2	D156
0.5	3.0	0.586	0.2	D158
			1.2	D160
			2.4	D162
	7.7	-0.101	0.4	D164
			4.4	D167
			8.4	D170
		0.304	0.4	D172
			4.4	D174
			8.4	D176
		0.489	0.4	D178
			4.4	D180
			8.4	D182
	12.1	-0.118	0.4	D184
			4.4	D186
			8.4	D188
		0.287	0.4	D190
			4.4	D192
			8.4	D194
		0.431	0.4	D196
			4.4	D198
			8.4	D200

E. Filtered Auto and Cross Correlations

m	X/D	R/D	ΔX (in.)	Filtered Frequency	Page
0.3	6.8	0.496	3.3	0.1 - 0.25 KHz	E1
				0.25 - 0.63 KHz	E3
				0.63 - 1.60 KHz	E5
				1.60 - 4.00 KHz	E6

F. Normalized Cross Correlation Coefficients

m	X/D	R/D	ΔX (in.)	Page
		0.363, 0.507, 0.665	0.6, 3.0, 5.4	F2
0	3.0	0.304, 0.462, 0.665	1.0, 6.0, 11.0	F3
0	5.0	0.381, 0.471, 0.687	0.5, 3.0, 5.5	F4
0.1	3.0	0.290, 0.484, 0.700	0.3, 3.3, 6.3	F5
0.1	5.5	-0.006, 0.462, 0.782	0.5, 3.0, 515	F6
0.1	7.7	0.410, 0.518, 0.608	0.3, 1.8, 3.3	F7
0.3	3.0	0.352, 0.496, 0.658	0.3, 3.3, 6.3	F8
0.3	6.8	-0.045, 0.450, 0.518	0.4, 4.4, 8.4	F9
0.3	9.5	0.401, 0.518, 0.586	0.2, 1.2, 2.2	F10
0.5	3.0	-0.101, 0.304, 0.489	0.4, 4.4, 8.4	F11
0.5	7.7	-0.118, 0.287, 0.431	0.4, 4.4, 8.4	F12
0.5	12.1	0.496	3.3	F13
0.3*	6.8			

*Filtered Frequency: 0.1 - 0.25 KHz
0.25- 0.63 KHz
0.63- 1.60 KHz
1.60- 4.00 KHz

A. Mean Velocity Profiles

The mean velocities were obtained from the mean voltage signals from the radial probe. The voltage signals were read from a digital DC voltmeter and a calibration curve was used to determine the mean velocity from the voltage output. Plots of mean velocity versus normalized radial position, R/D, are shown in Figures A1 through A4 for the various velocity ratios and axial locations.

MEAN VELOCITY PROFILES
$M_2 = 0.1$
X/D = 3.0
X/D = 5.5
X/D = 7.7
VELOCITY ~ FT./SEC.
0
100
200
300
400
500
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
RADIAL POSITION, R/D

MEAN VELOCITY PROFILES
M = 0.3
X/D = 3.0
X/D = 6.0
X/D = 9.0
ORIGINAL PAGE IS
OF POOR QUALITY
VELOCITY, FT/SEC
0
100
200
300
400
500
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
RADIAL POSITION, R/D

MEAN VELOCITY PROFILES
M = 0.5
X/D = 3.0
X/D = 7.7
X/D = 12.1
VELOCITY - FT./SEC.
500
400
300
200
100
0
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
RADIAL POSITION, R/D

B. Turbulence Intensity Profiles

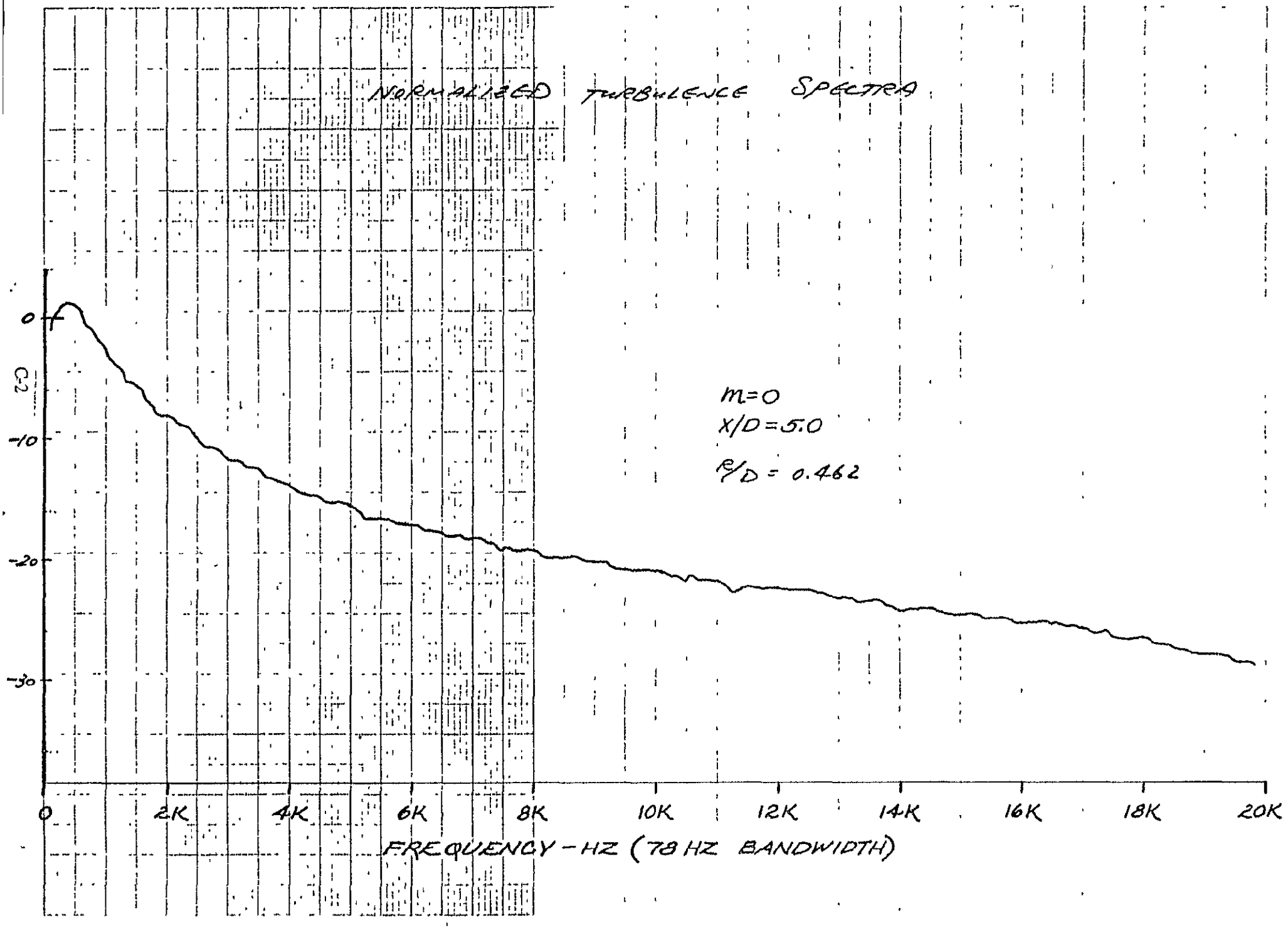
The turbulence intensities were obtained from the fluctuating voltage signals from the radial probe. The voltage signals were proportional to the turbulence intensities which were read from an RMS AC voltmeter. Plots of turbulence intensity versus normalized radial position, R/D, are shown in Figures B1 through B4 for the various velocity ratios and axial locations.

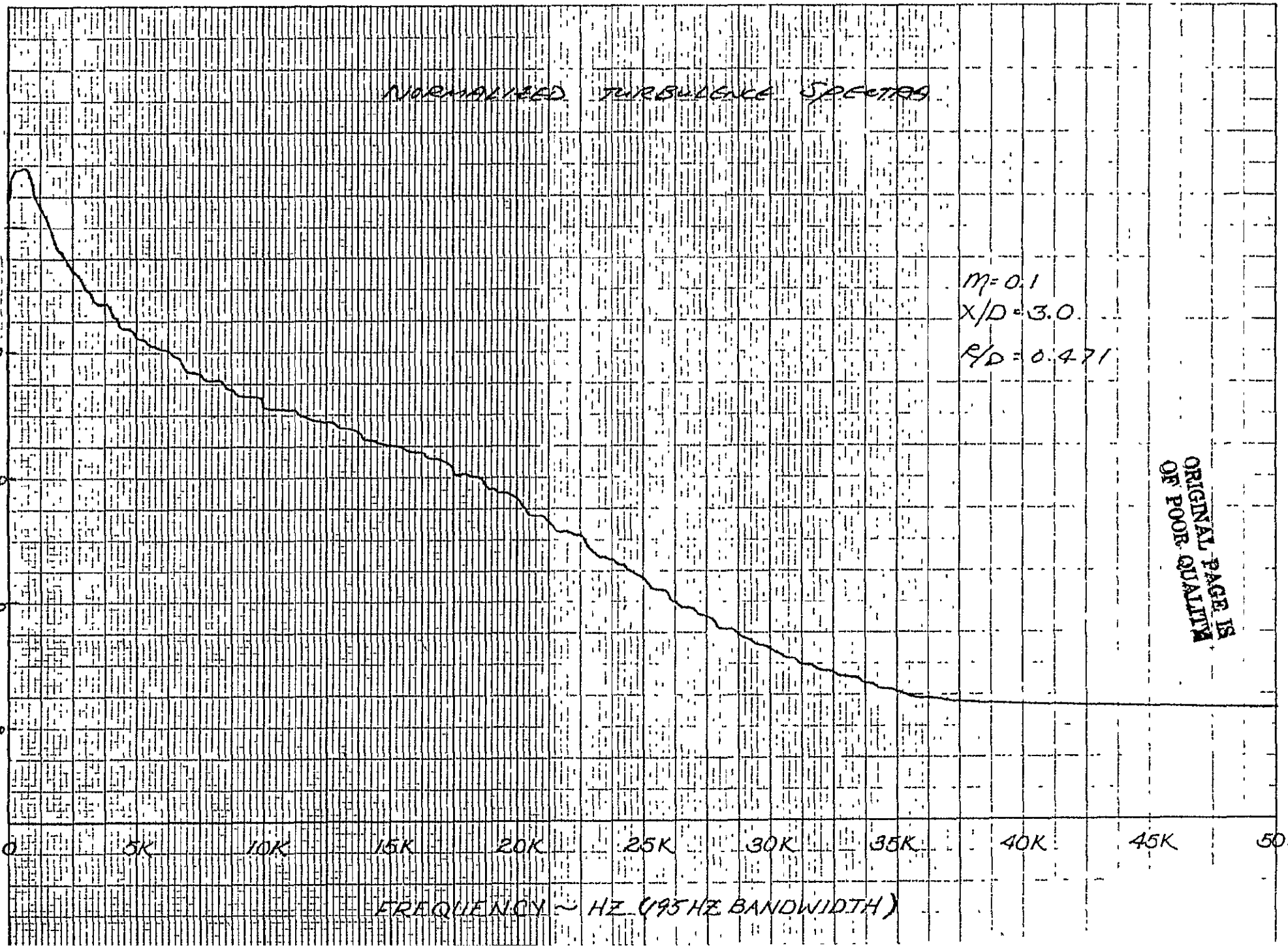
TURBULENCE INTENSITY PROFILES
M = 0.1
X/D = 3.0
X/D = 5.5
X/D = 7.7
% TURBULENCE
0
1
2
3
4
5
6
7
8
9
10
11
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
RADIAL POSITION, R/D

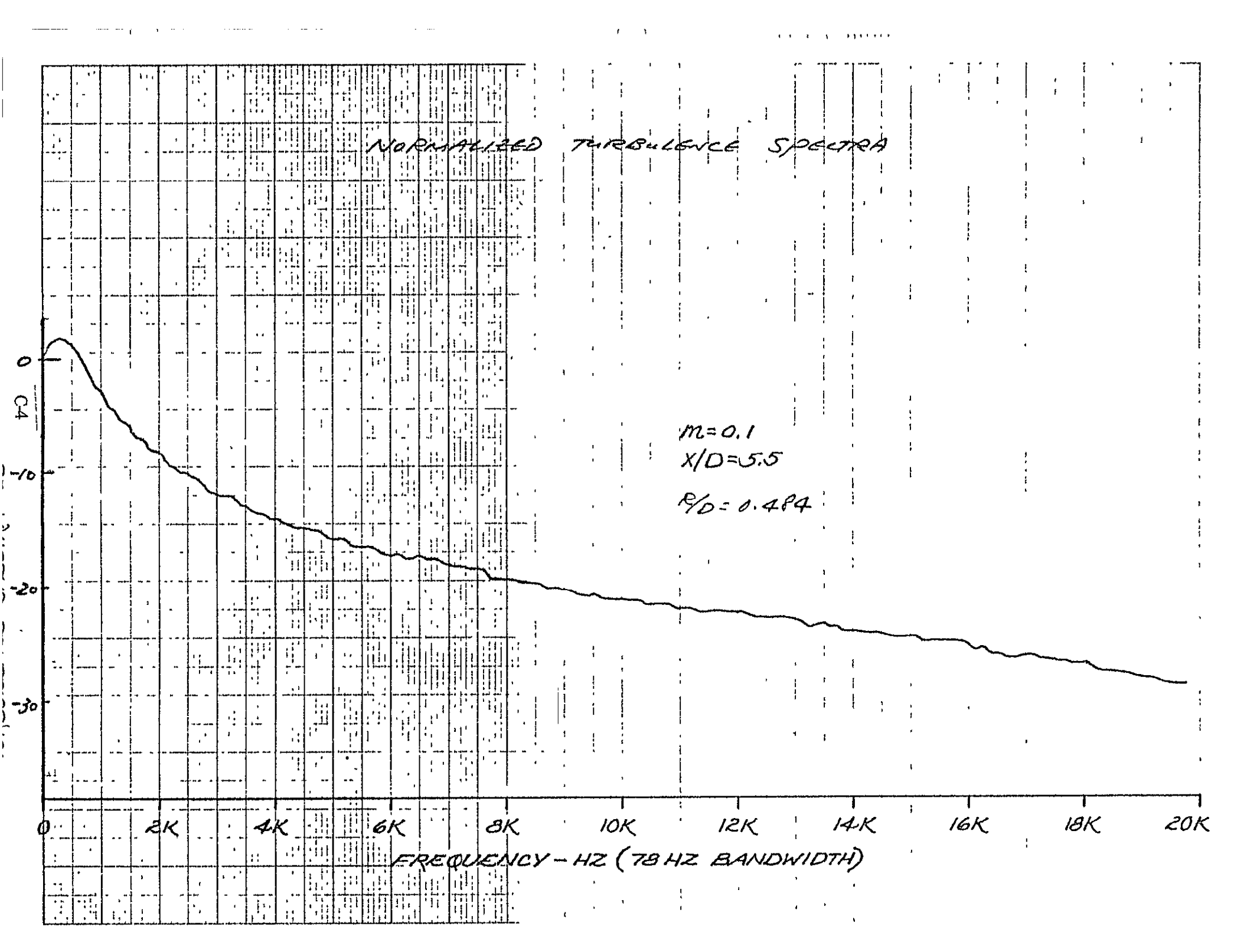
TURBULENCE INTENSITY PROFILES
$\phi_L = 0.5$
X/D = 3.0
X/D = 7.7
X/D = 12.1
% TURBULENCE
0
1
2
3
4
5
6
7
8
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
RADIAL POSITION, R/D

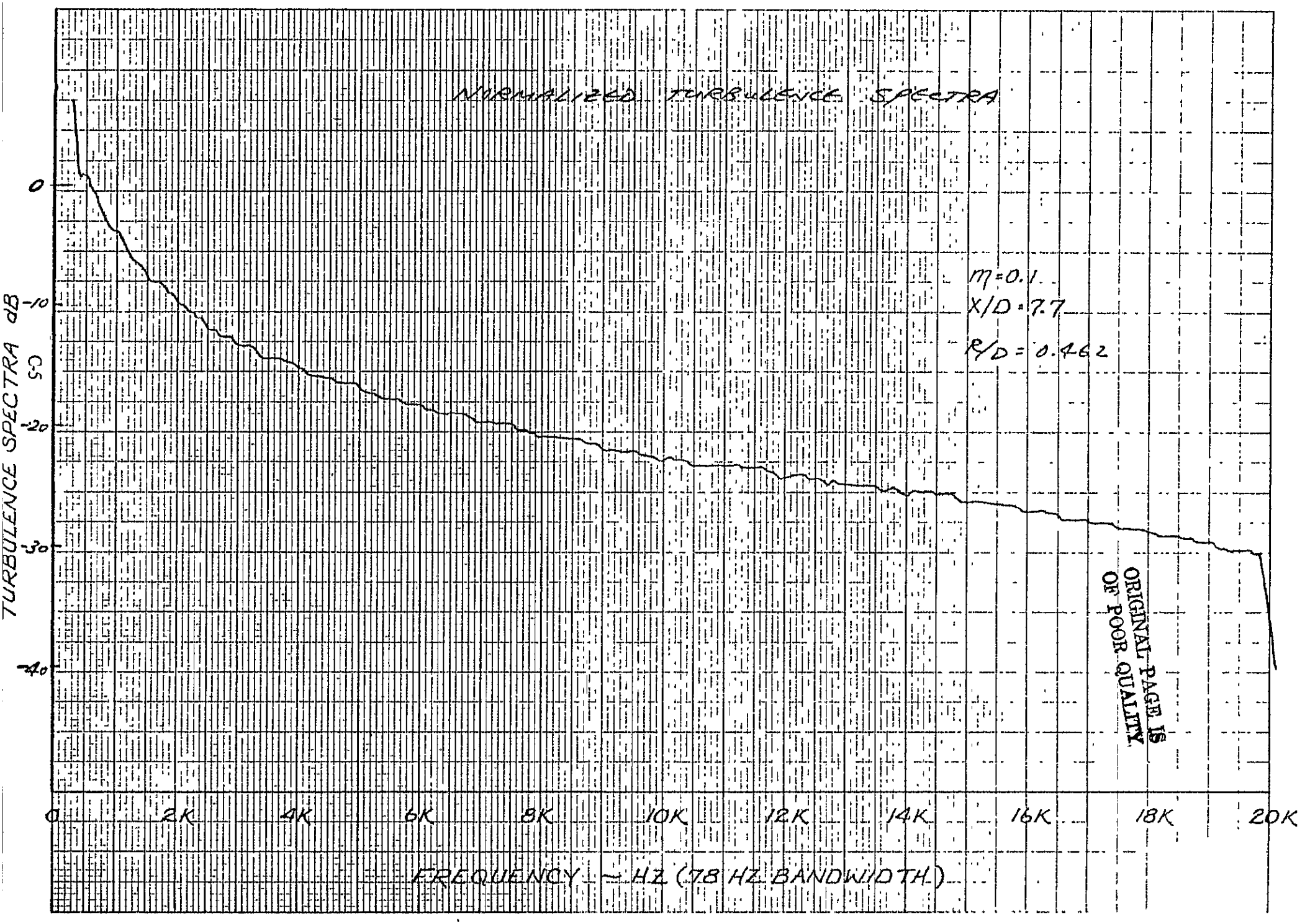
C. Normalized Turbulence Spectra

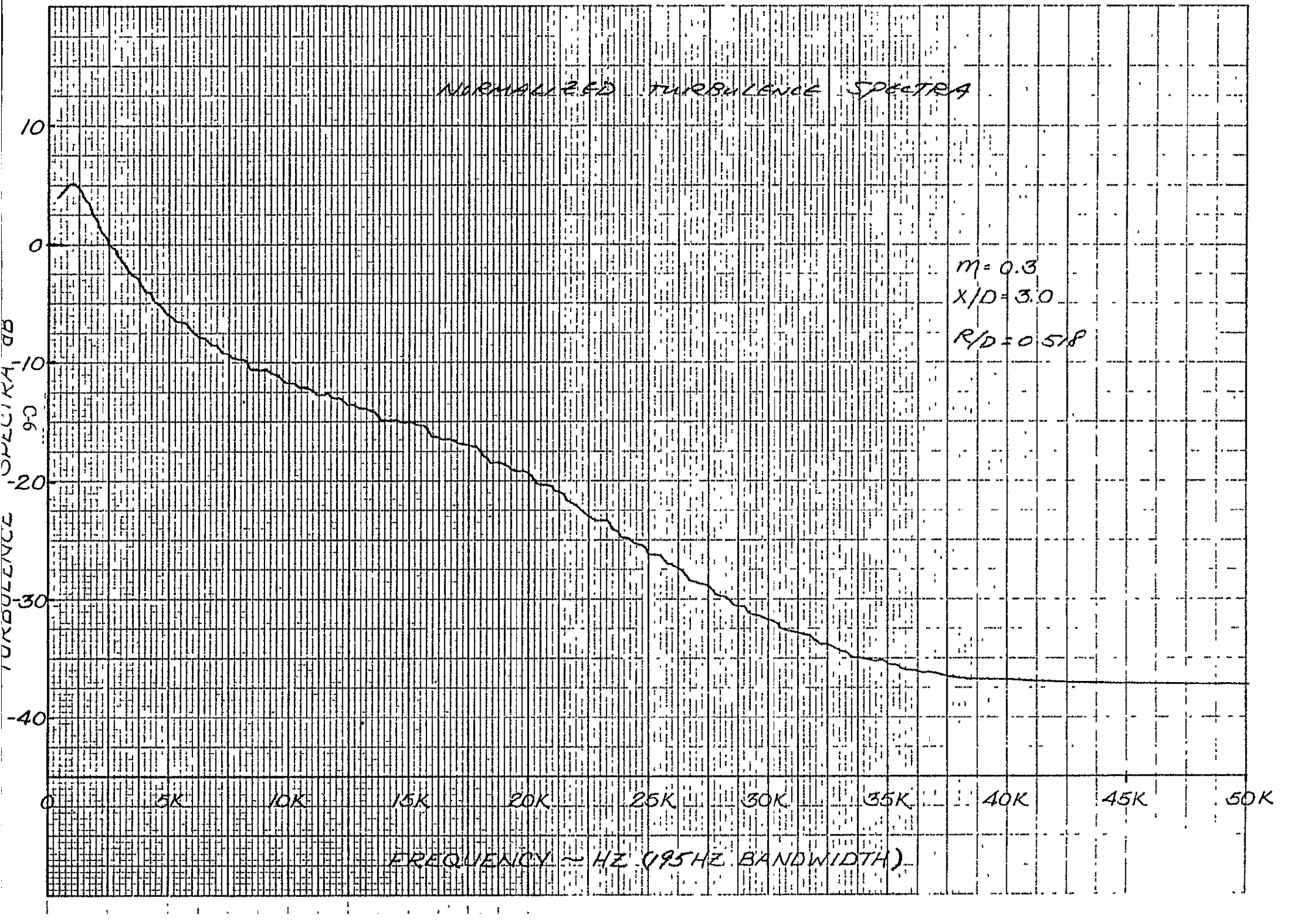
All turbulence spectra were normalized to the same relative level by subtracting the recorded attenuations from the raw data spectra. The frequency bandwidth for the 0-50 KHz spectra is 195 Hz, and the frequency bandwidth for the 0-20 KHz spectra is 78 Hz.

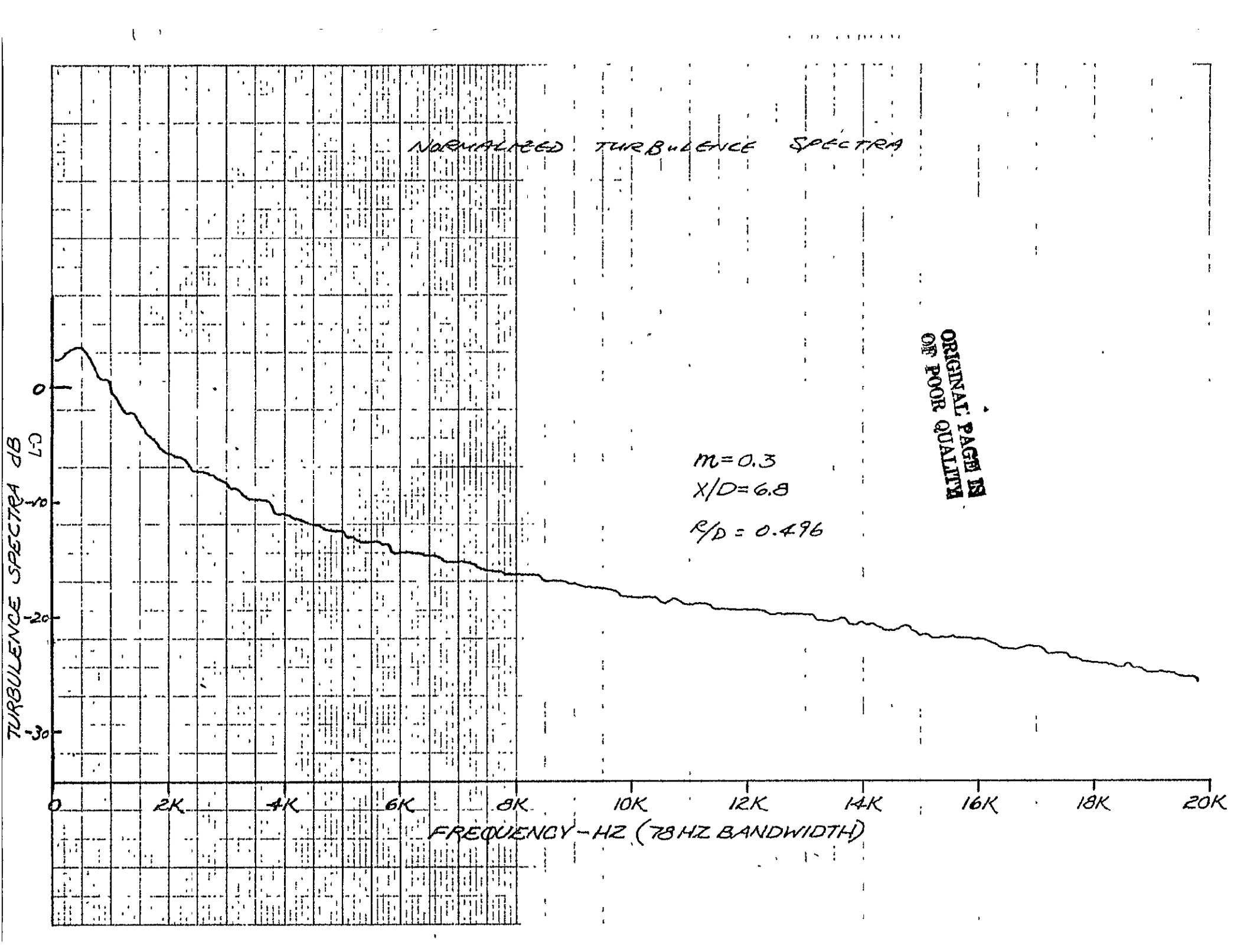

NORMALIZED TURBULENCE SPECTRA
m=0
X/D=5.0
r/D = 0.462
0
-10
-20
-30
C2
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)

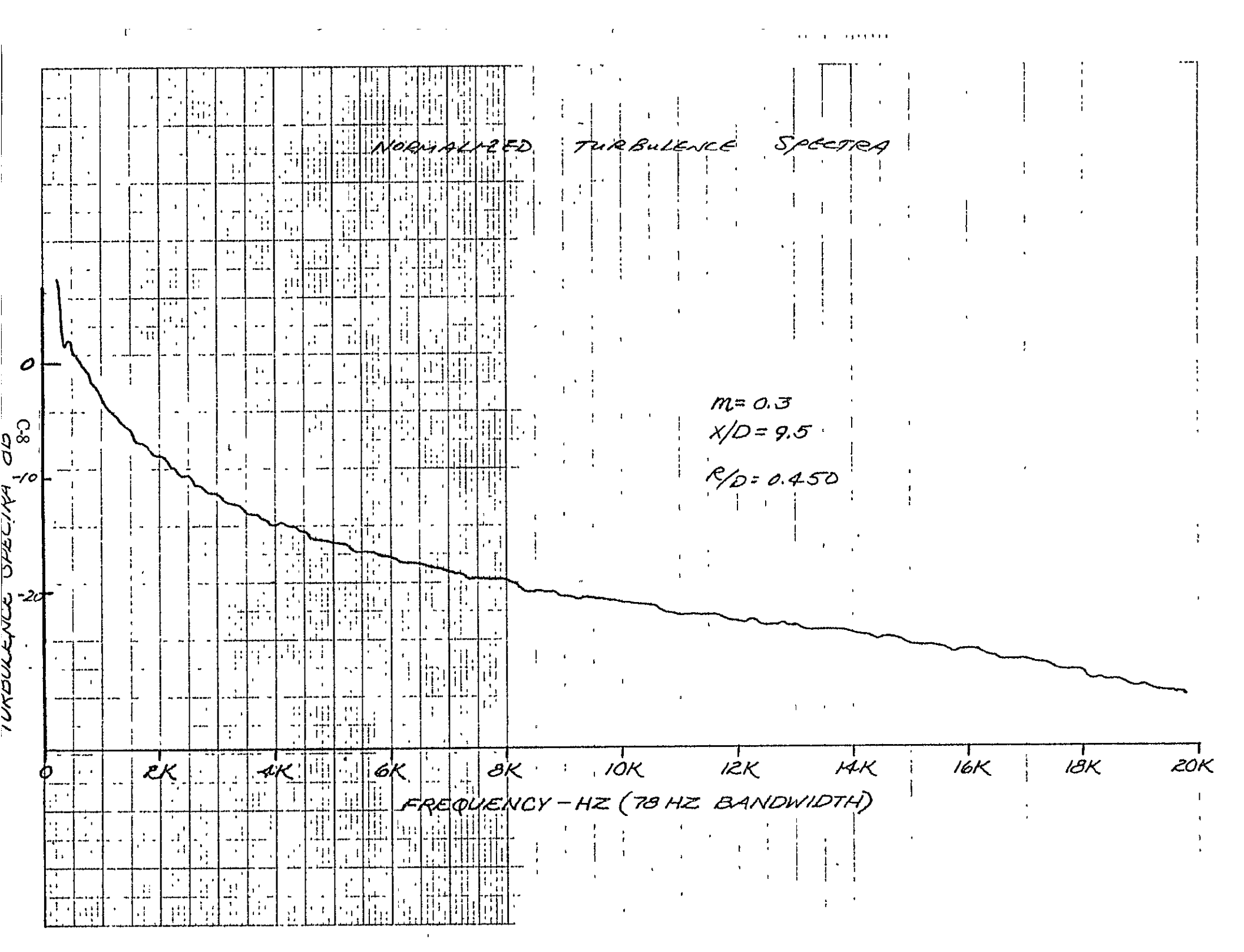


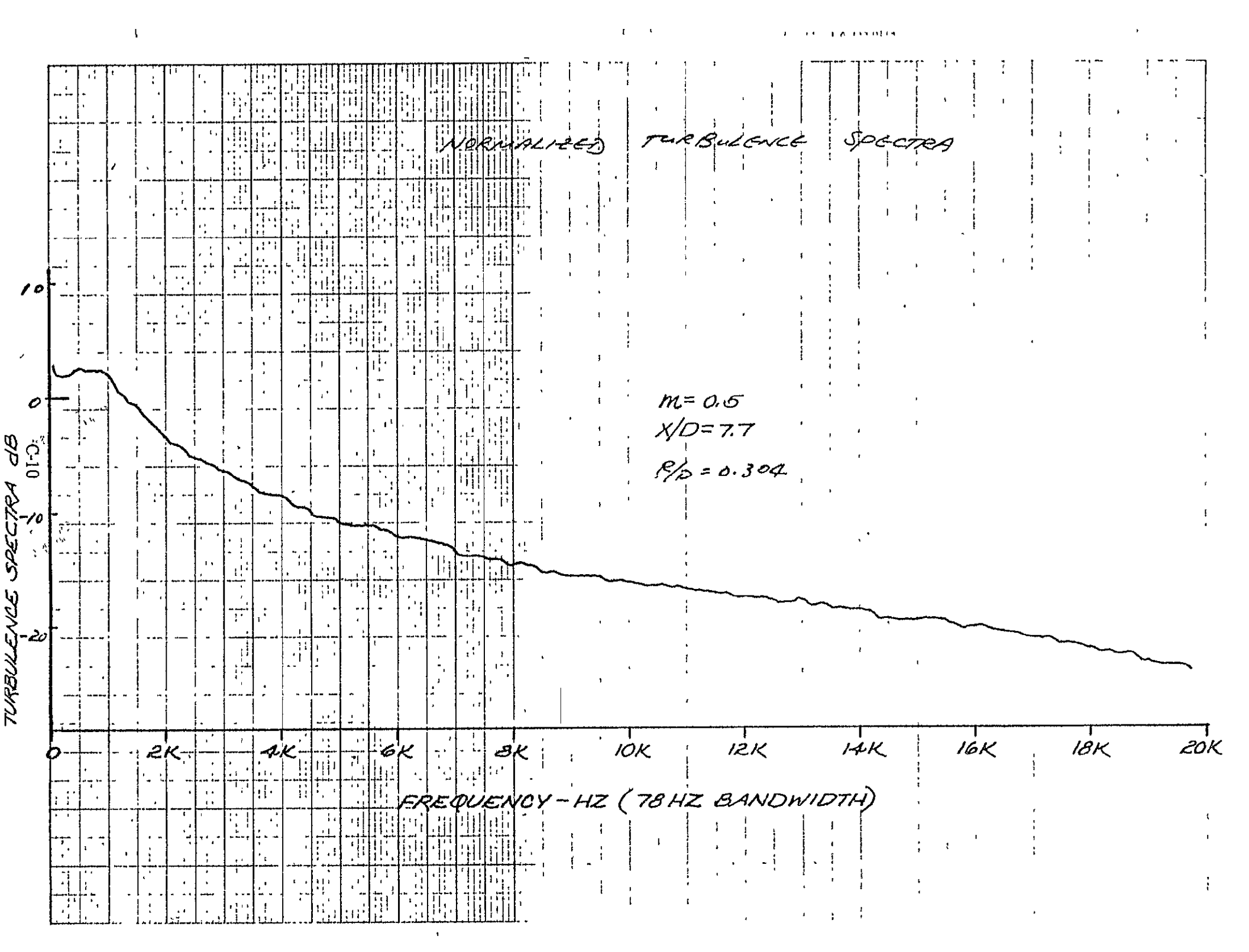

NORMALIZED TURBULENCE SPECTRA
M=0.1
X/D=5.5
R/D=0.484
0
-10
-20
-30
C4
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)

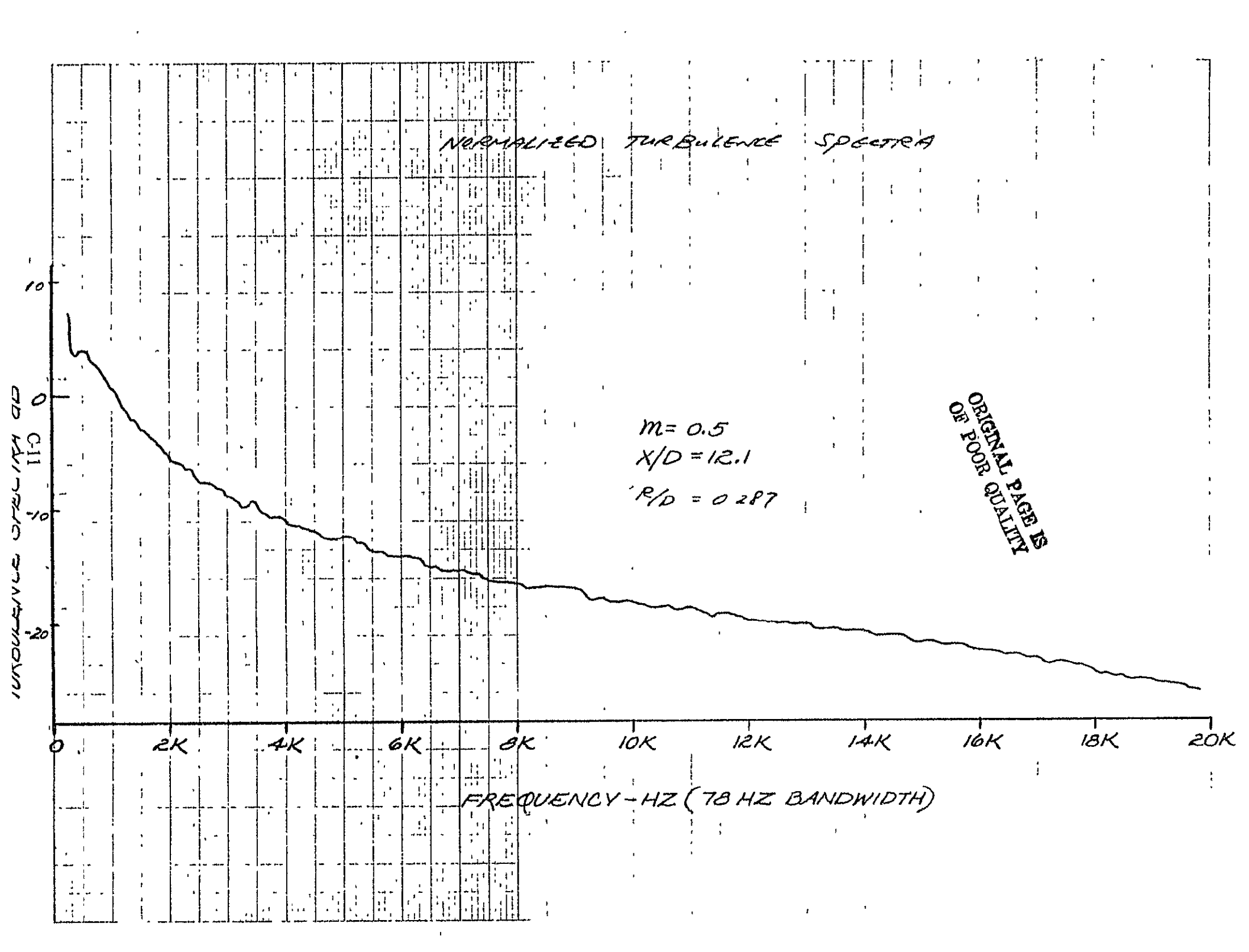





NORMALIZED TURBULENCE SPECTRA
ORIGINAL PAGE IS OF POOR QUALITY
M = 0.3
X/D = 6.8
R/D = 0.496
TURBULENCE SPECTRA dB
0
-10
-20
-30
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)


NORMALIZED TURBULENCE SPECTRA
M = 0.3
X/D = 9.5
R/D = 0.450
TURBULENCE SPECTRA dB
0
-10
-20
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)


NORMALIZED TURBULENCE SPECTRA
M = 0.5
X/D = 7.7
R/D = 0.304
TURBULENCE SPECTRA dB
10
0
-10
-20
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)


NORMALIZED TURBULENCE SPECTRA
m = 0.5
X/D = 12.1
R/D = 0.287
ORIGINAL PAGE IS
OF POOR QUALITY
10
0
-10
-20
0
2K
4K
6K
8K
10K
12K
14K
16K
18K
20K
FREQUENCY - HZ (78 HZ BANDWIDTH)

D. Auto and Cross Correlations

This section contains the raw data from the two probe correlations. The probes were mounted on traverse mechanisms. The upstream probe, denoted as probe "A", traversed radially, while the downstream probe, denoted as probe "B", traversed axially along the jet. The signals from probes "A" and "B" were analyzed to provide autocorrelations and cross correlations for varying values of probe separation. Such correlations are shown in this section. For each radial location, the autocorrelations of probes "A" and "B" are presented first then followed by the cross correlation of probes "A" and "B". For each correlation, the velocity ratio (m), axial location (X/D), radial location (R/D), and probe separation (ΔX) in inches are listed on the bottom center of the plots. Additional information necessary to calculate the normalized cross correlation coefficients are also recorded.

On the left top corner the attenuation of probes "A" and "B" are listed under (A Atten) and (B Atten), respectively. On the right top corner the increments of each unit on the time axis (X coordinate) in microseconds (μ sec. or 10^{-6} seconds) are listed under sample increment (Sample Inc) where the origin of the time axis is listed under (Recomp Del) in terms of units from the left. On the vertical axis (Y coordinate), each unit is equivalent to 1. Other information, such as the word position (Word Pos) and resumes (Resumes) are also recorded. The word position refers to the vertical scale expansion. A word position of 2-3 means that the displayed vertical scale was expanded by a factor of 2^3 or 8, and therefore the actual level must be multiplied by 1/8. Each resume increases the number of data points in the ensemble average by an equal amount. The procedure to calculate the cross correlation coefficients using the preceding information is described in Section F.

In this section the signals from both probes were band-pass filtered from 0-20 KHz to remove a spurious electrical resonance in the frequency range of 200 to 500 KHz.

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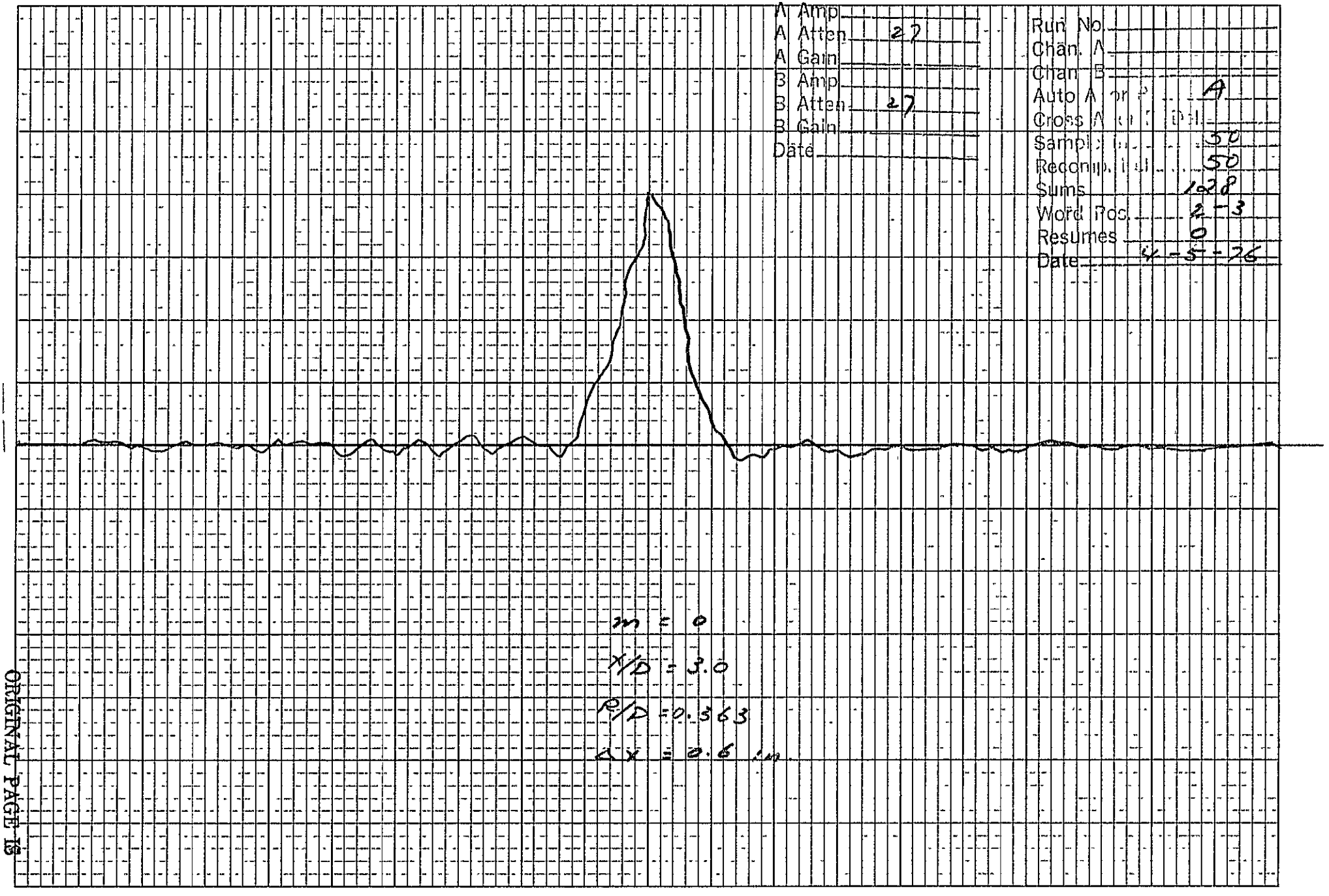

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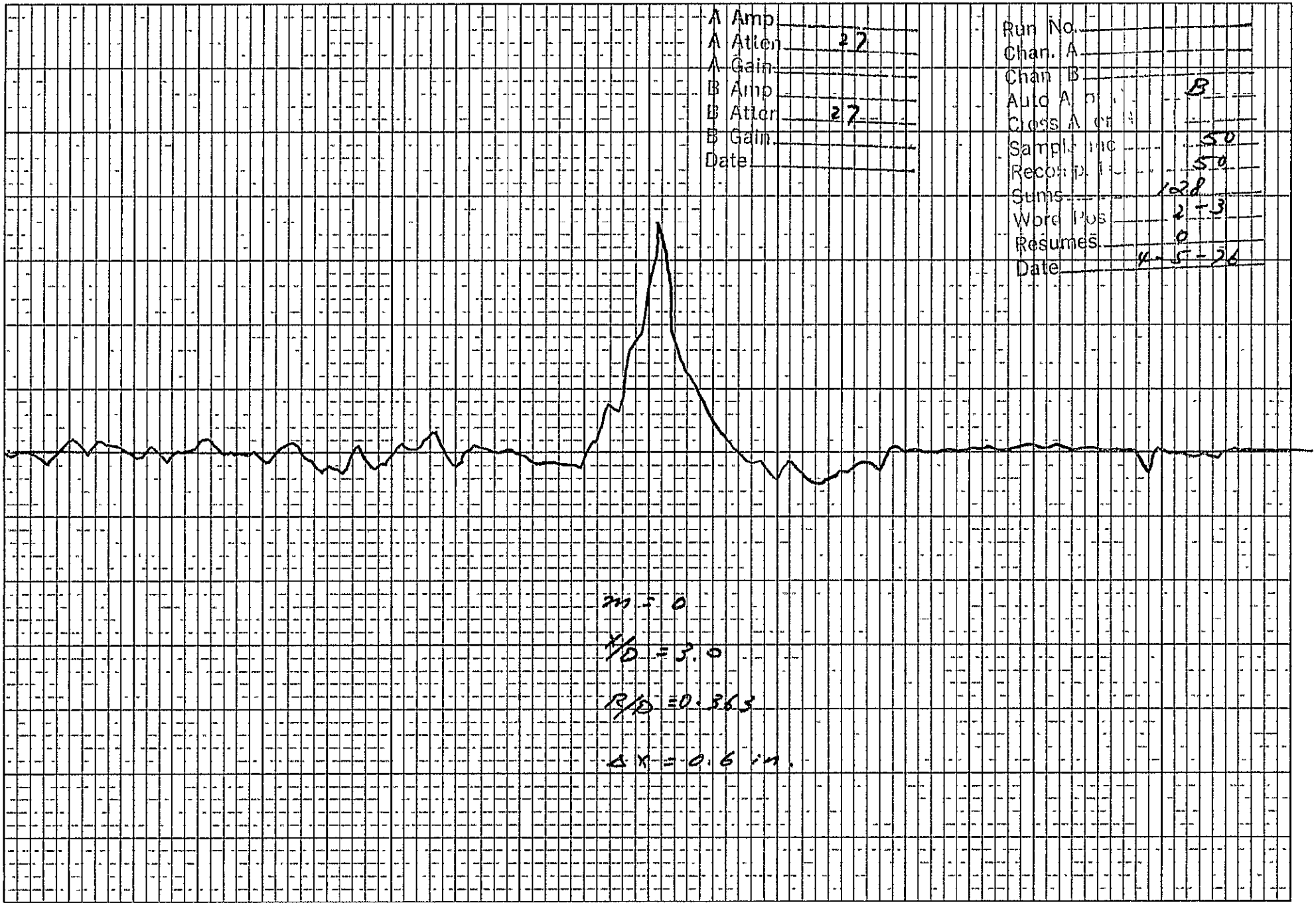
A Amp
A Atten 27
A Gain
B Amp
B Atten 27
B Gain
Date
Run No.
Chan. A
Chan B B
Auto A
Cross A
Sample Inc 50
Recor 50
Sums 128
Word Pos 2-3
Resumes 0
Date 4-5-96
20.5.0
T/D = 3.0
B/D = 0.363
ΔX = 0.6 in.

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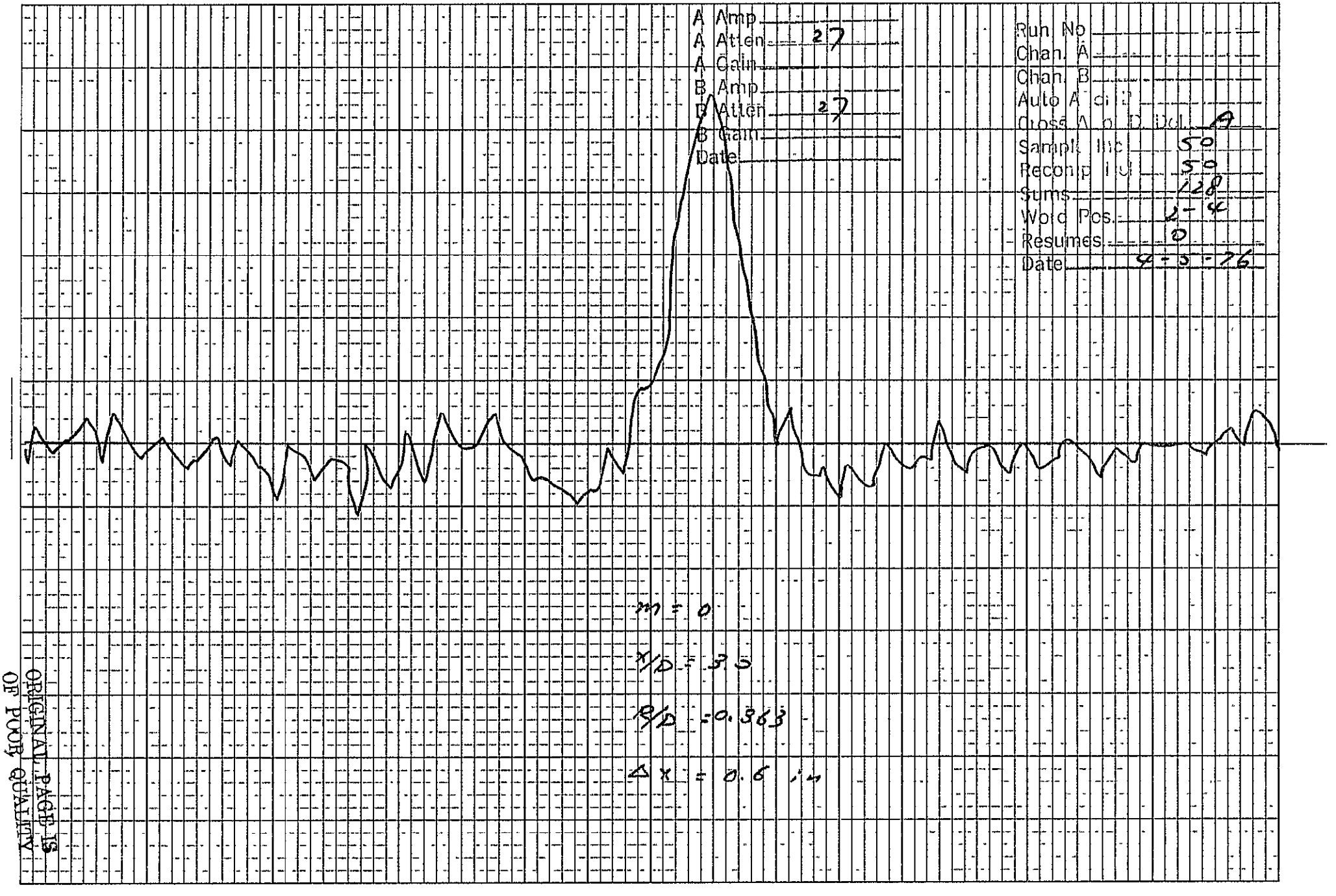

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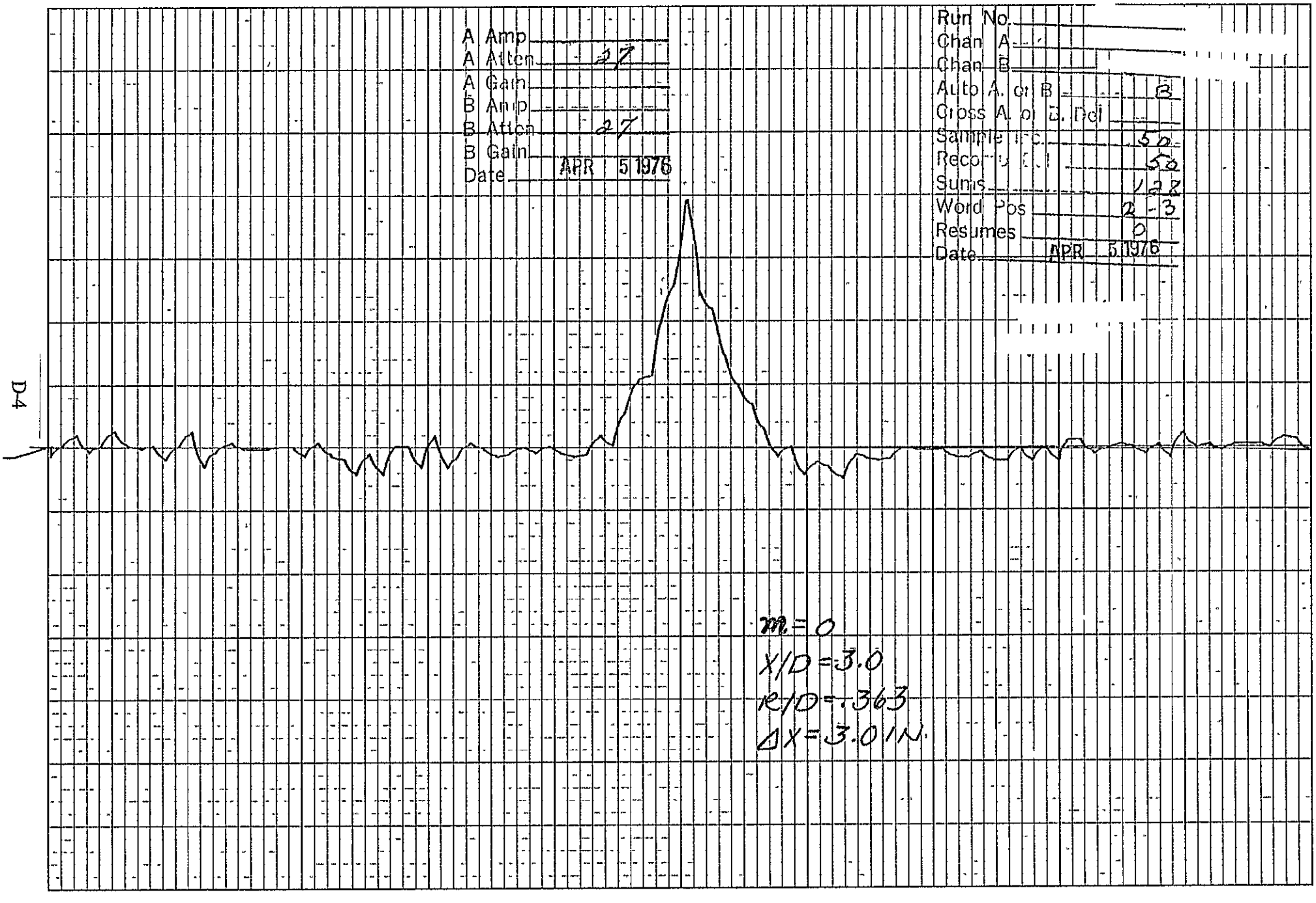
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A Atten 27
A Gain
B Amp
B Atten 27
B Gain
Date APR 5 1976
Run No.
Chan A
Chan B
Auto A. or B B
Cross A. or B. Del
Sample Rec. 50
Record Del 50
Sums 128
Word Pos 2 - 3
Resumes 0
Date APR 5 1976
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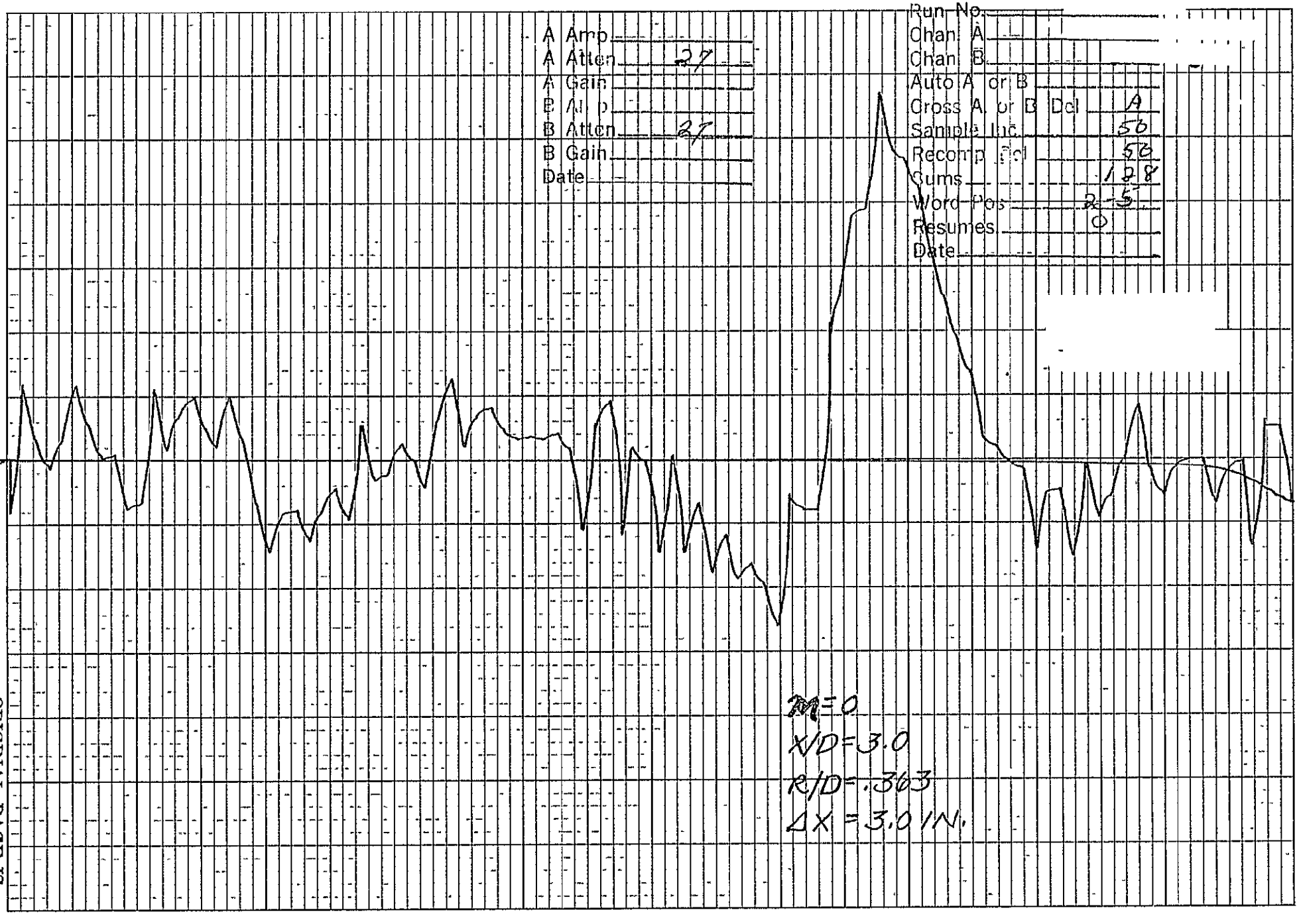
R/D = .363
ΔX = 3.0 IN.



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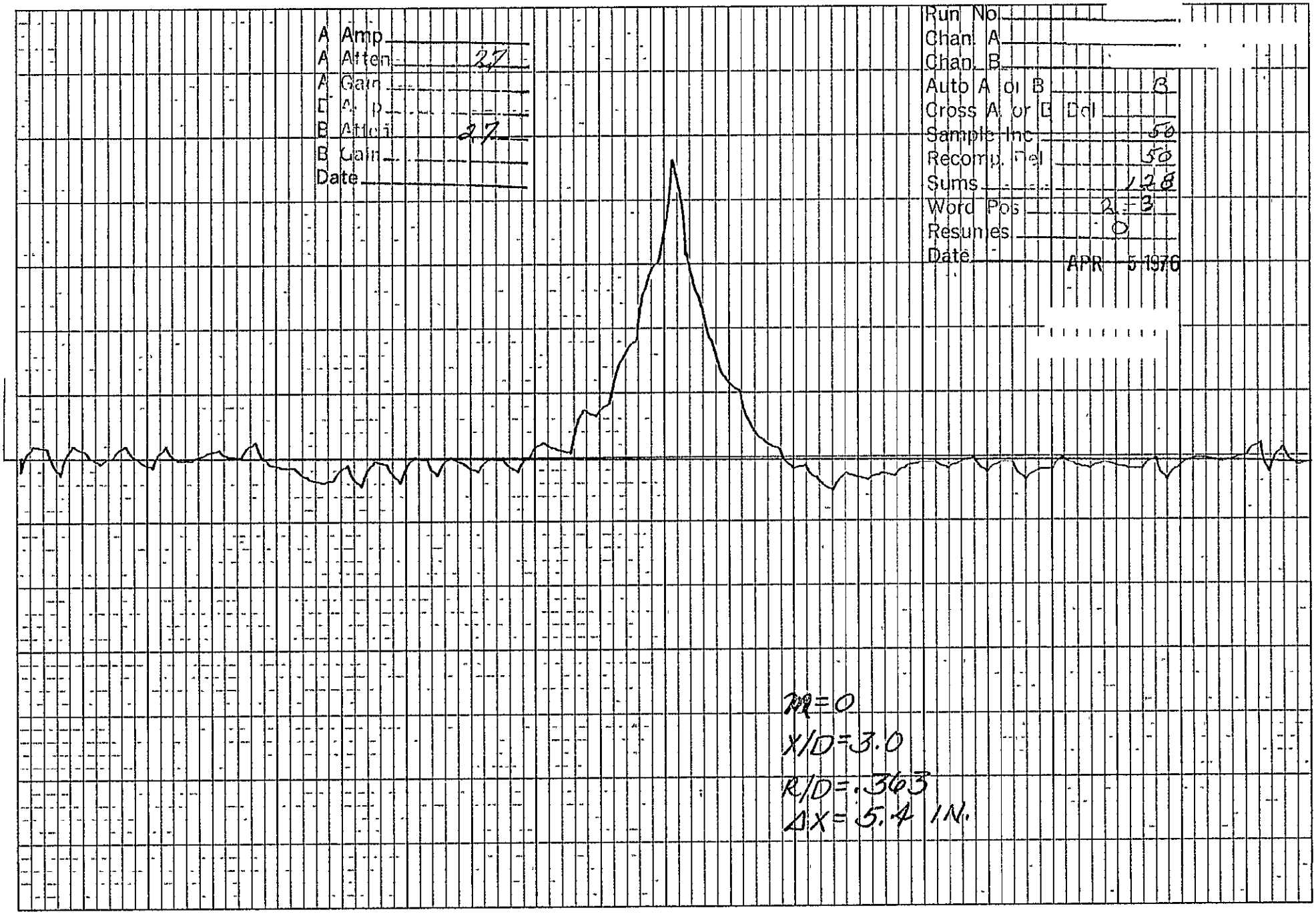

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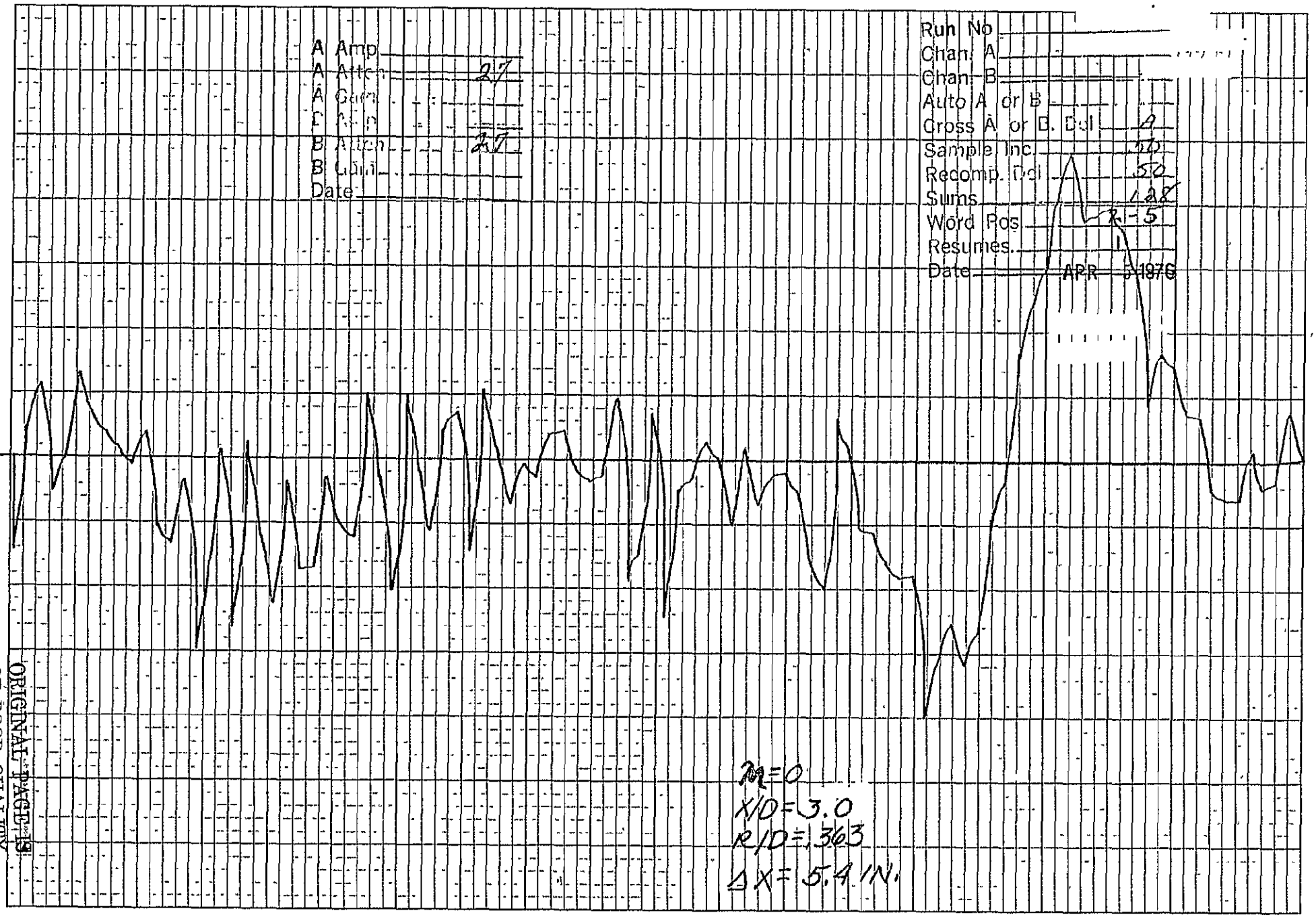

D-7

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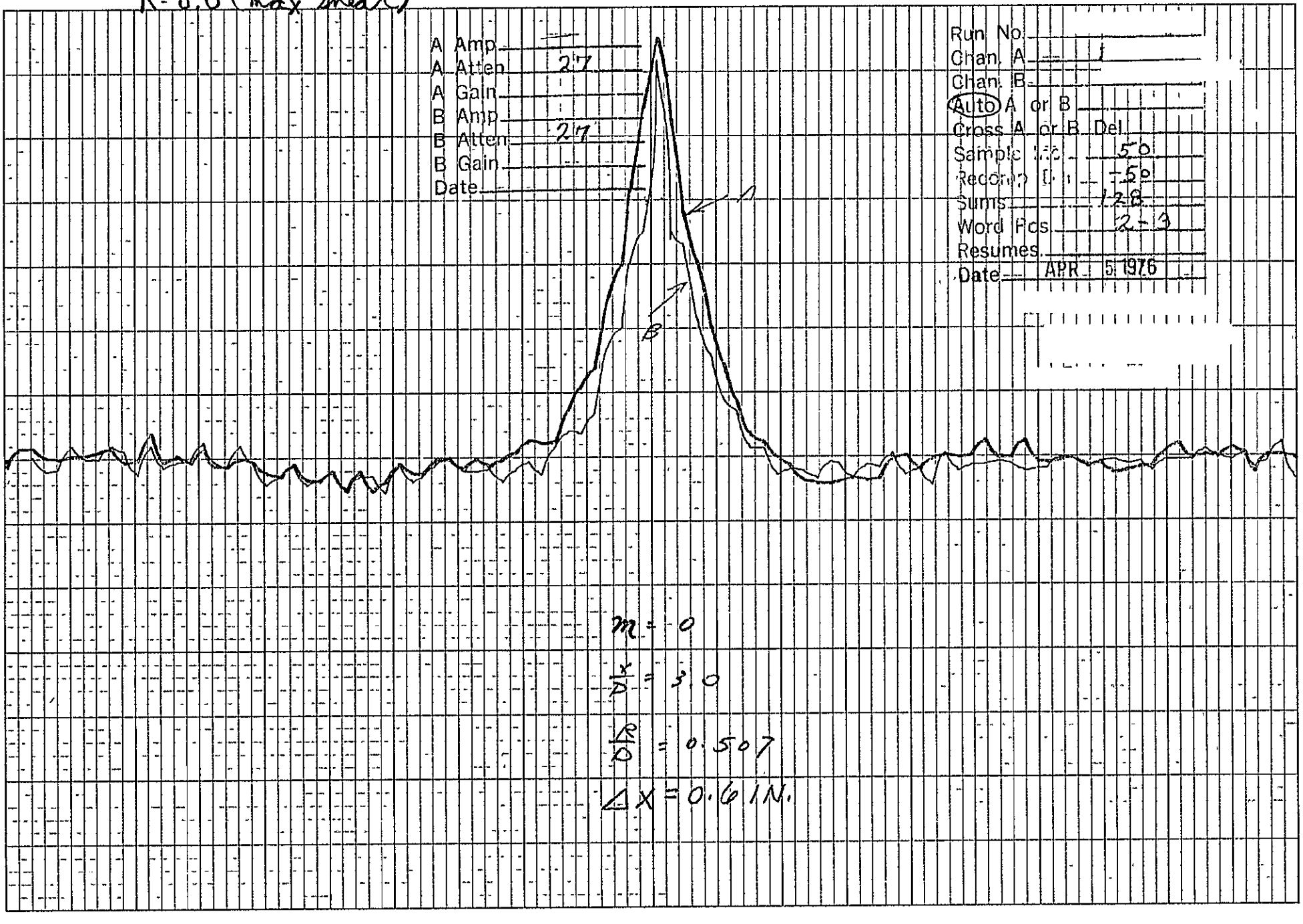

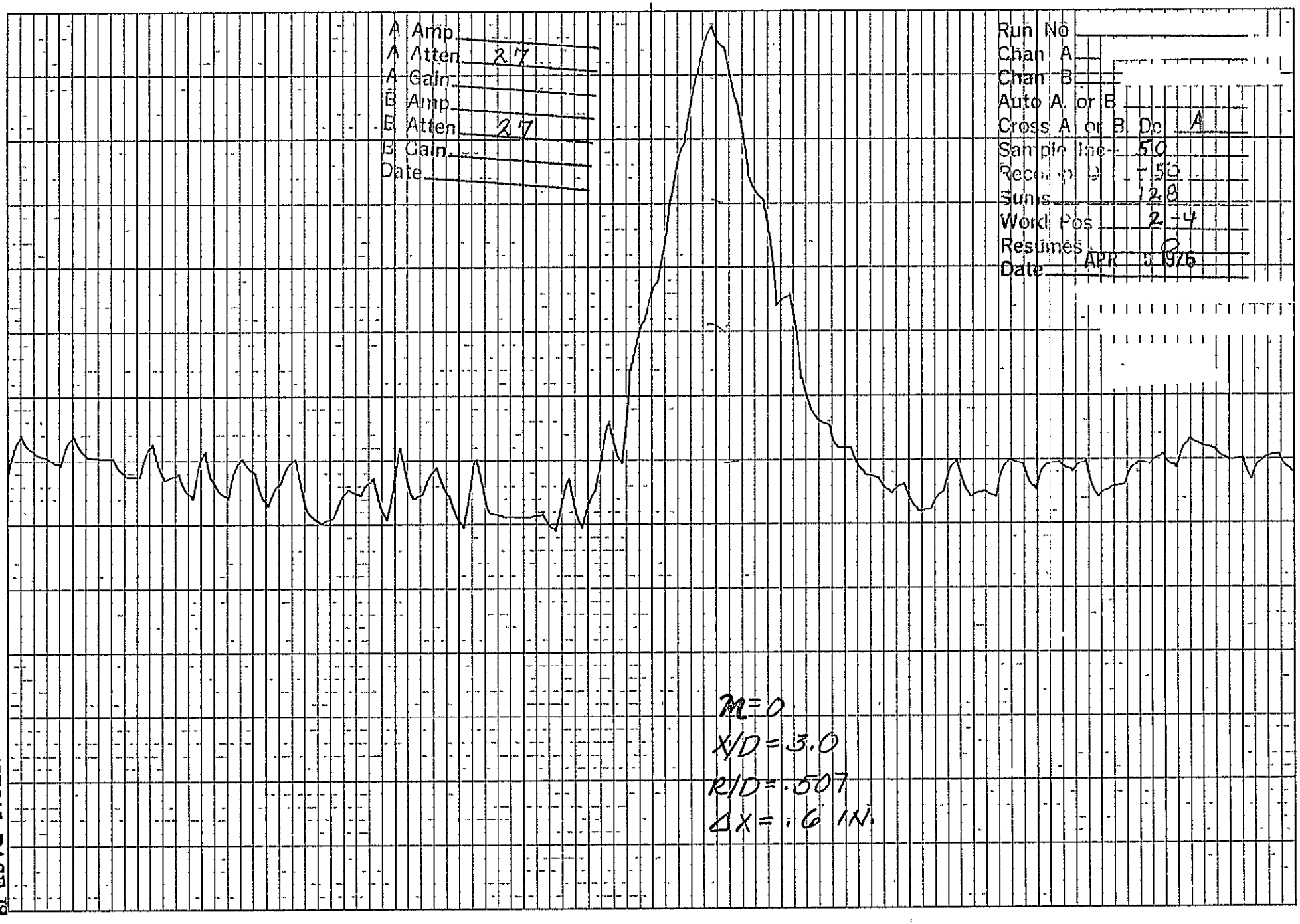

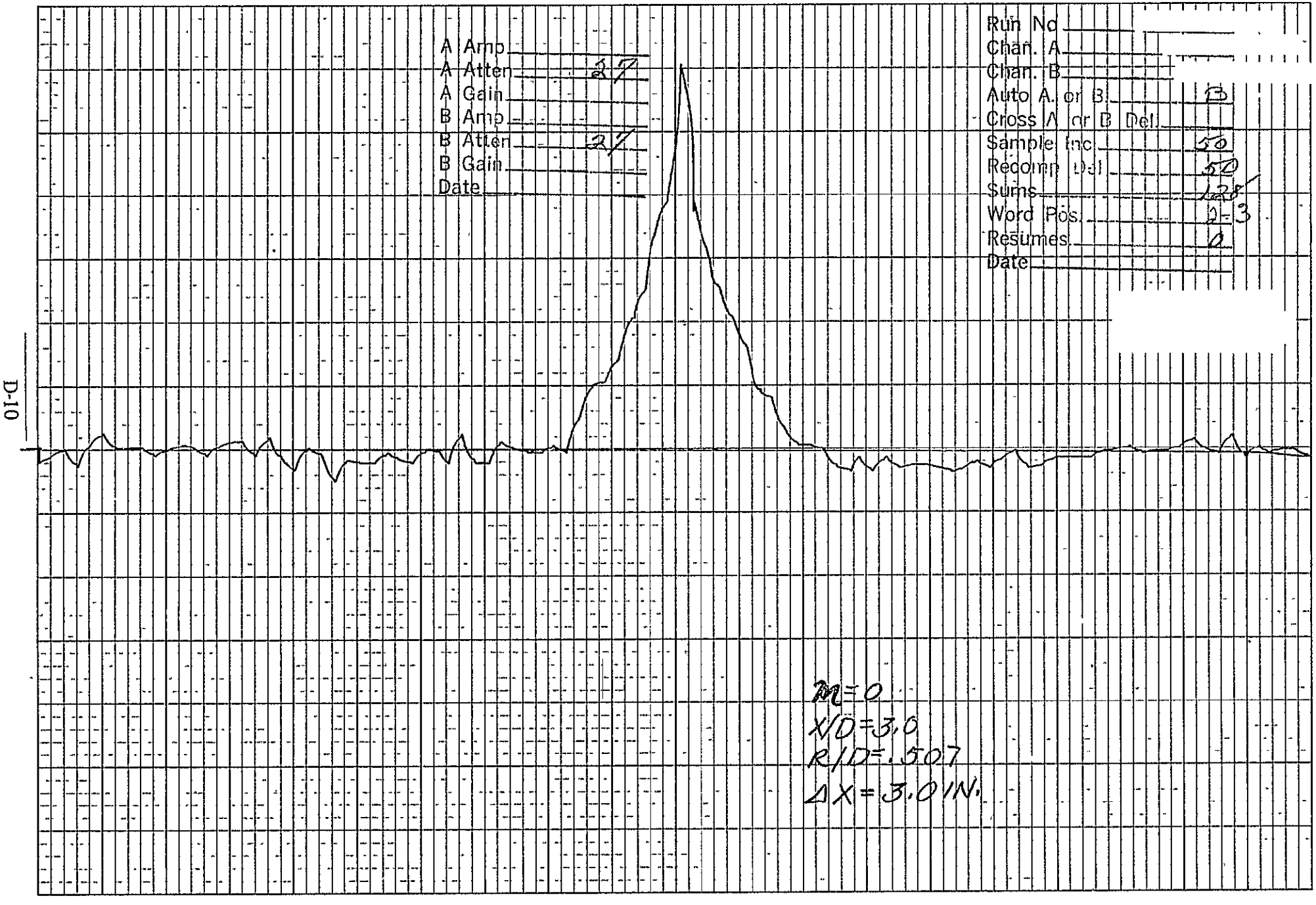
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B Gain
Date
Run No
Chan. A
Chan. B
Auto A. or B. B
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Sample Inc 50
Recomp Del 50
Sums 128
Word Pos. 1-3
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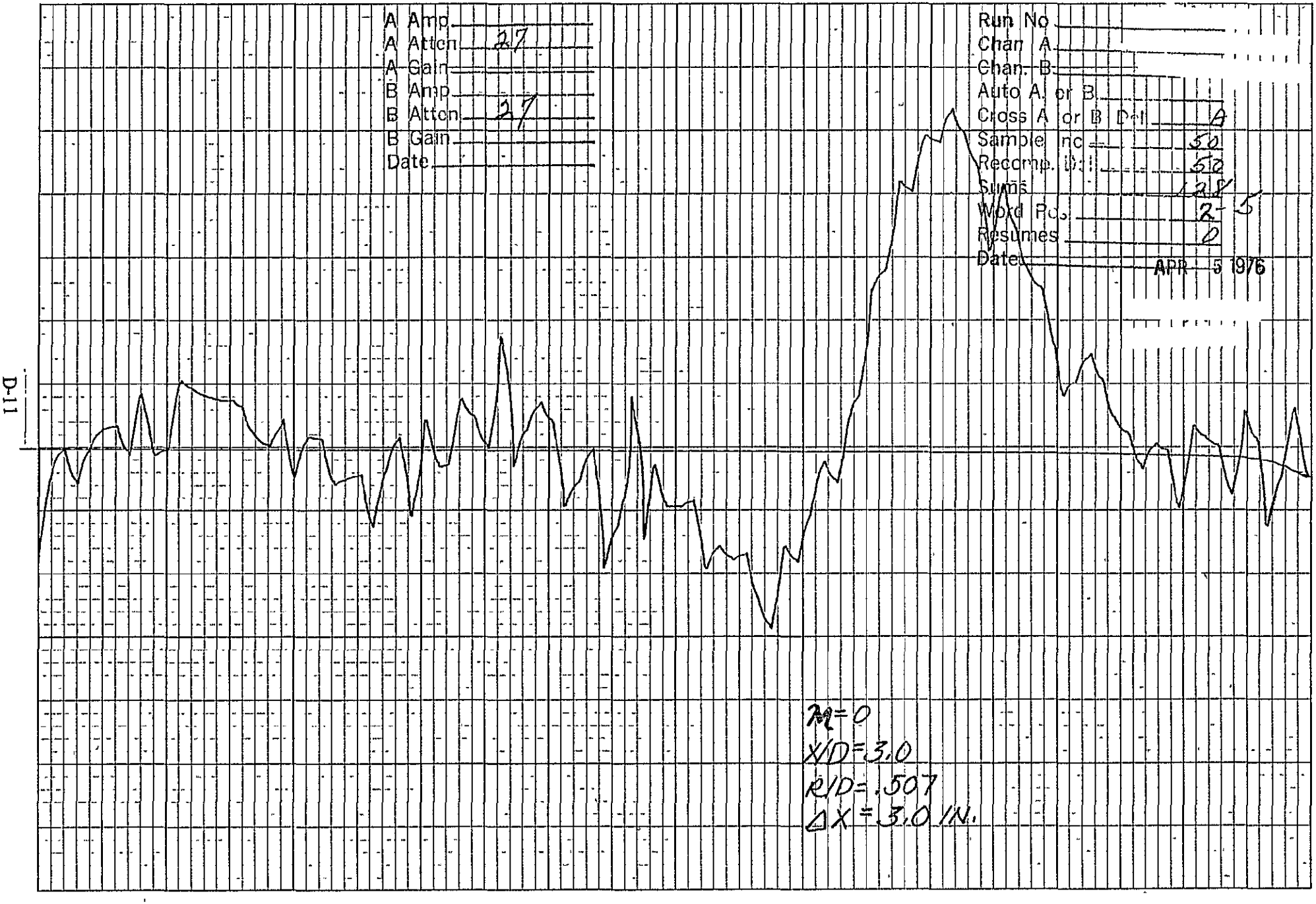

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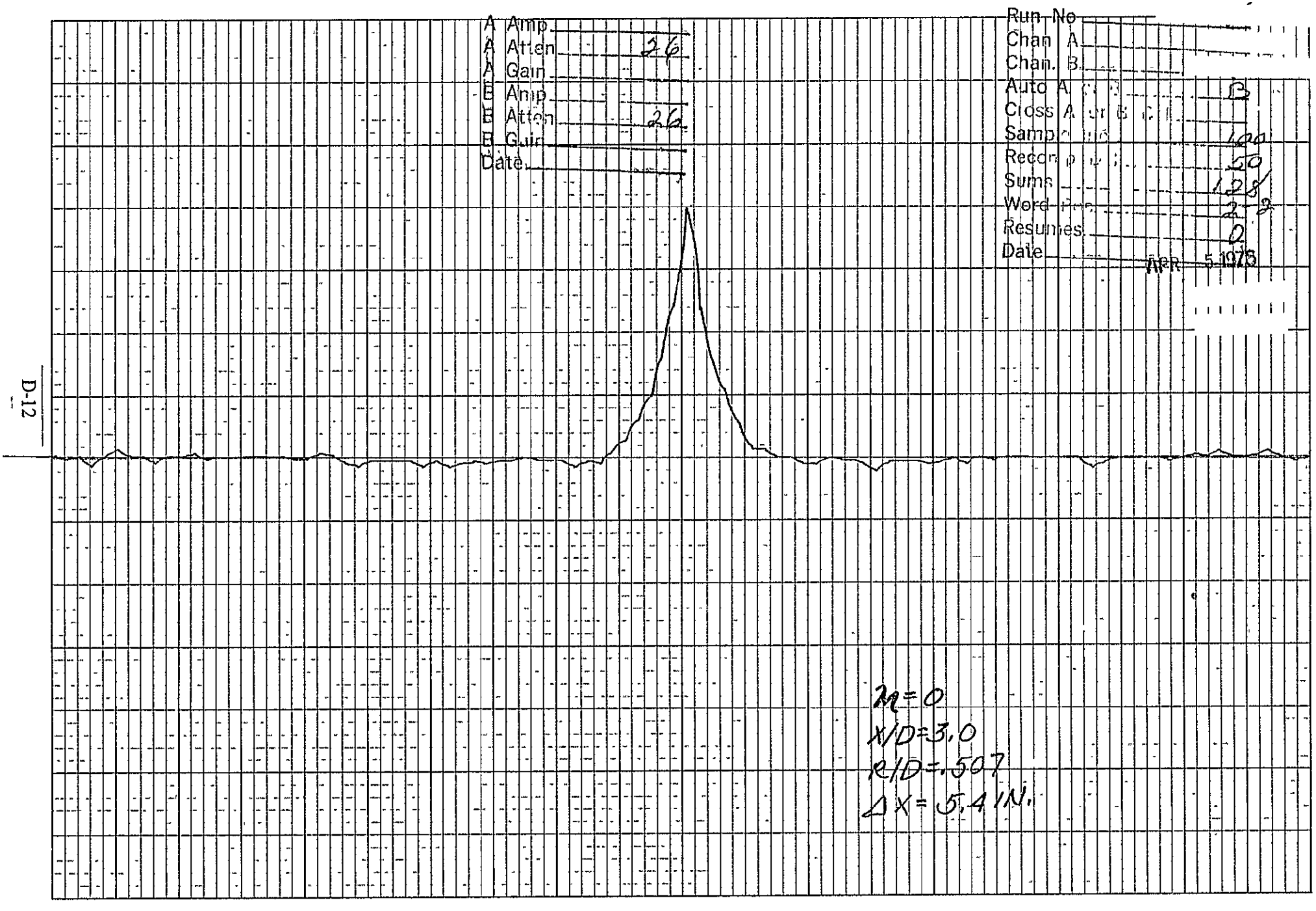
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A Atten 26
A Gain
B Amp
B Atten 26
B Gain
Date
Run No
Chan A
Chan. B
Auto A or B
Cross A or B
Samp
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Sums 128
Word
Resumes 0
Date MAR 5 1975
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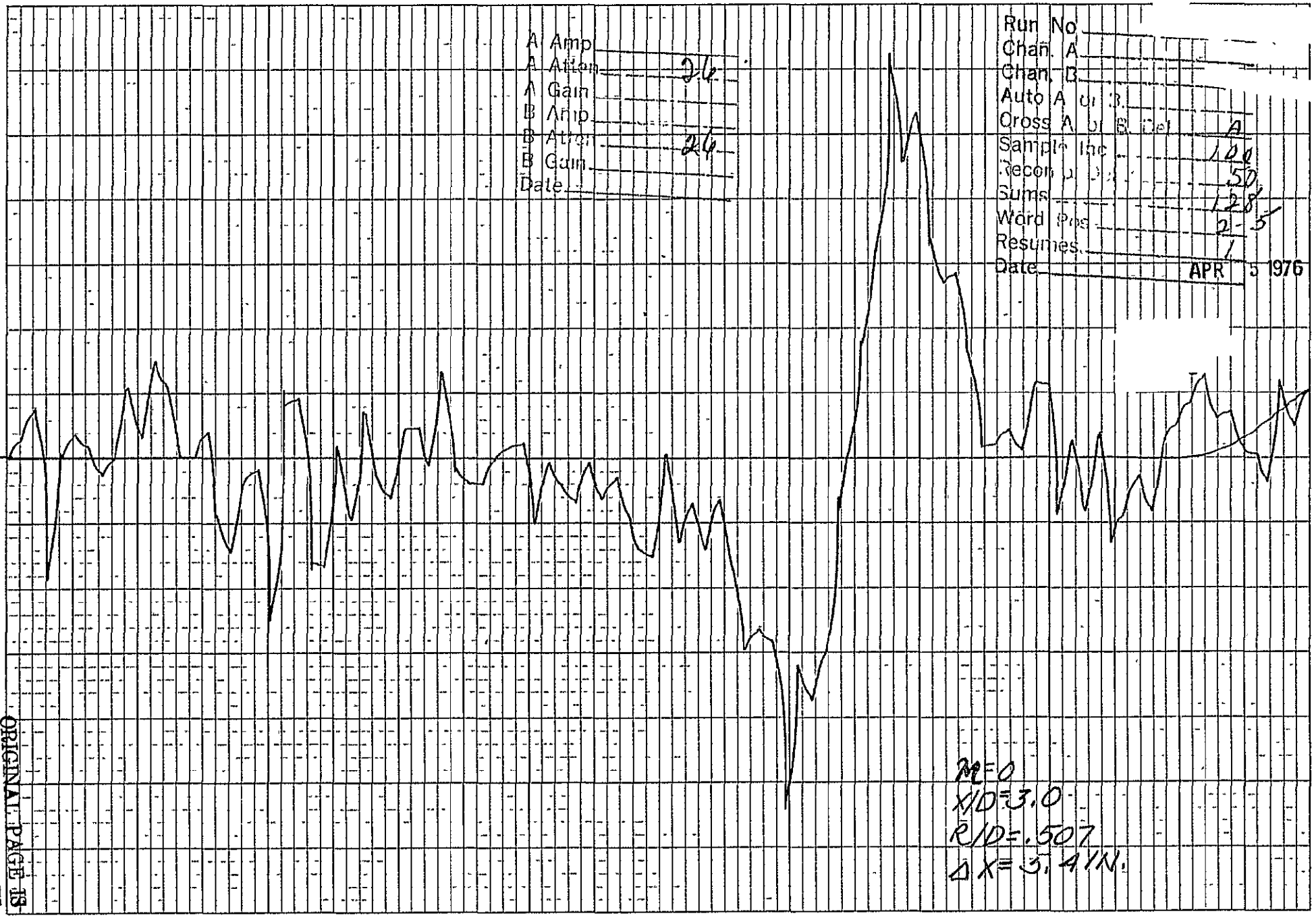

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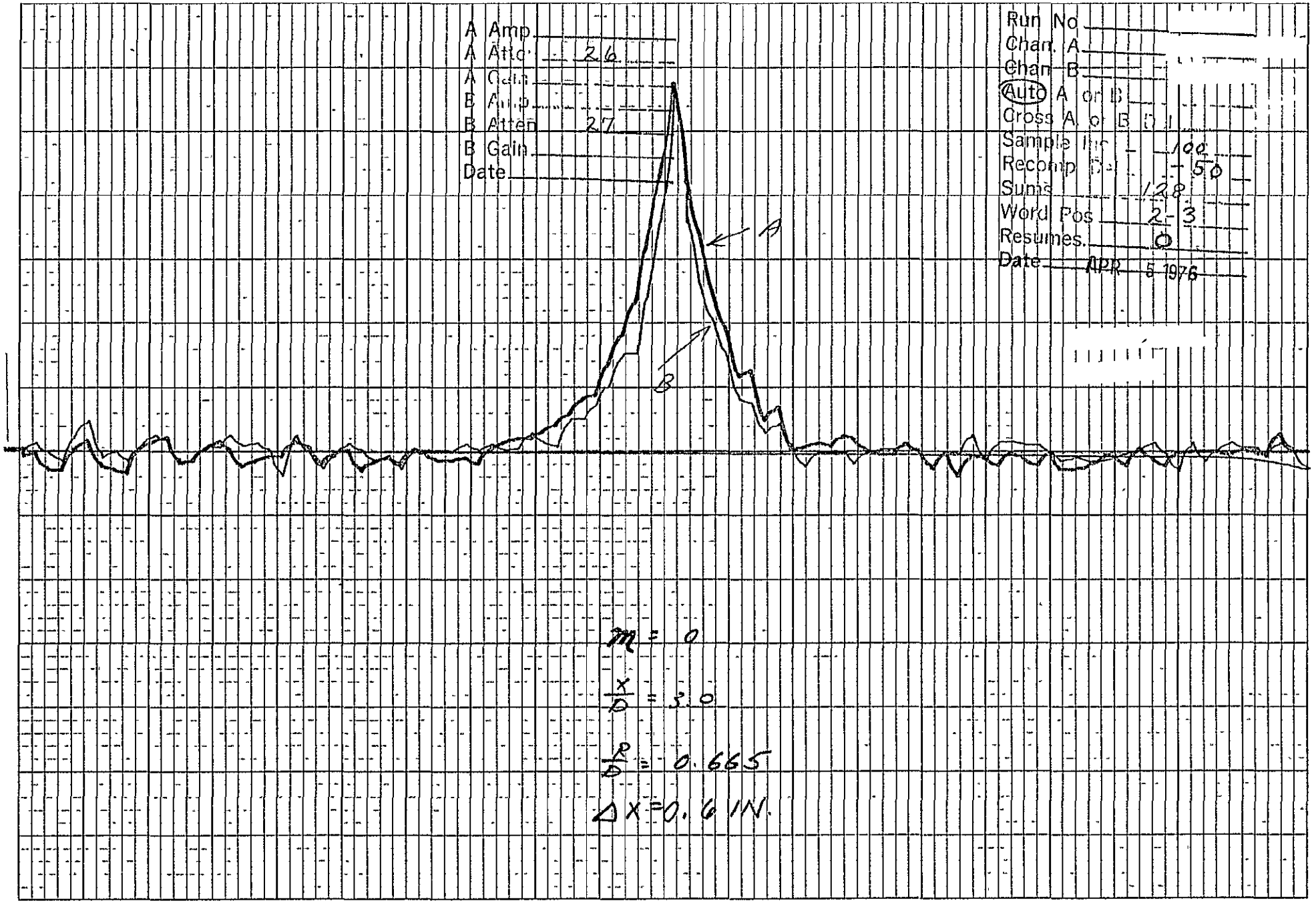

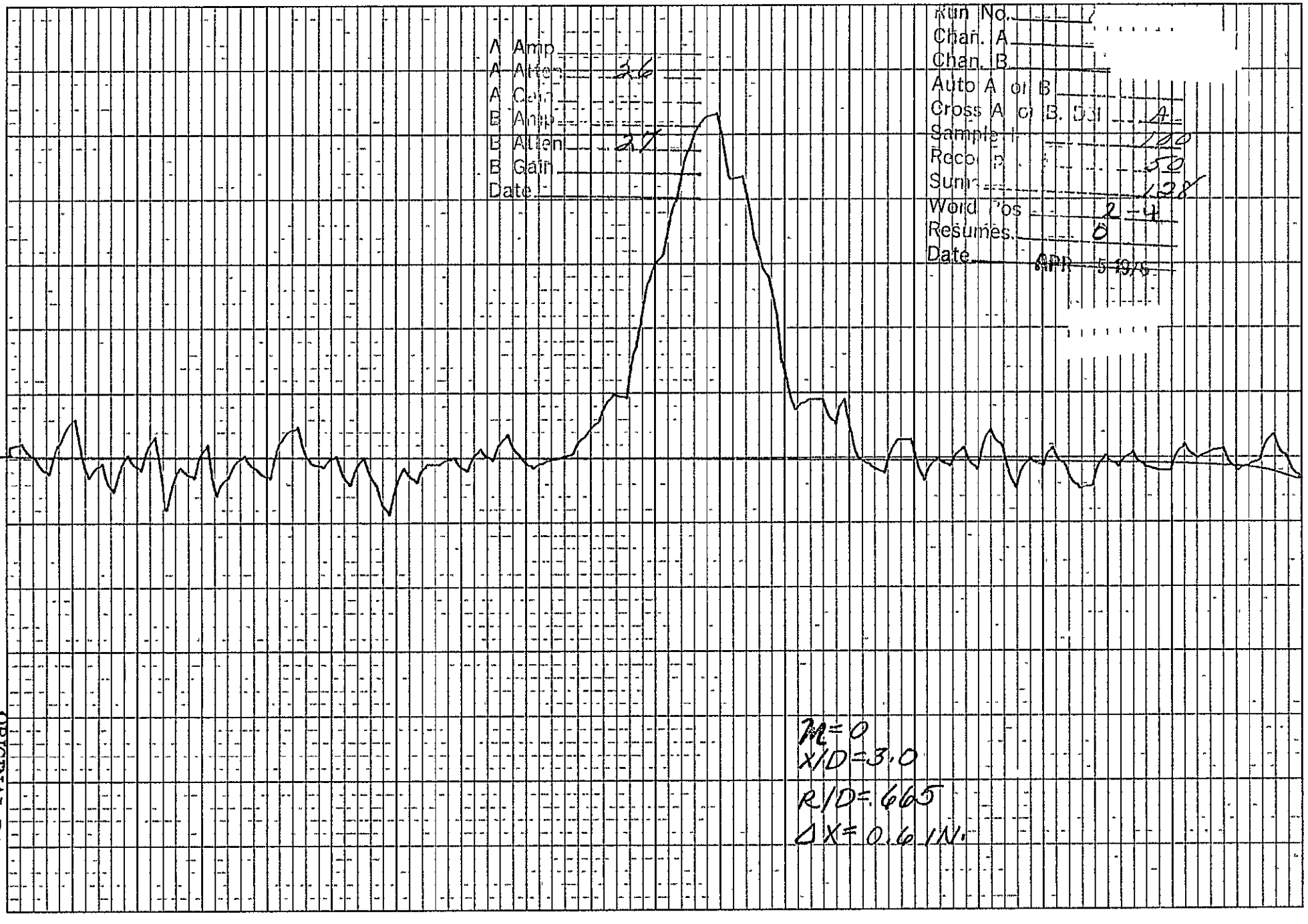

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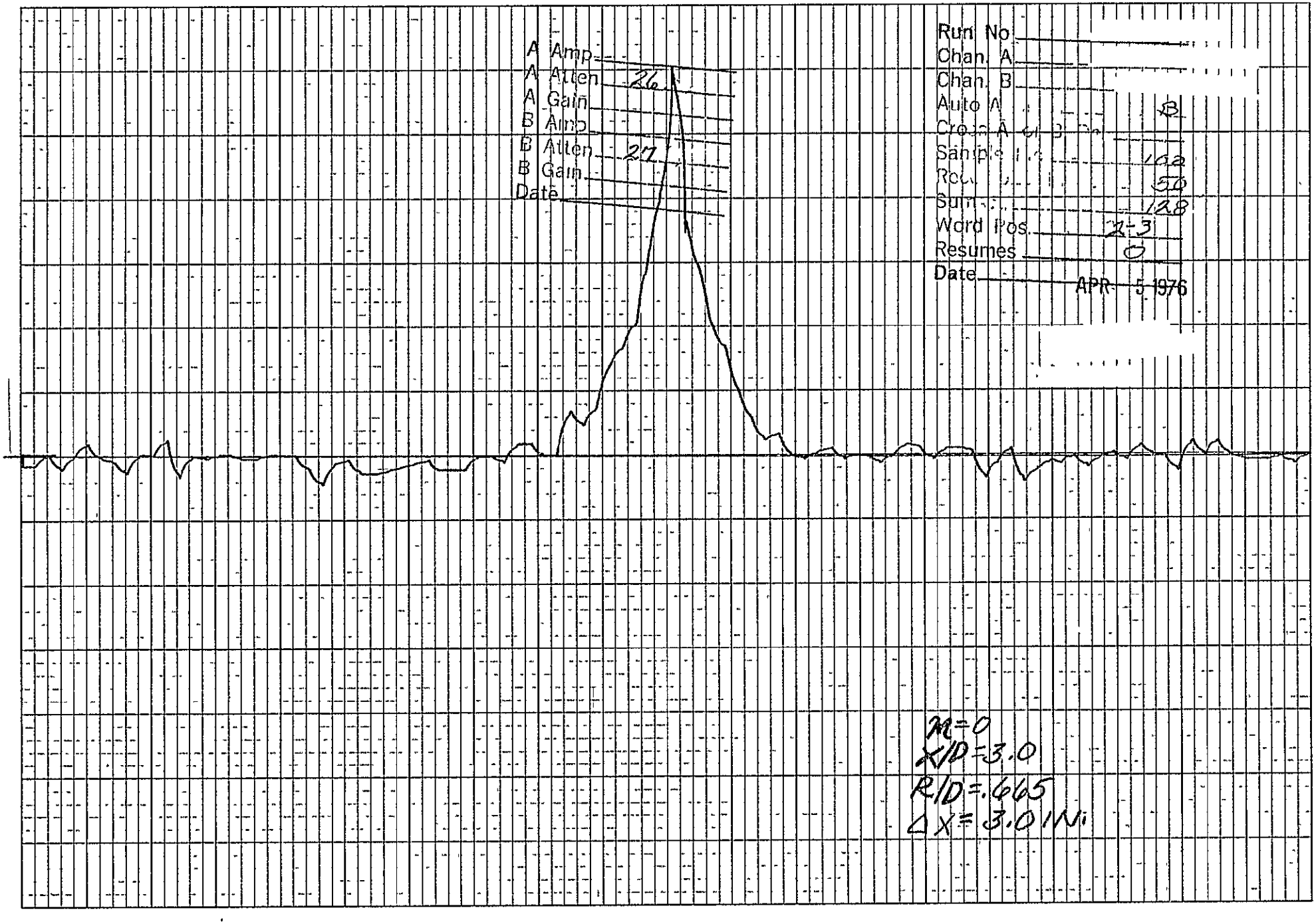

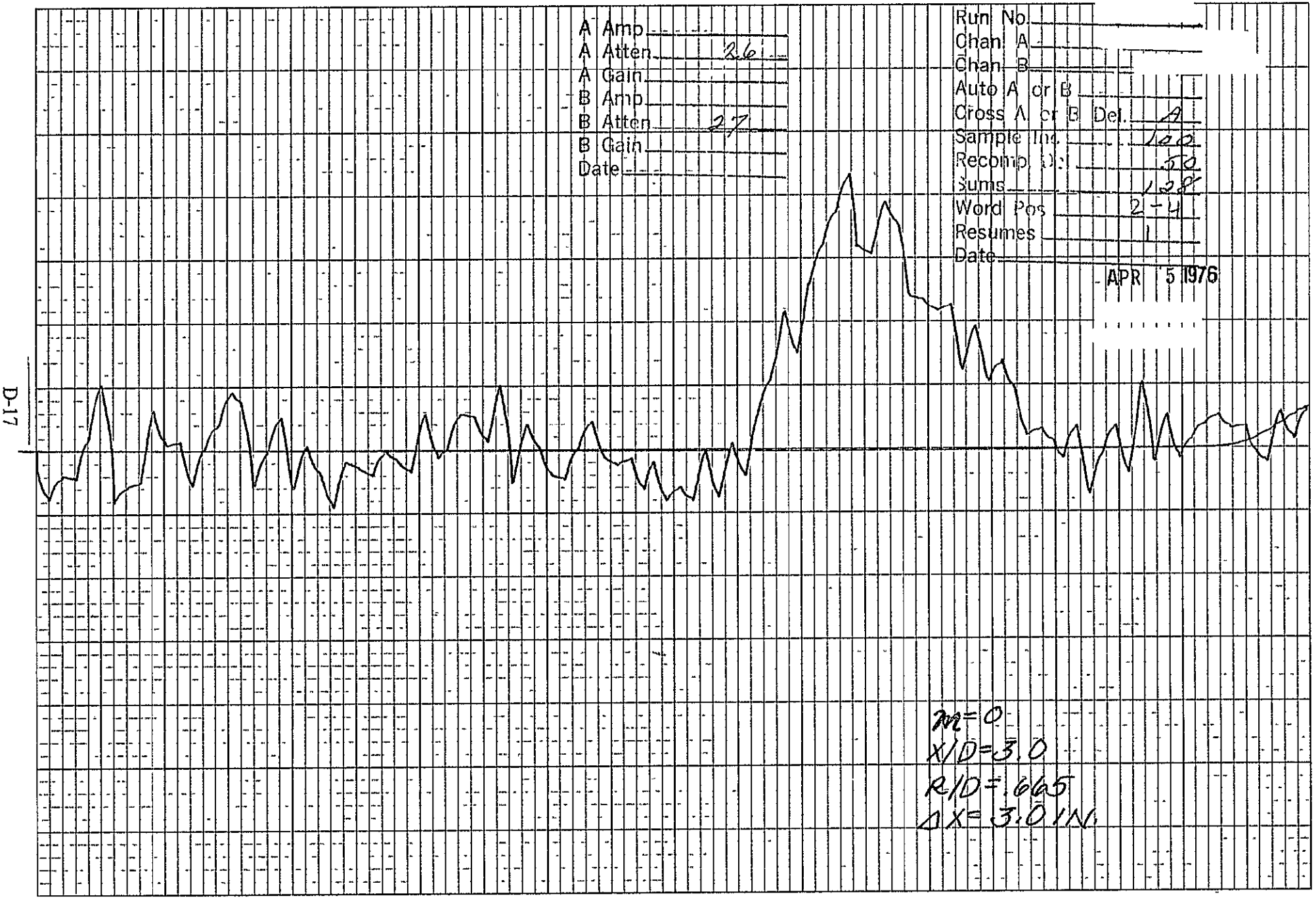
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Chan B
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Cross A or B Del. 4
Sample Inc. 100
Recomp. Del. 50
Sums 128
Word Pos 2-4
Resumes 1
Date APR 5 1976
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No XY-1001-SP [redacted]

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A Gain
B Amp
B Atten 27
B Gain
Date

Run No
Chan A
Chan B
Auto A or B A
Cross A or B Dc
Sample Inc 100
Recon p. /2 50
Sums 128
Word Pos 2-3
Resumes 0
Date APR 5 1976

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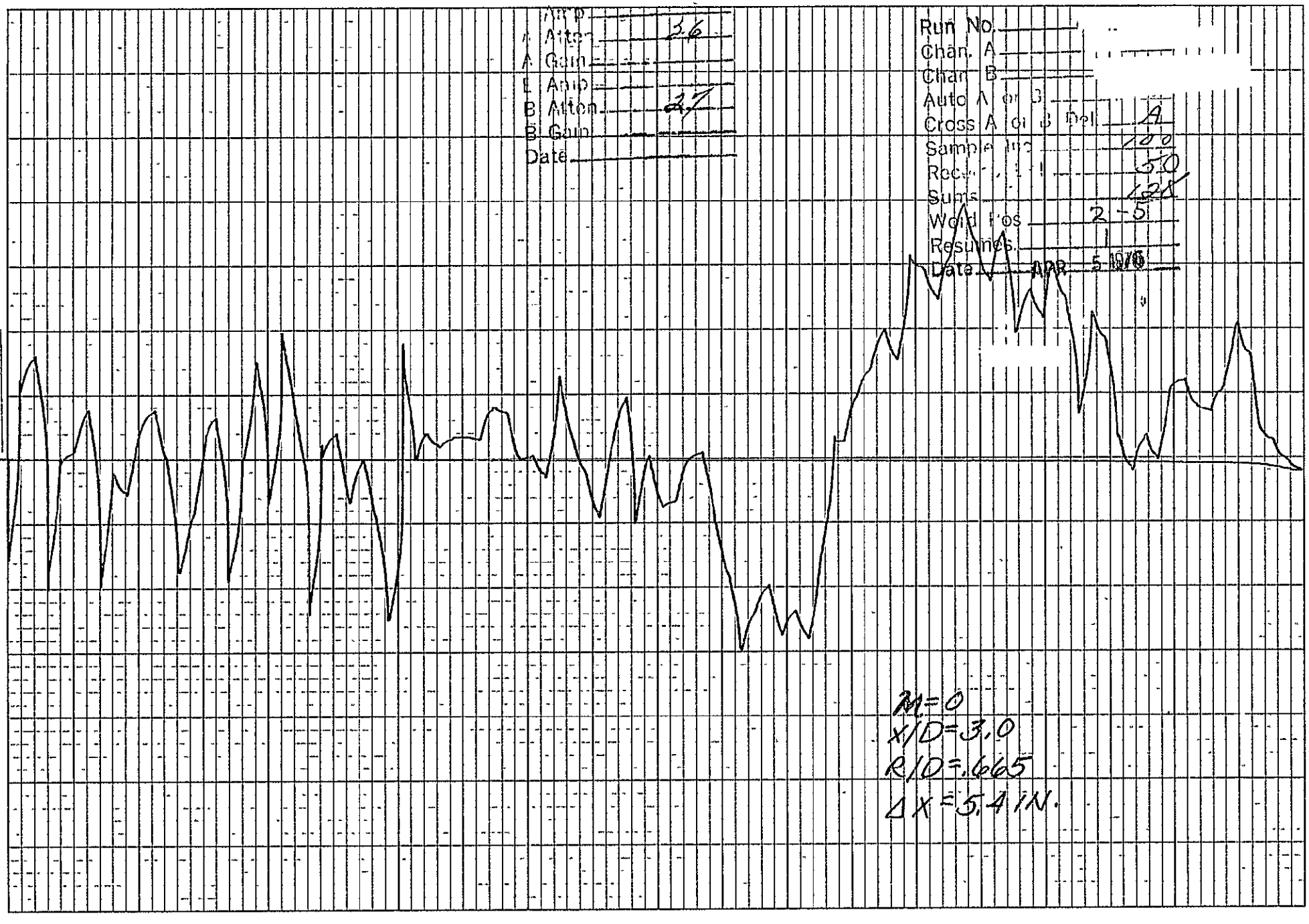

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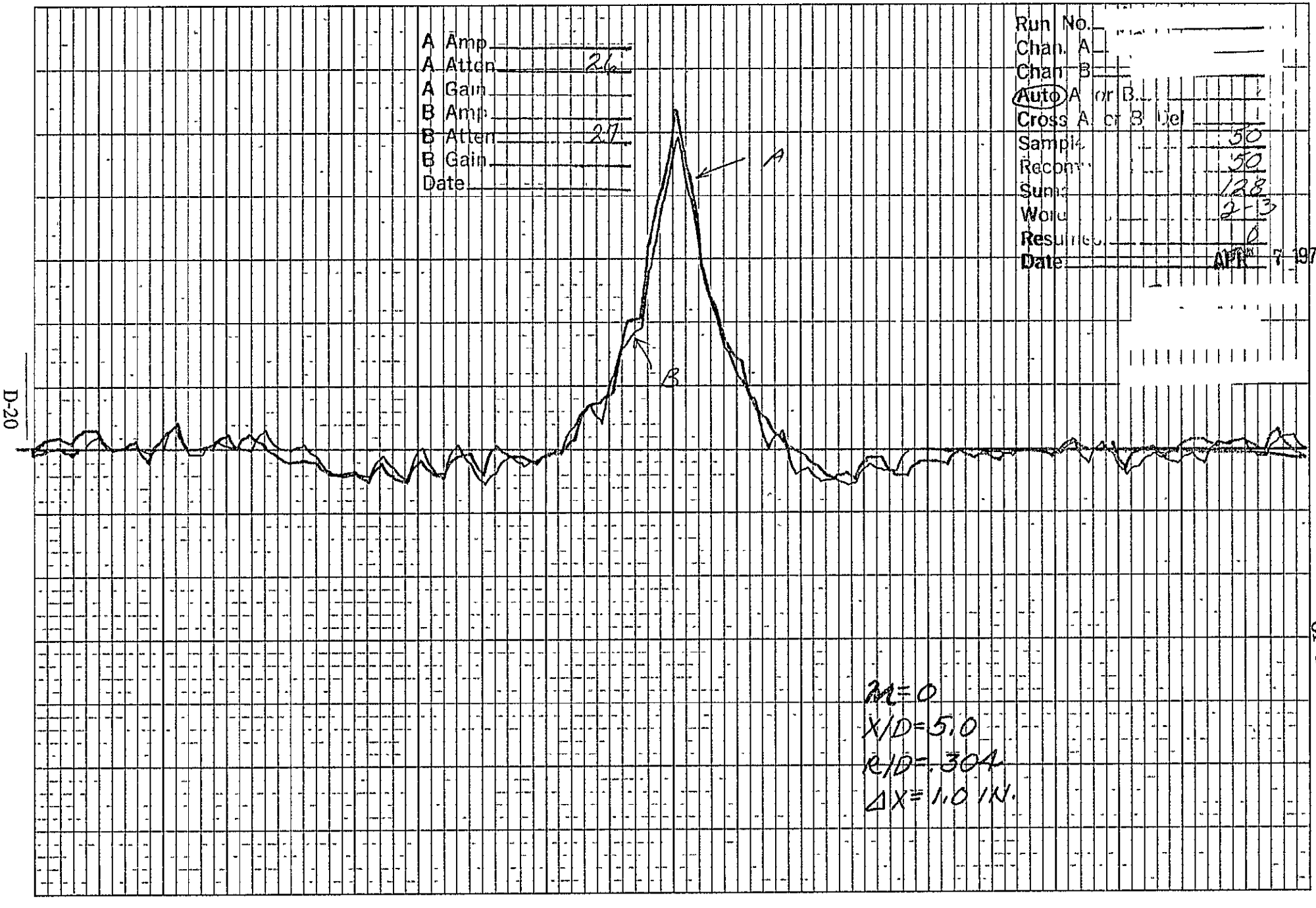

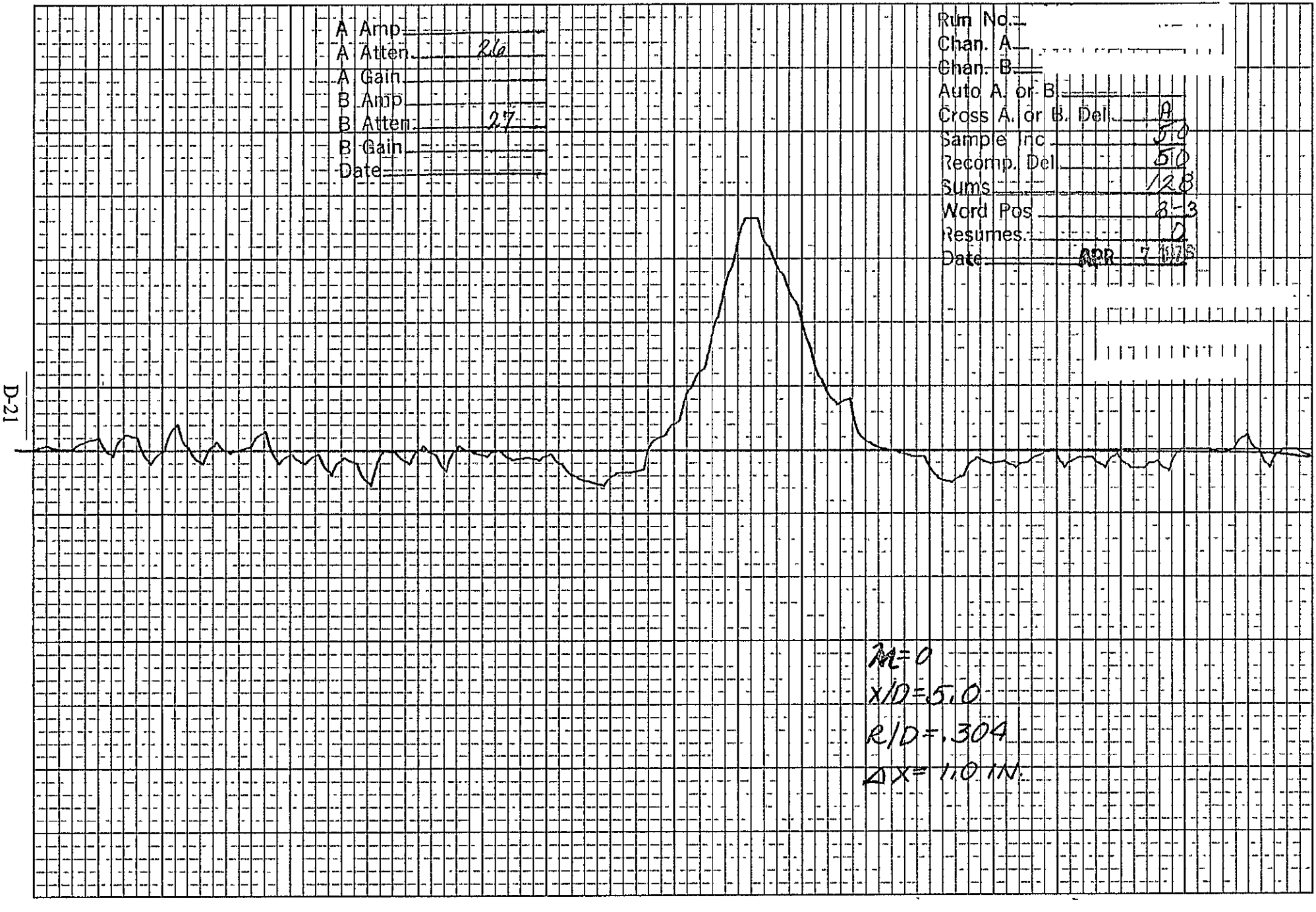
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Chan. B
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Cross A. or B. Del A
Sample Inc 50
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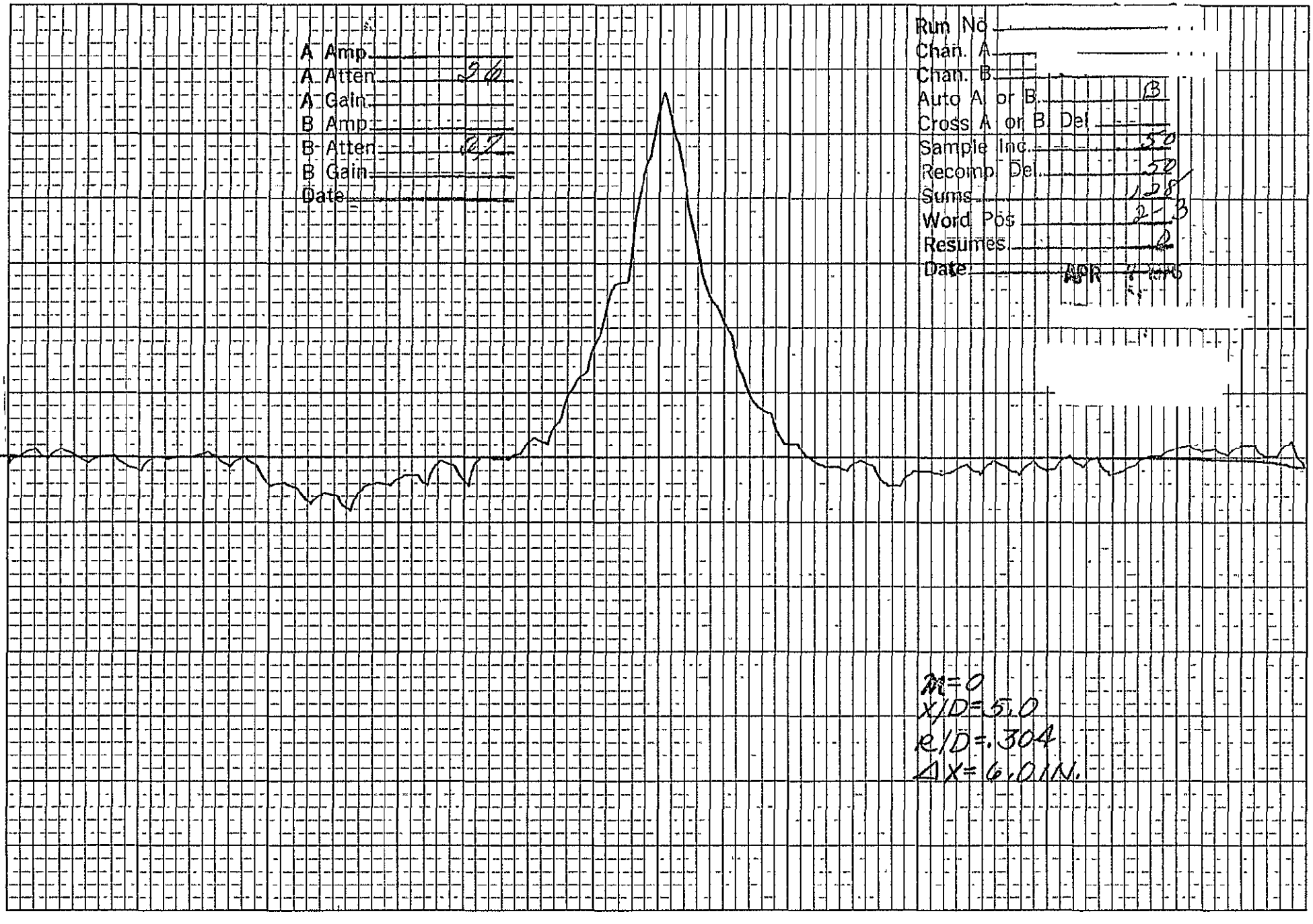
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Auto A or B
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Sample Inc
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Sums
Word Pos
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Date
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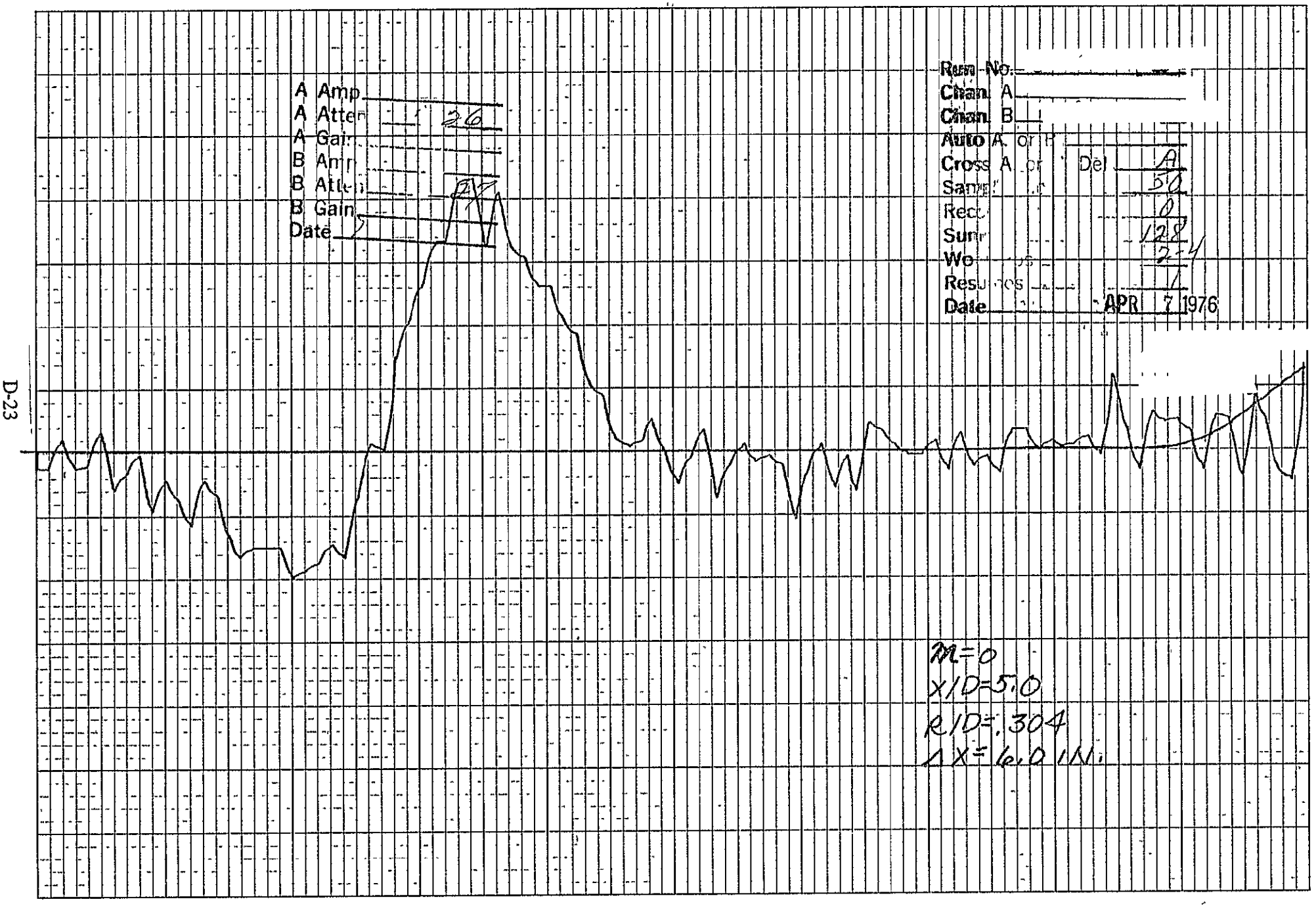

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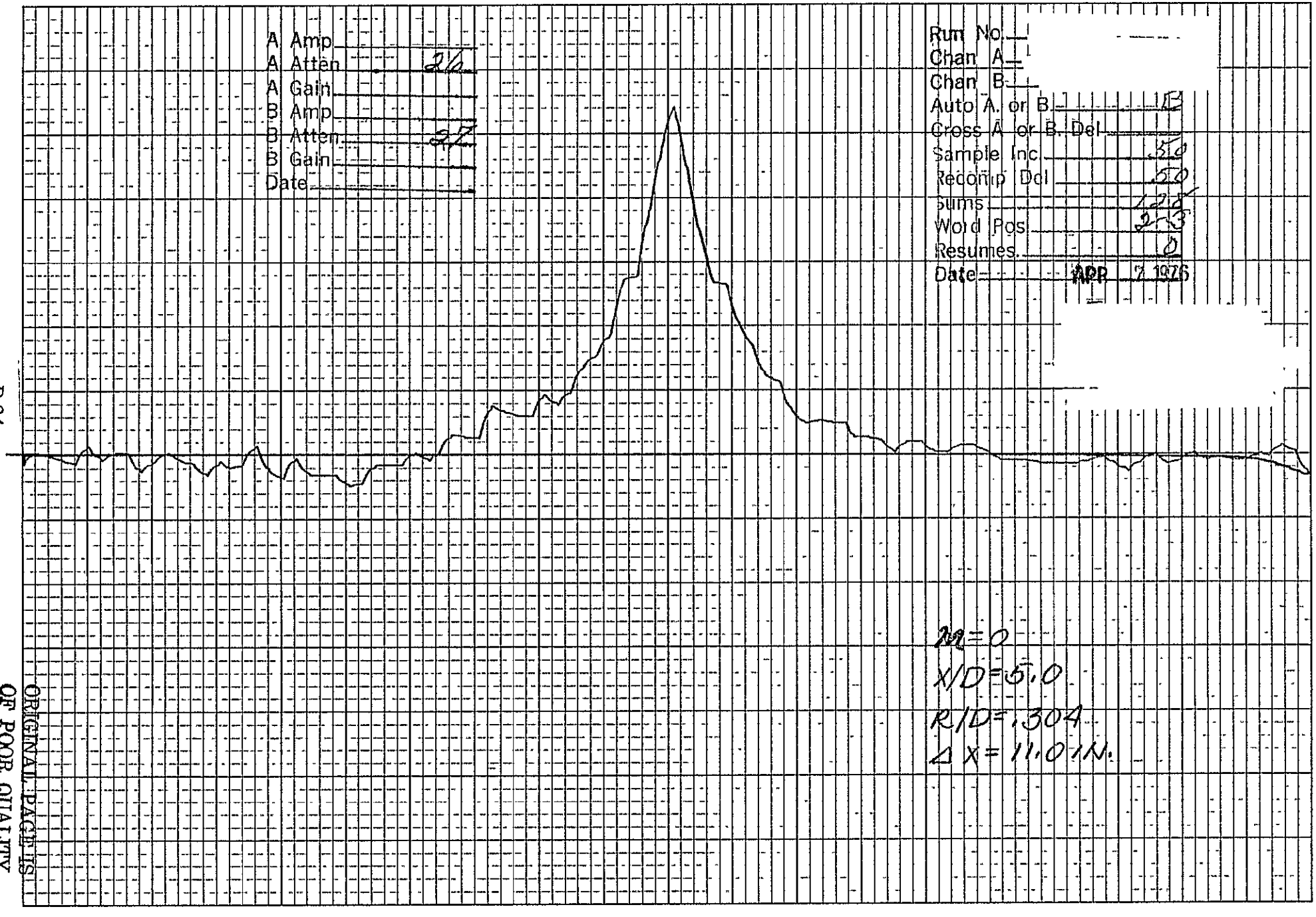

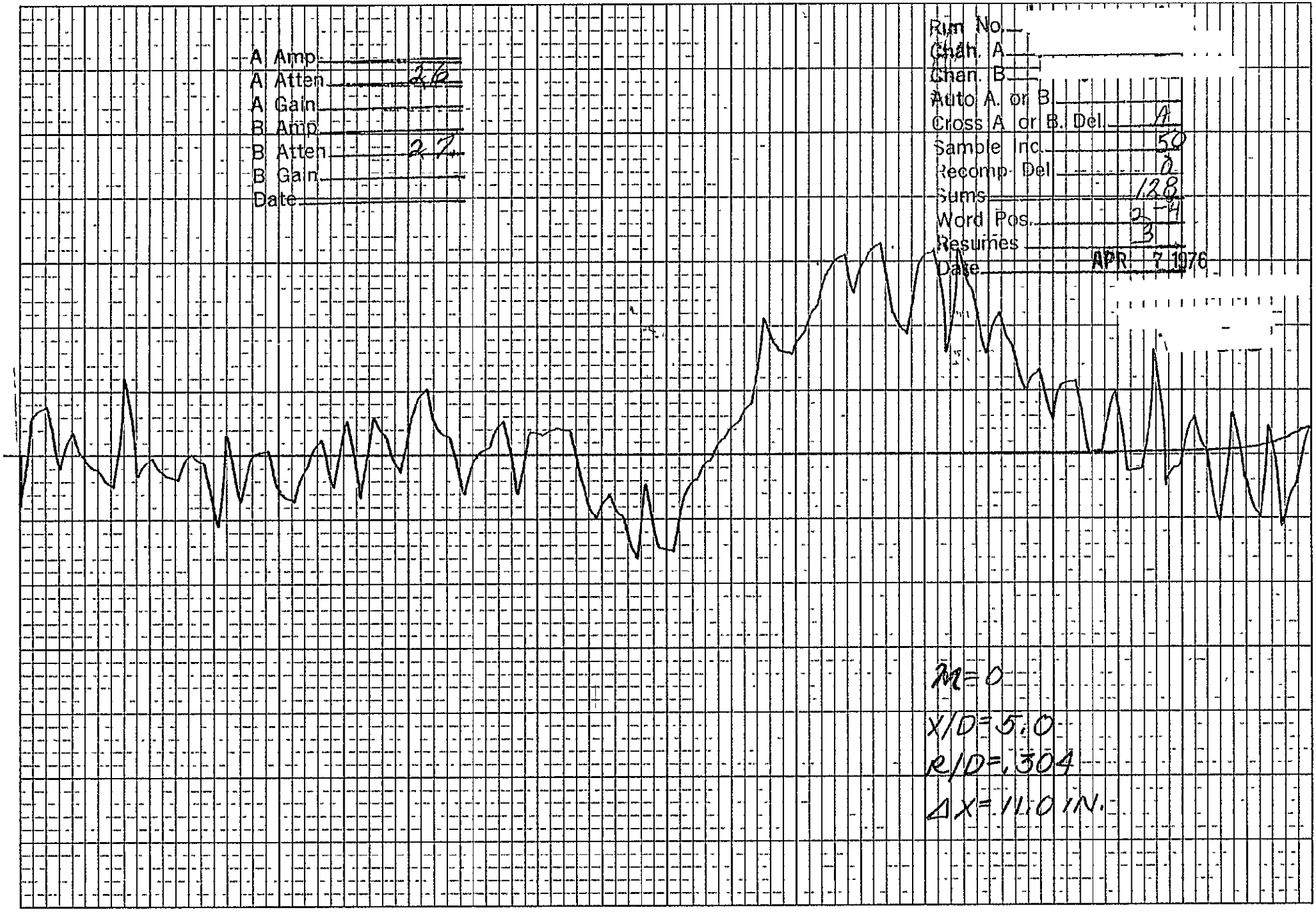
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Date
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Chan. B
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Cross A or B. Del. A
Sample Inc. 50
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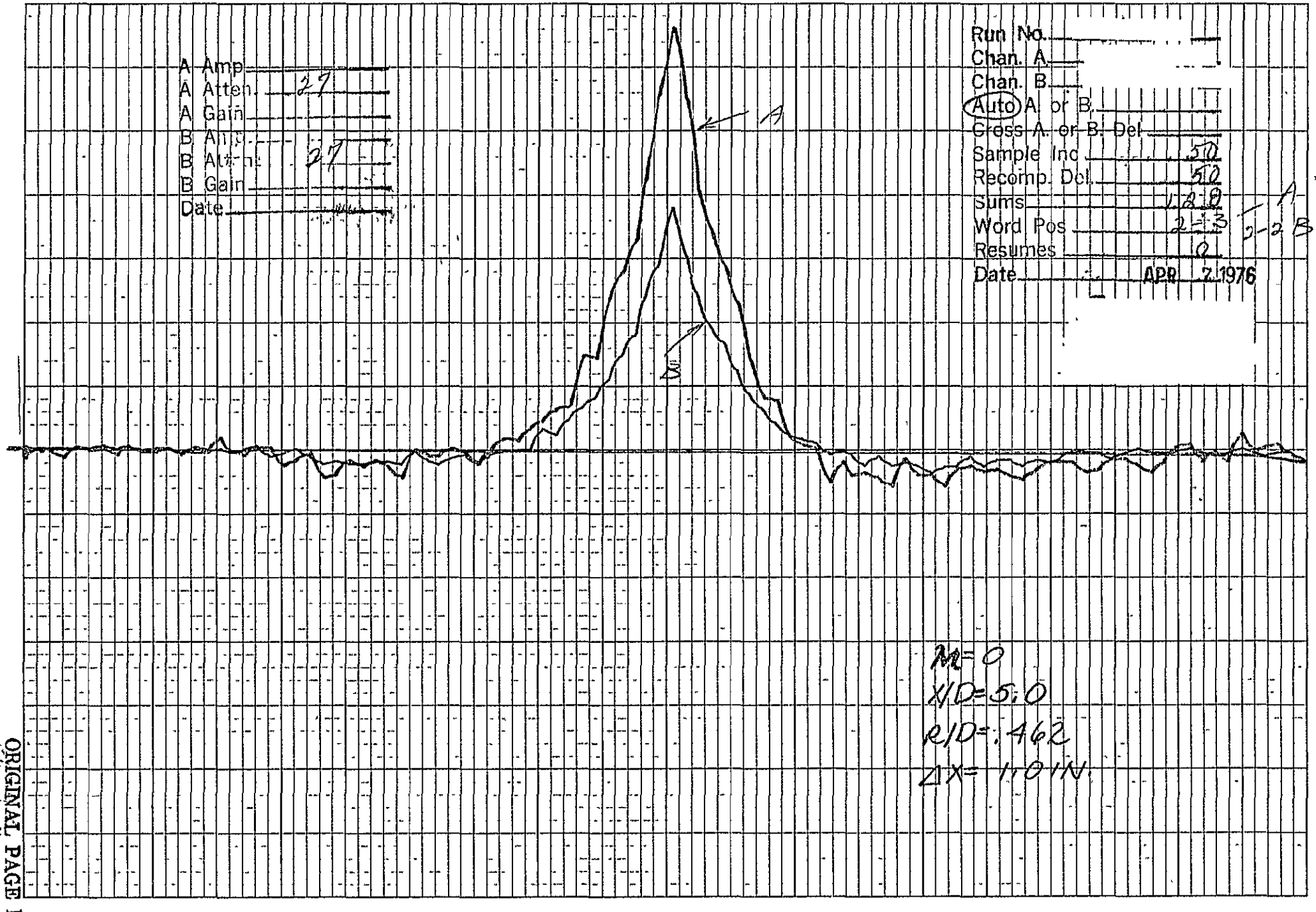

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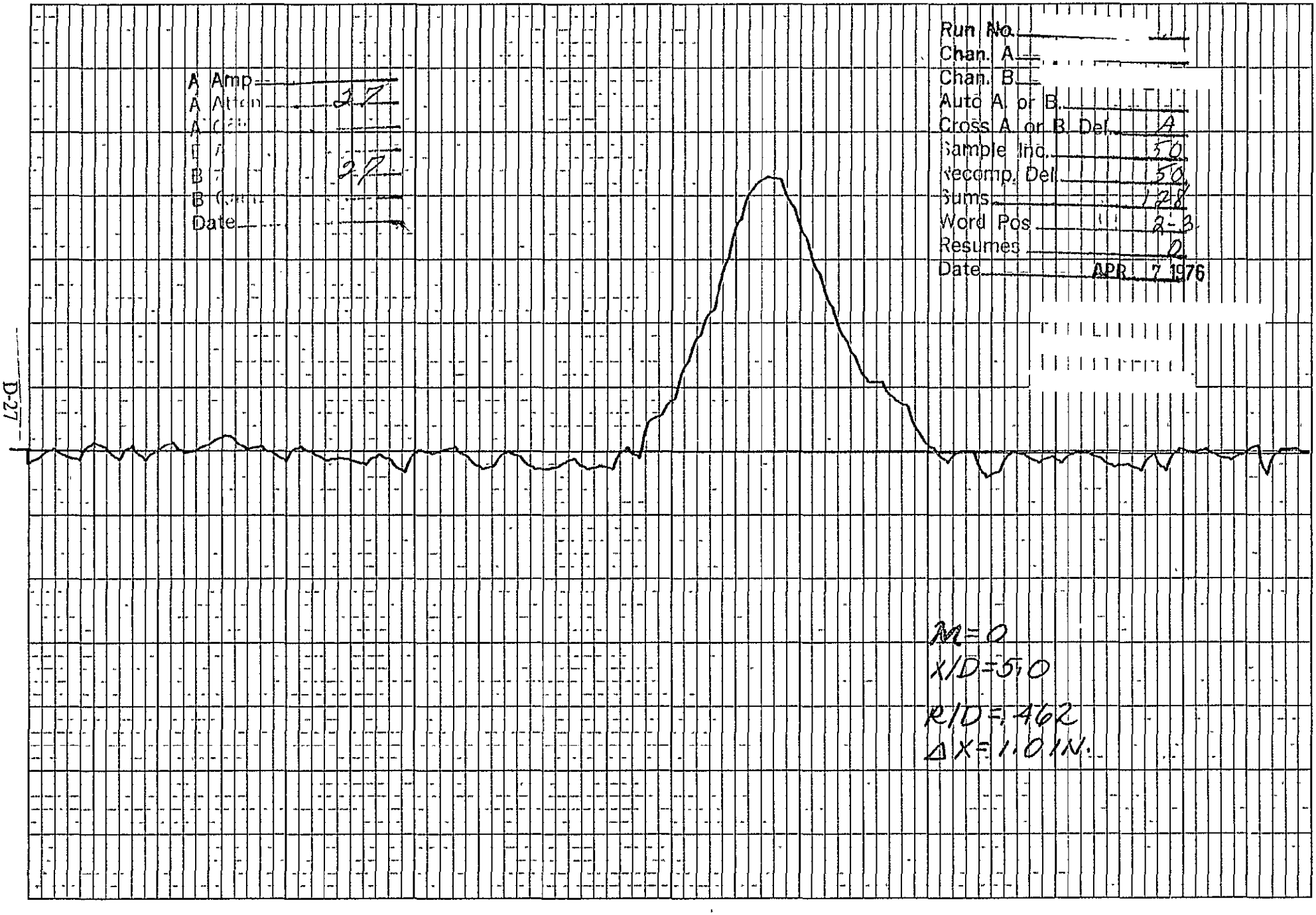

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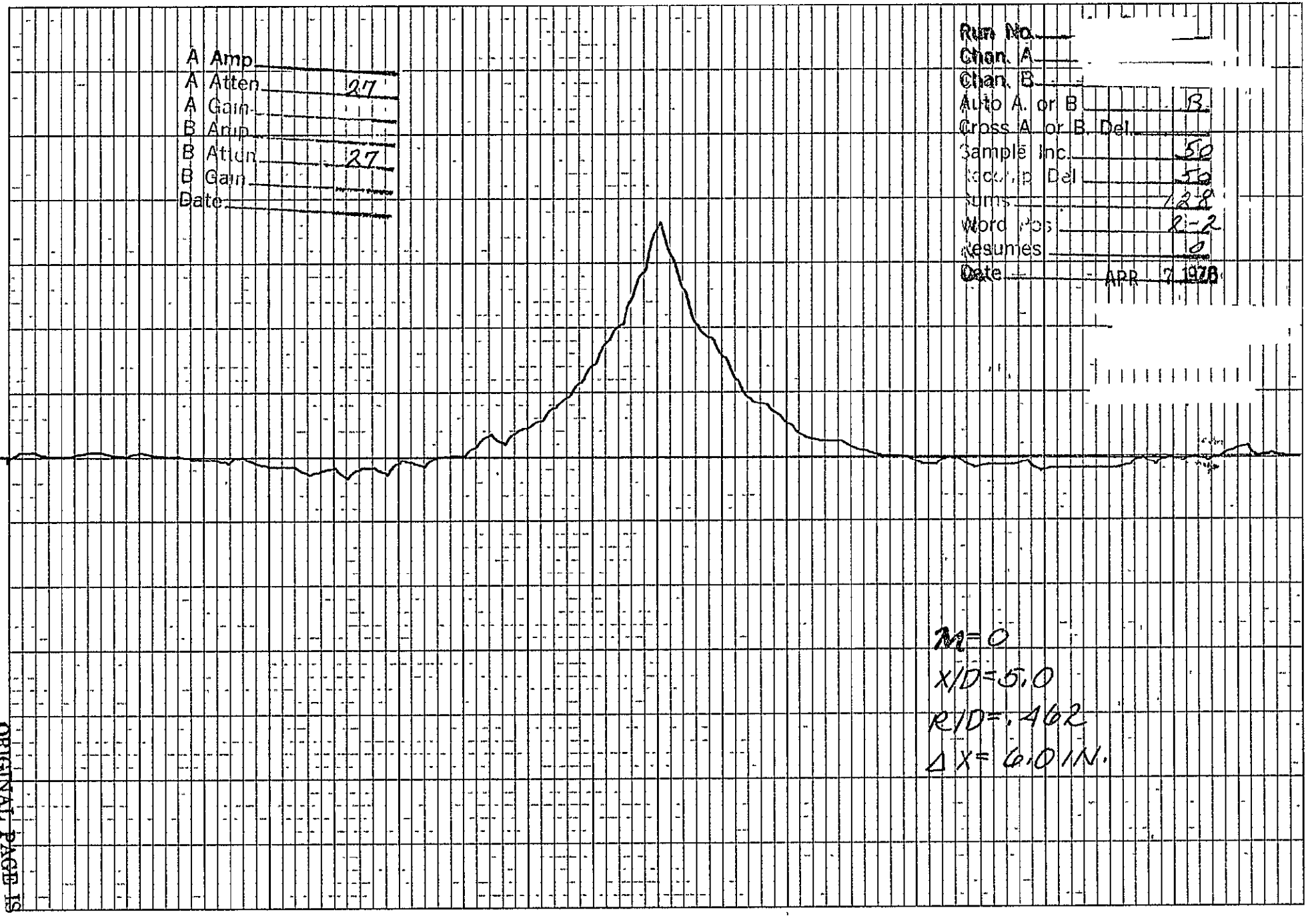

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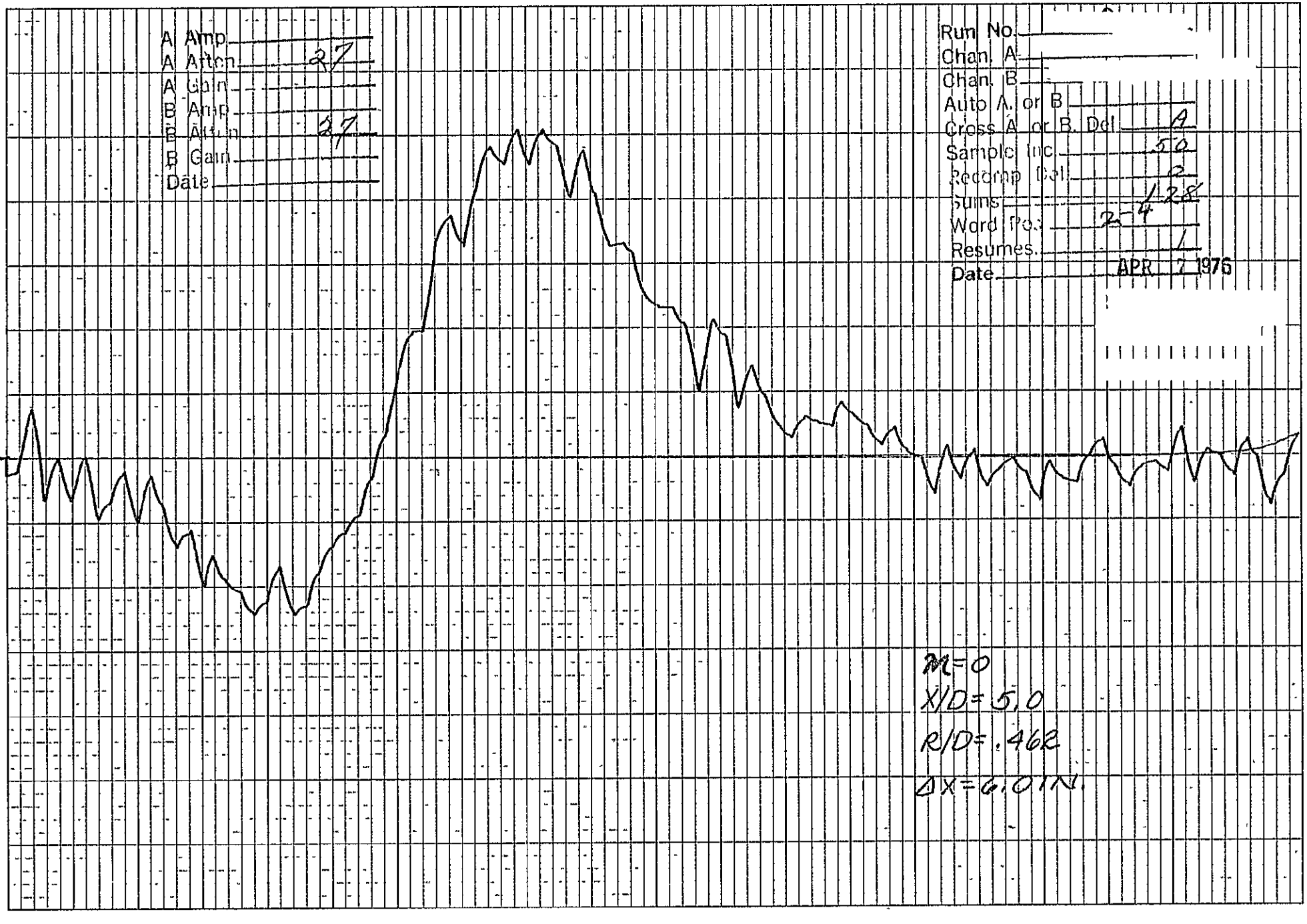

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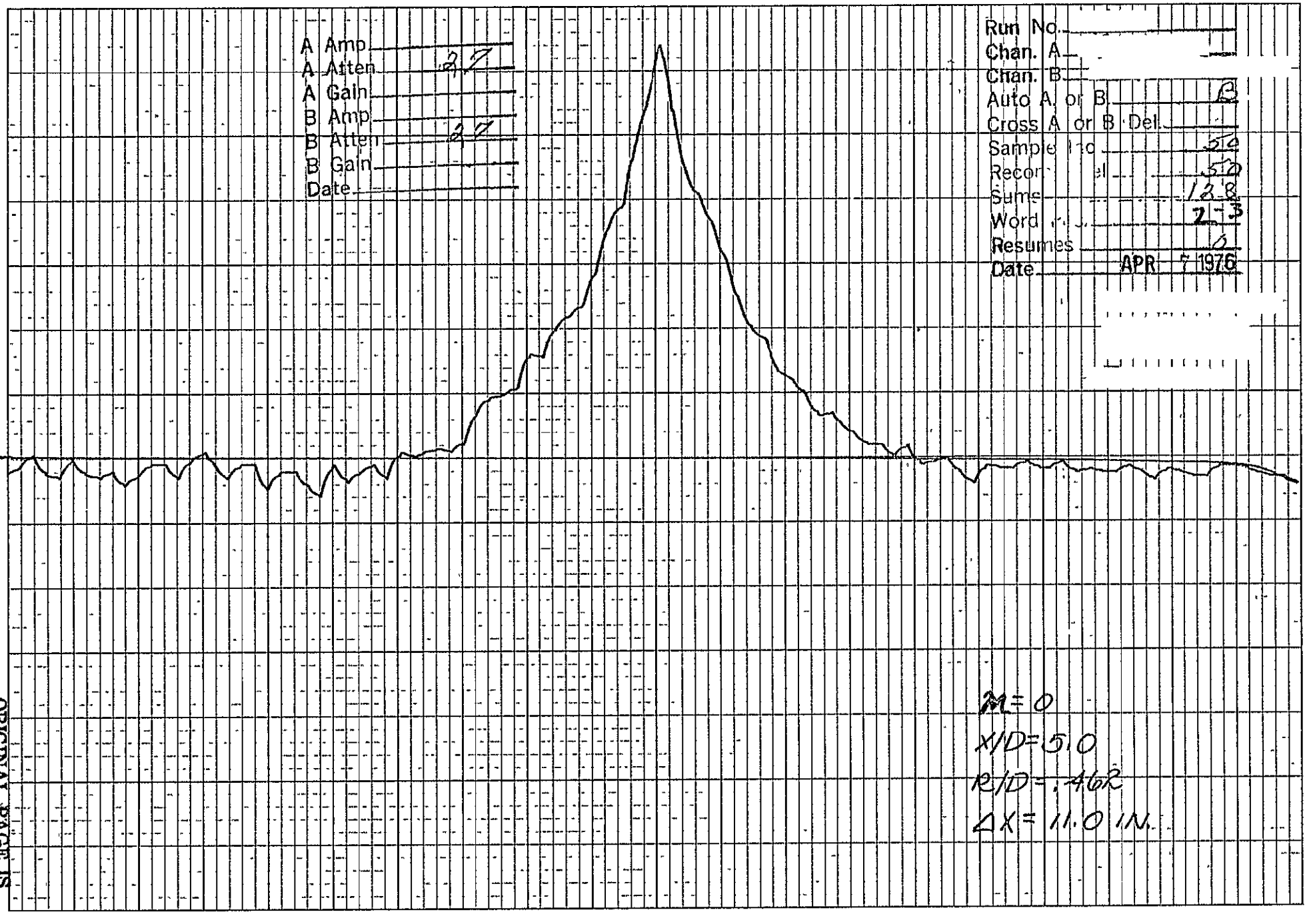

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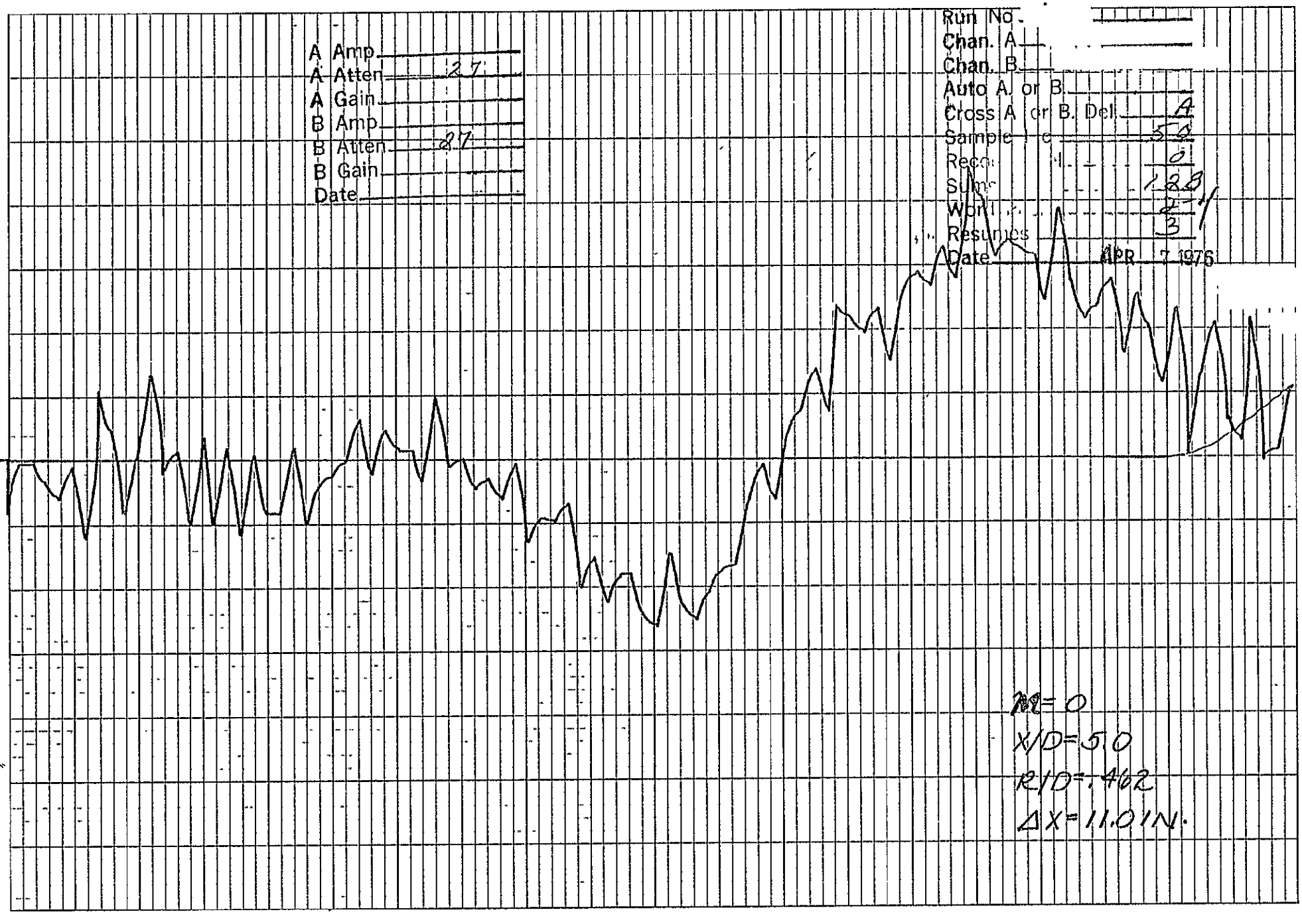

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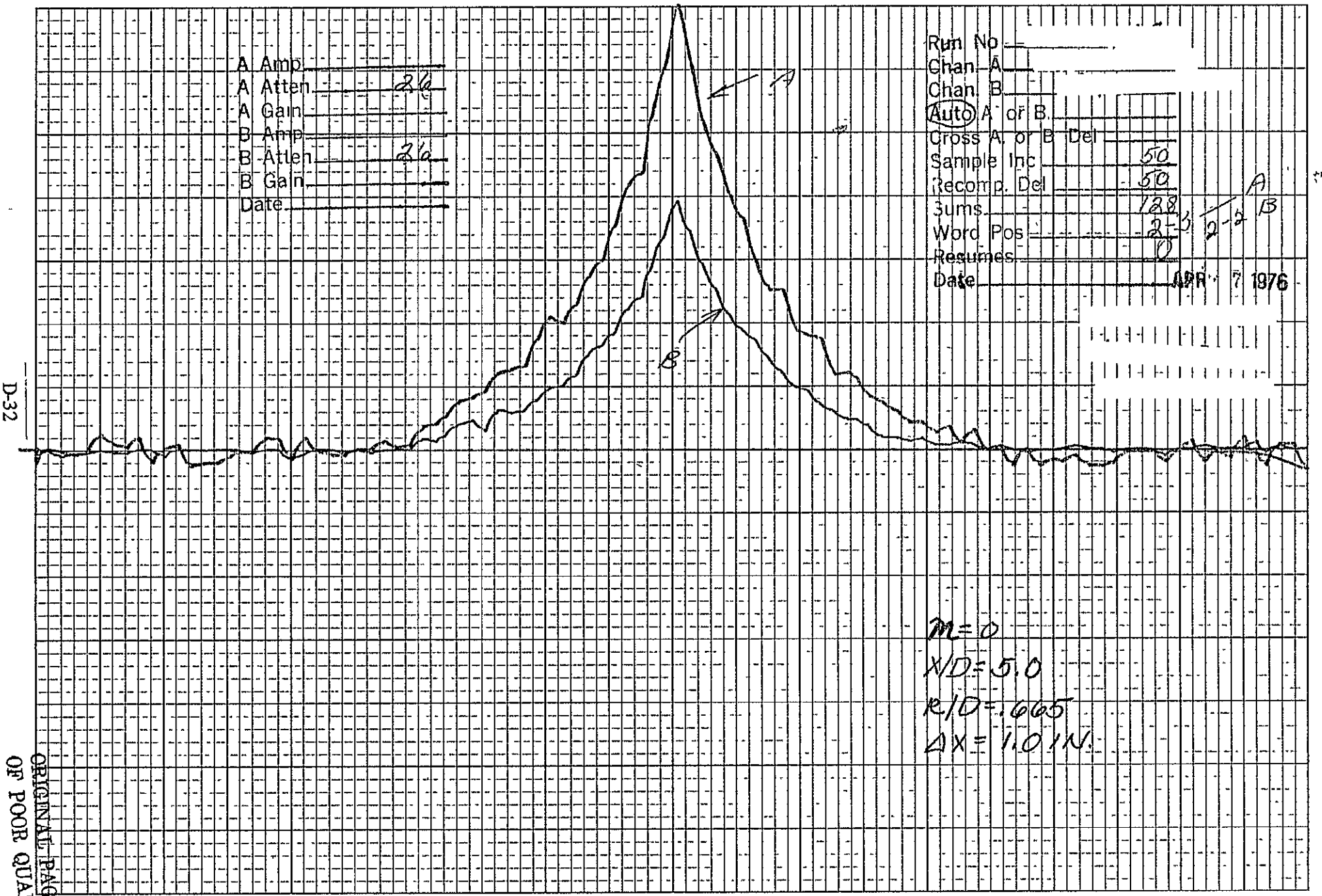

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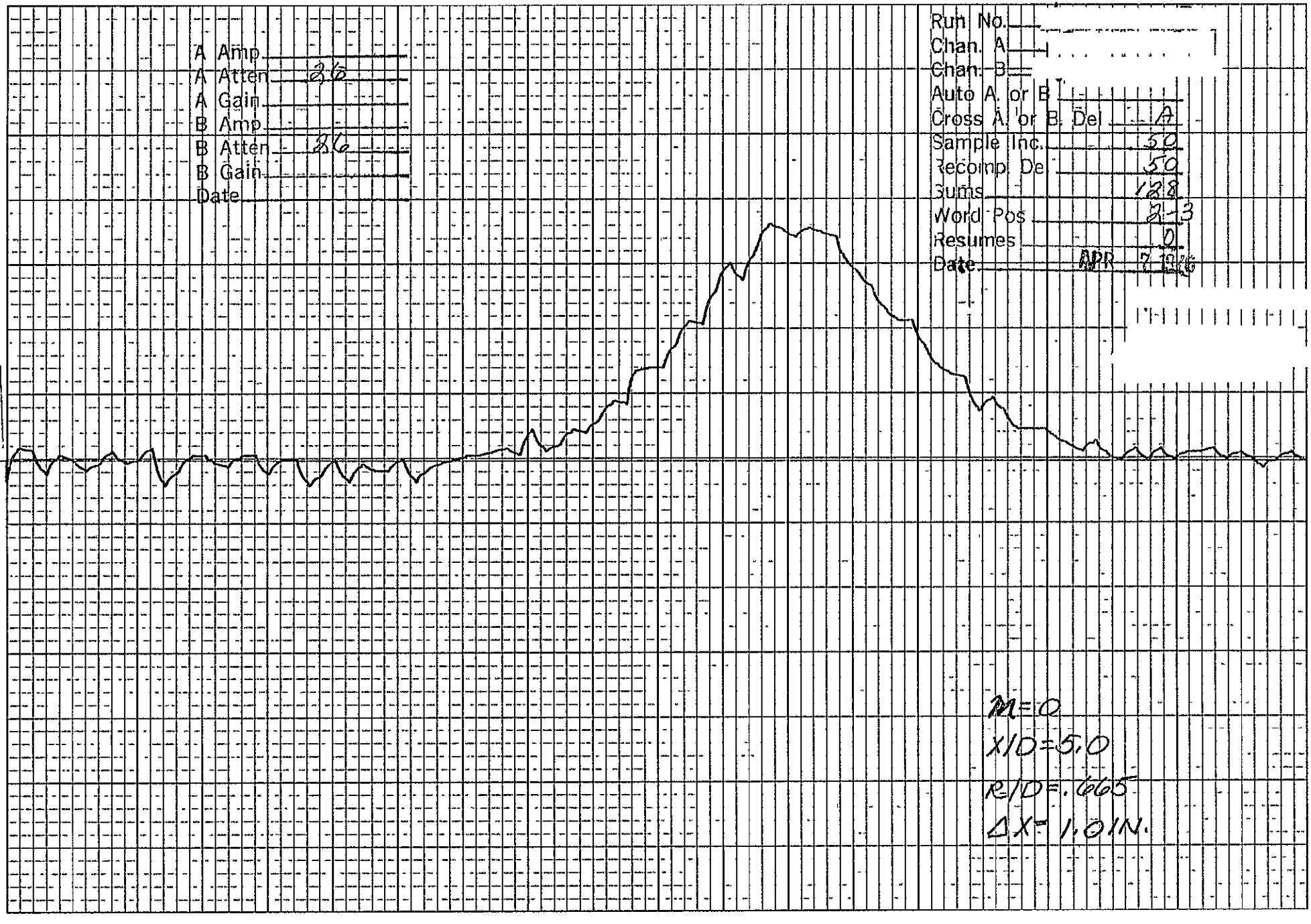

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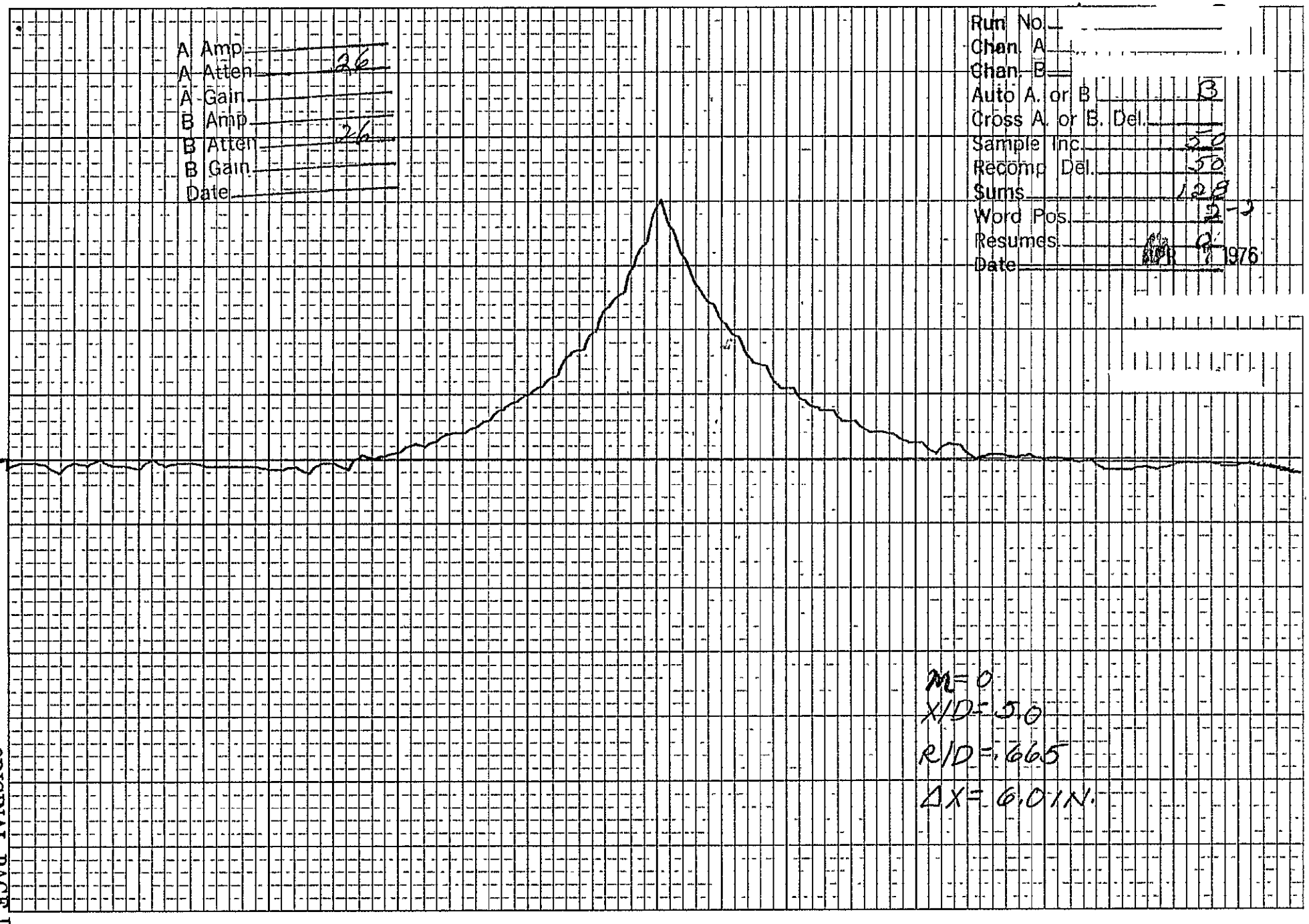

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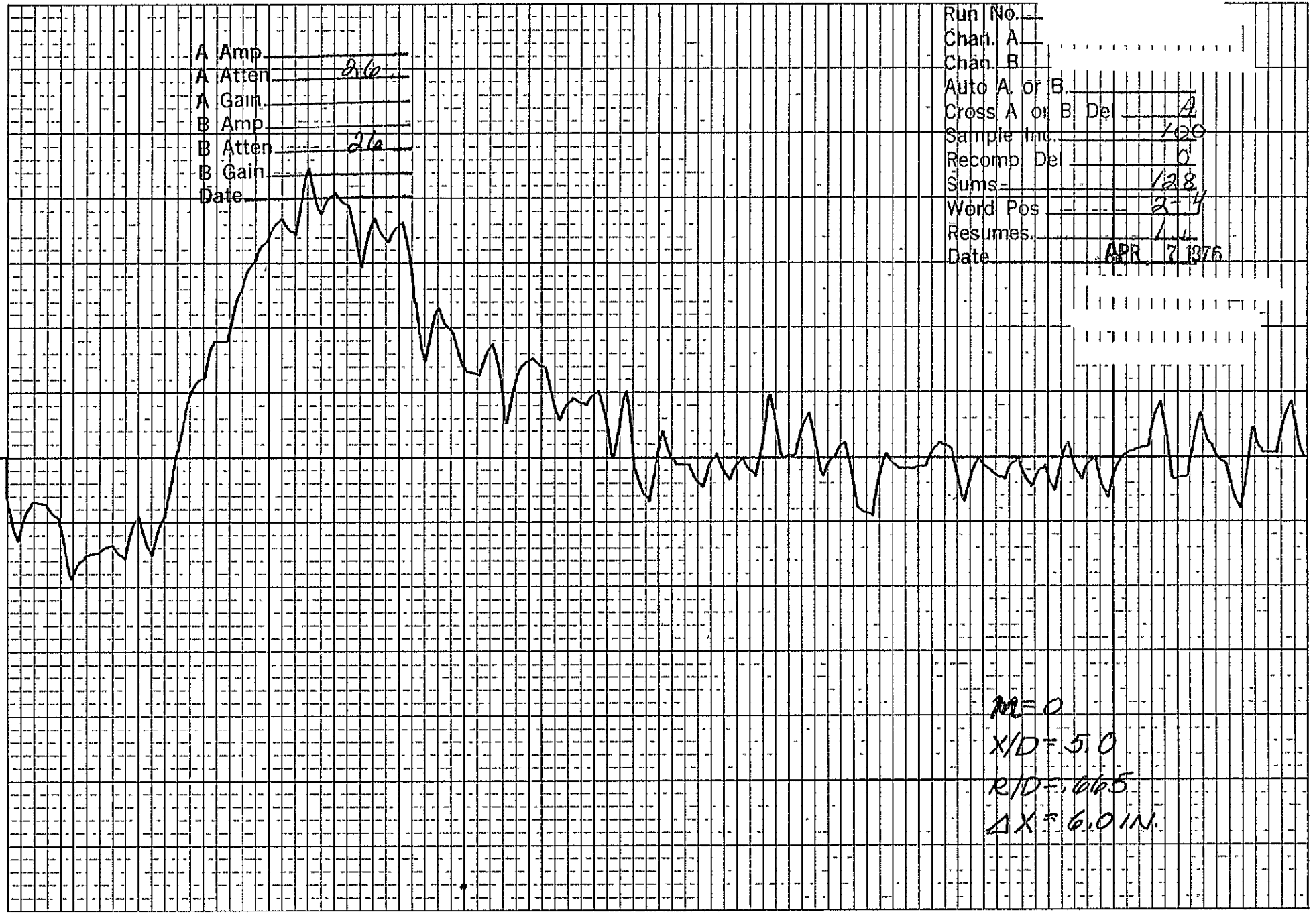

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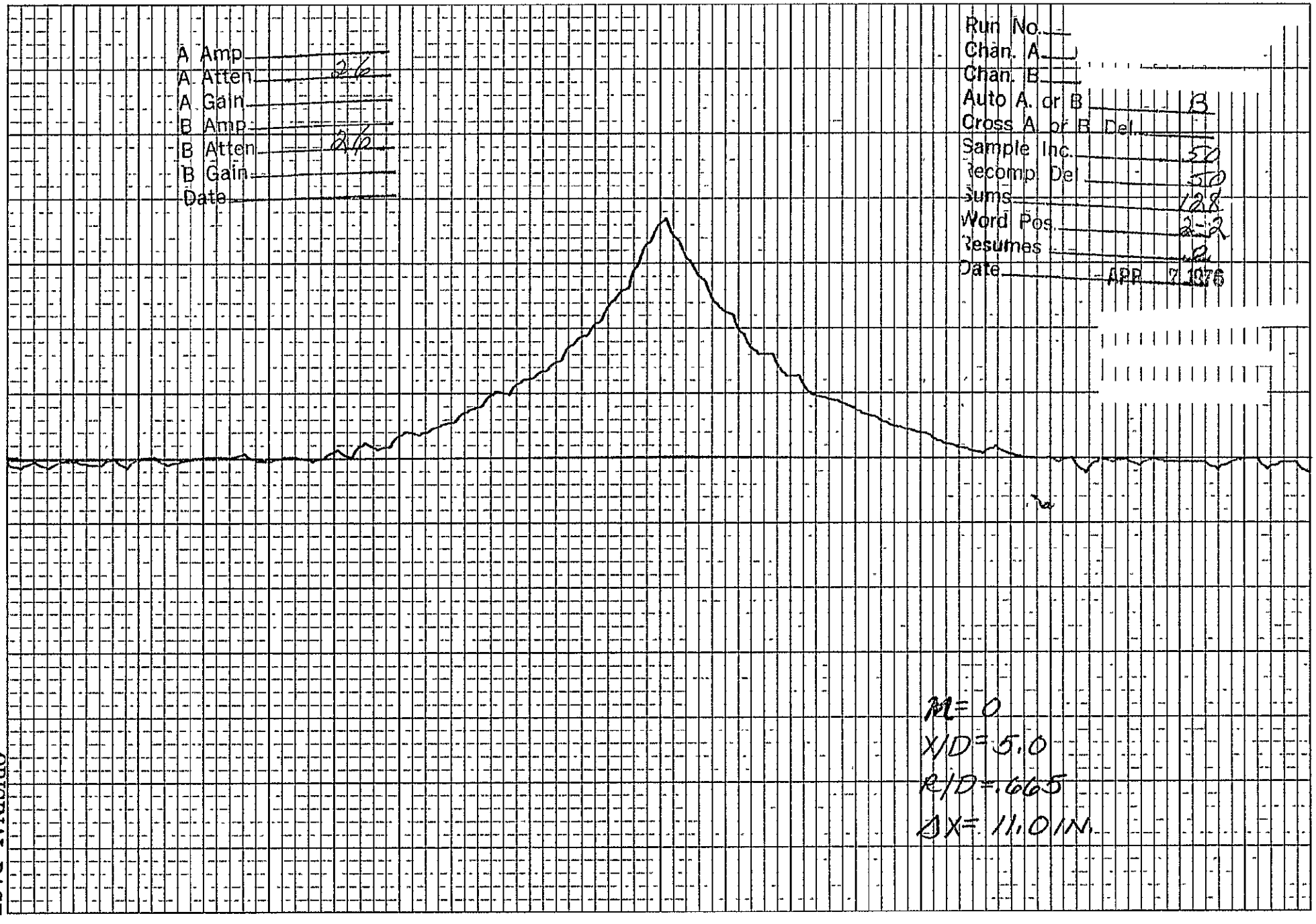

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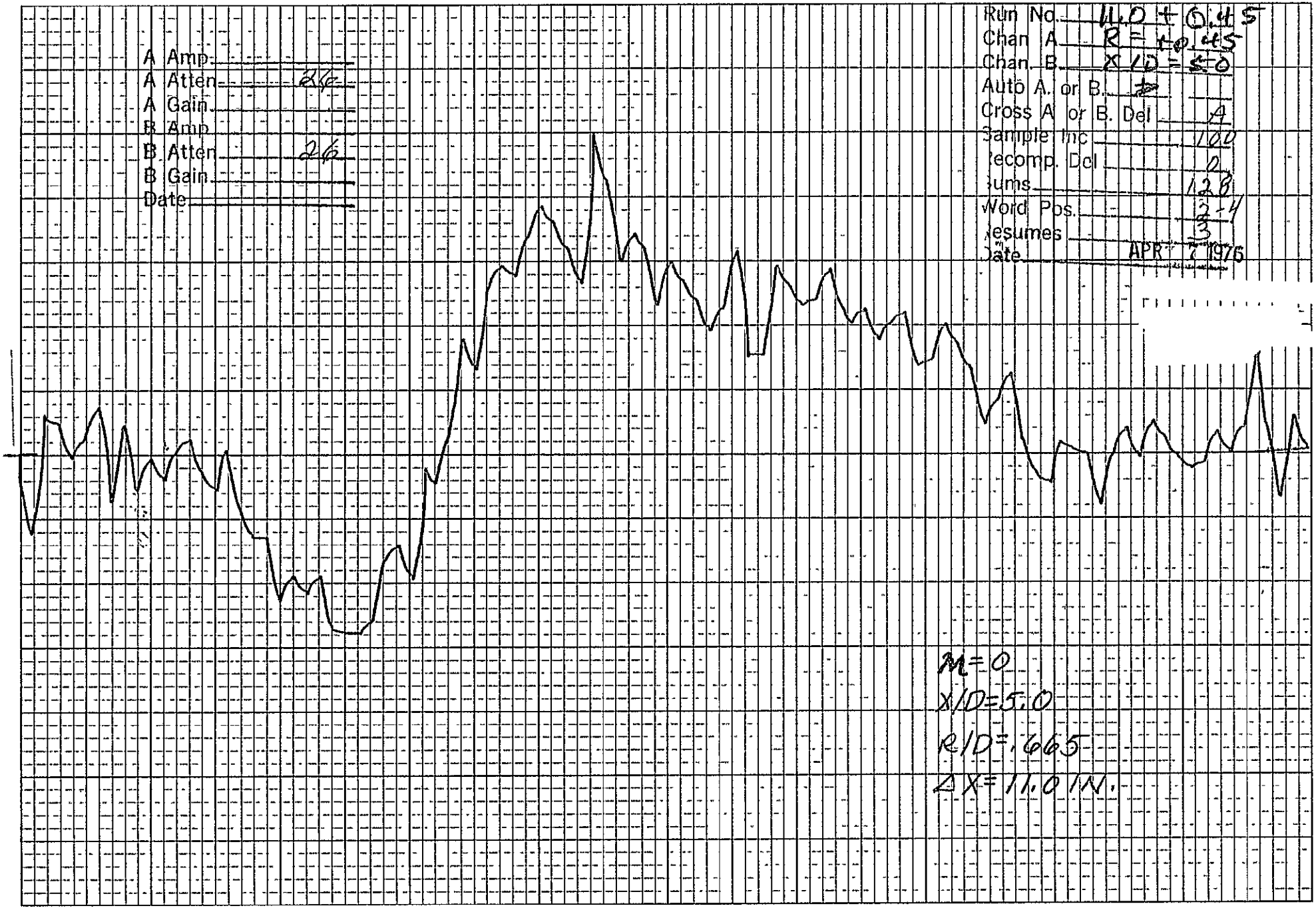

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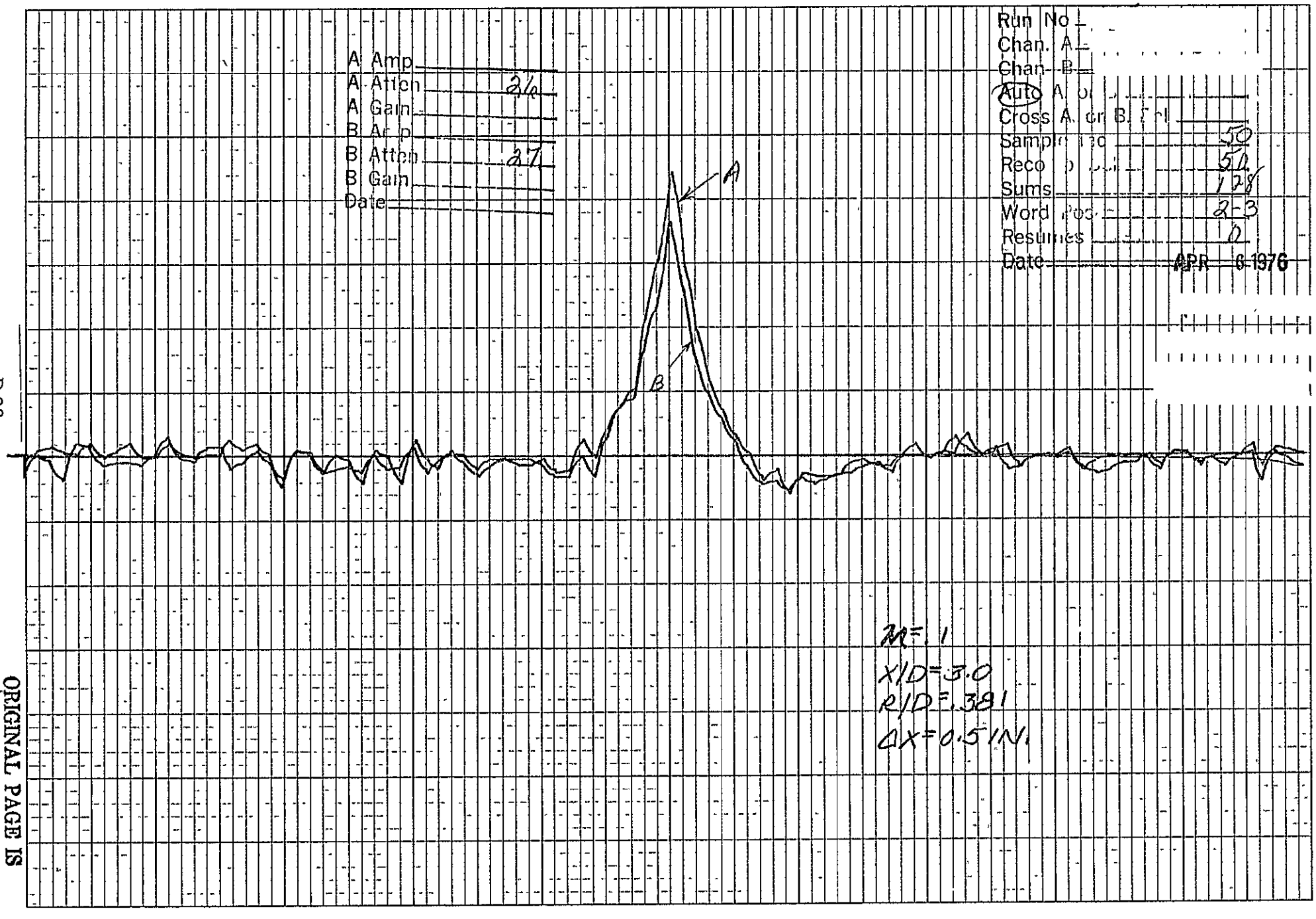

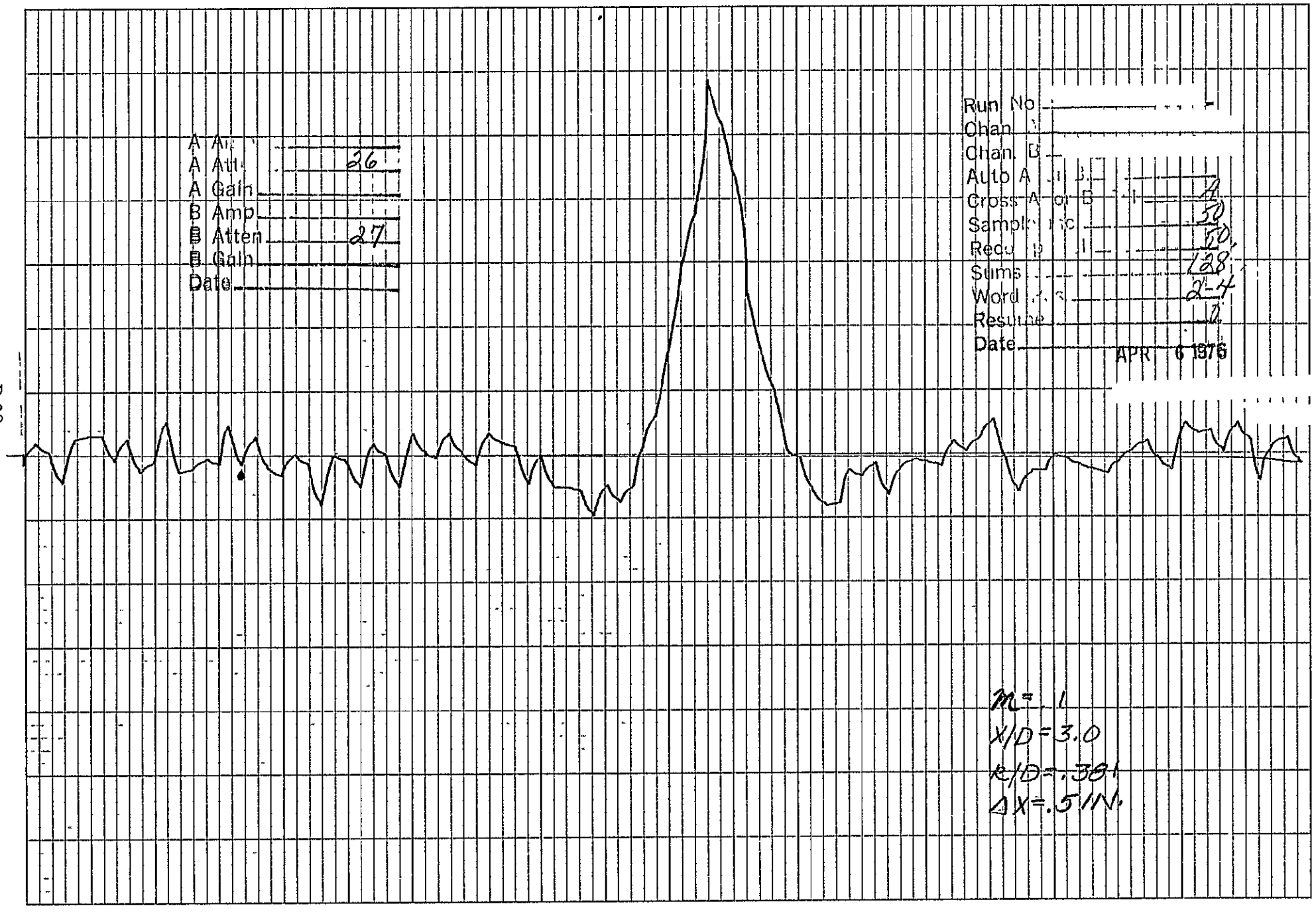
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Date
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Cross A or B 30
Sample Inc 50
Recd Pts 128
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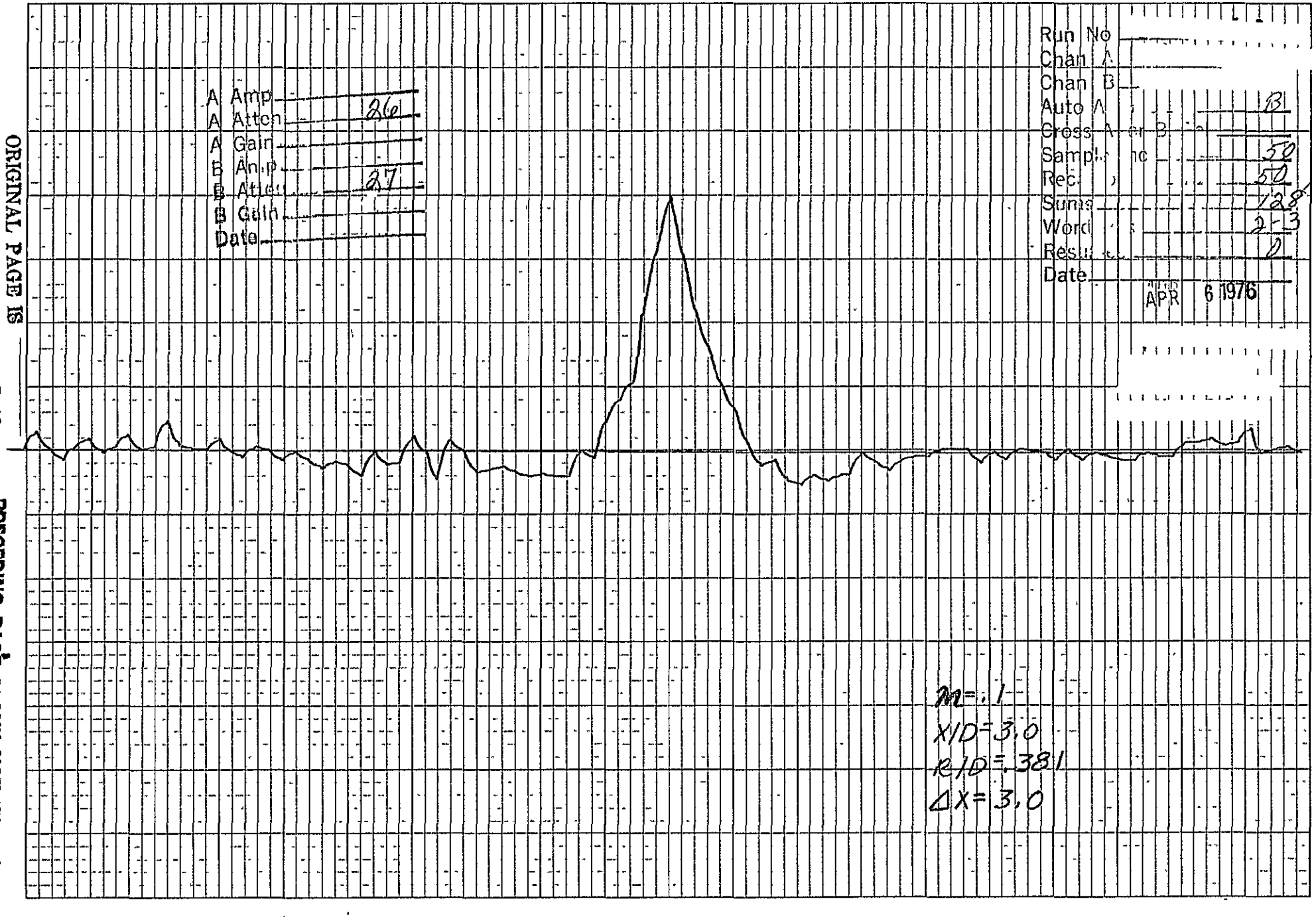

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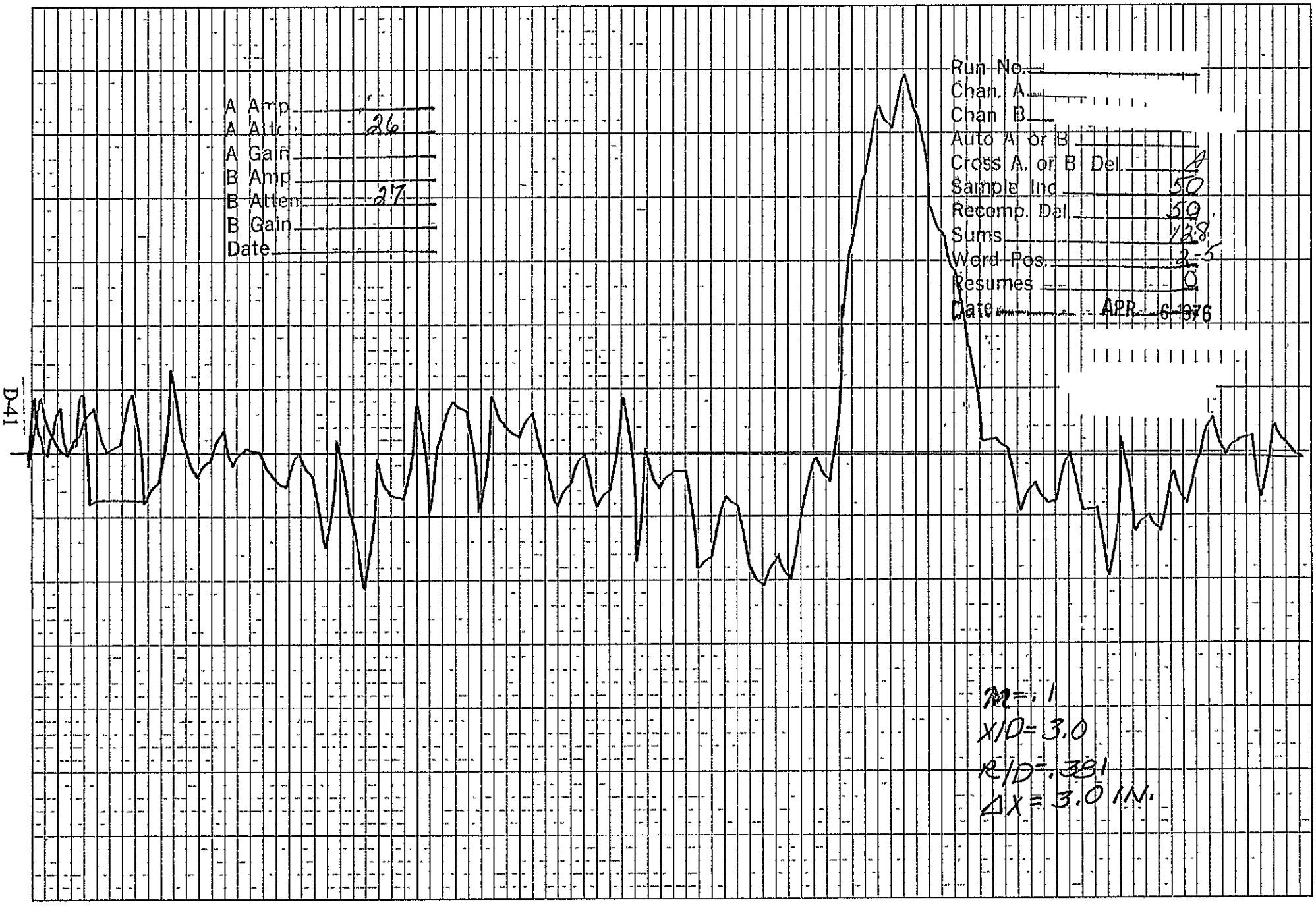

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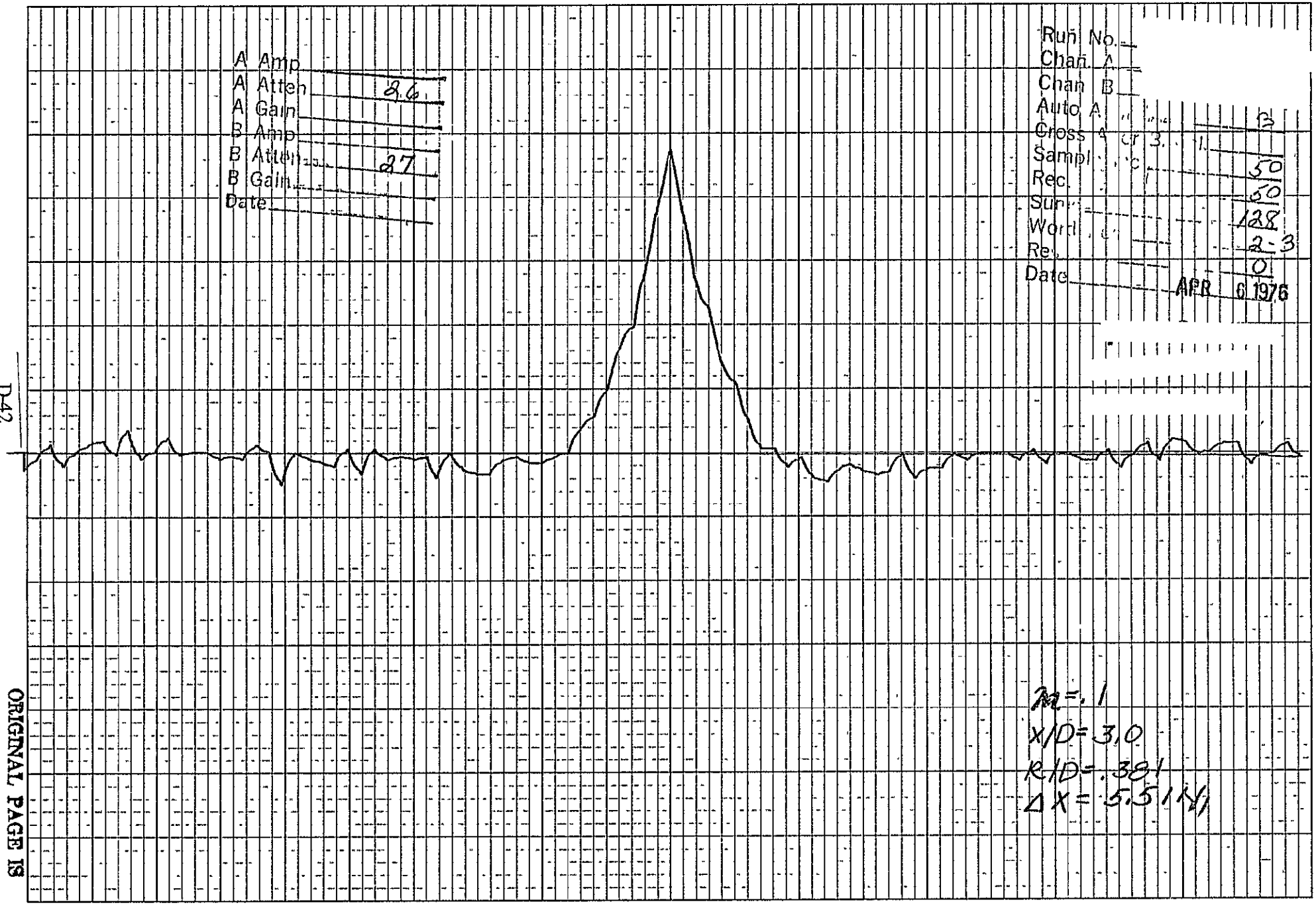

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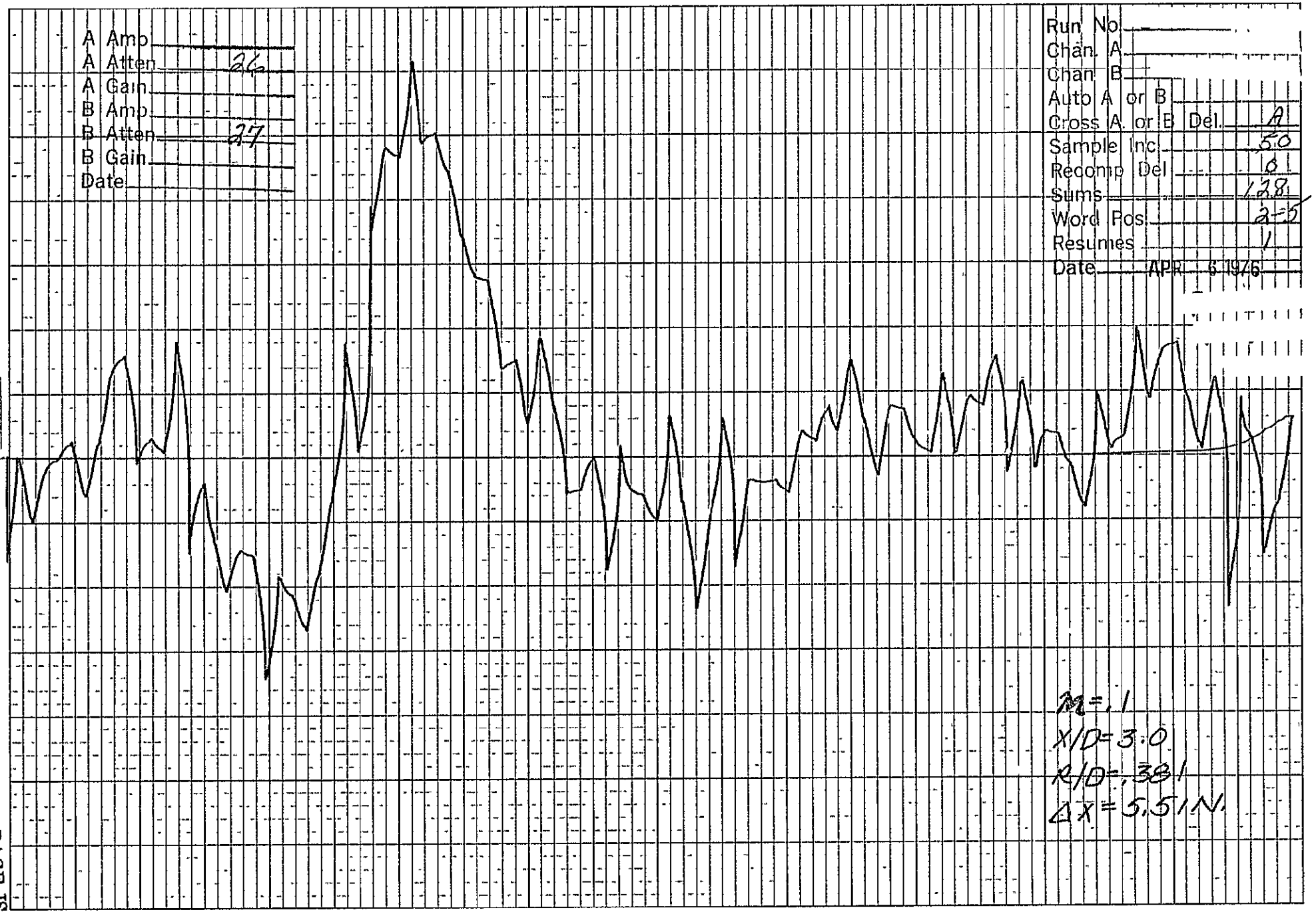

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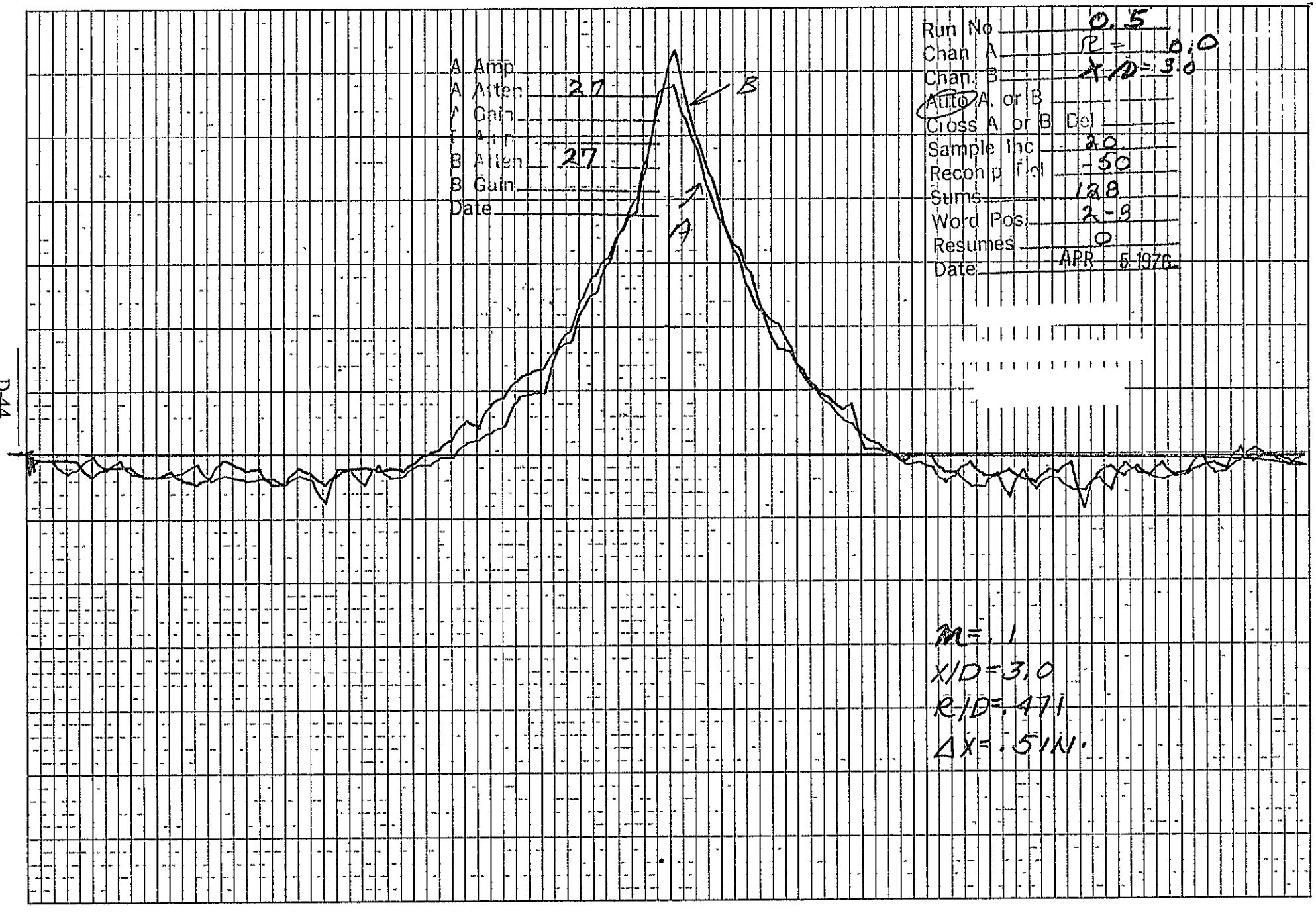

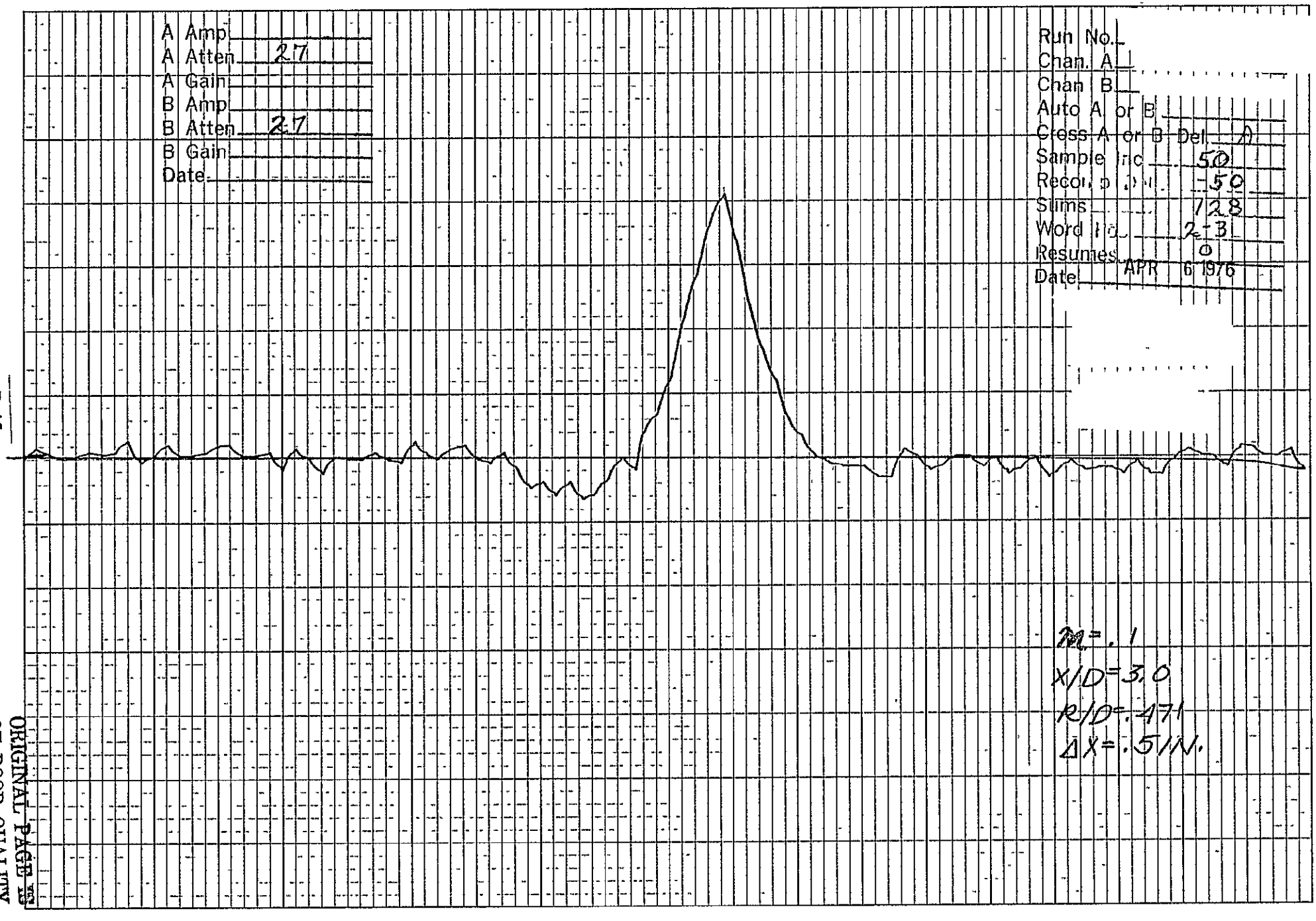

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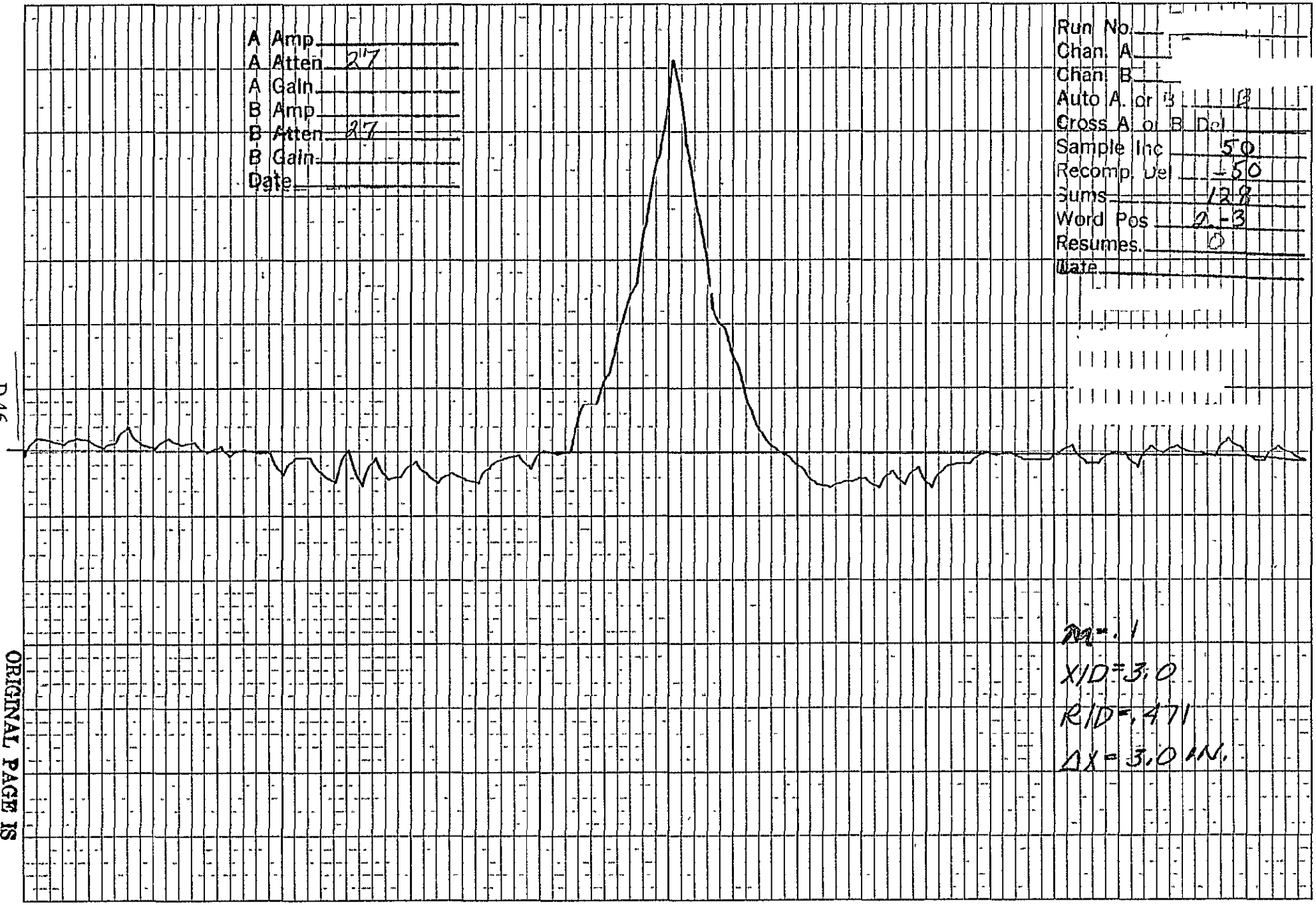

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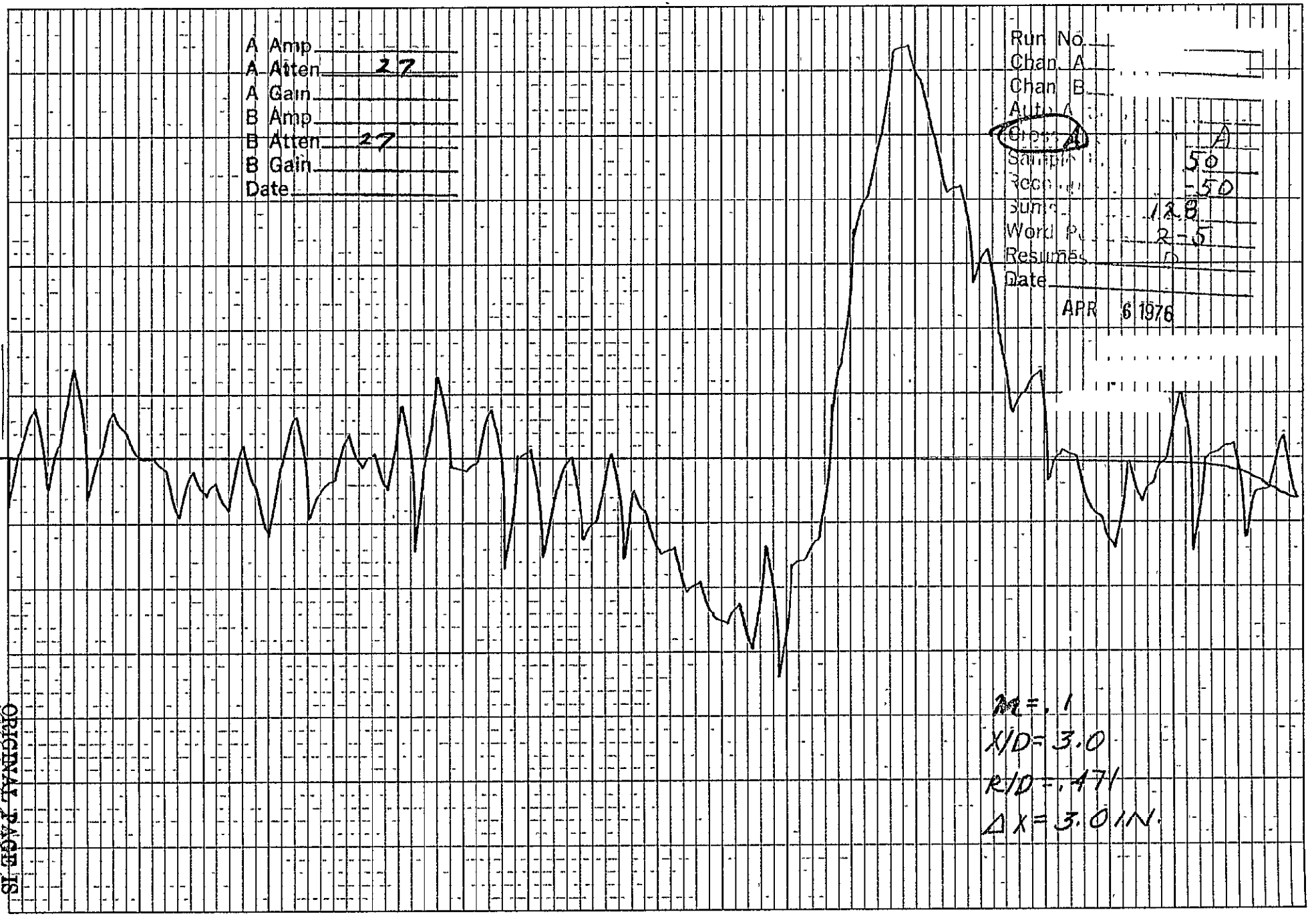

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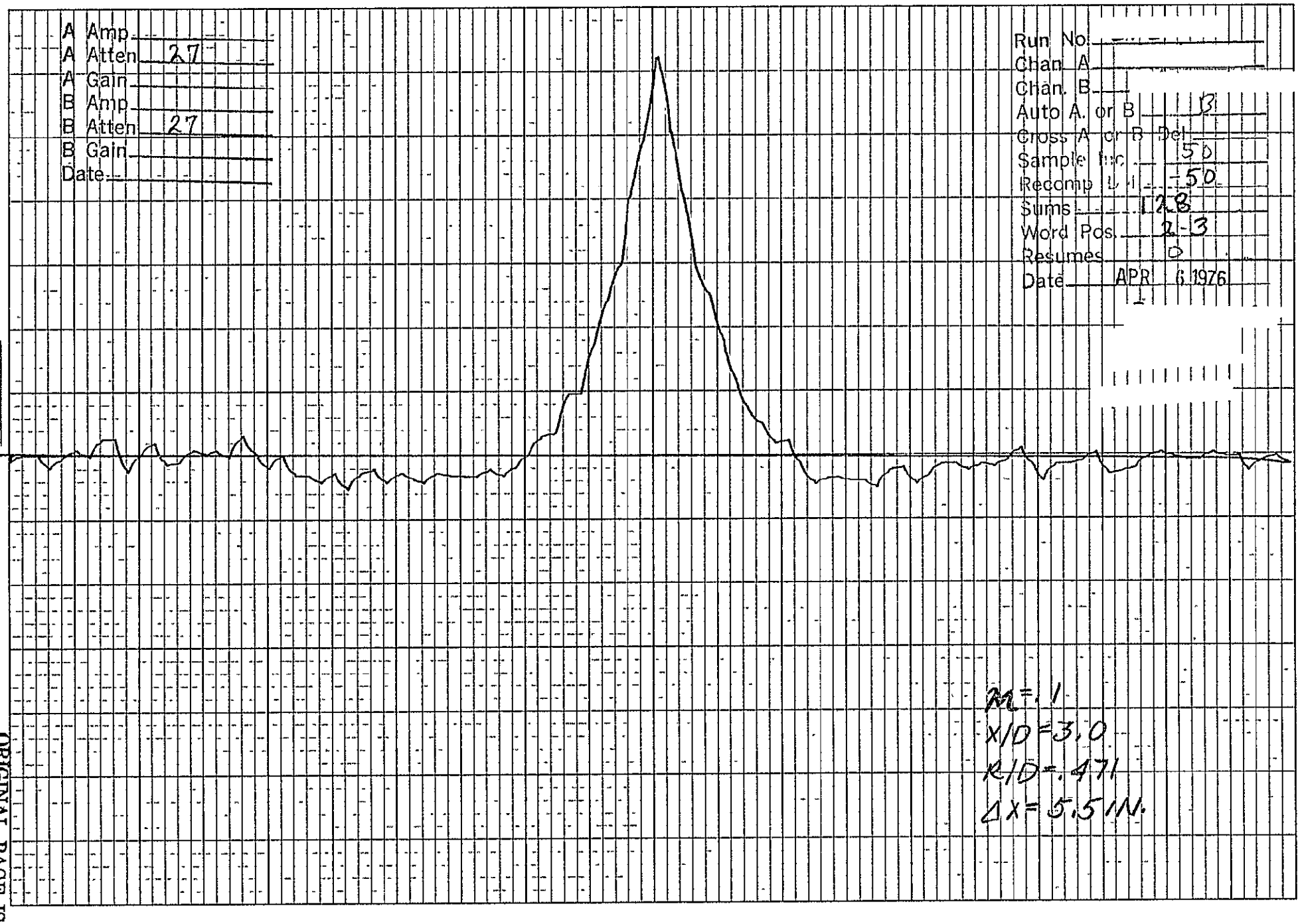

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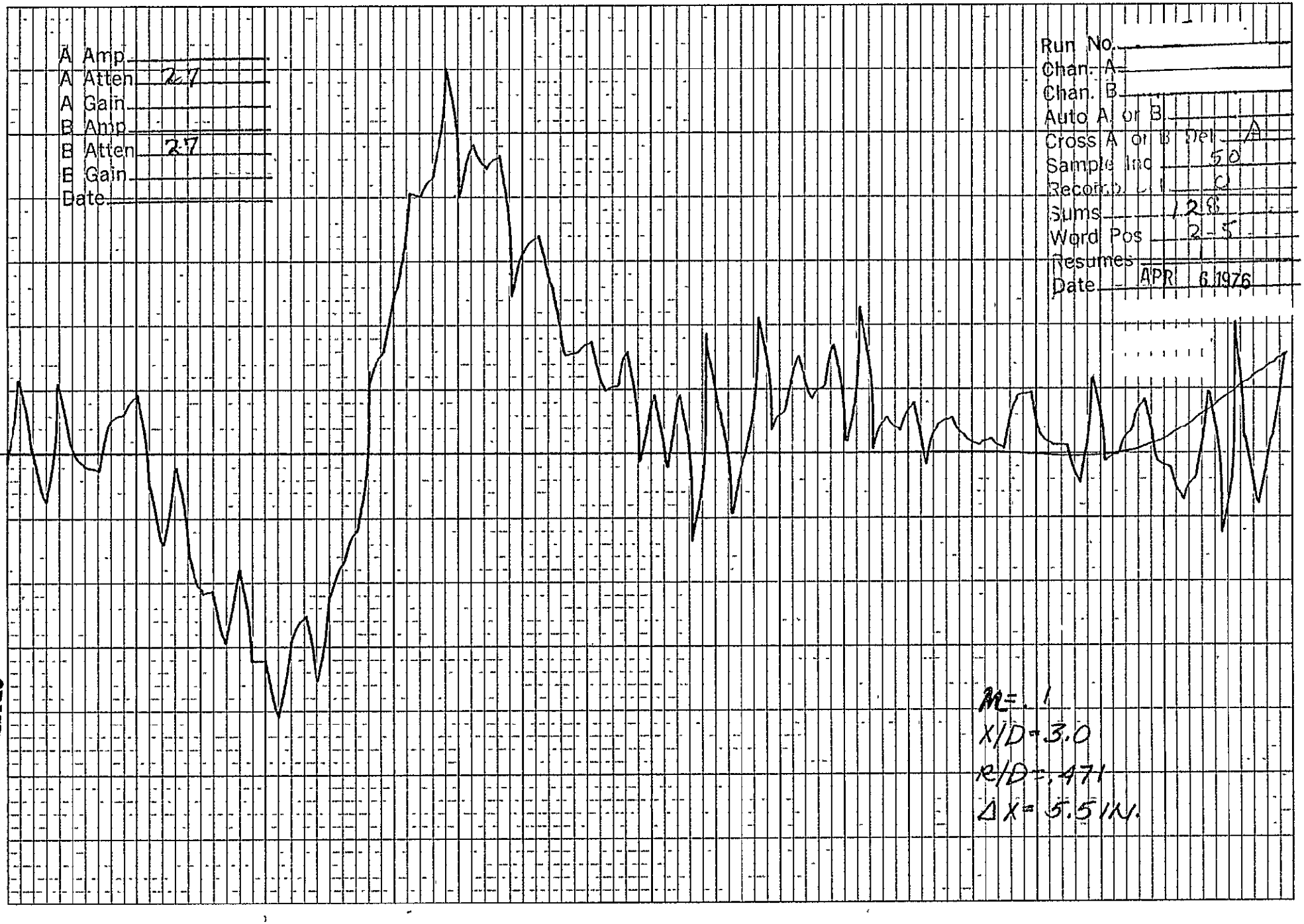

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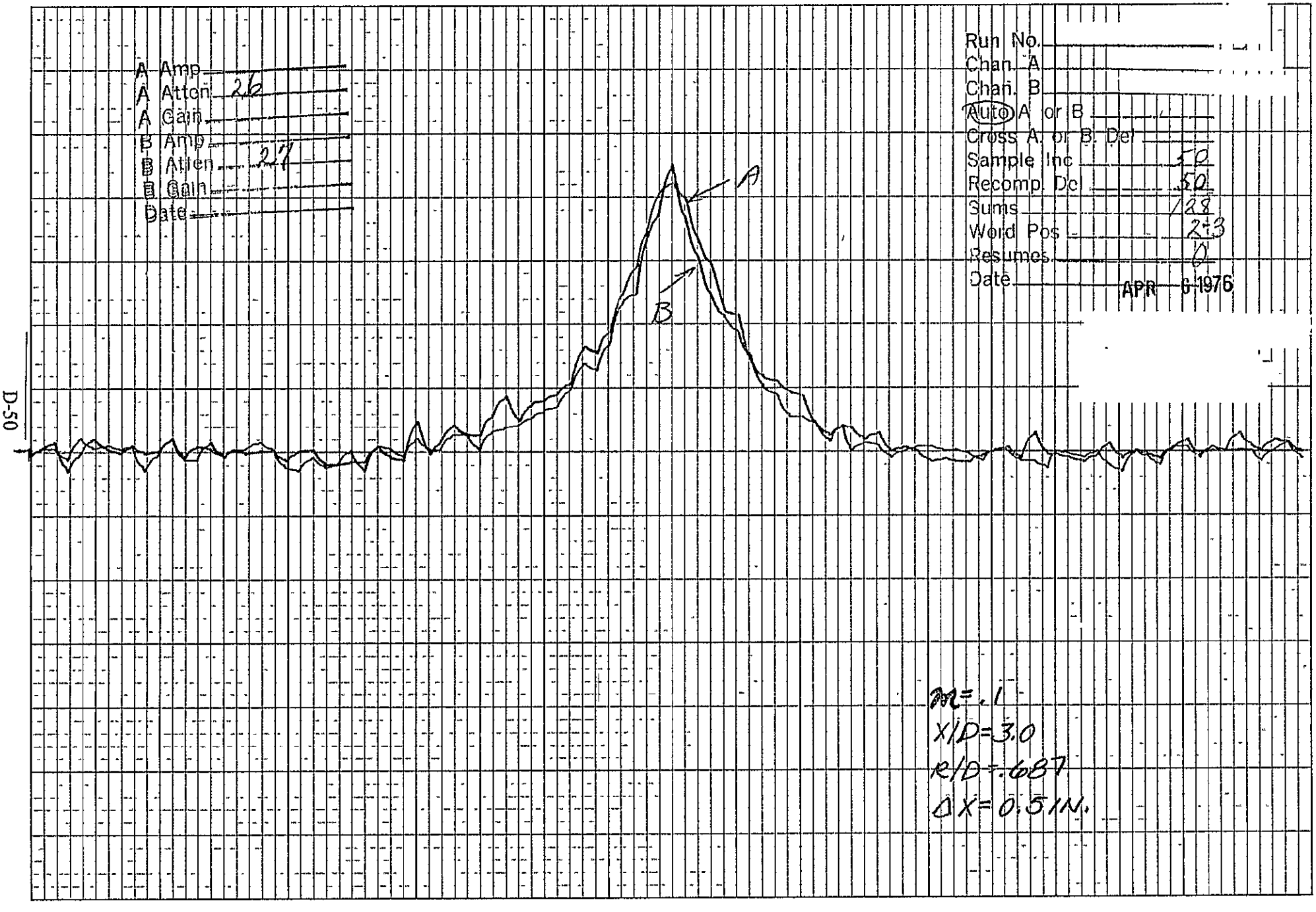

D-50

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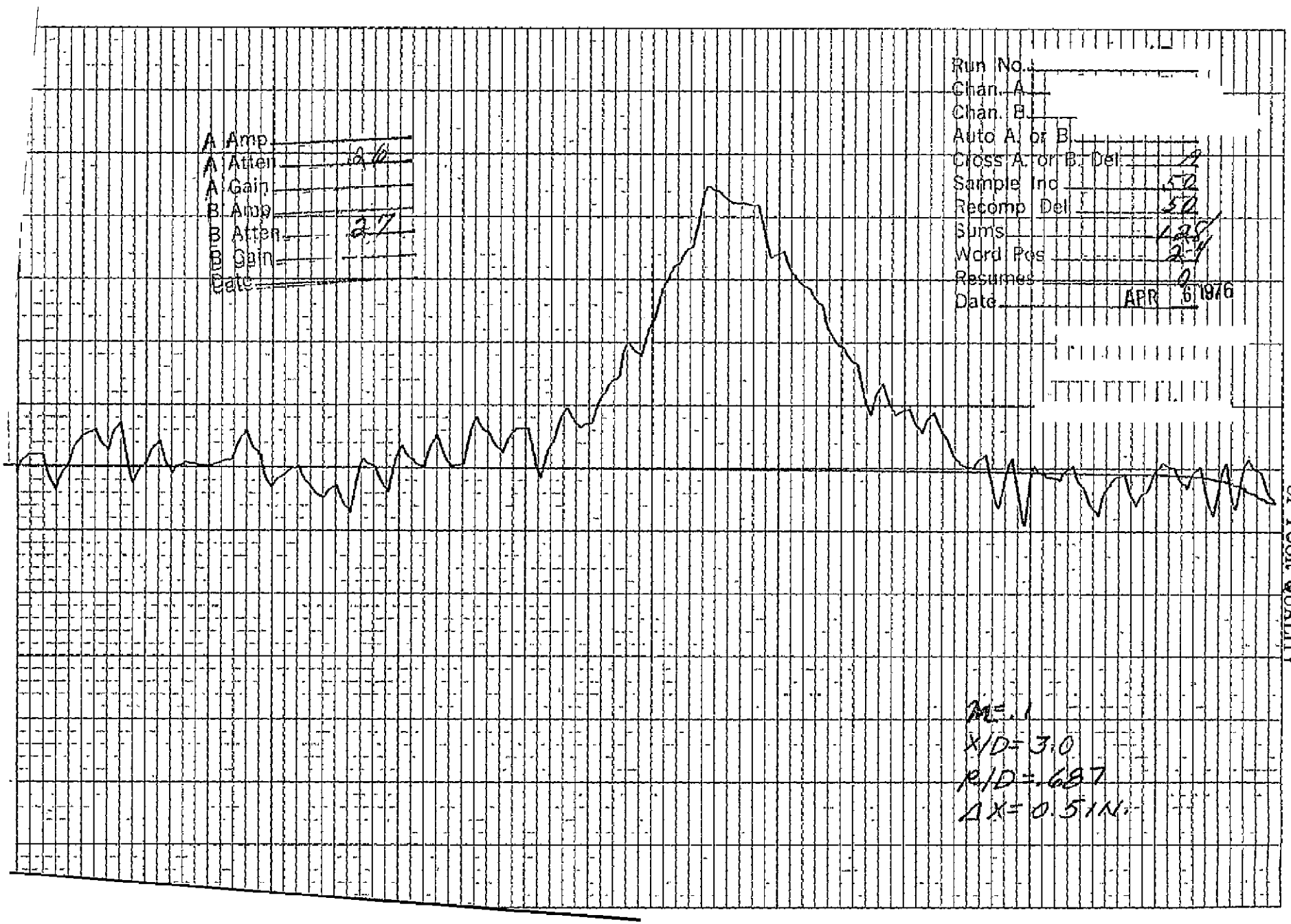

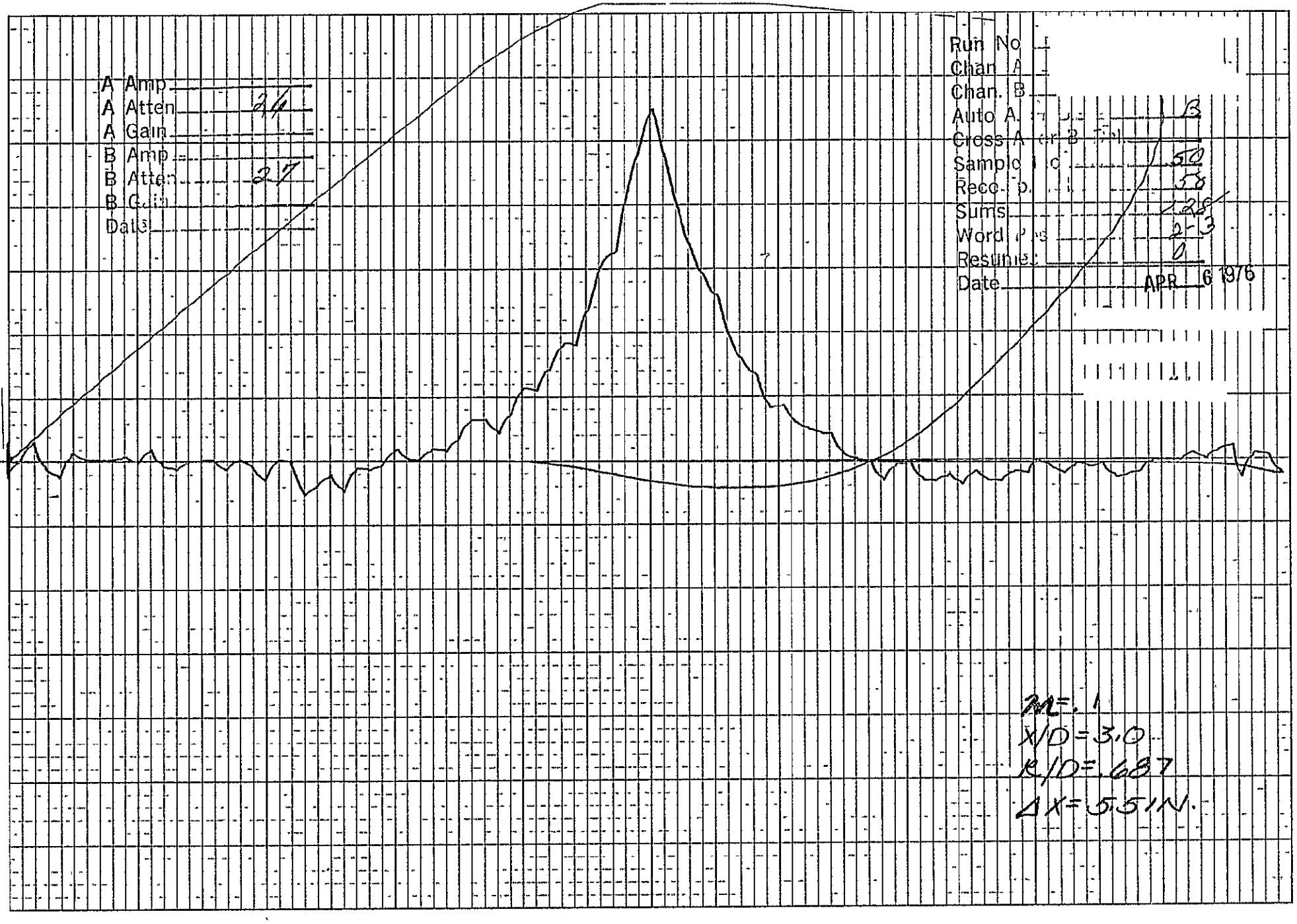

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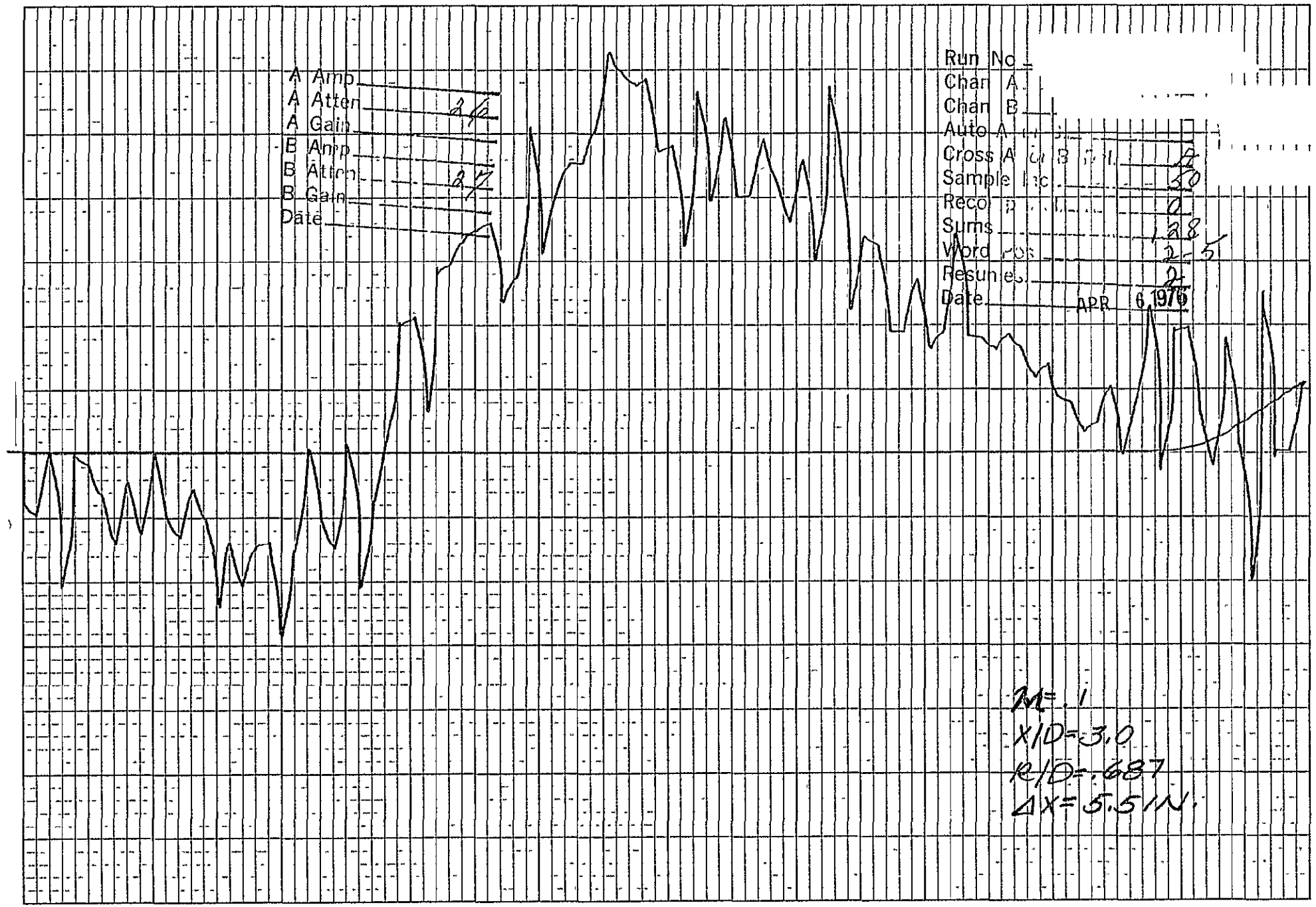

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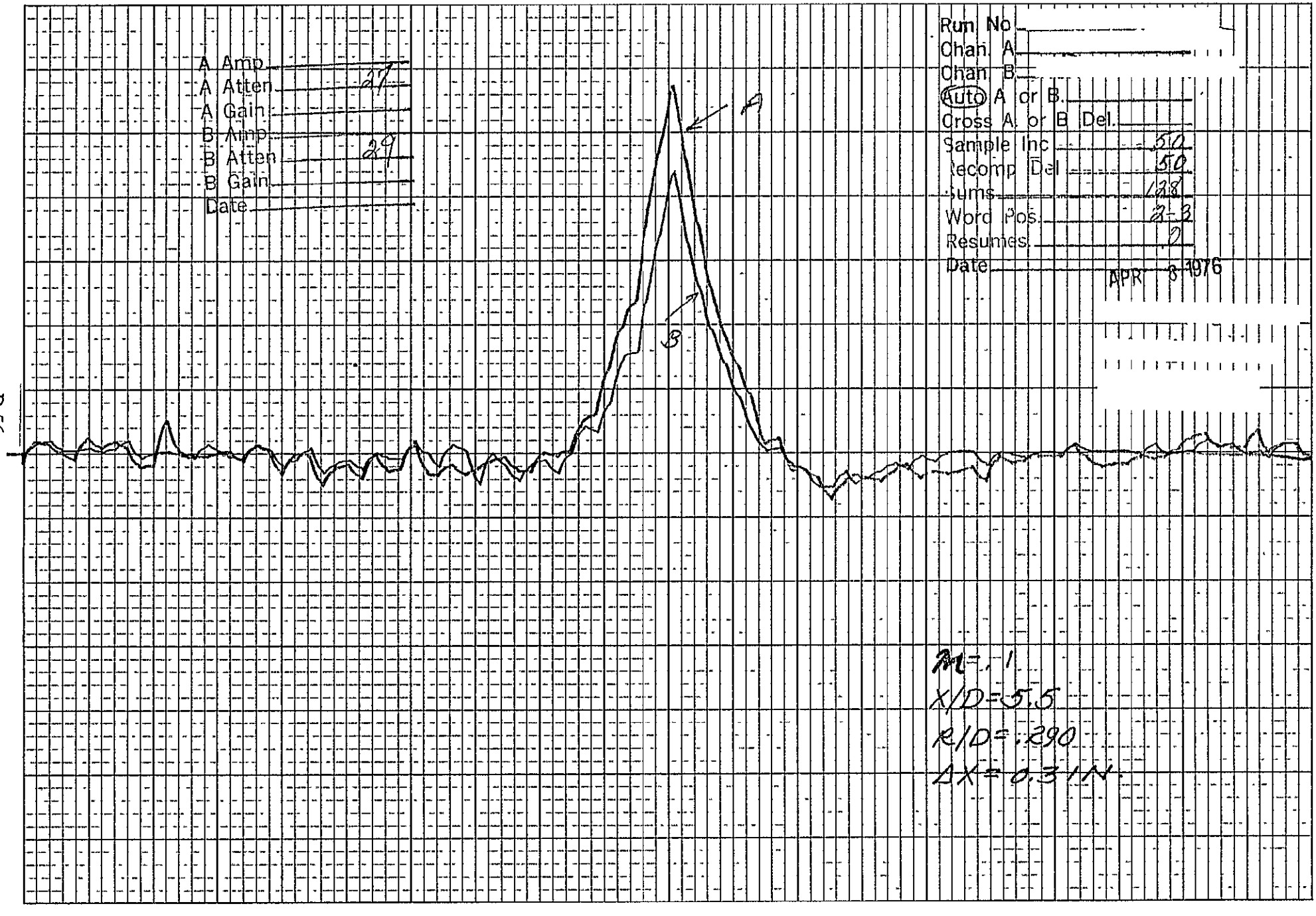

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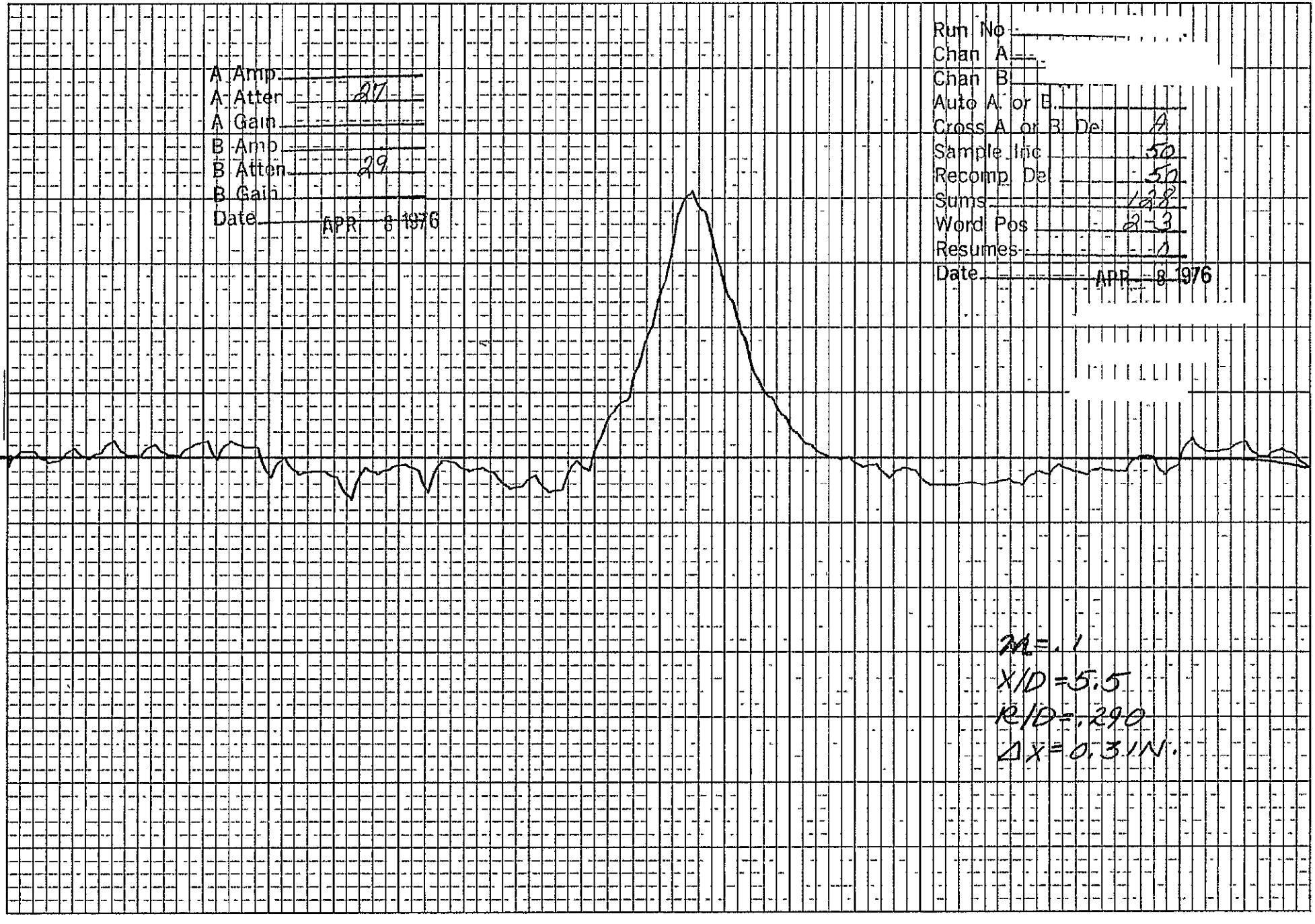

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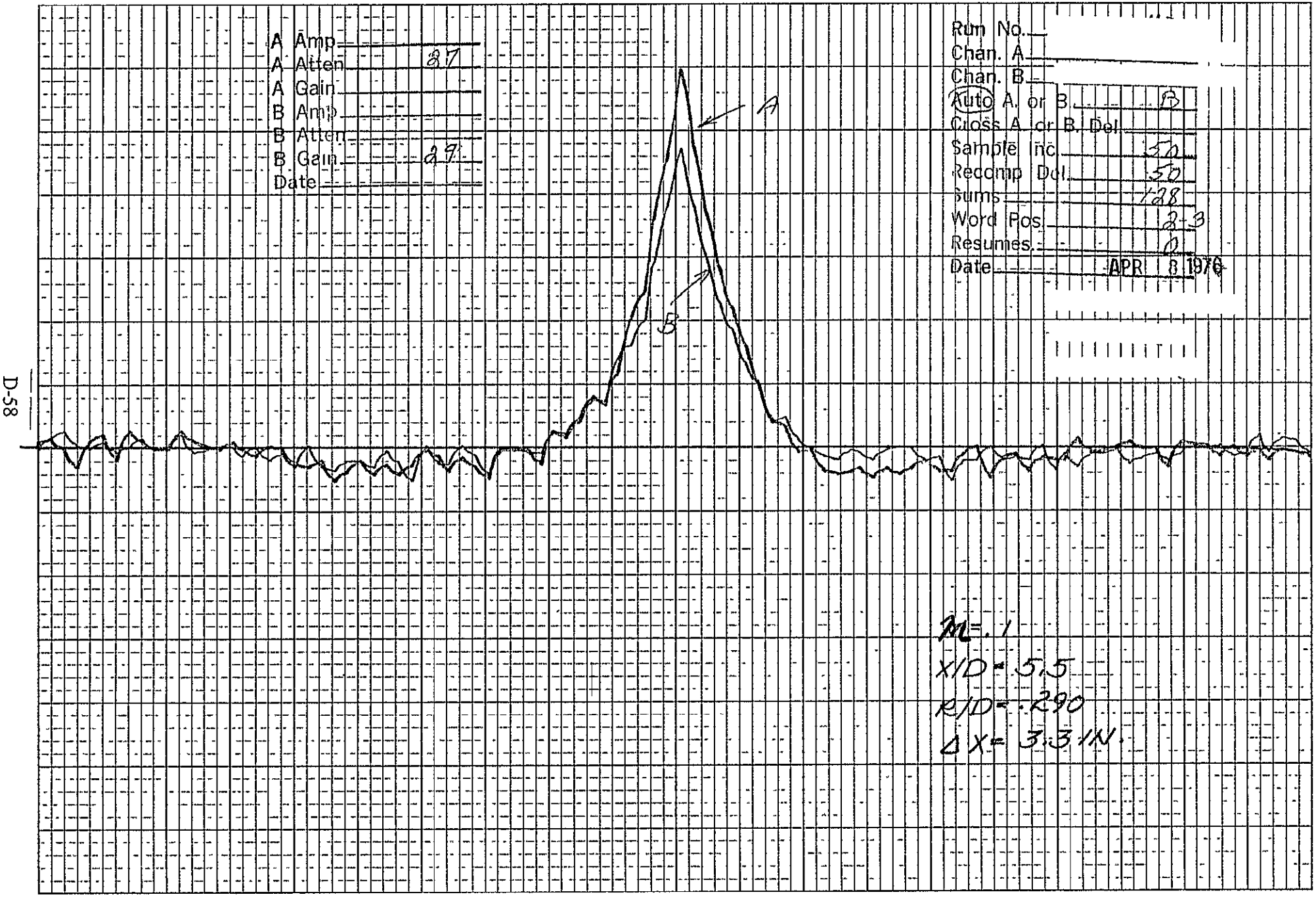

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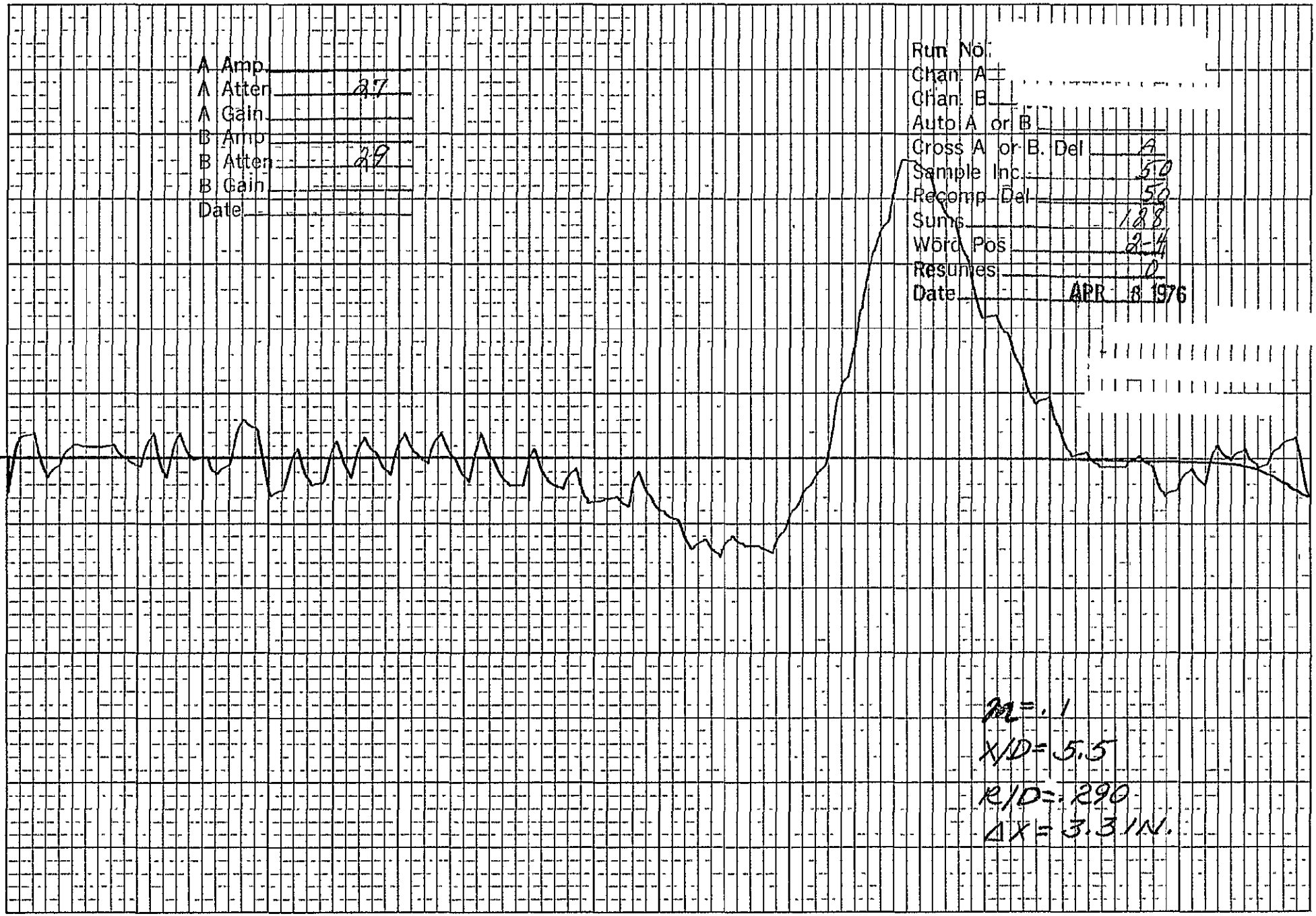

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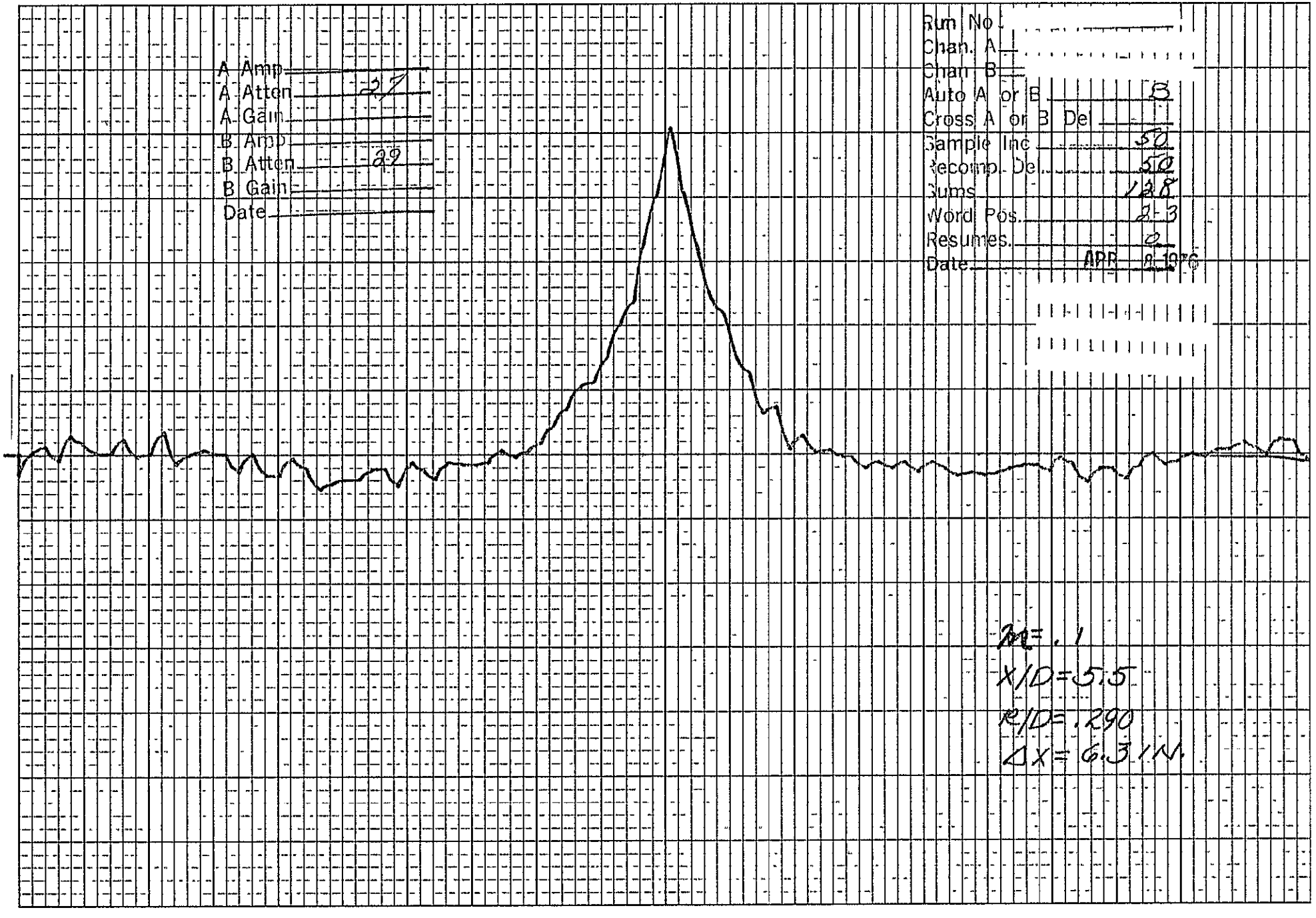

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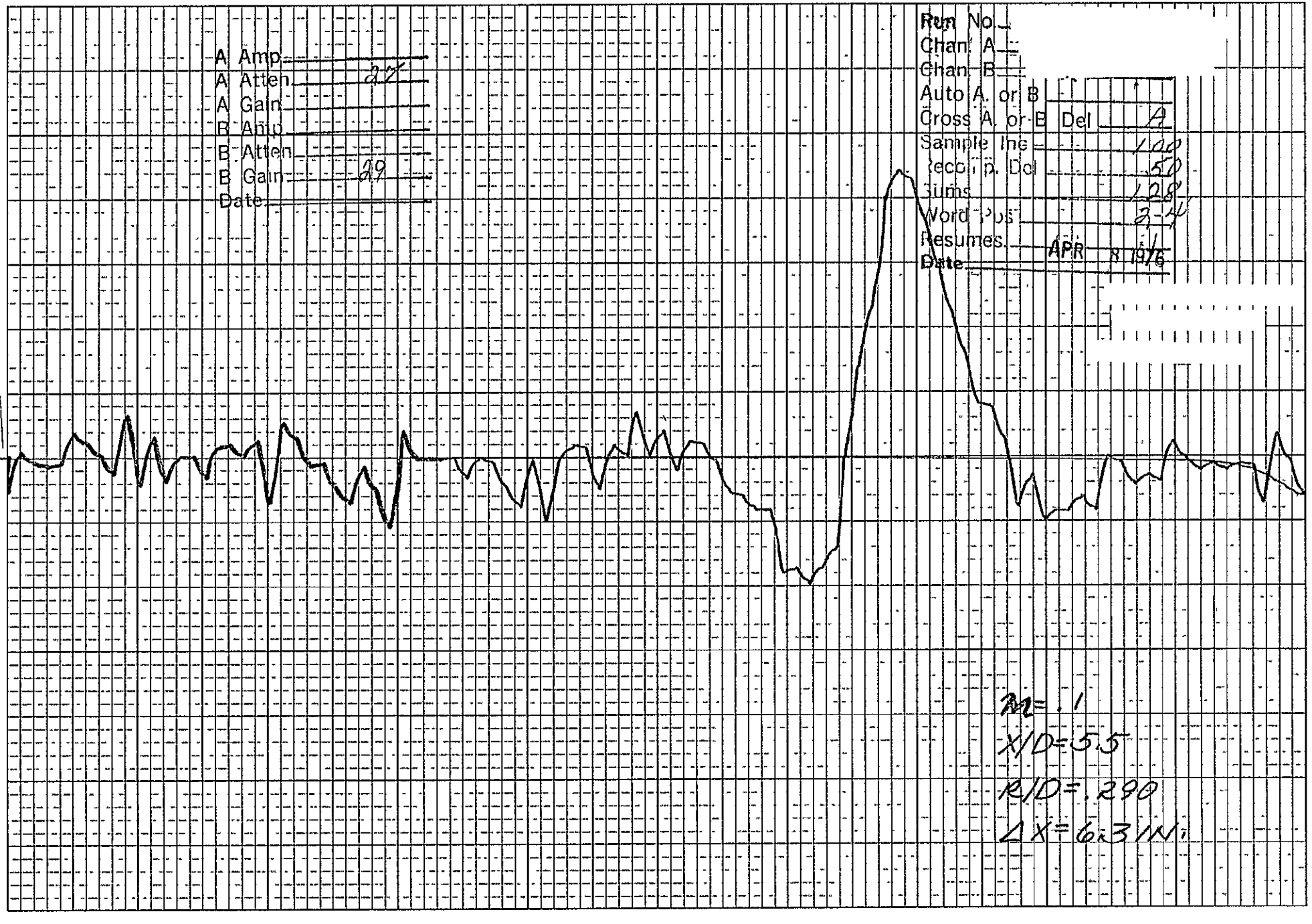

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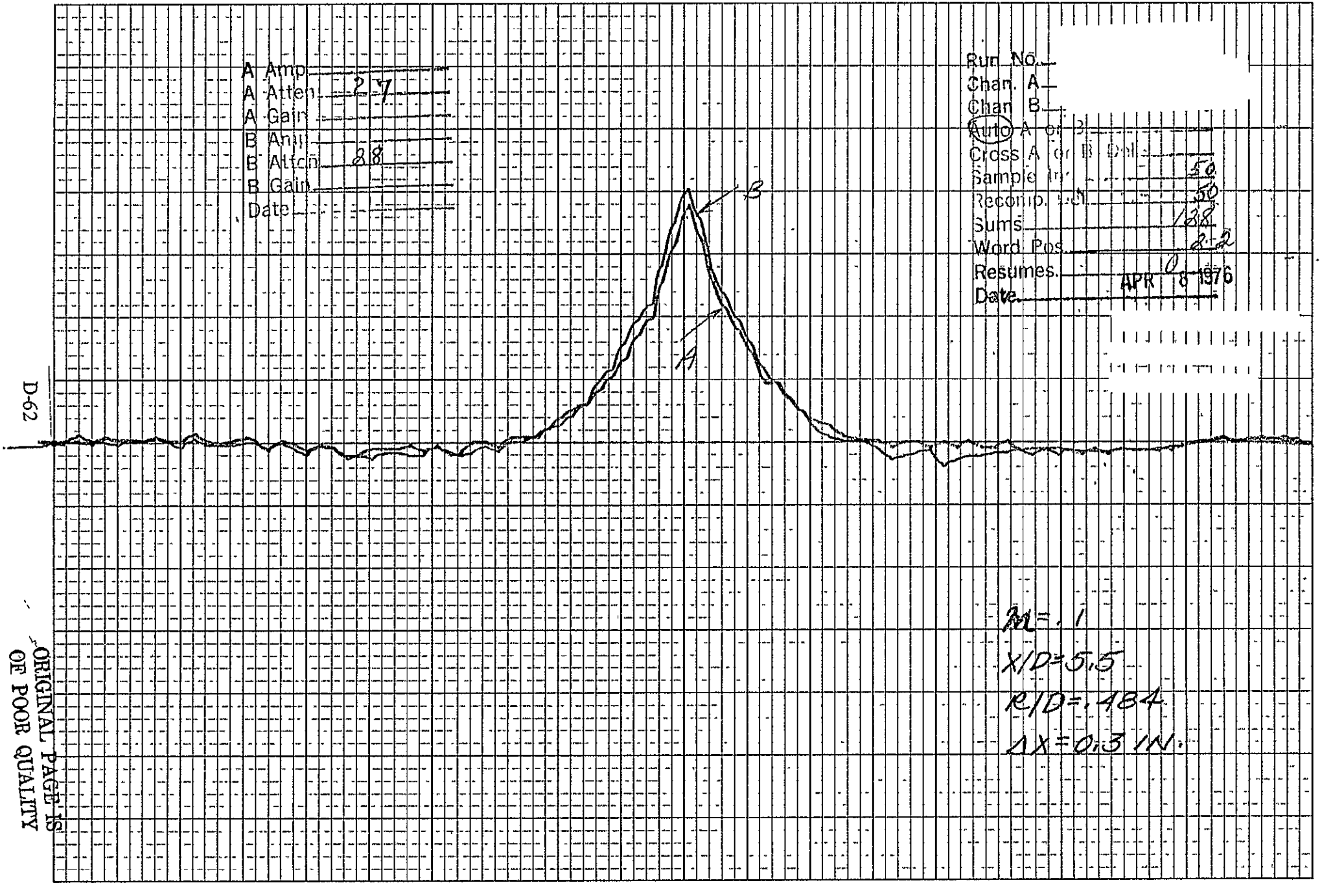

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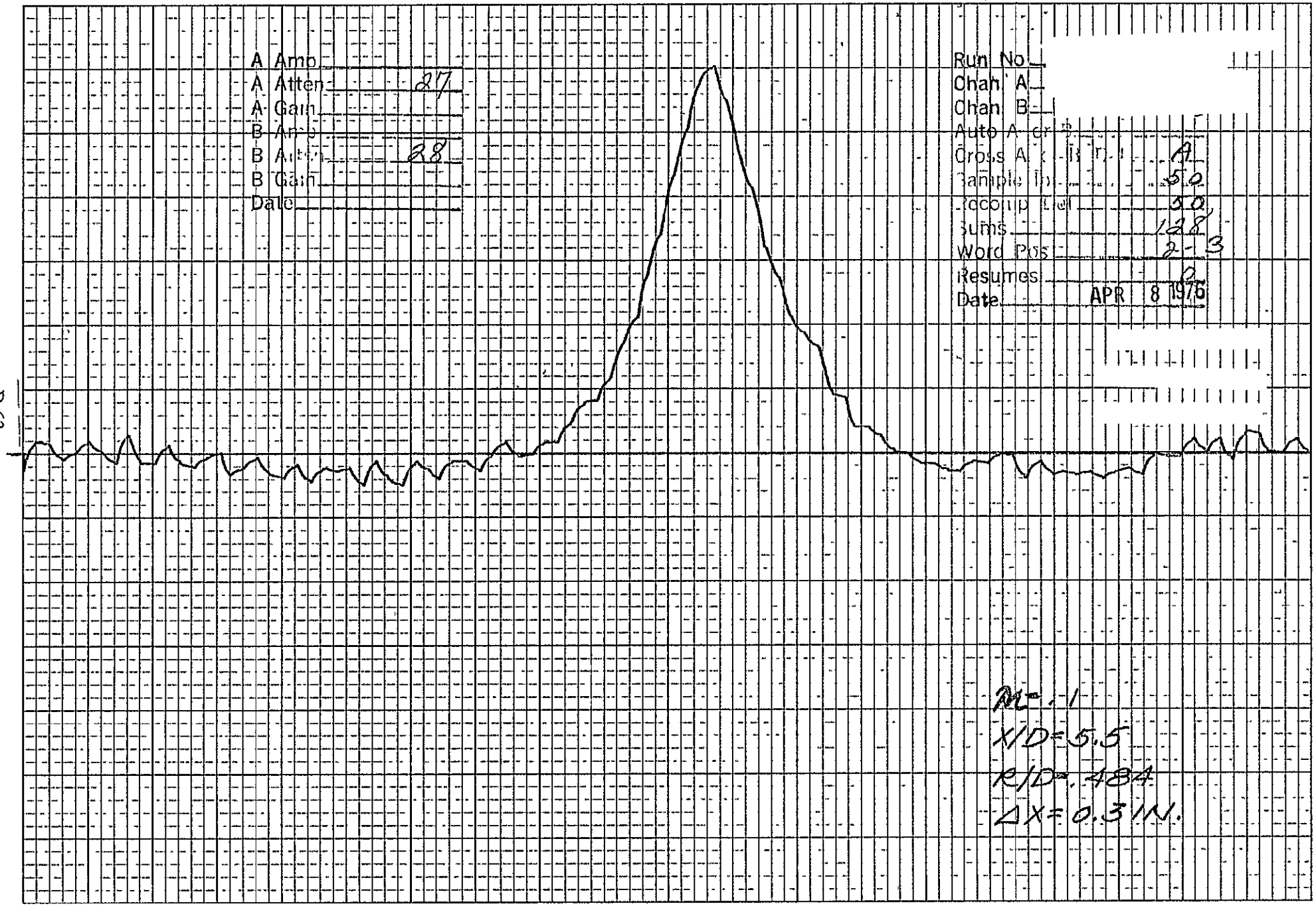

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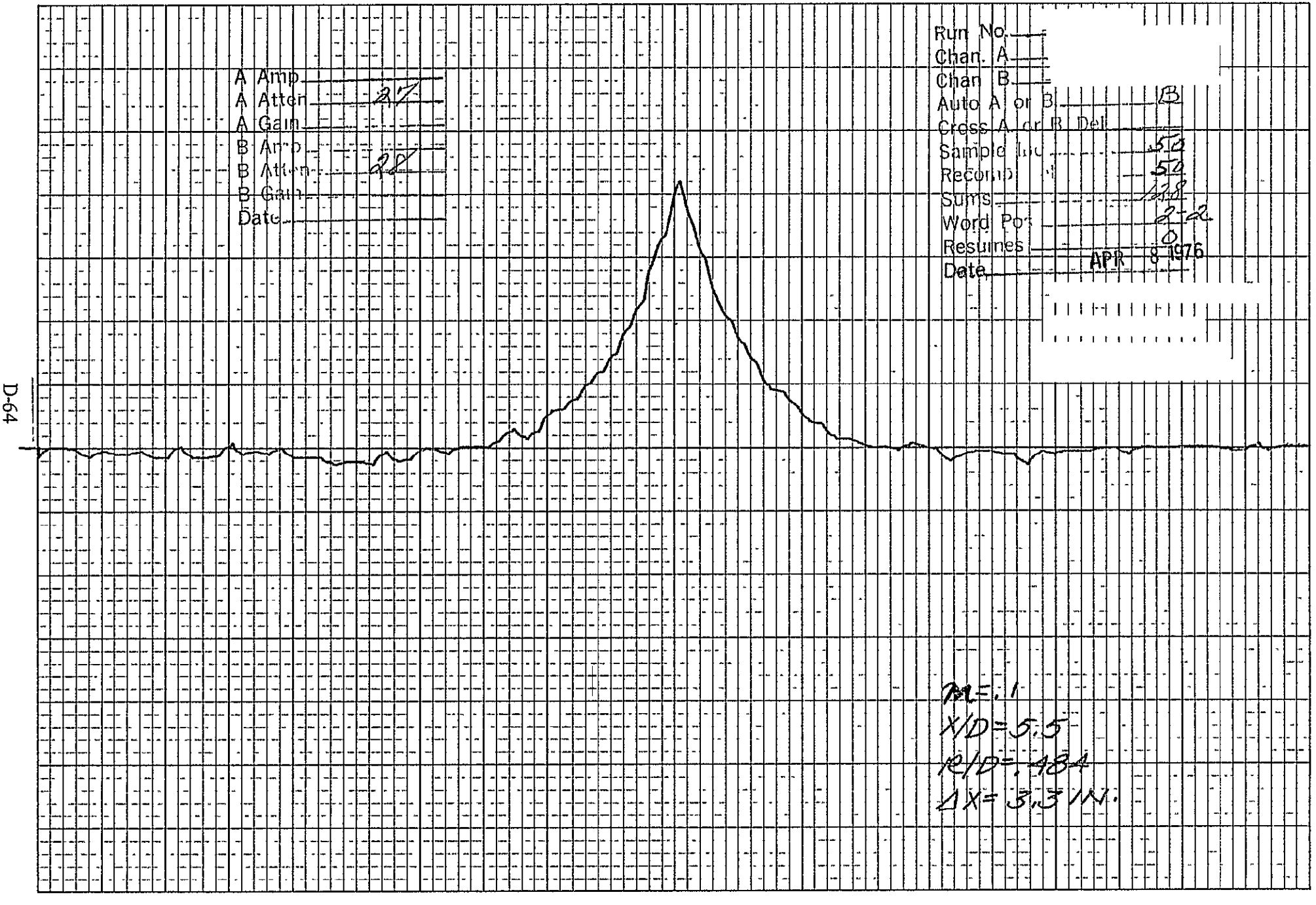

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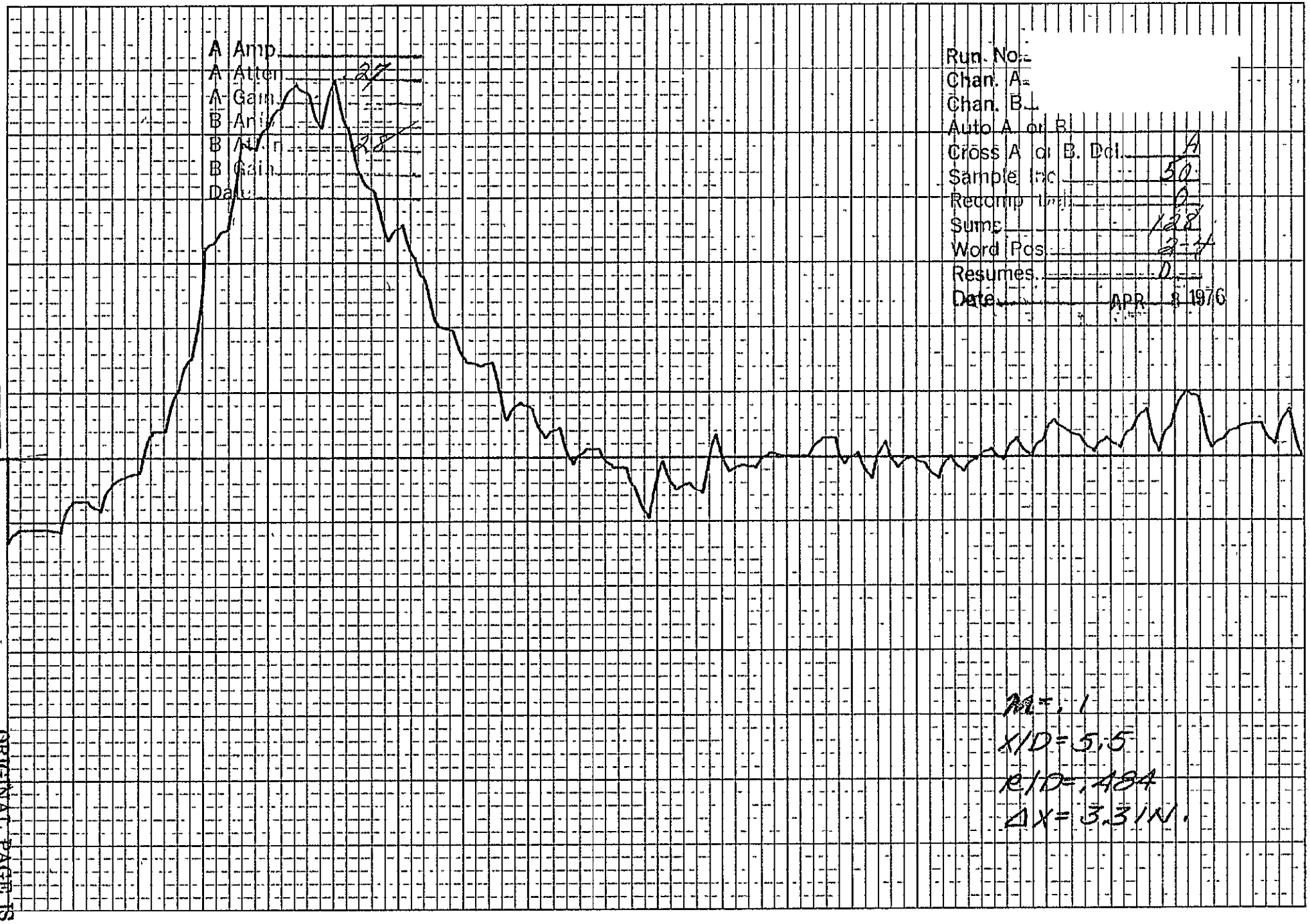

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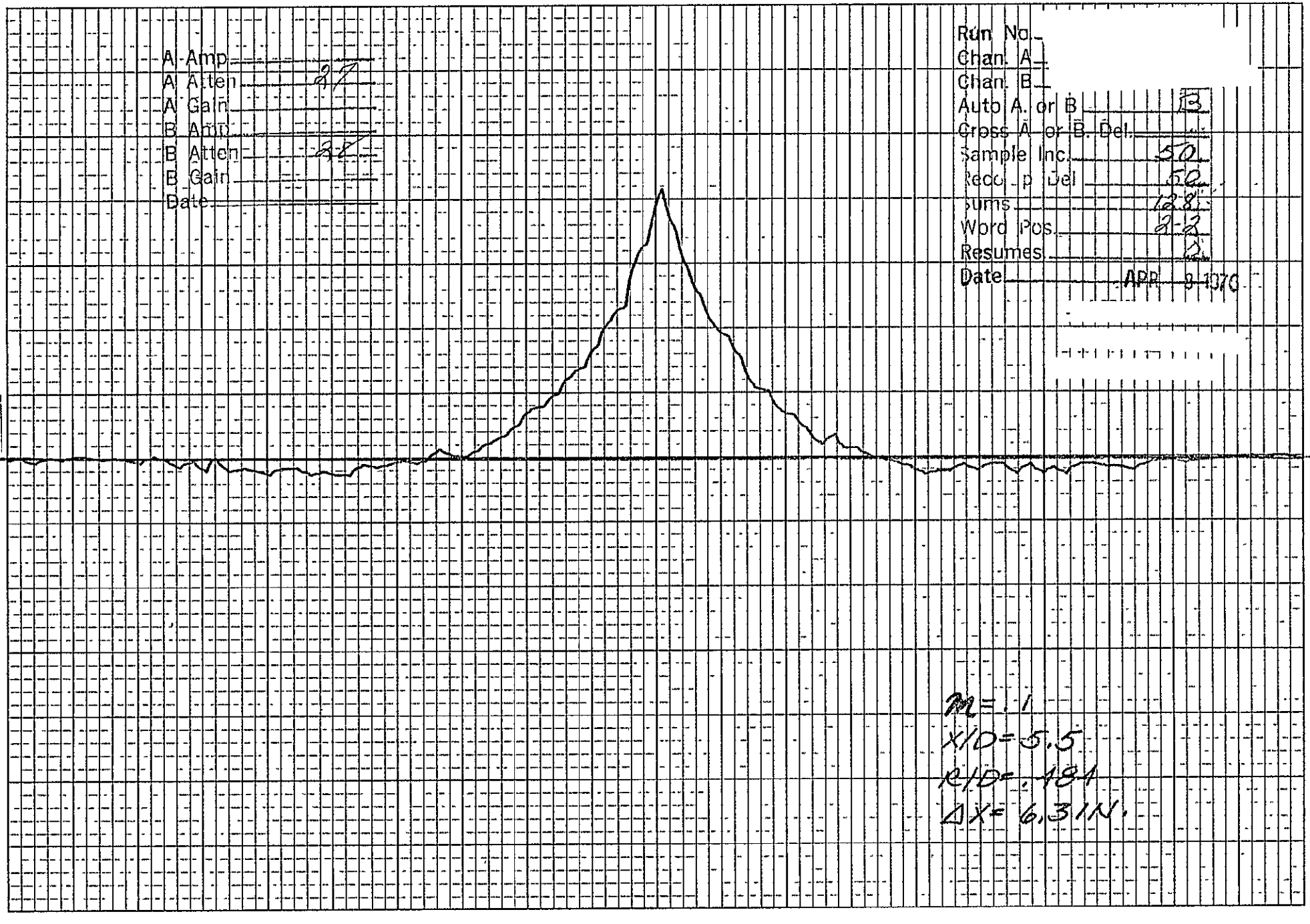
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A Atten
A Gain
B Amp
B Atten
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A. or B
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Sample Inc.
Sums
Word Pos.
Resumes
Date
APR 9 1970
M = .1
X/D = 5.5
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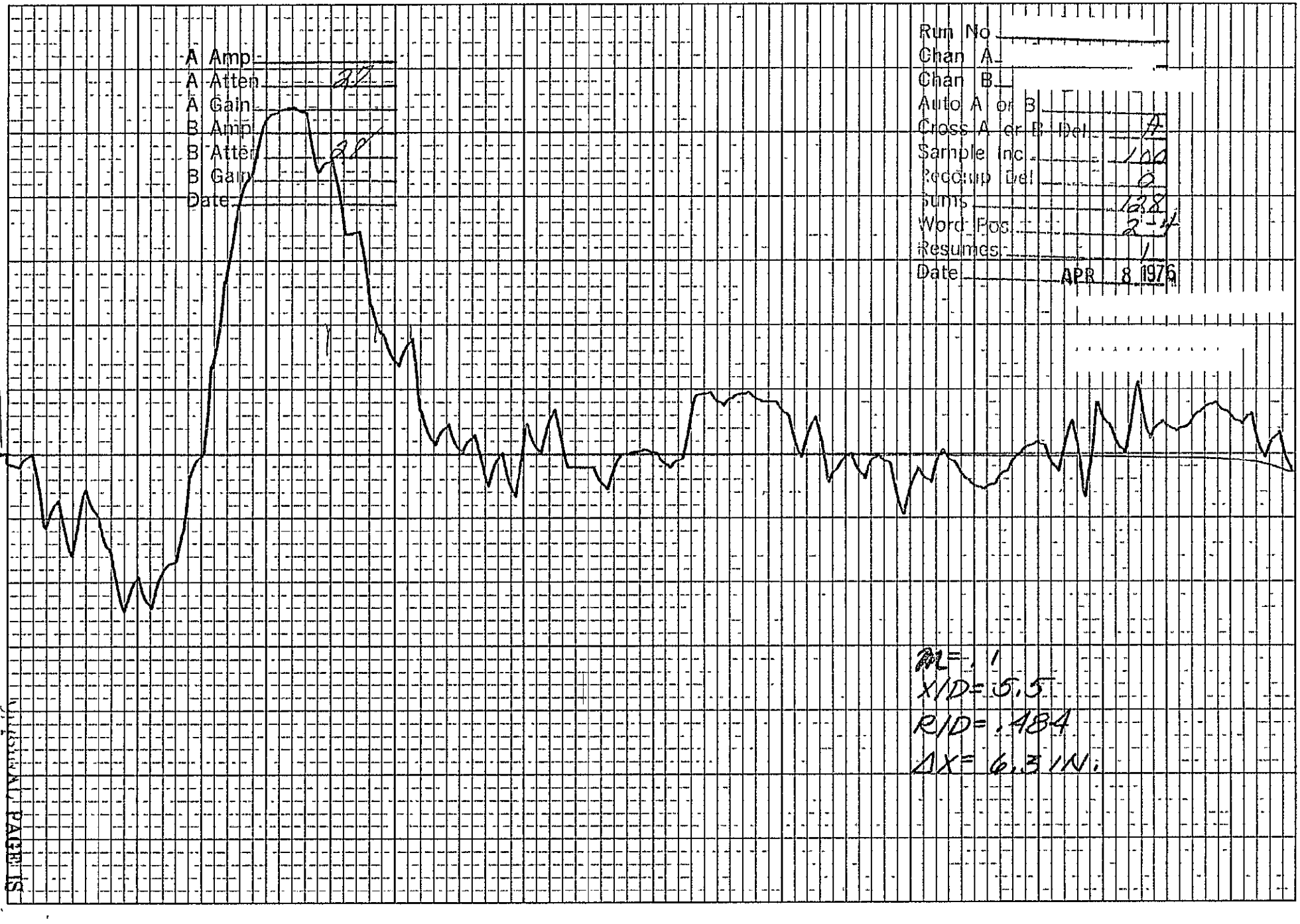

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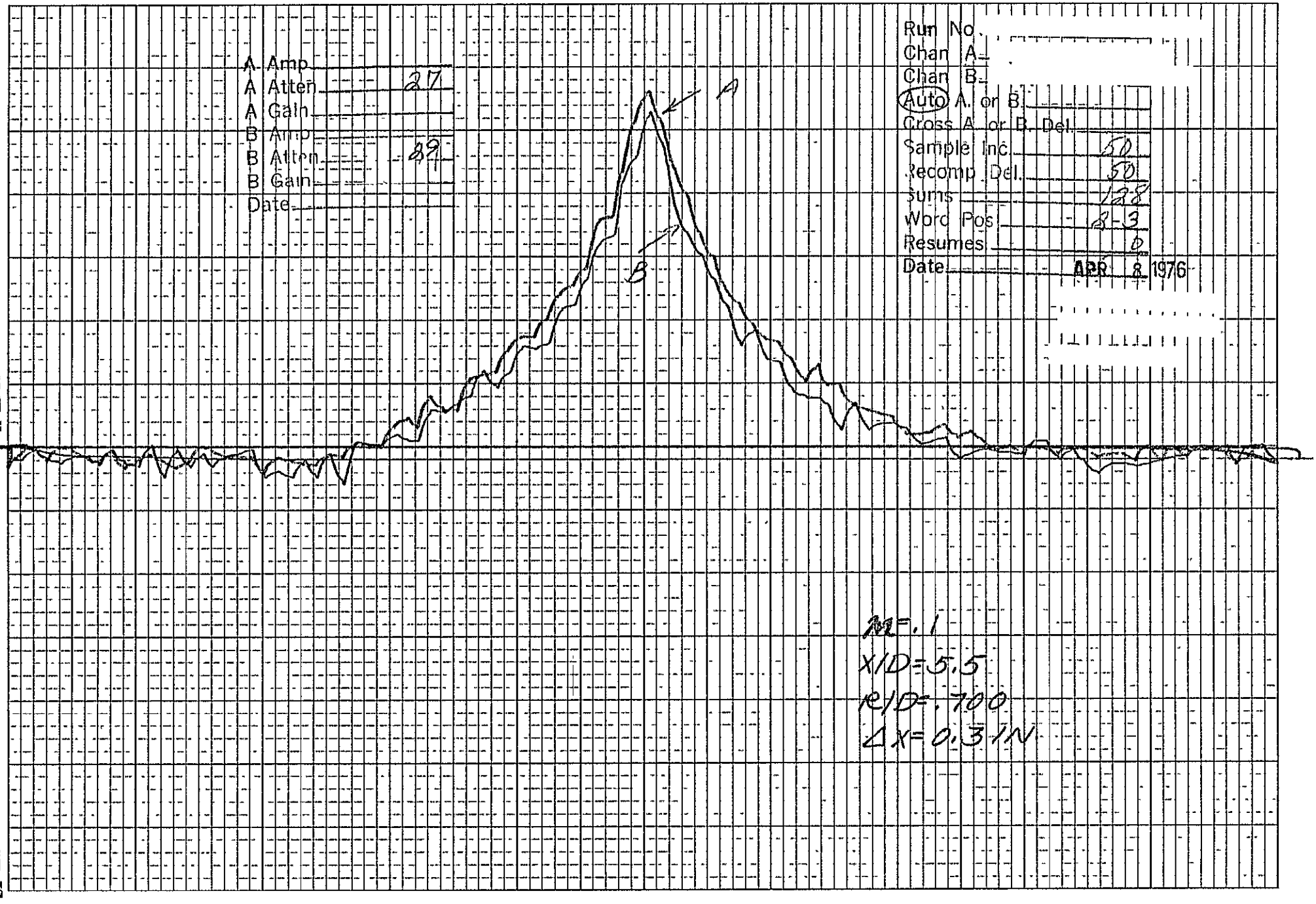

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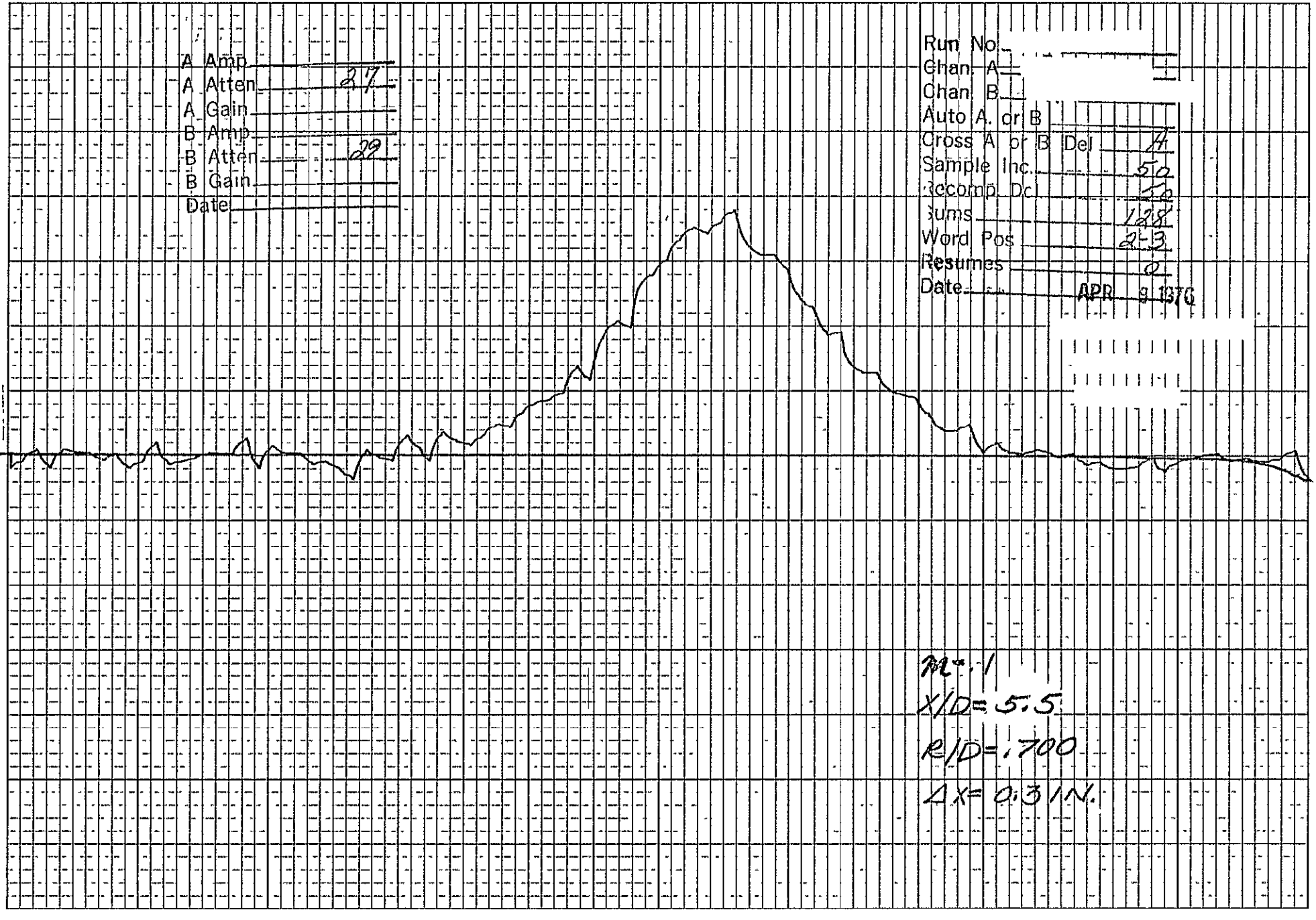

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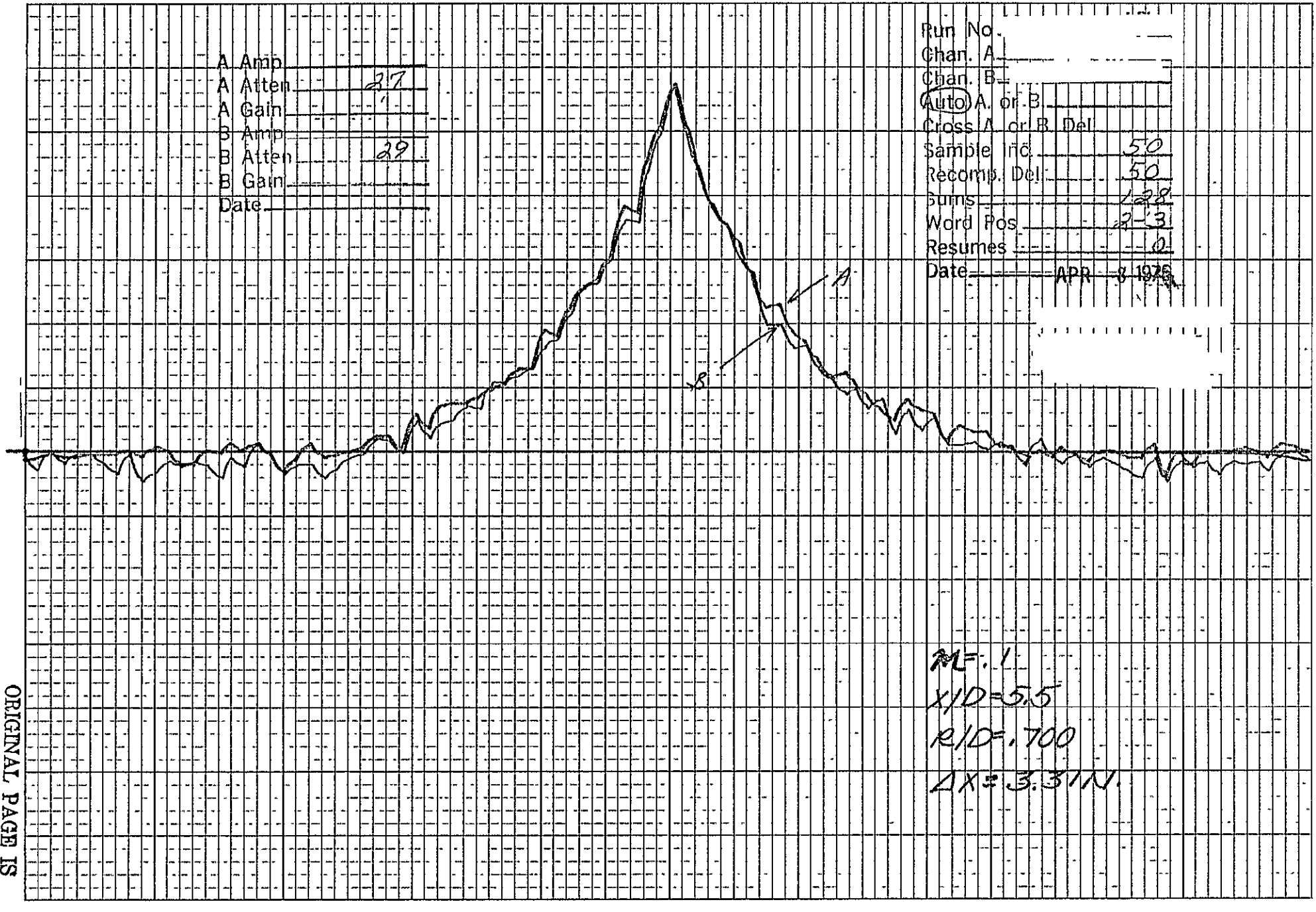

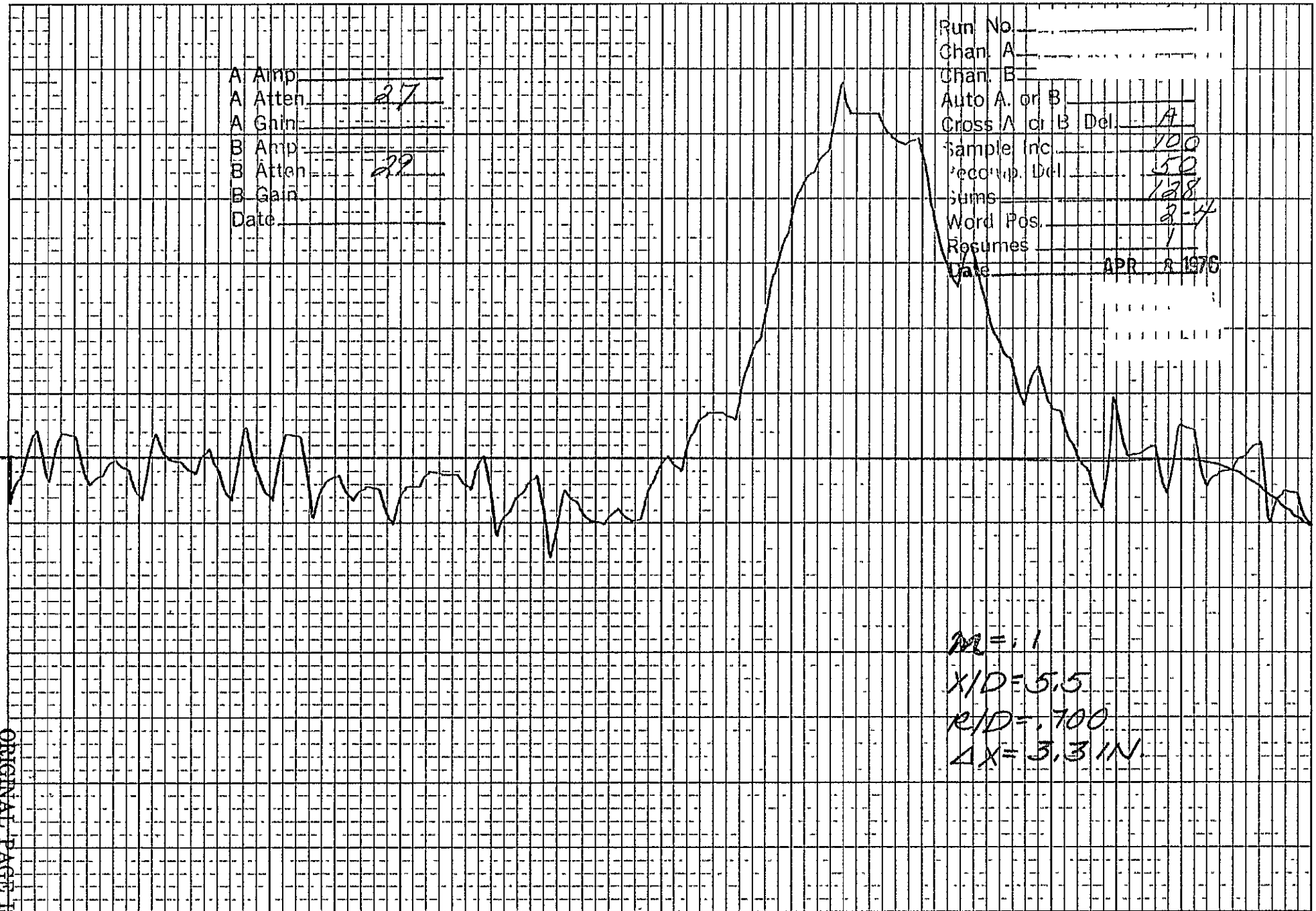

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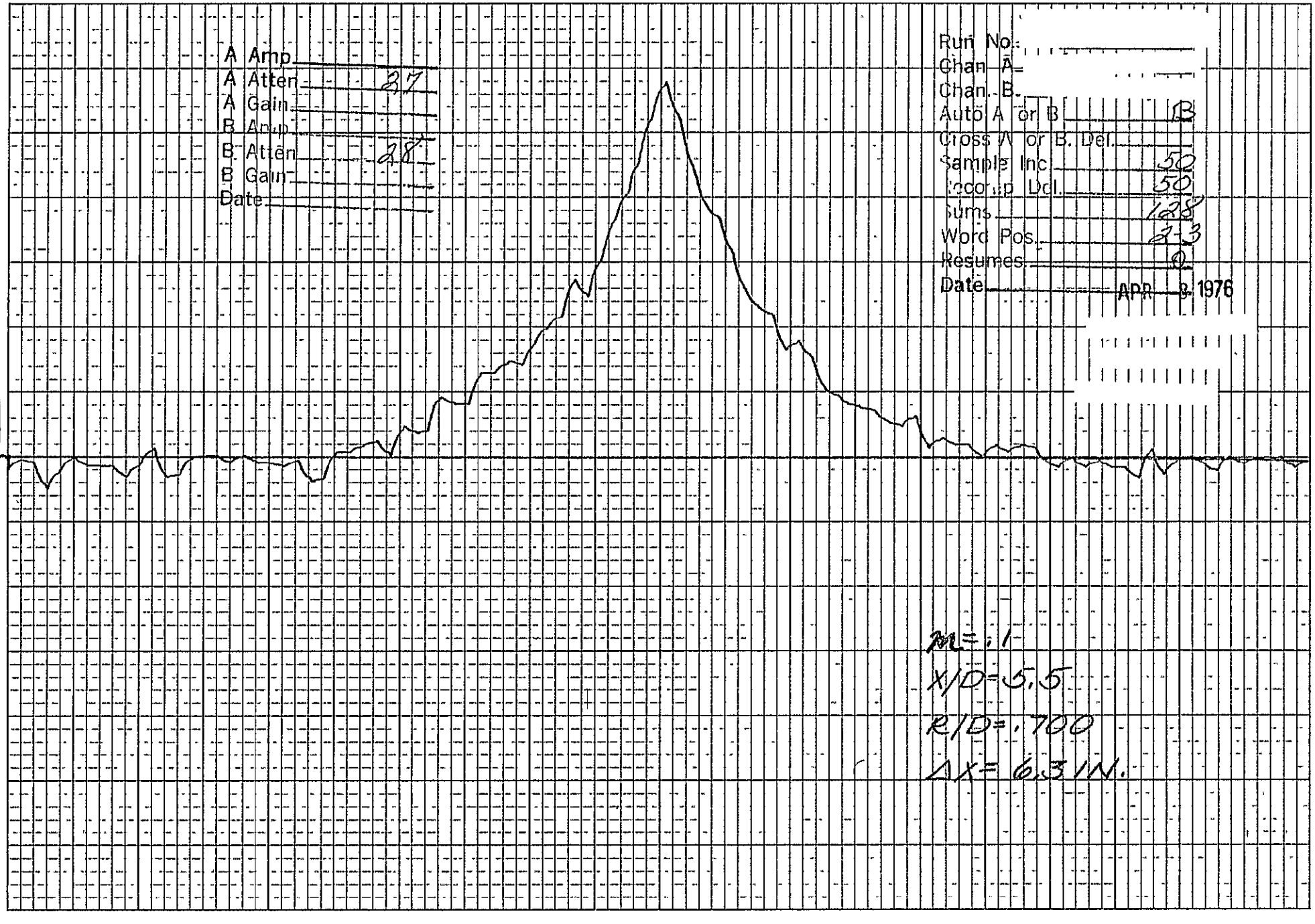

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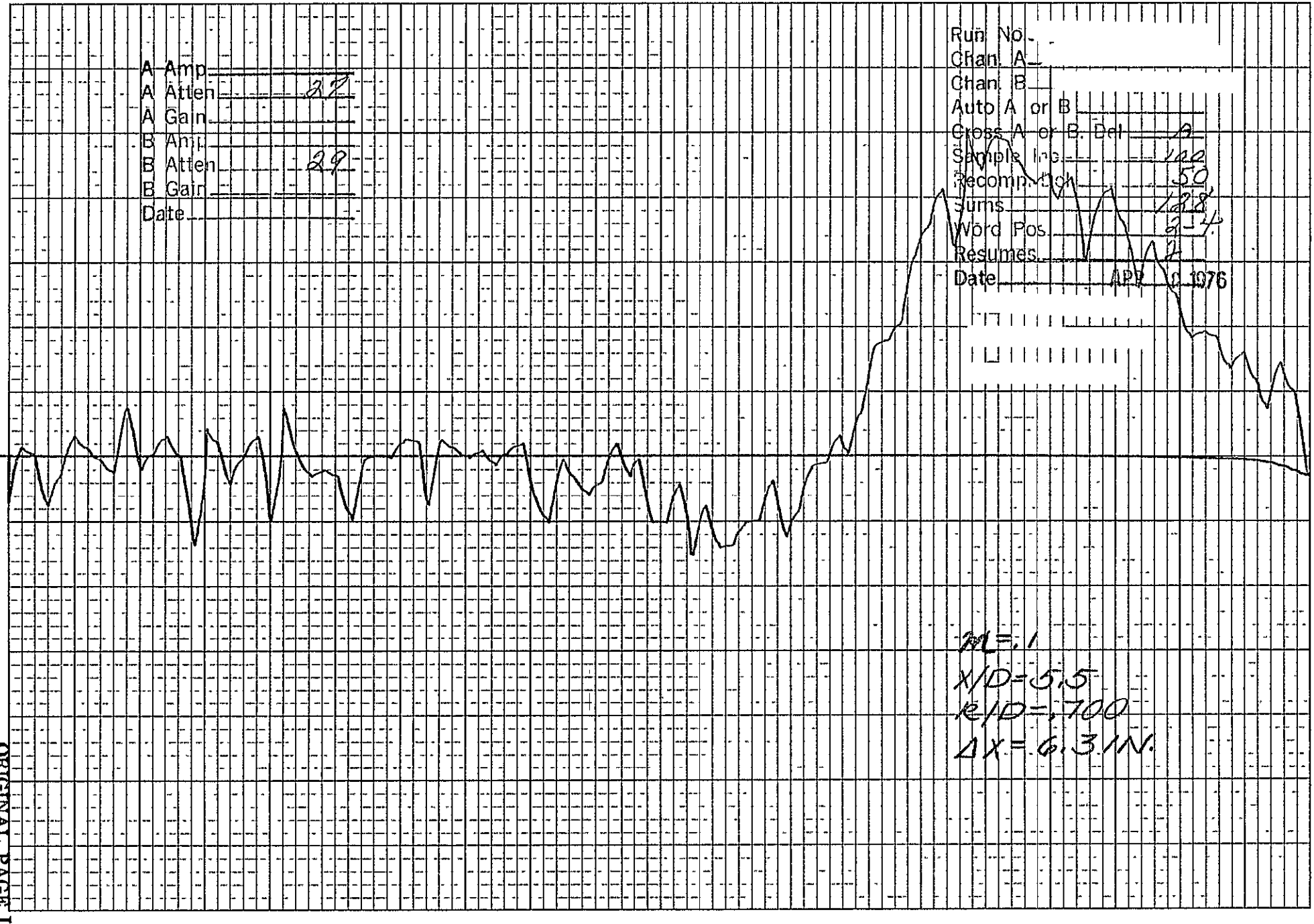

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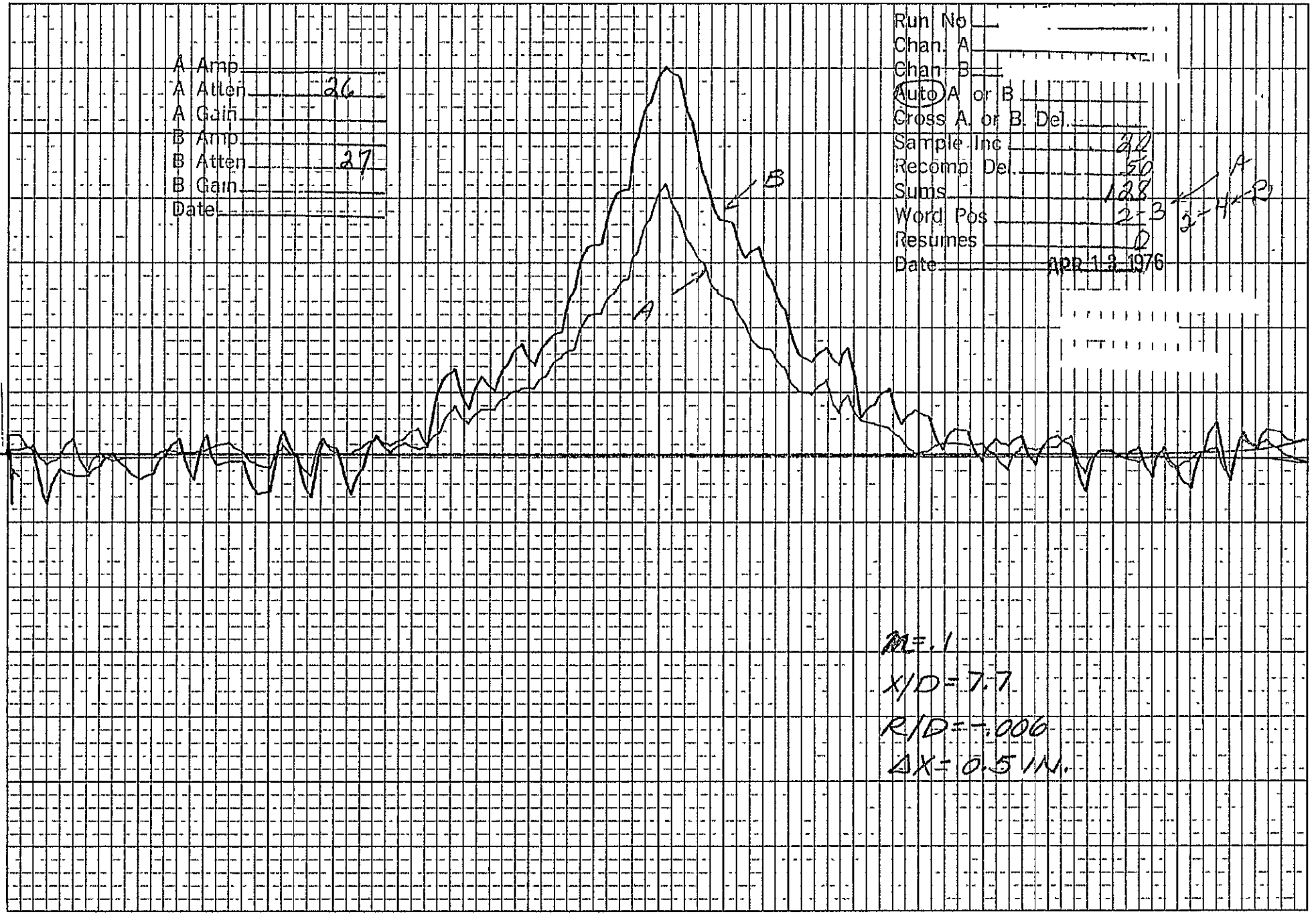

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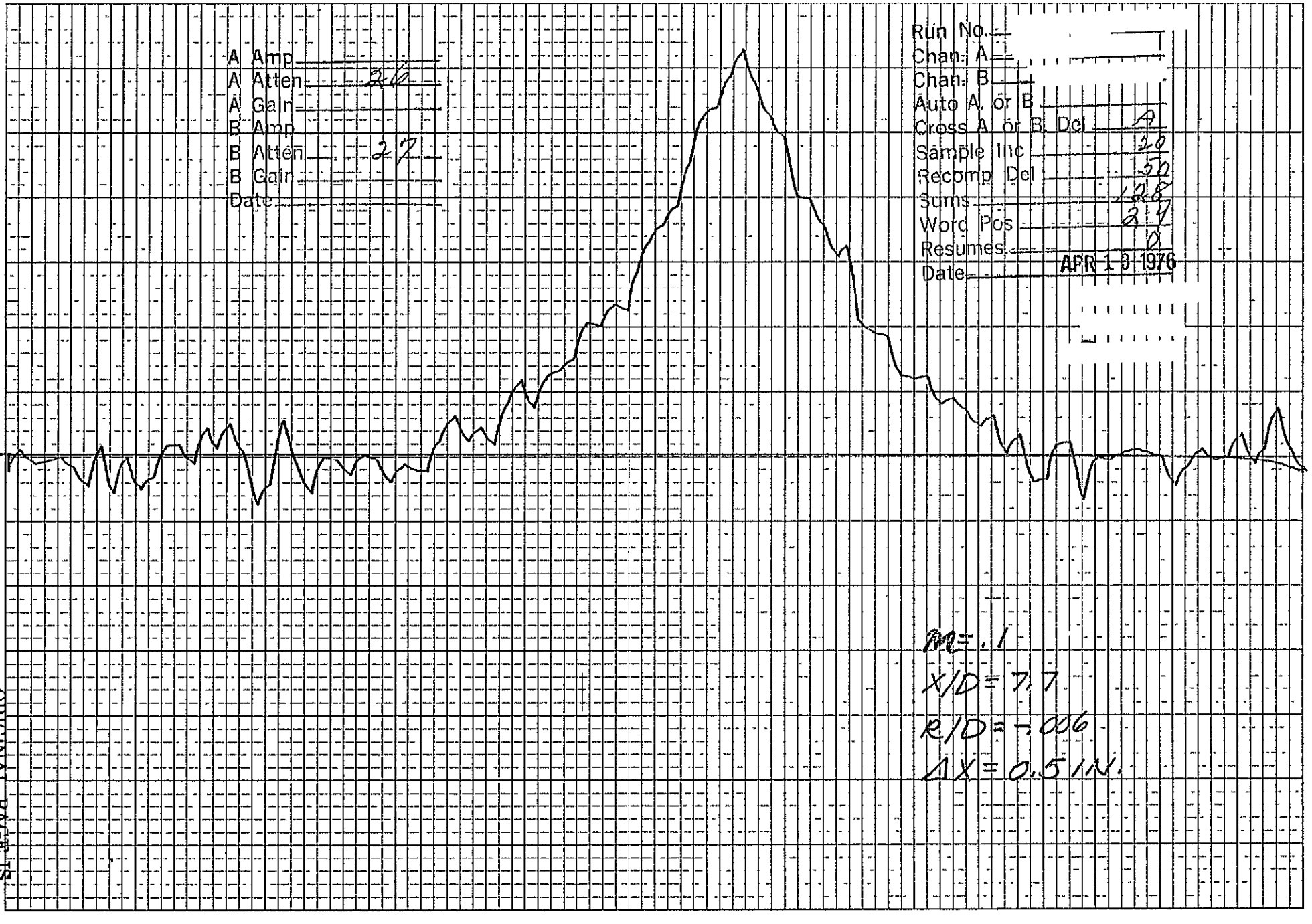

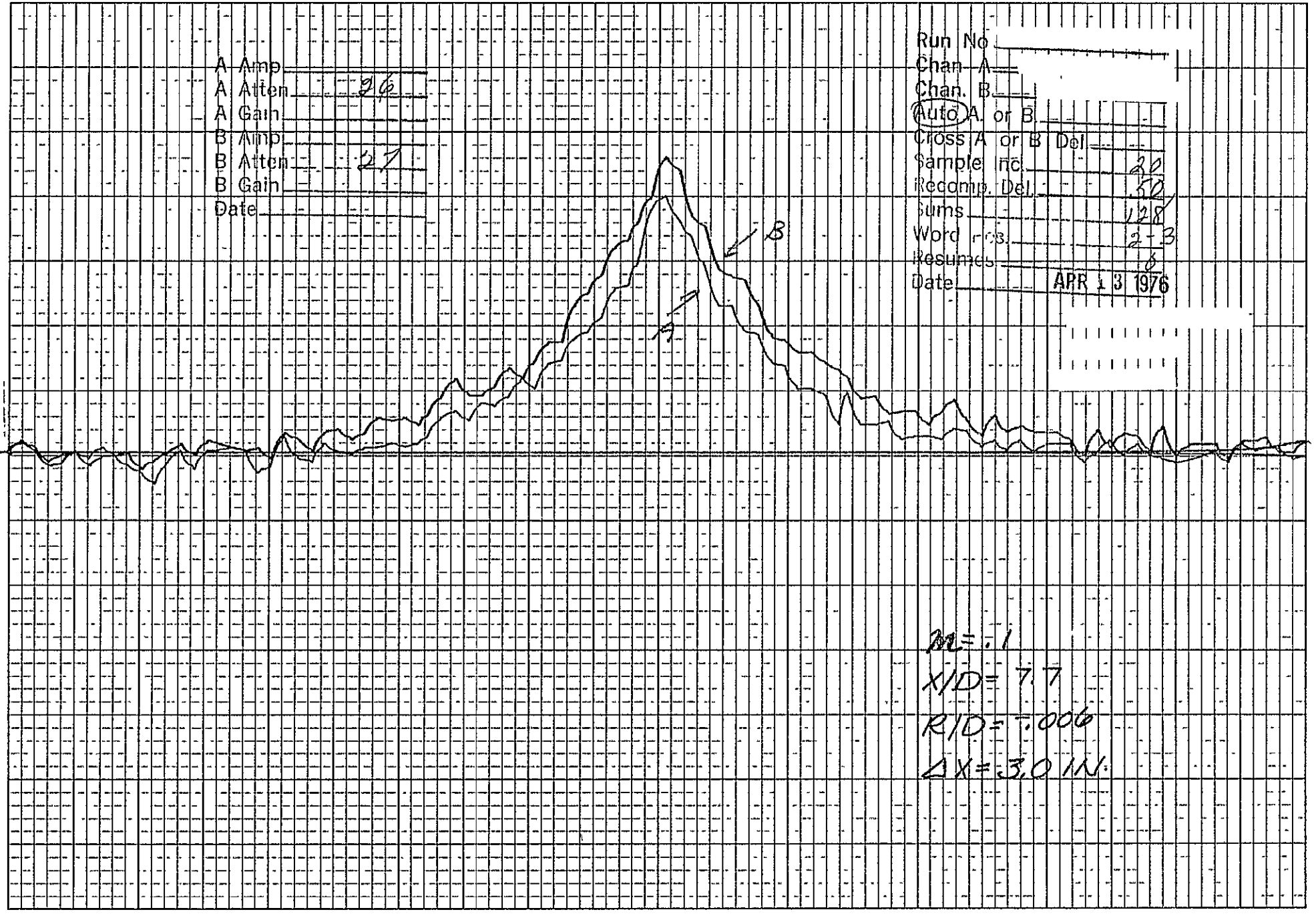
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A Atten 26
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B Amp
B Atten 27
B Gain
Date
Run No
Chan. A
Chan. B
Auto A. or B
Cross A or B Del
Sample inc 20
Recomp. Del 32
Sums 128
Word rec. 2-3
Resumes 8
Date APR 13 1976
B
A
M = .1
X/D = 7.7
R/D = .006
ΔX = 3.0 IN.

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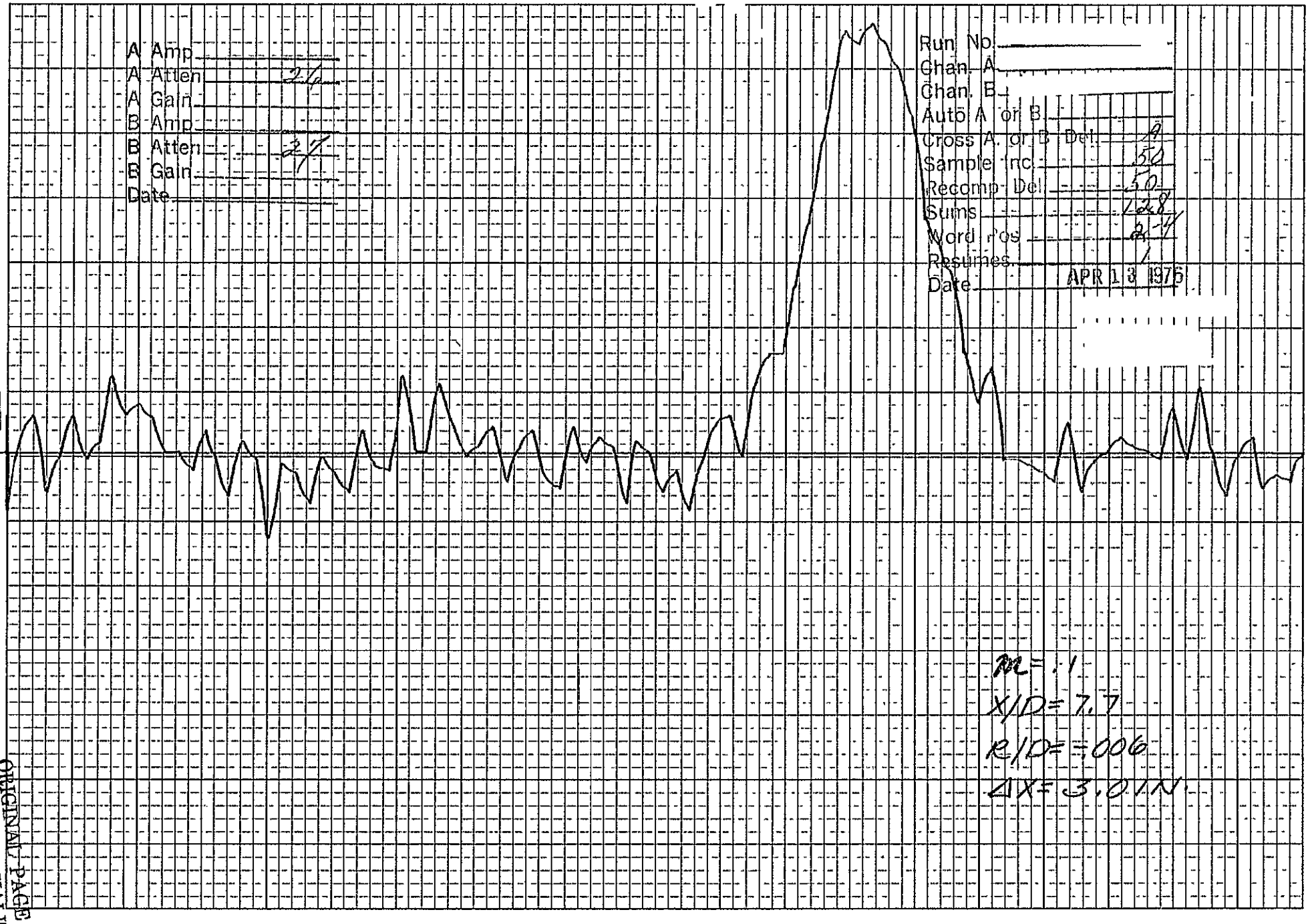

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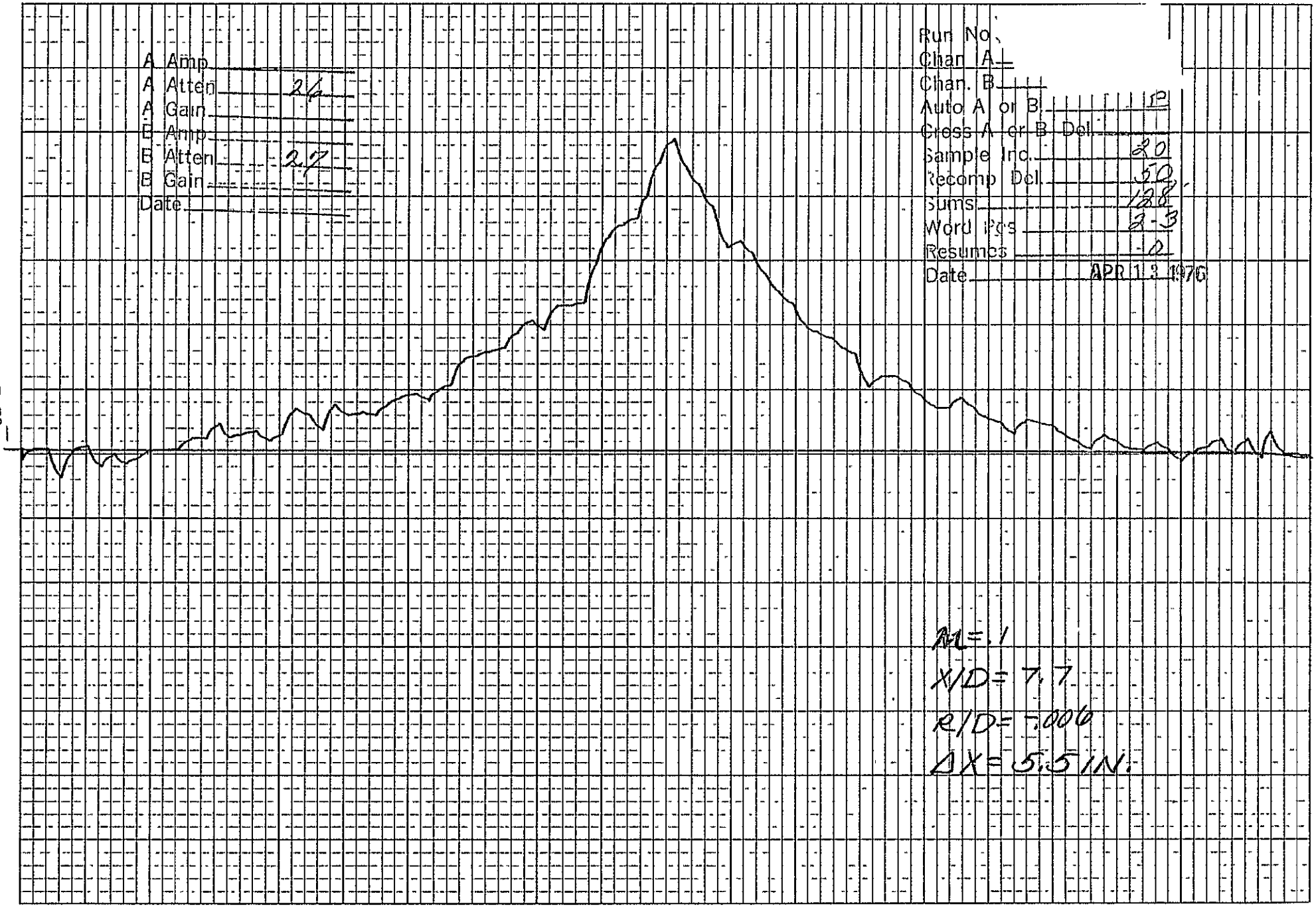
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A Atten 2
A Gain
B Amp
B Atten 2
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A or B 12
Cross A or B Del.
Sample Inc. 20
Recomp Del. 50
Sums 128
Word Pos 3-3
Resumes 2
Date APR 13 1976
M=.1
X/D= 7.7
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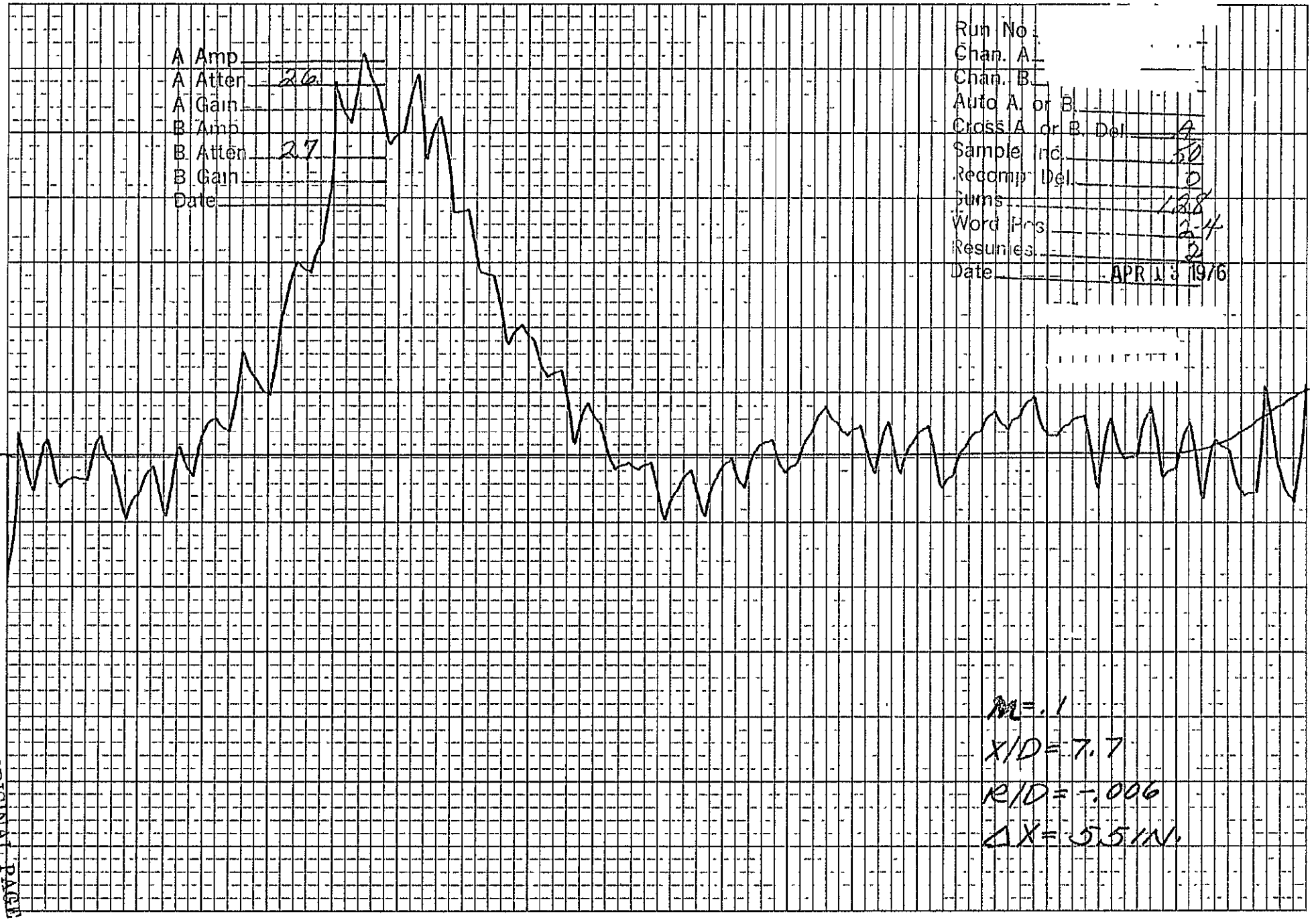

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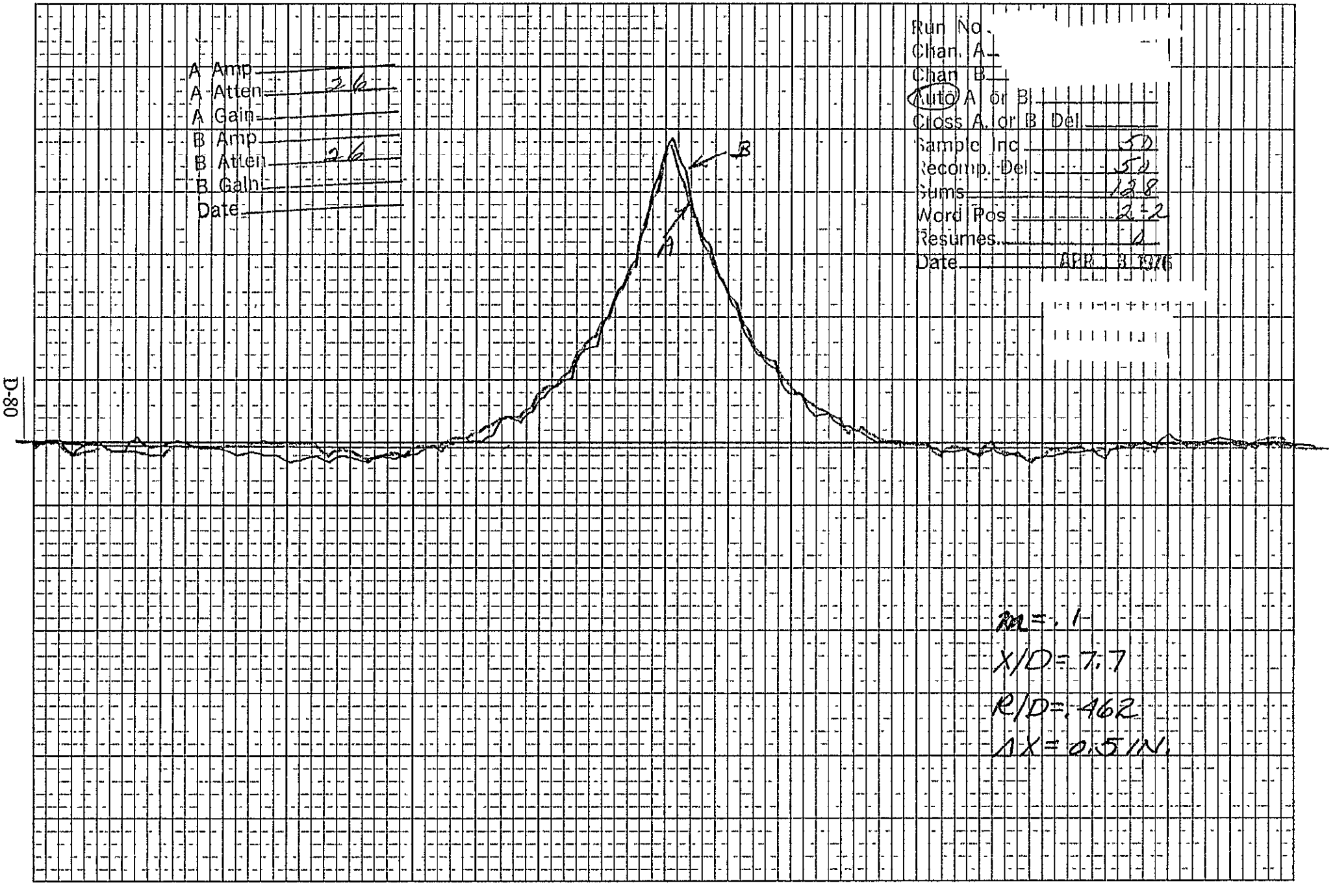

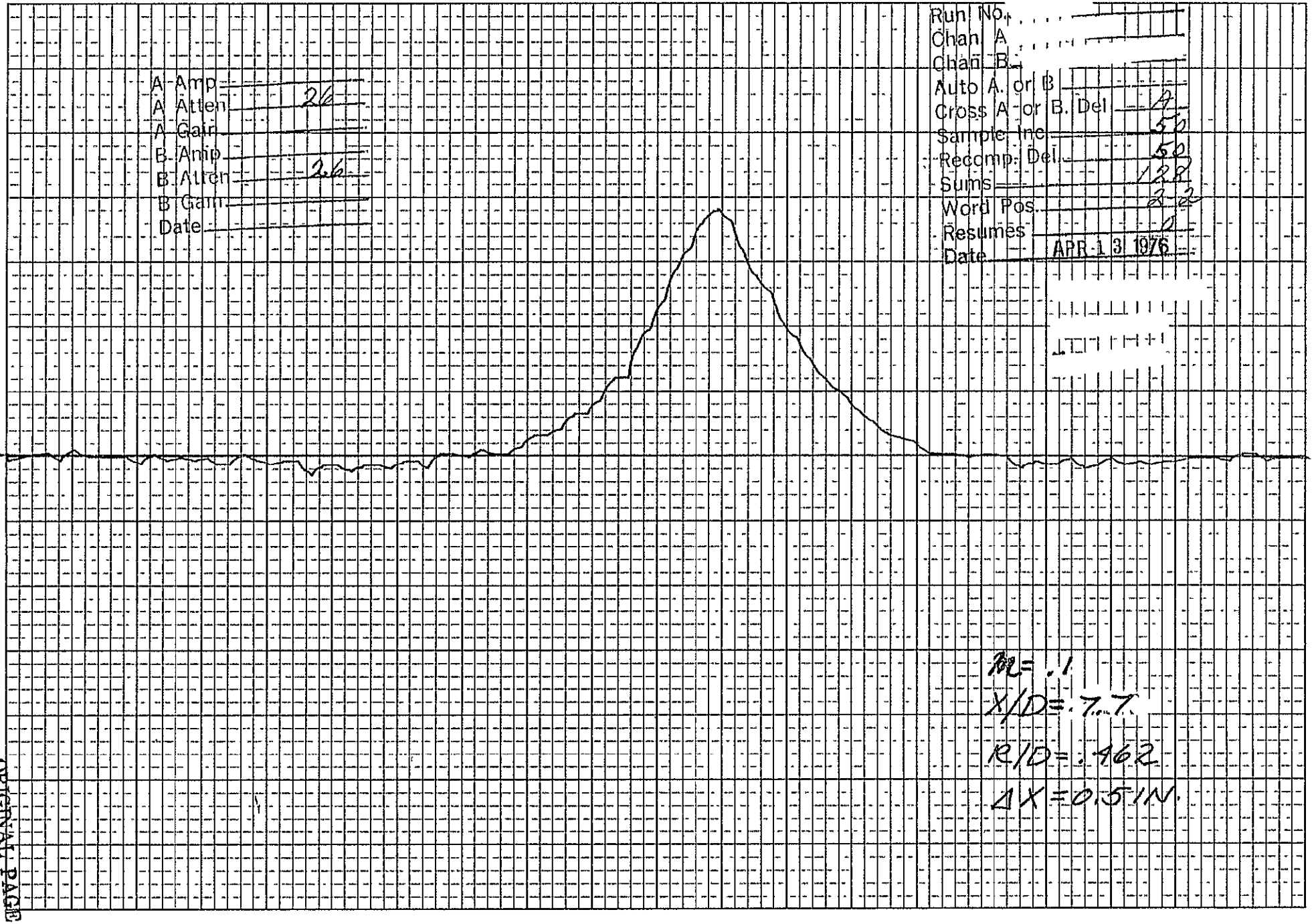

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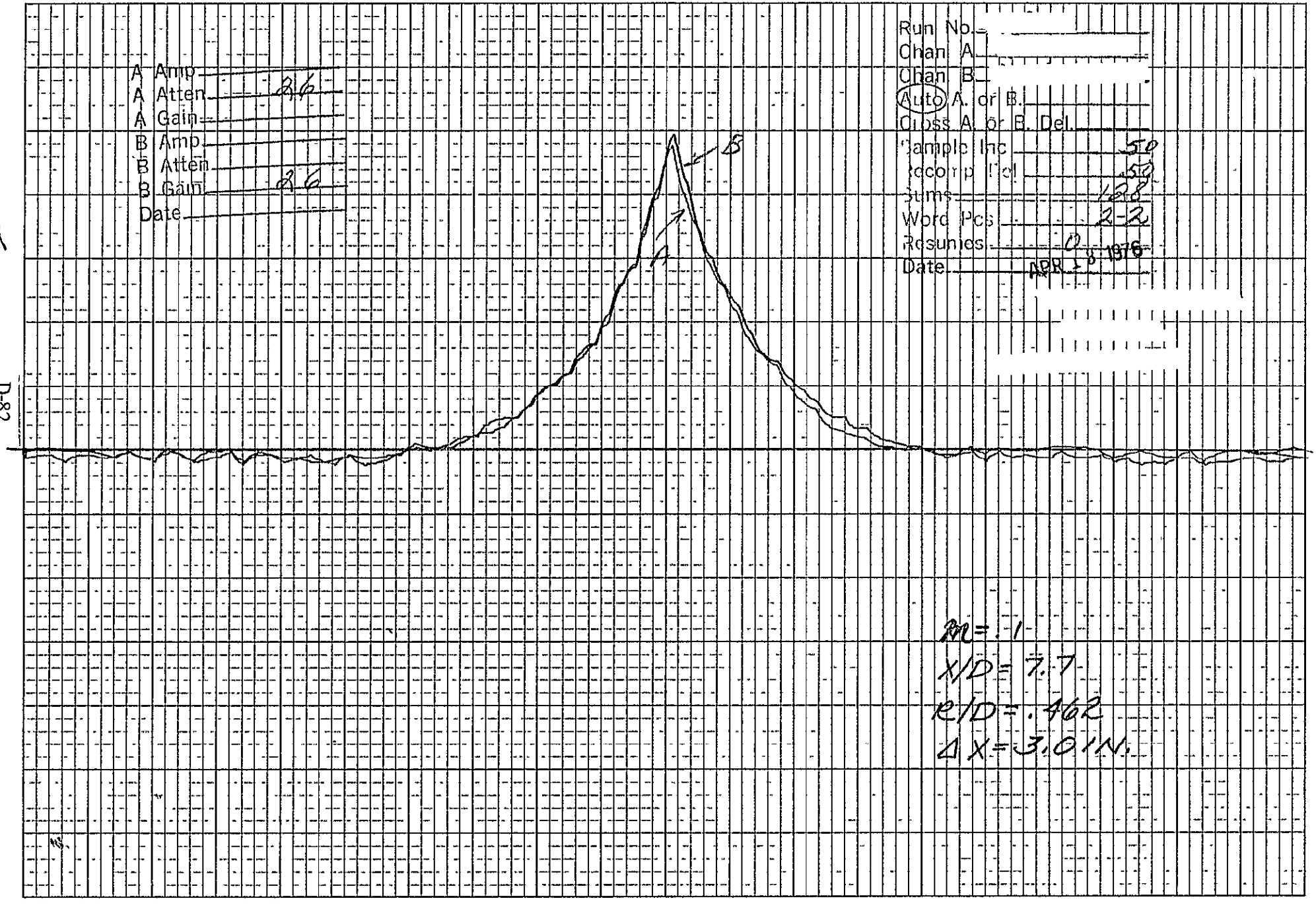

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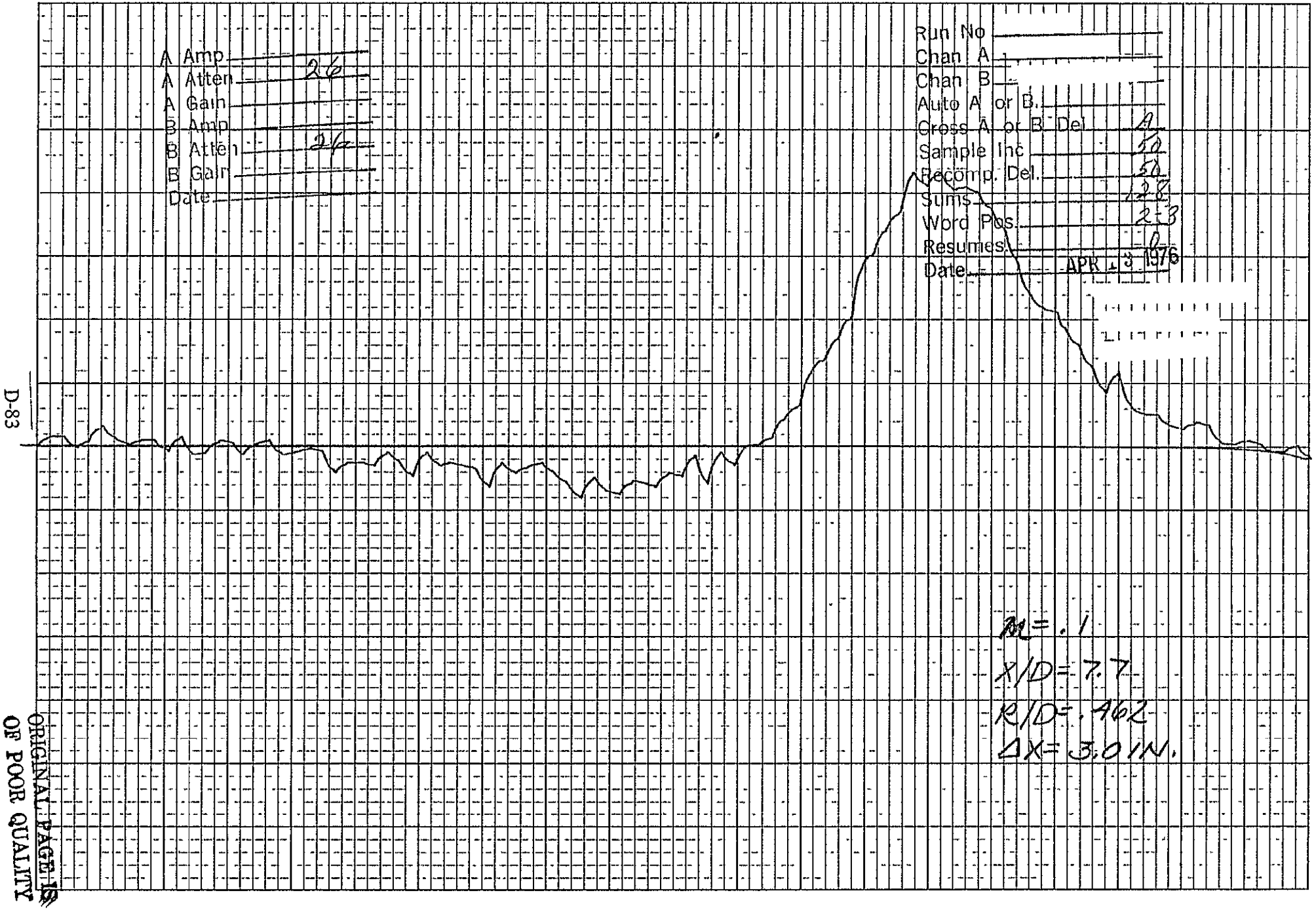

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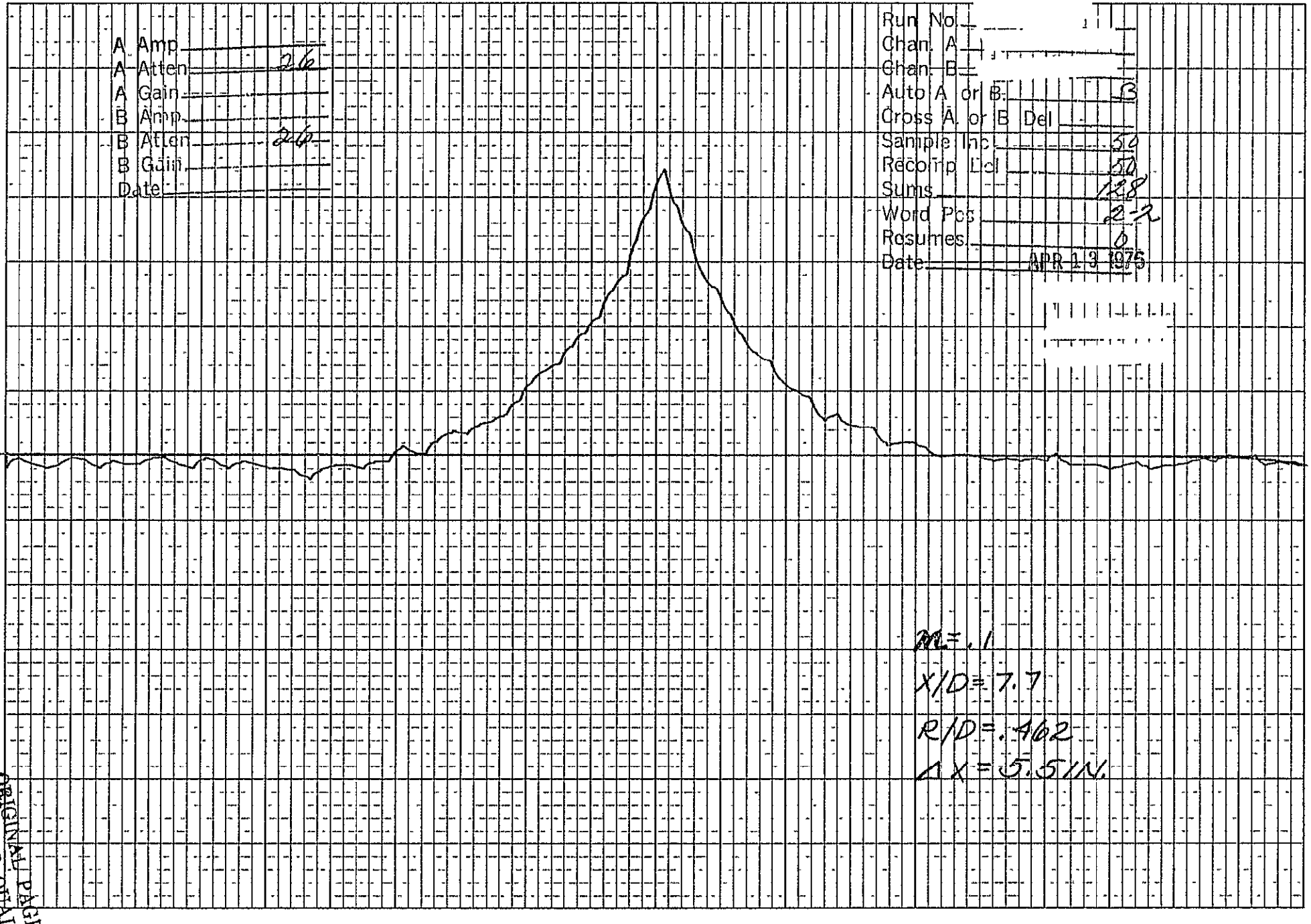

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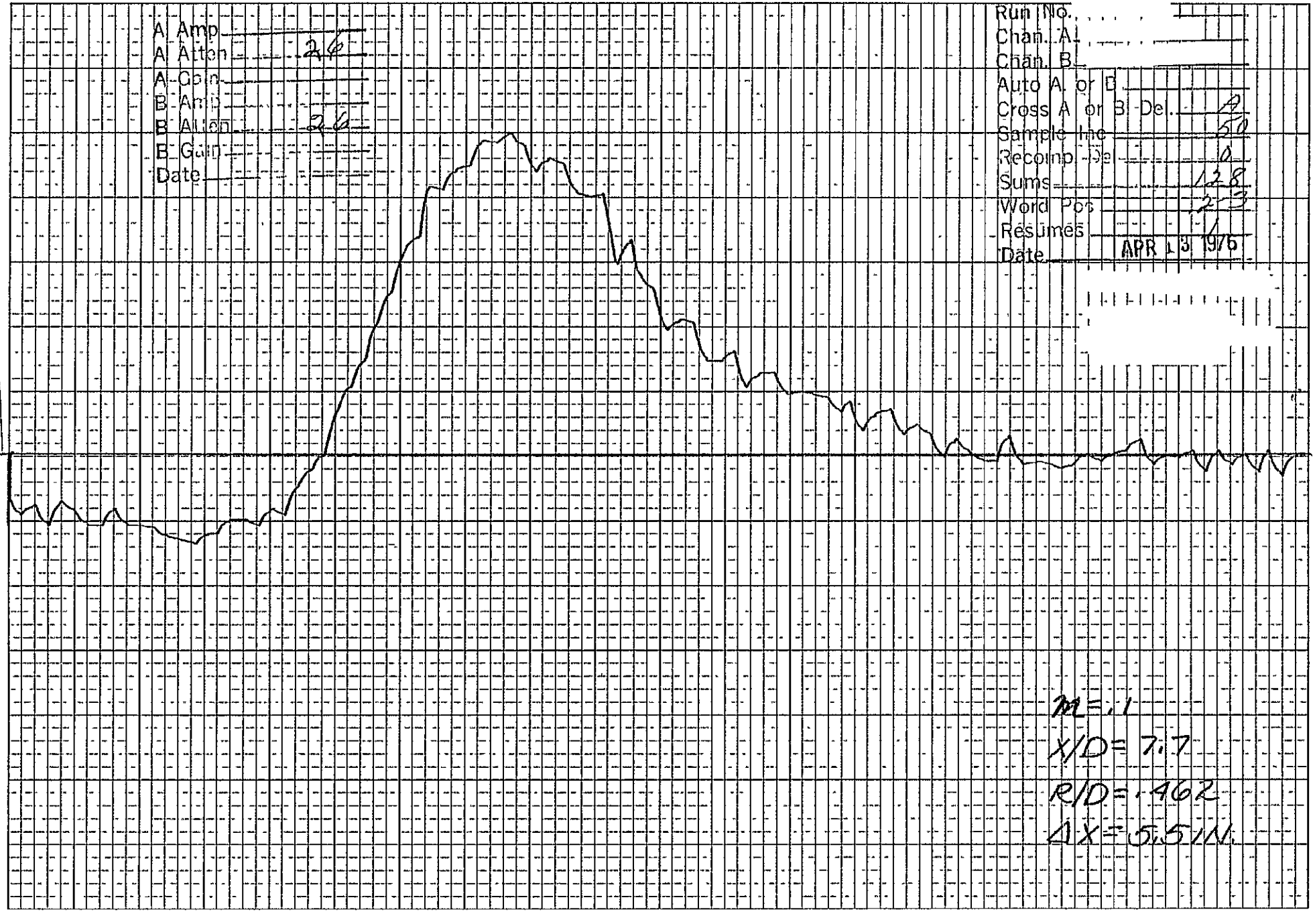

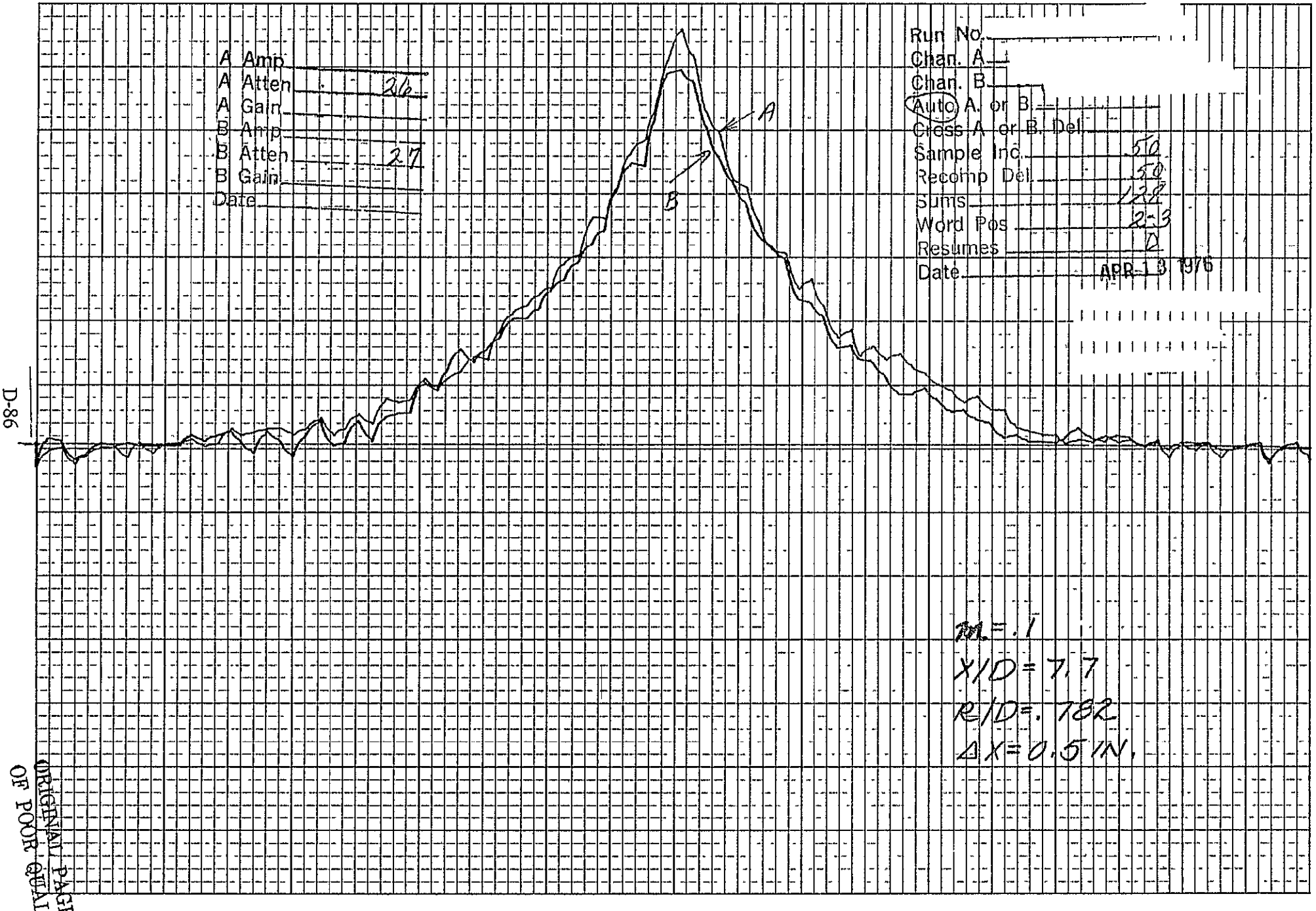

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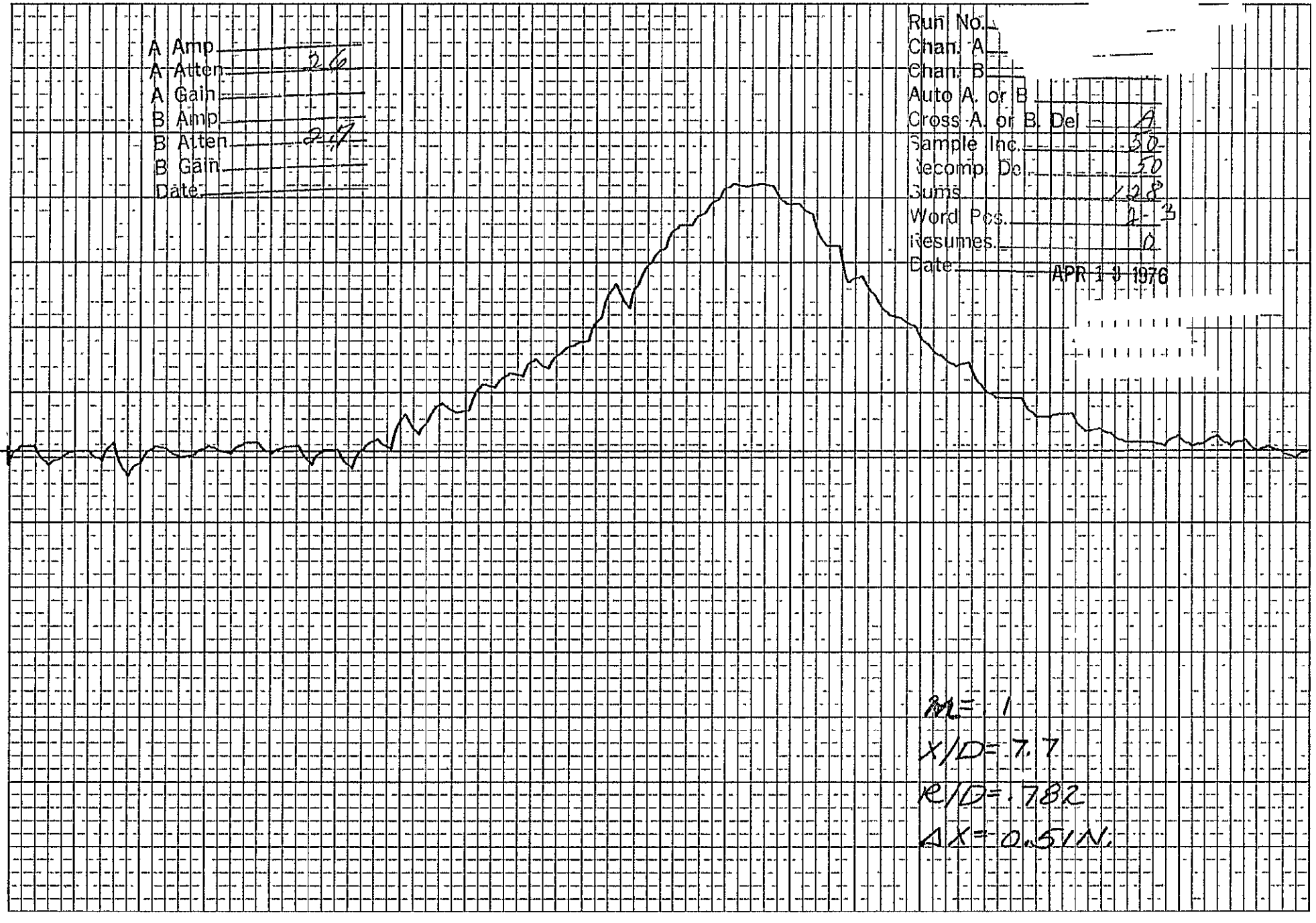

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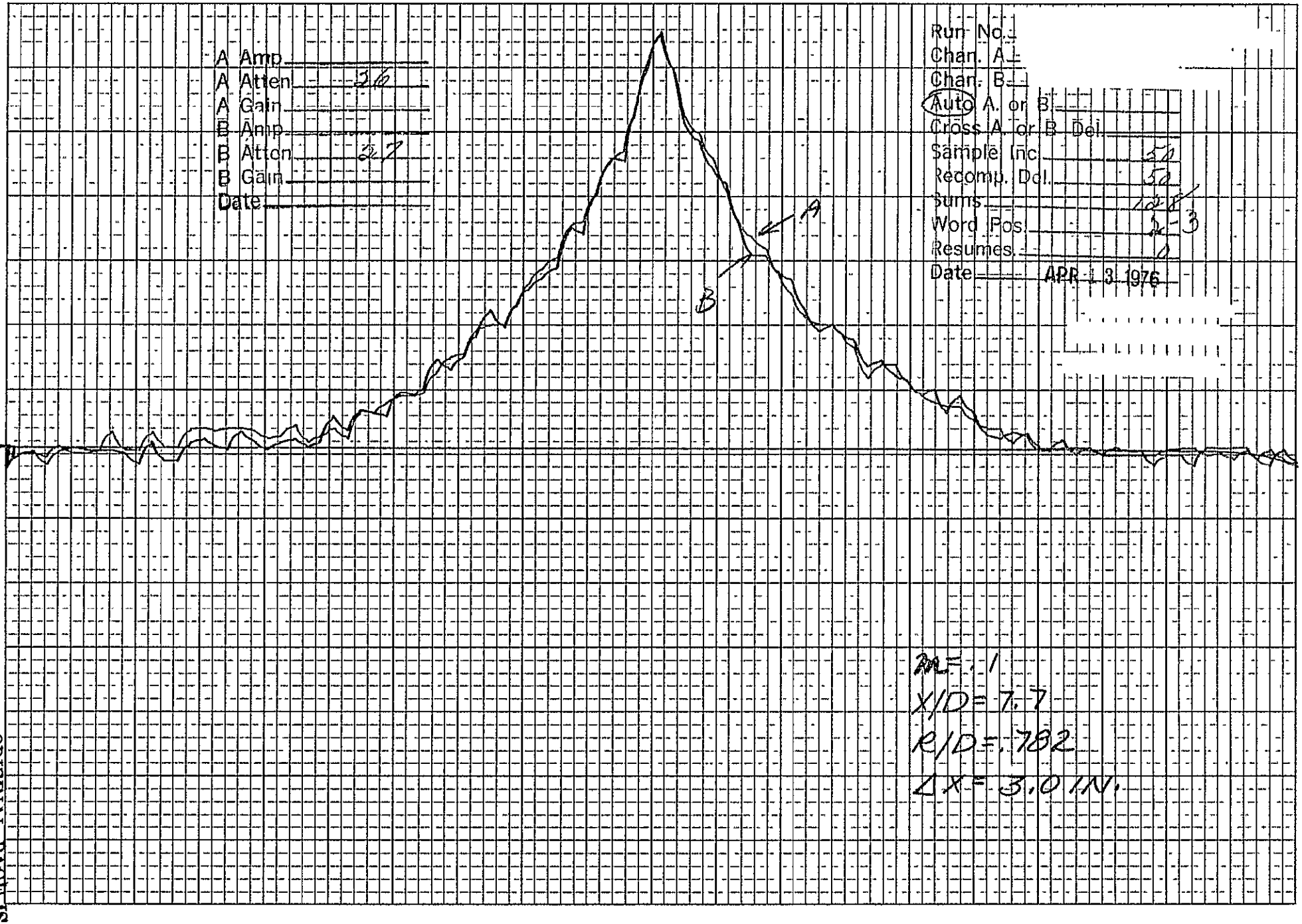

D-88

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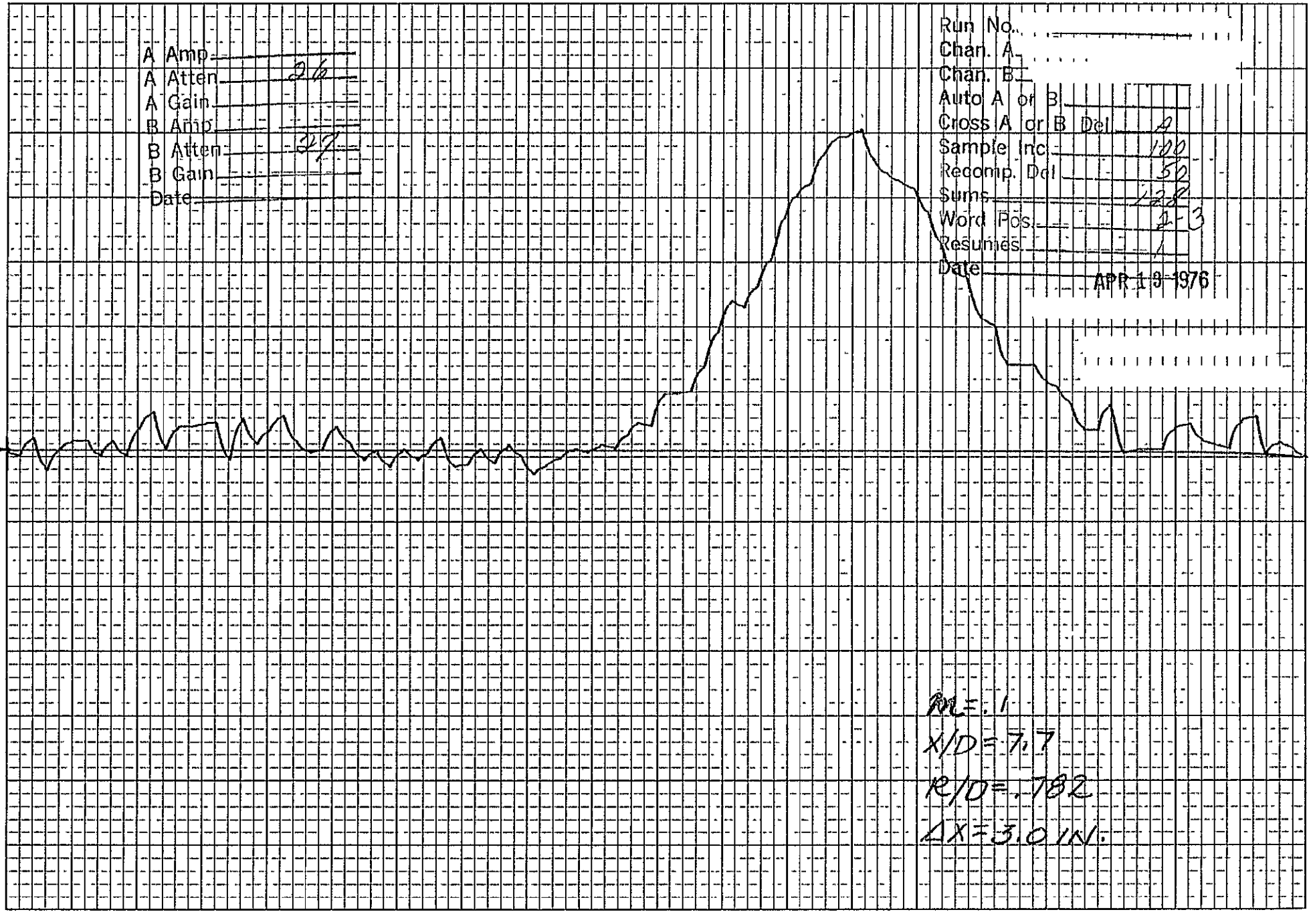

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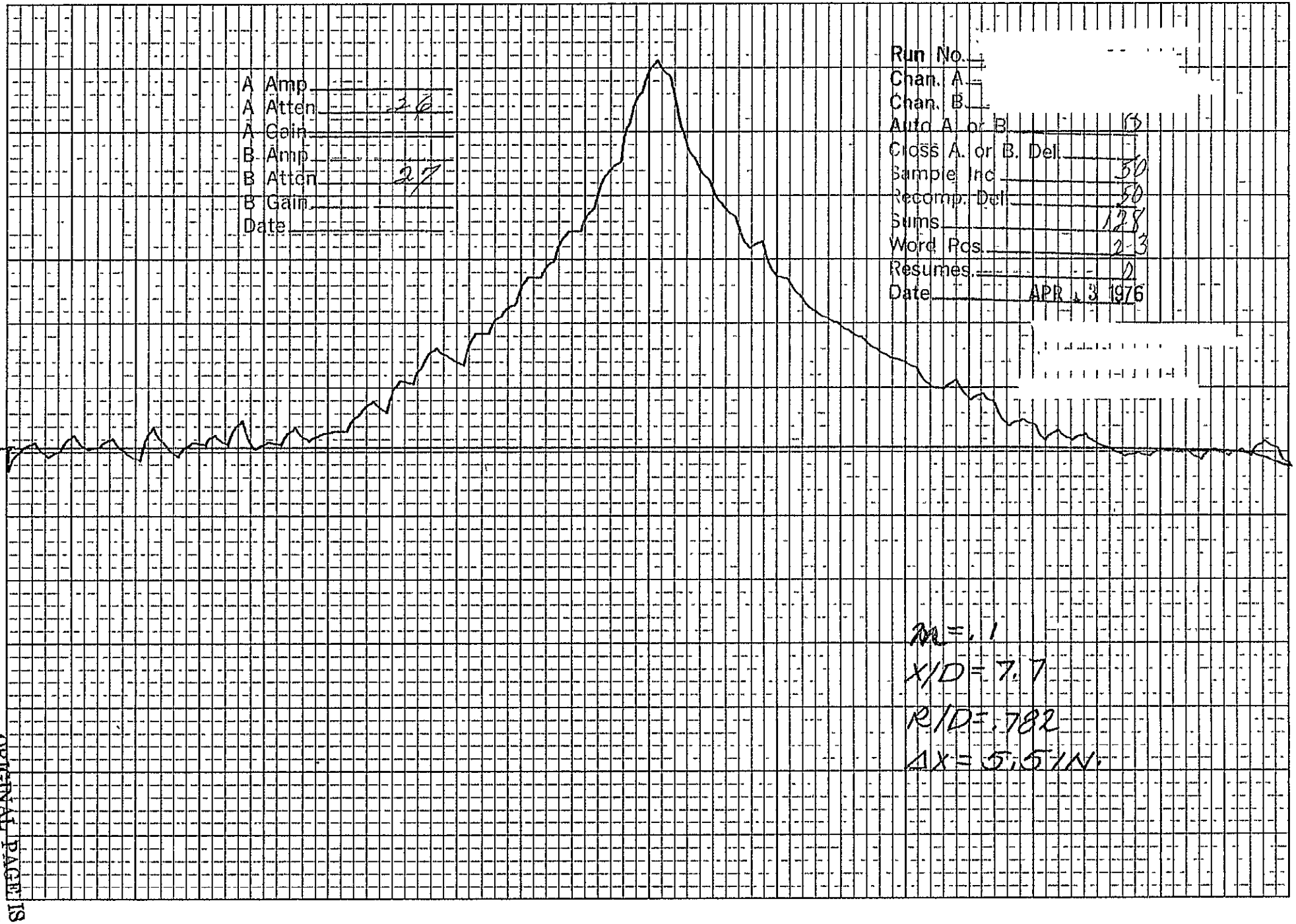

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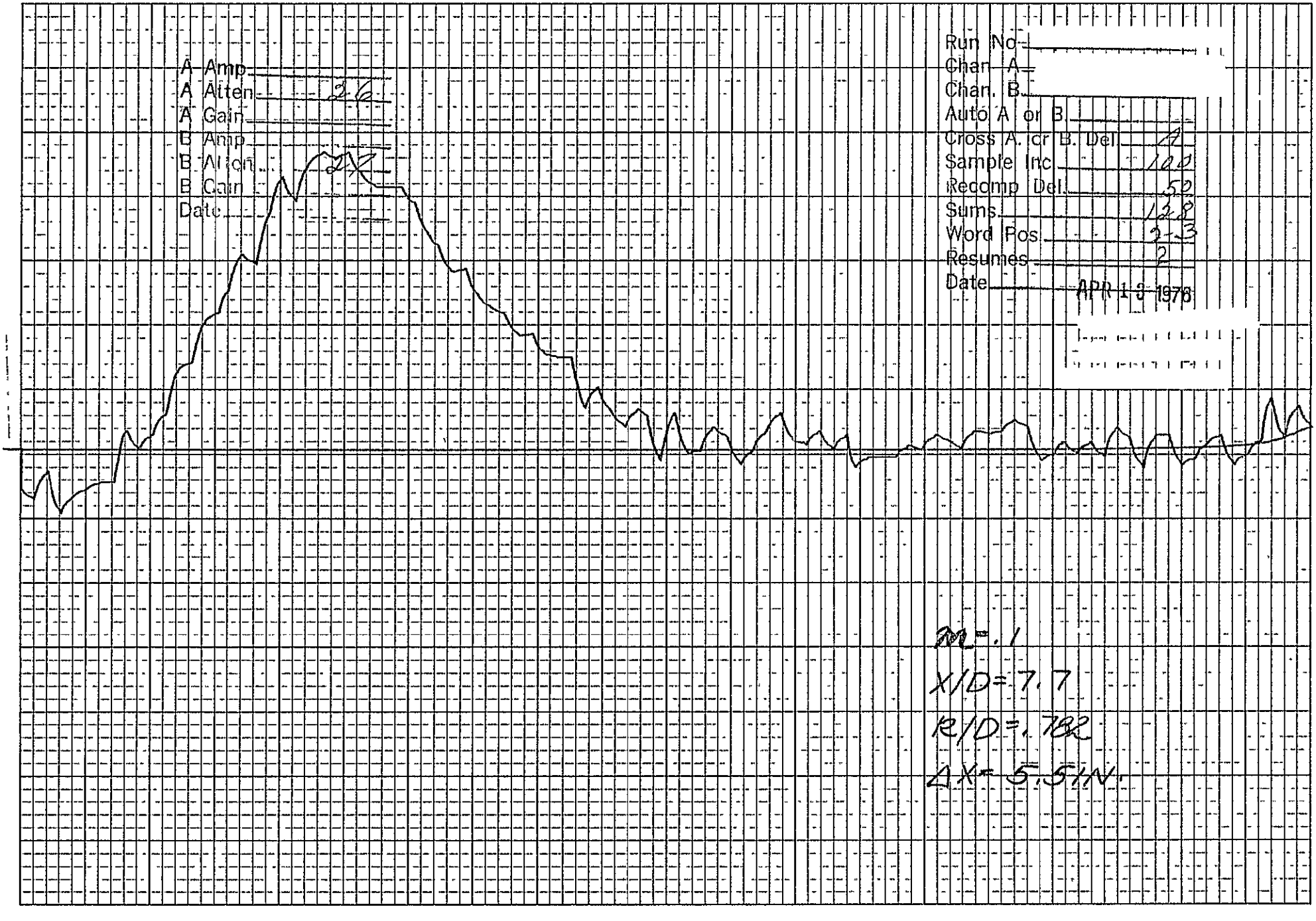

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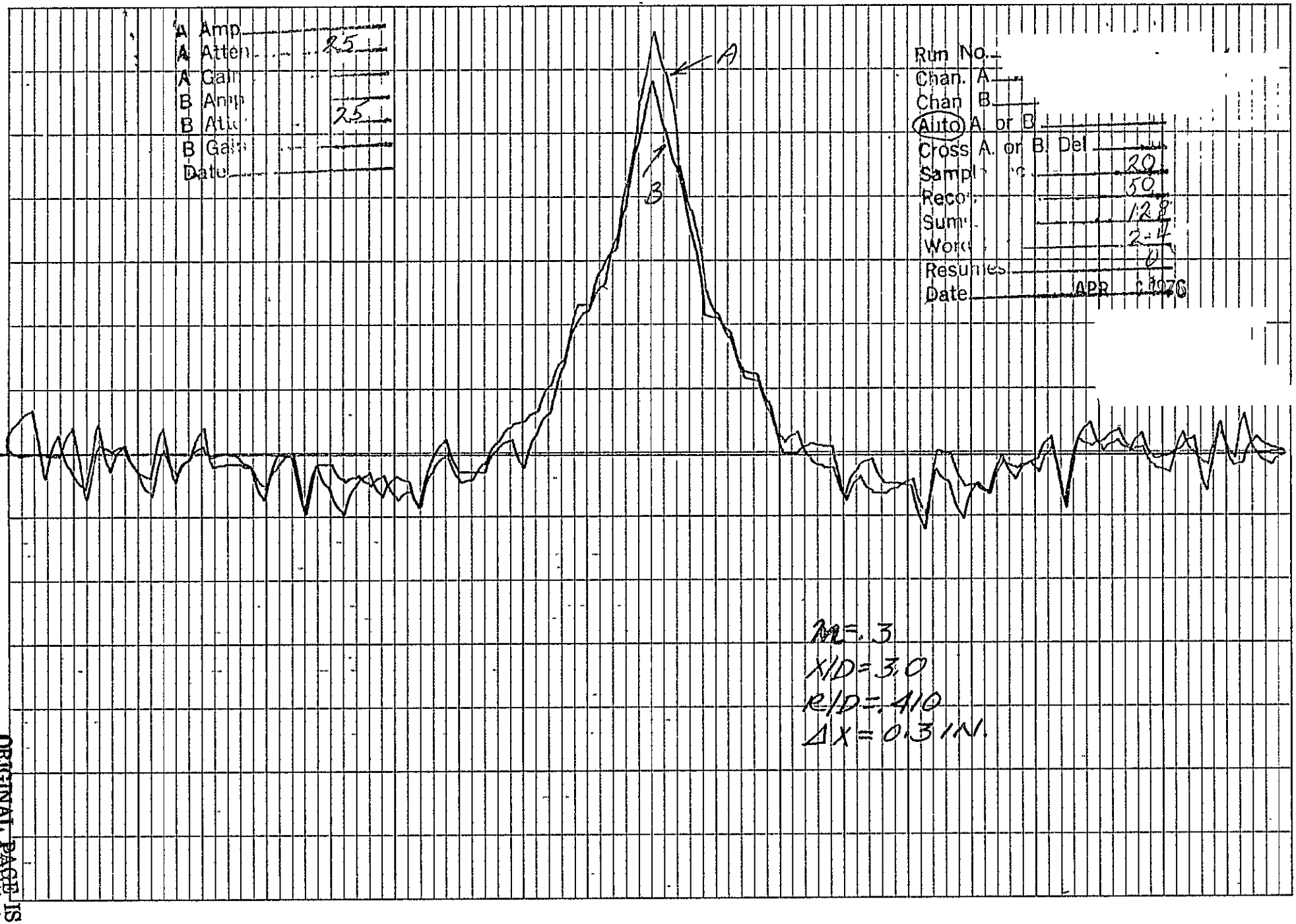

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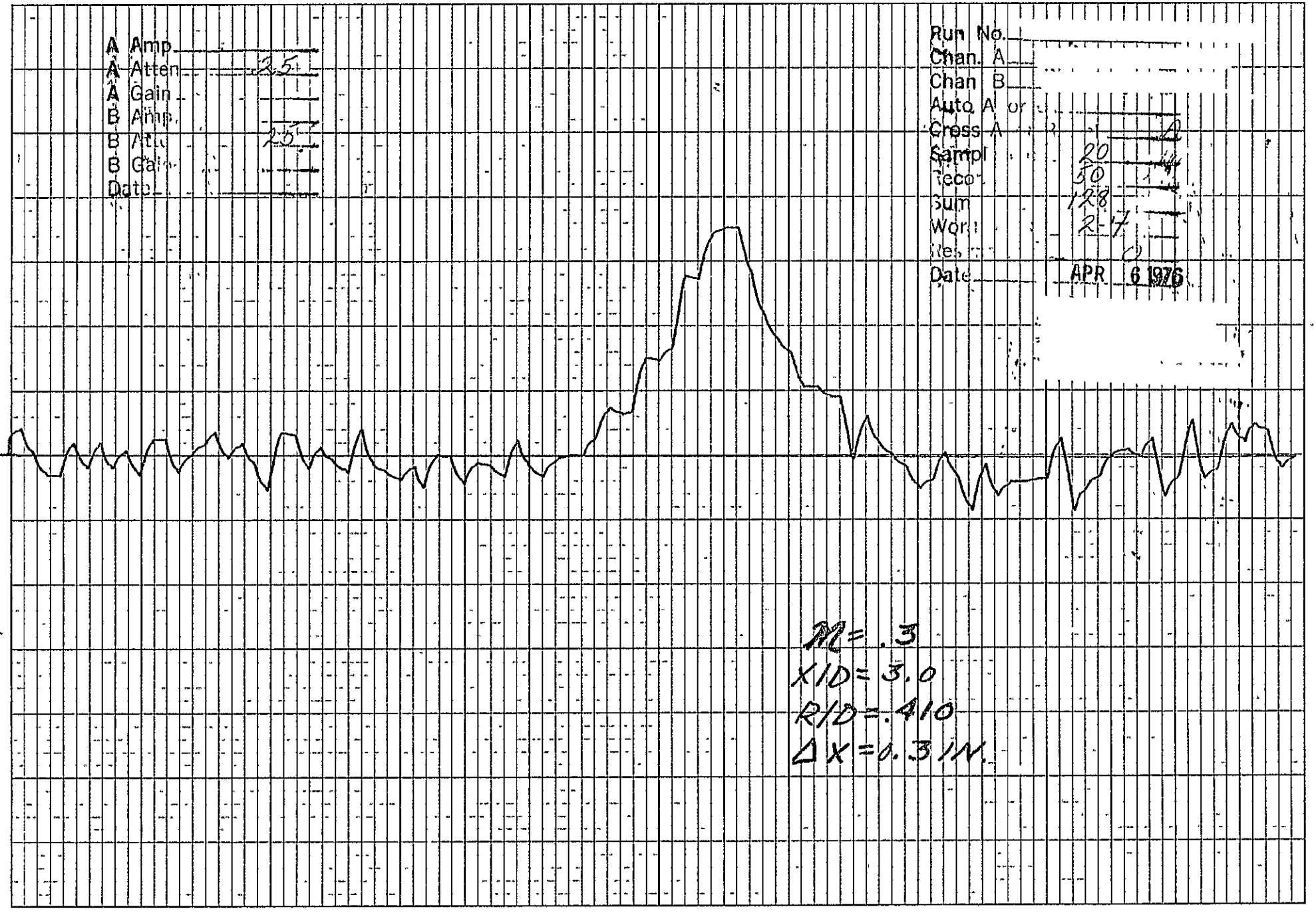

D-93

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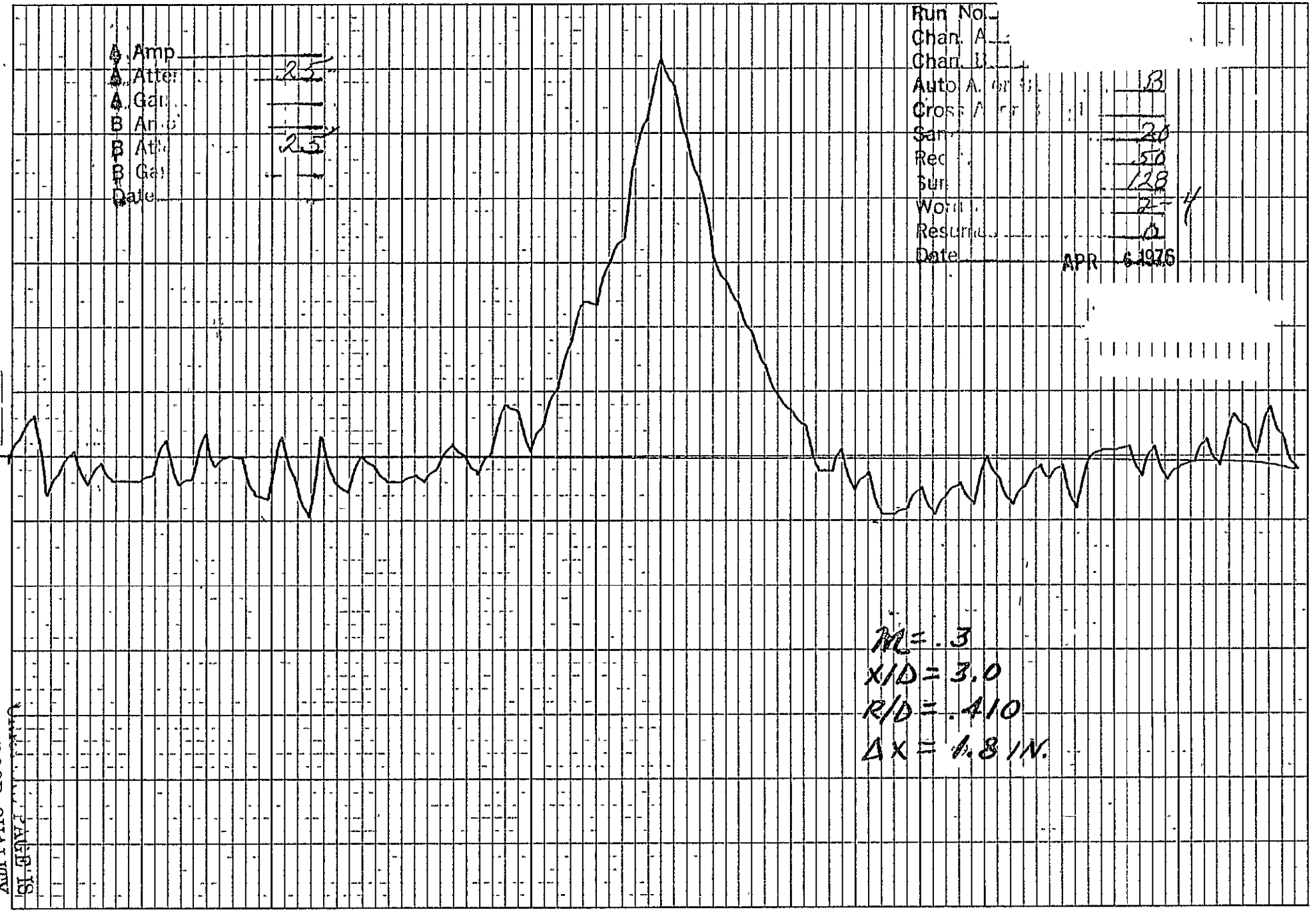

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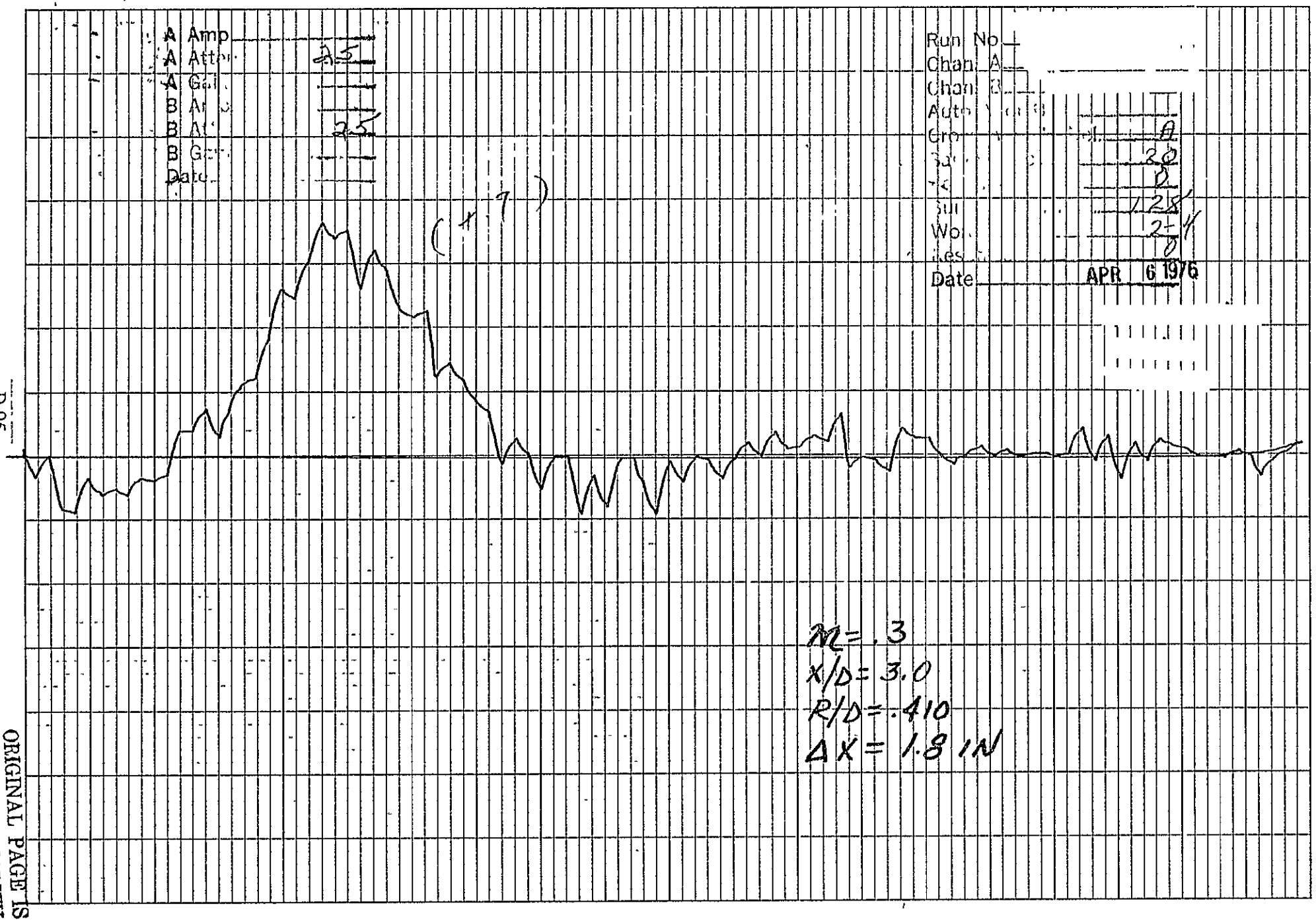

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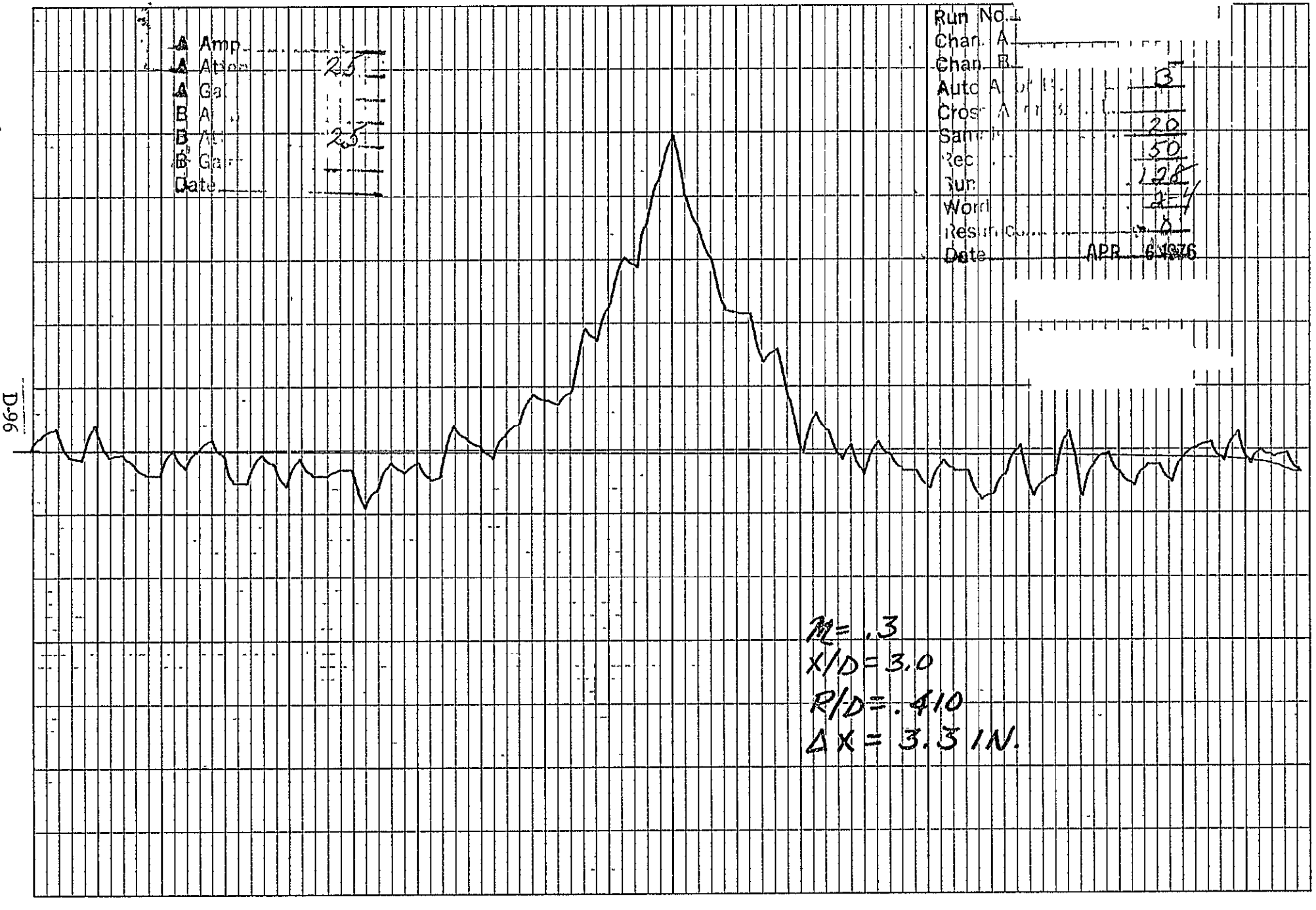

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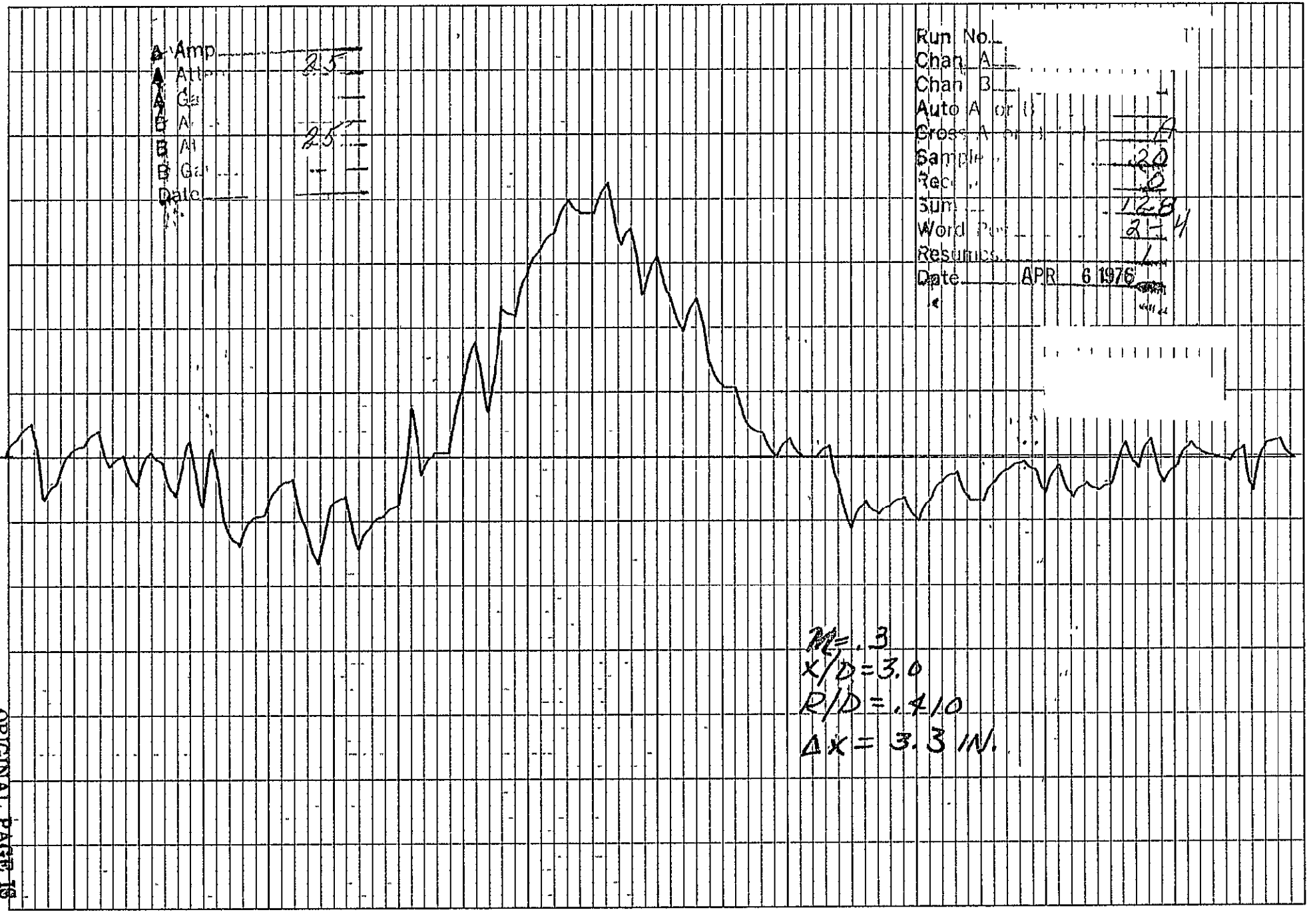

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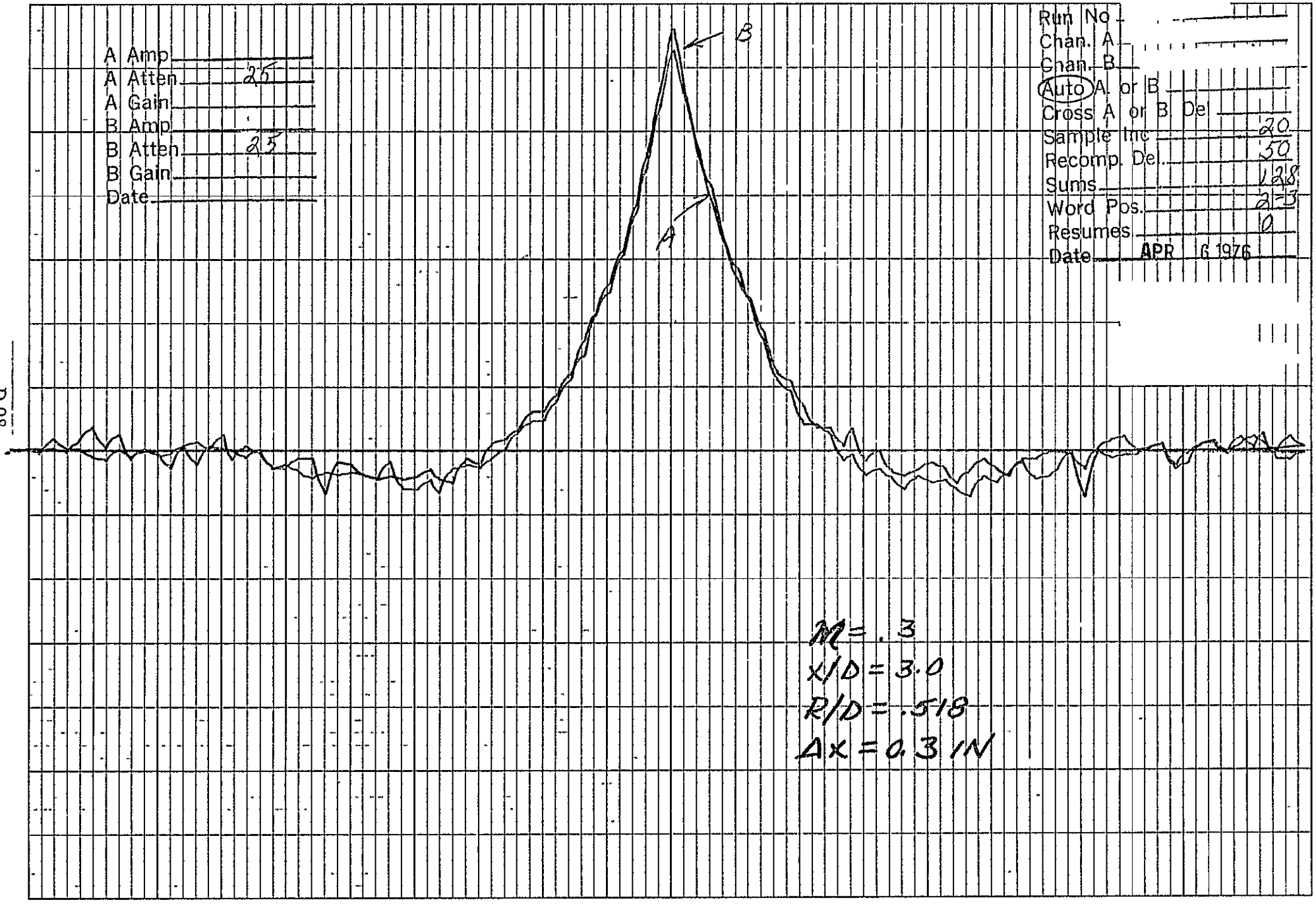

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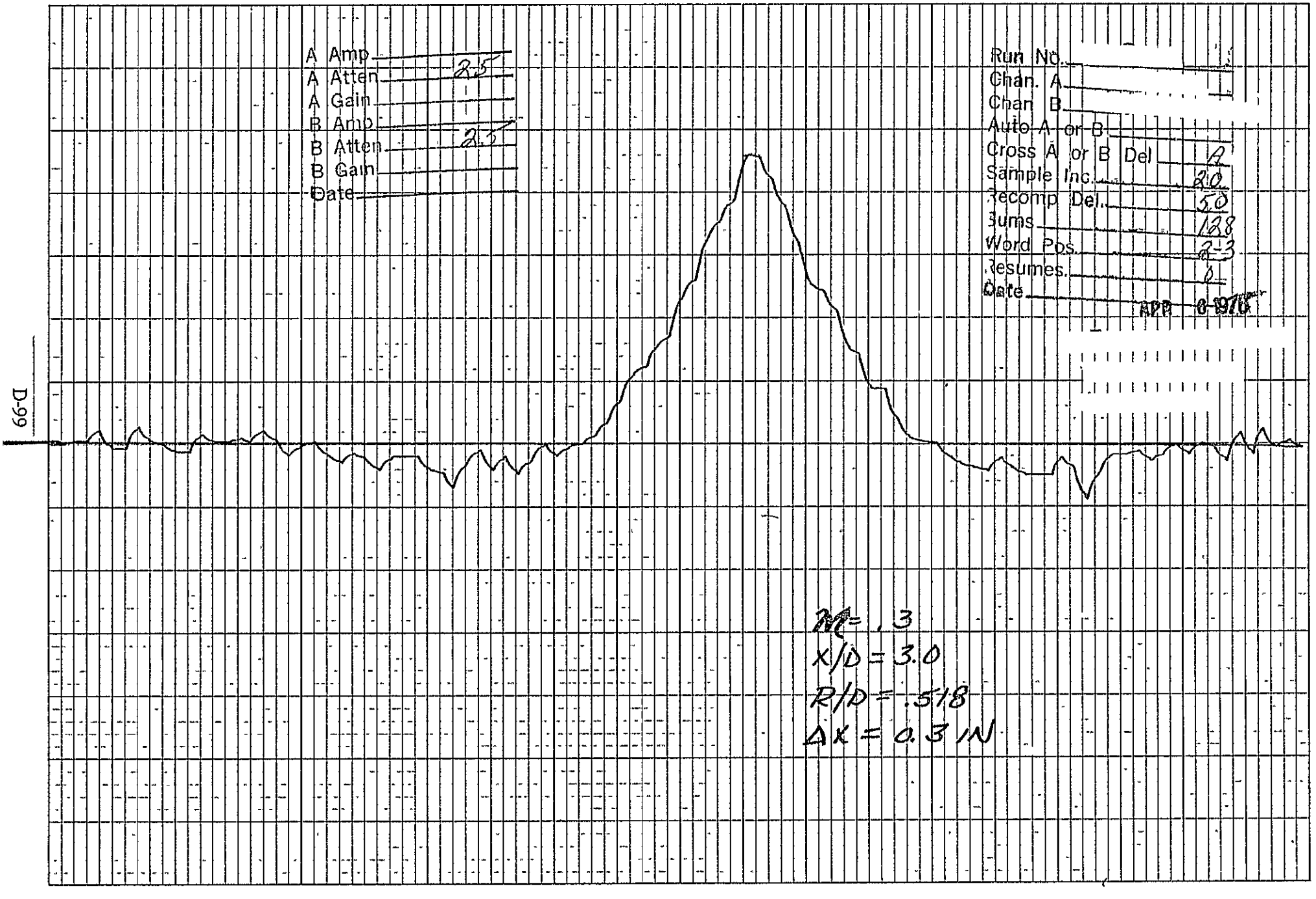
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A Atten 2.5
A Gain
B Amp
B Atten 2.5
B Gain
Date
Run No.
Chan. A
Chan B
Auto A or B
Cross A or B Del A
Sample Inc. 20
Recomp Del. 50
Sums 128
Word Pos. 2-3
Resumes. 0
Date APR 8 1976
D-99
RC = .3
X/D = 3.0
R/D = .518
Δx = 0.3 IN

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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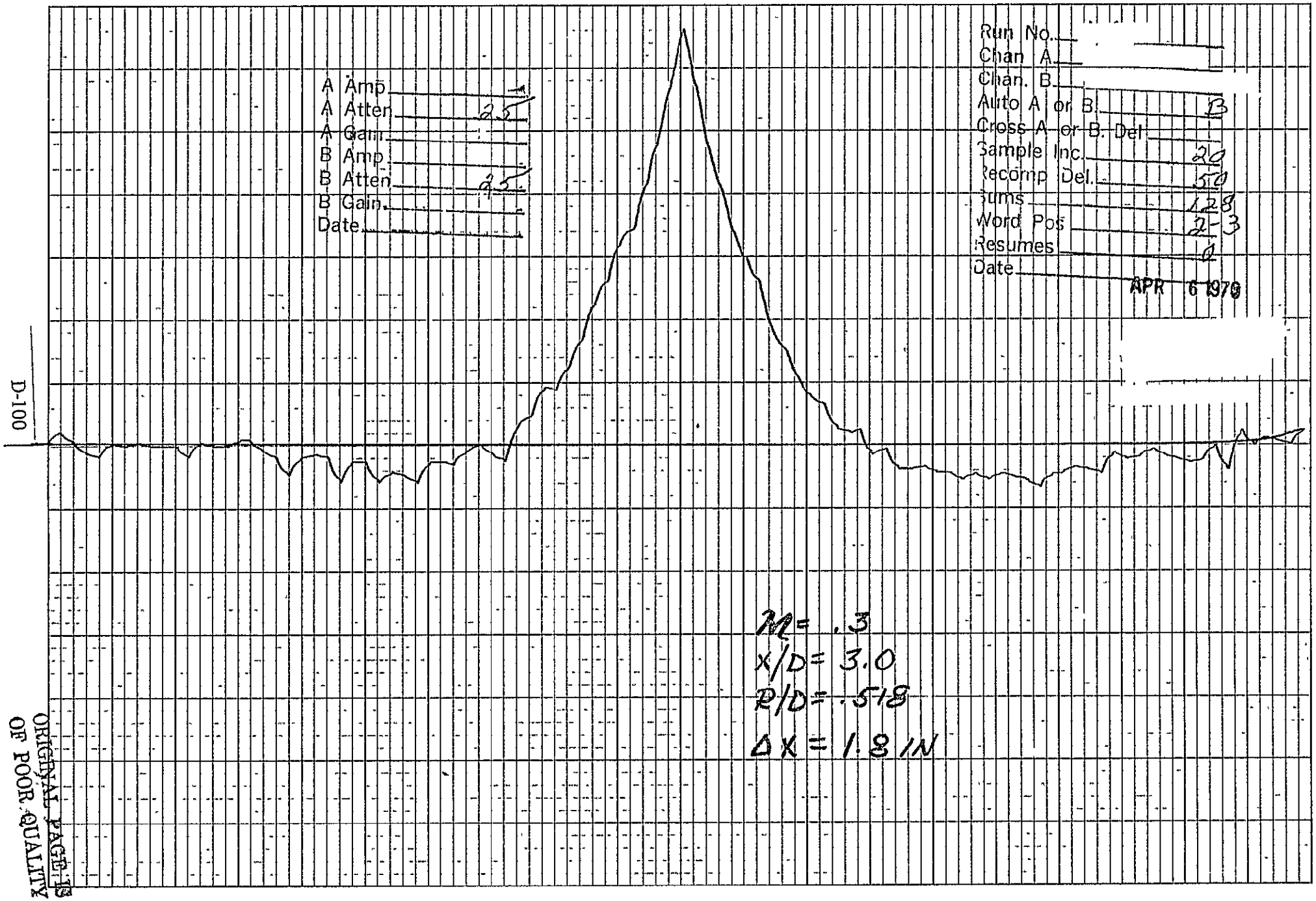
No XY-1001-SP 1



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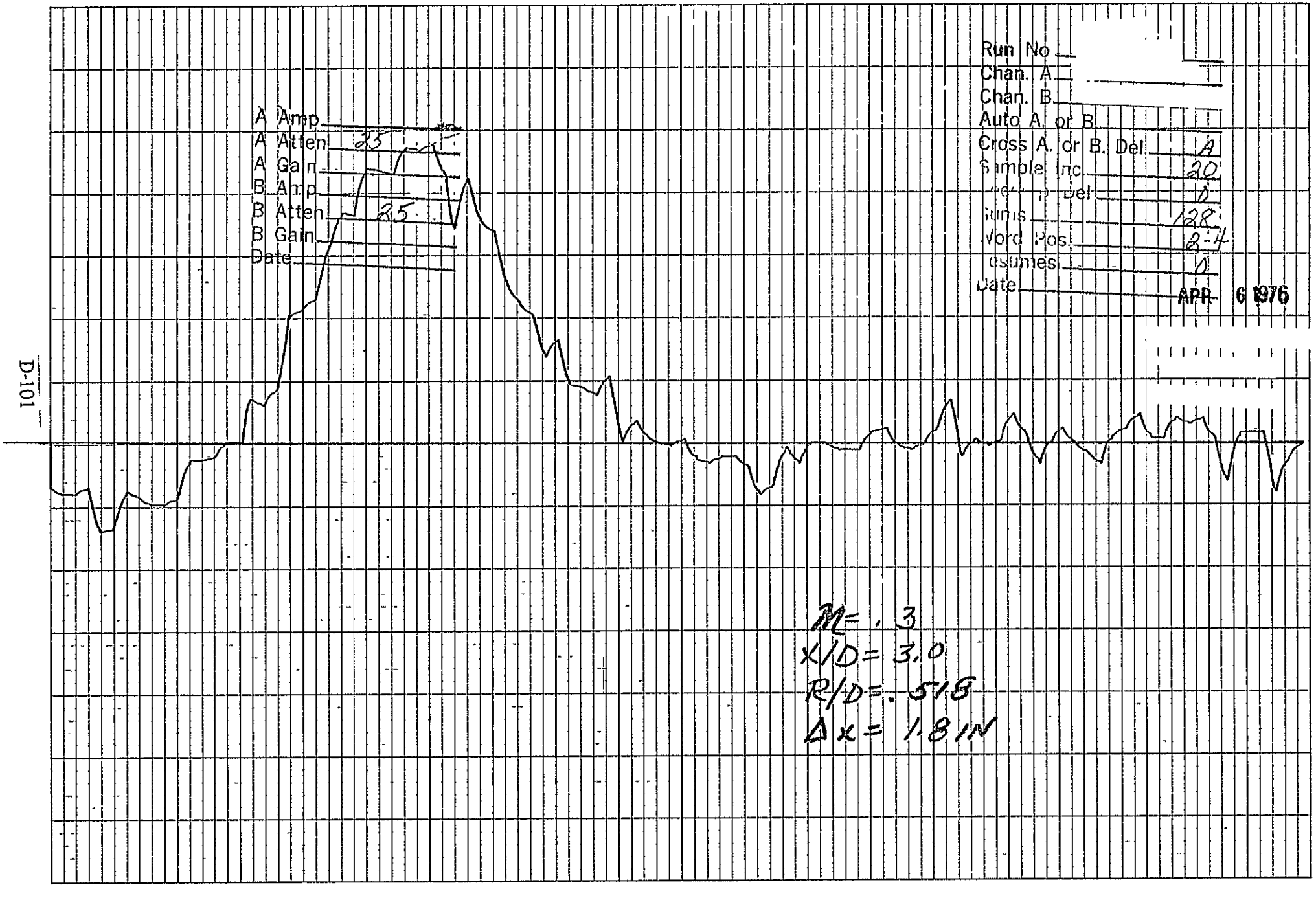
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-1001-SP 1



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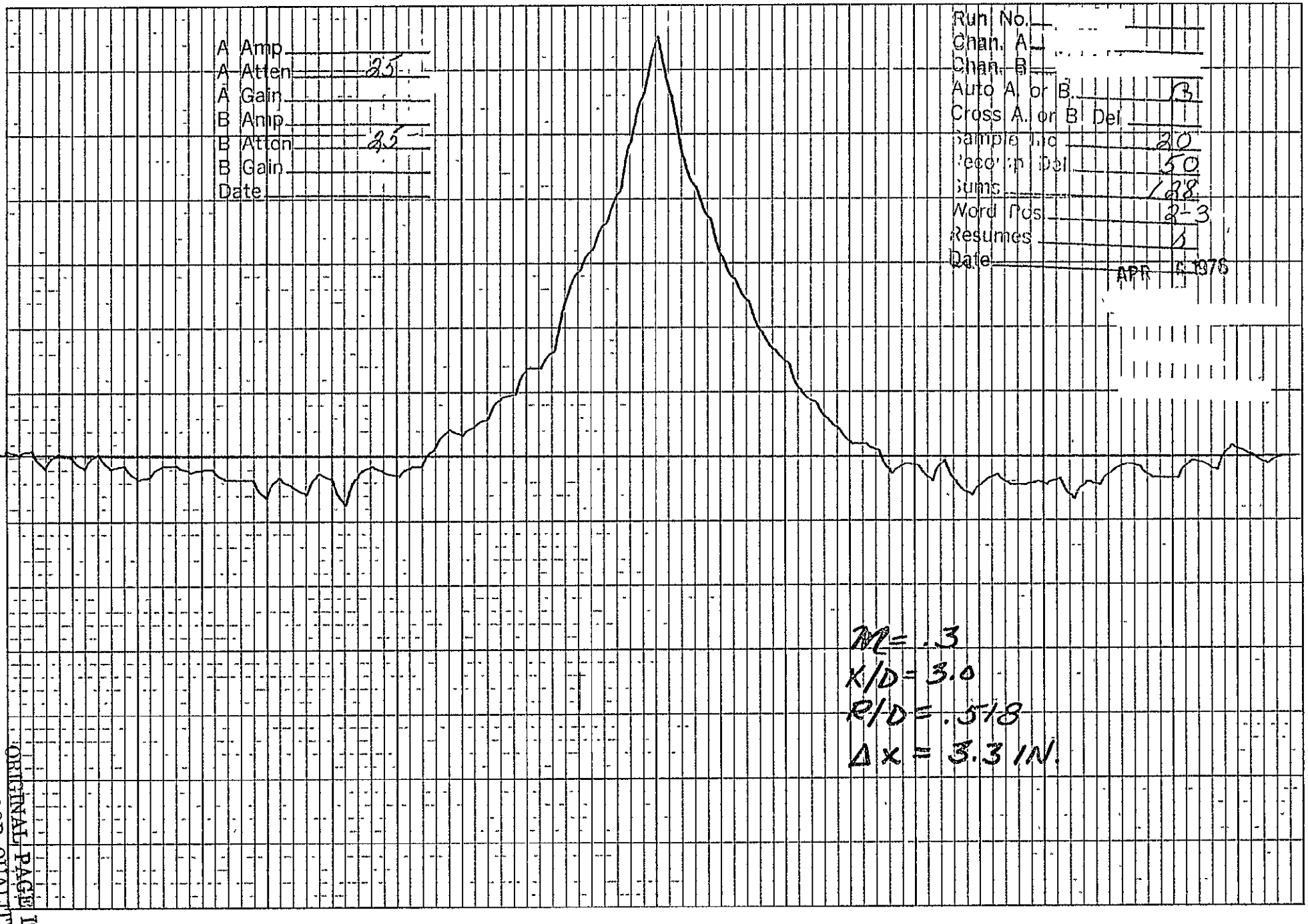

D-102

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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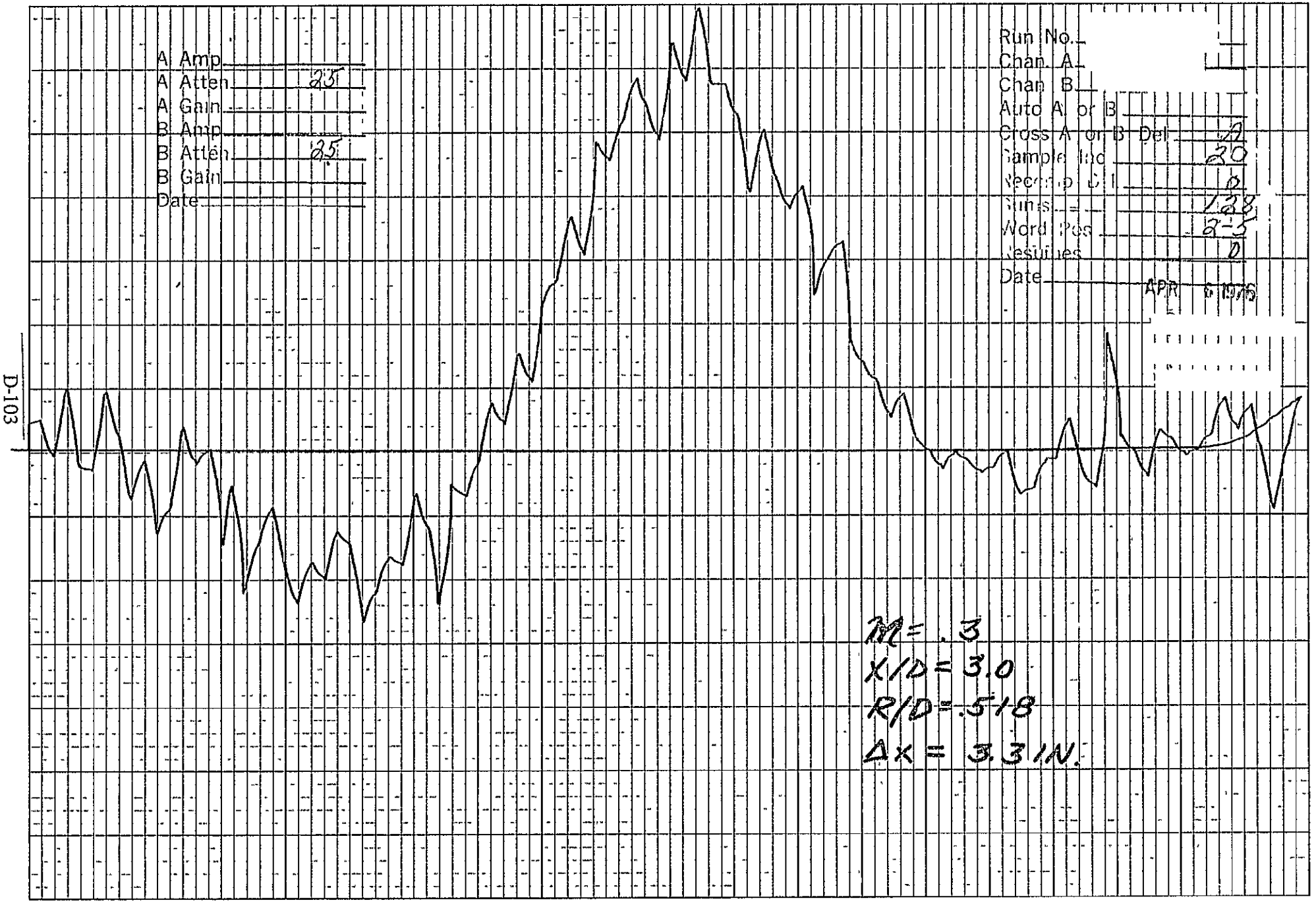
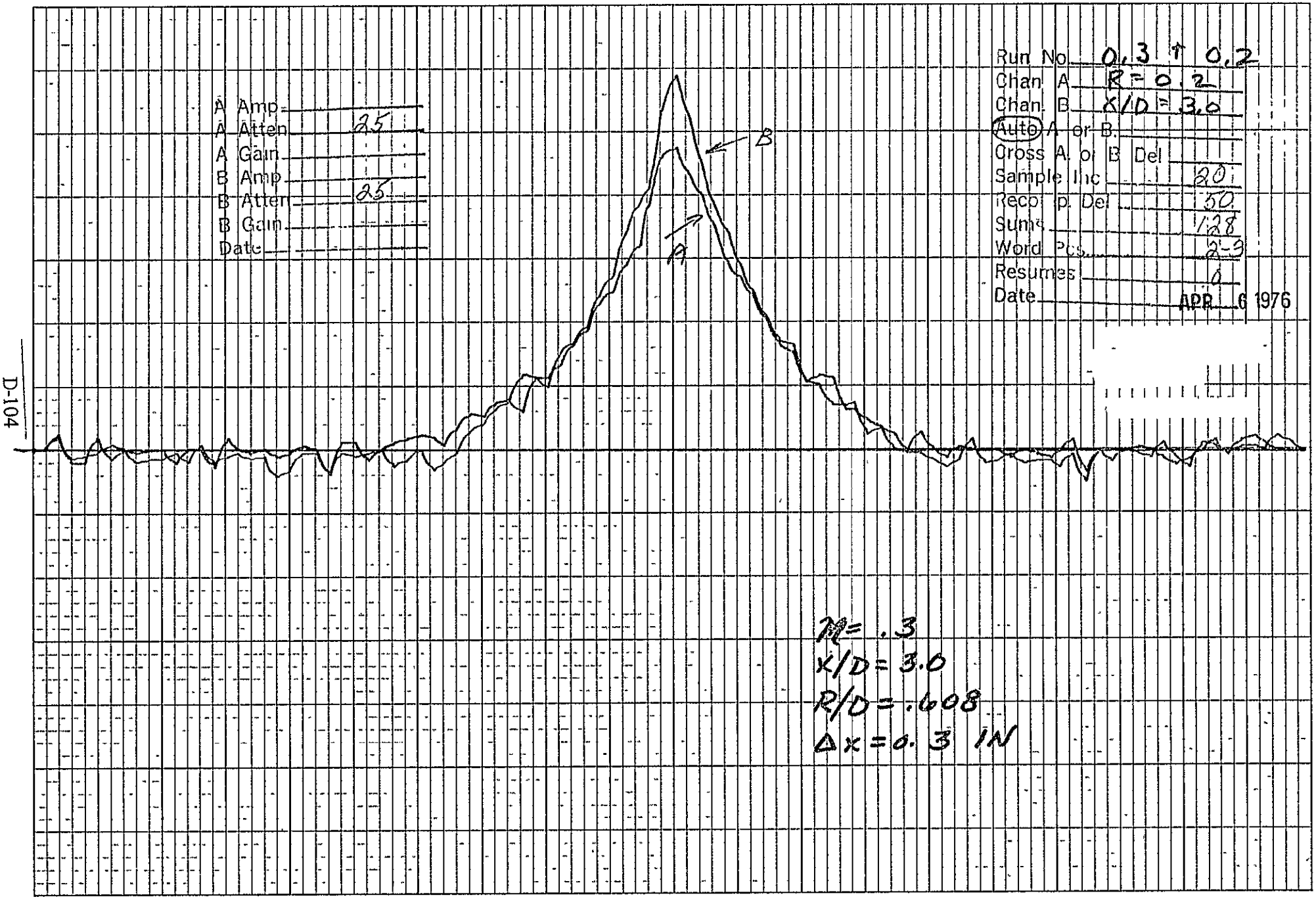
No XY-1001-SP 1



D-103

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-1001-SP 1



D-104

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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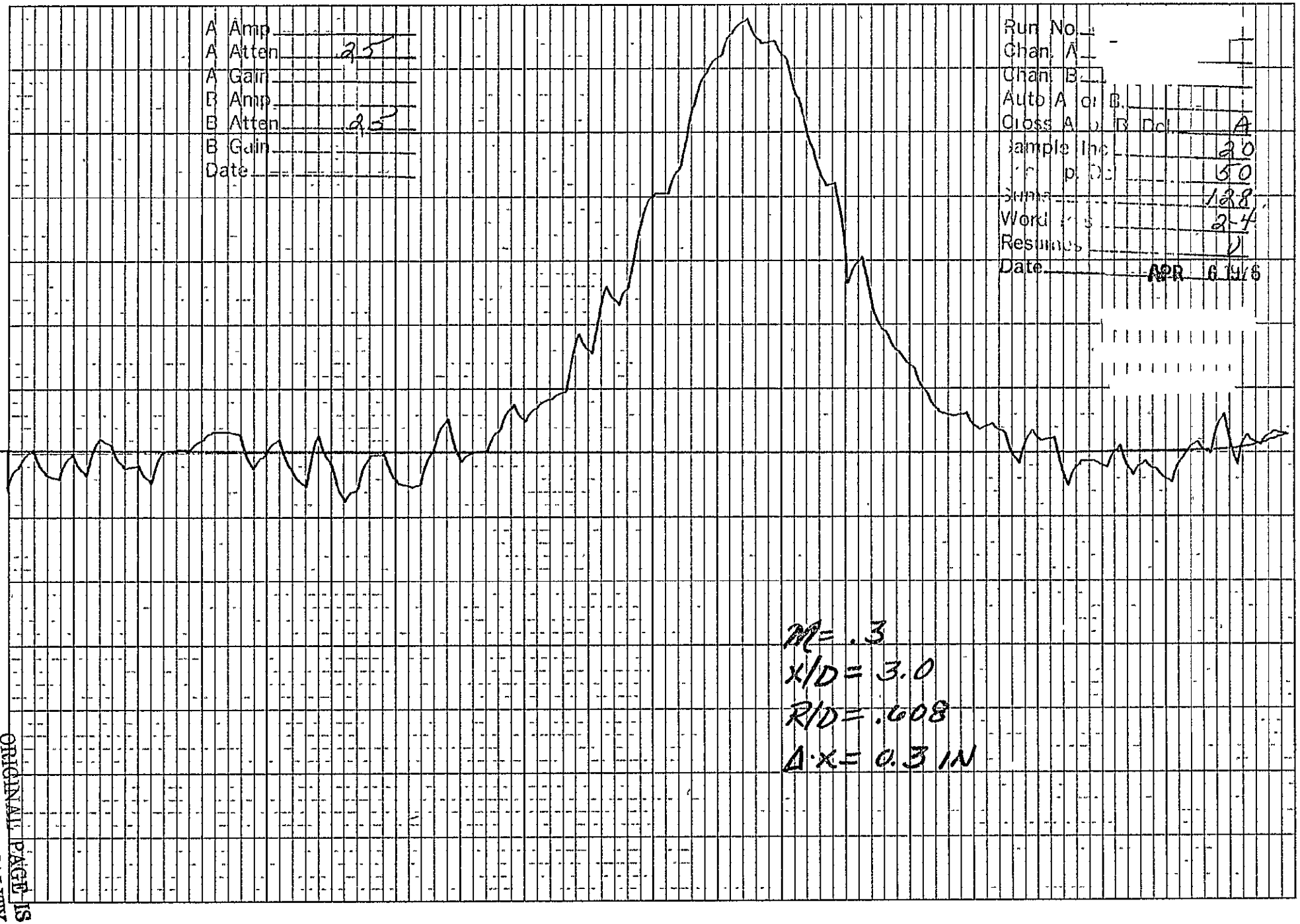
No XY-1001-SP 1



D-105

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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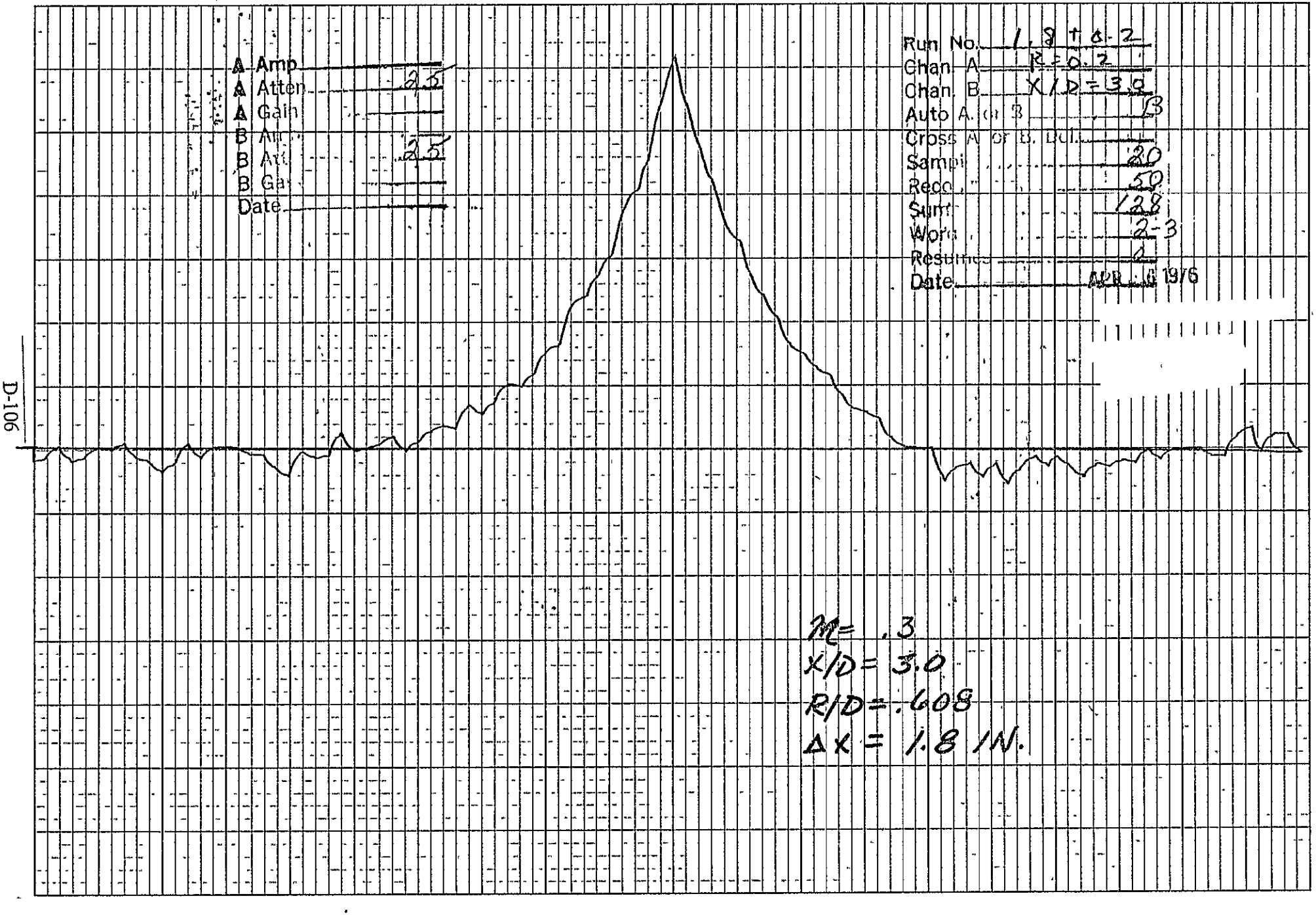

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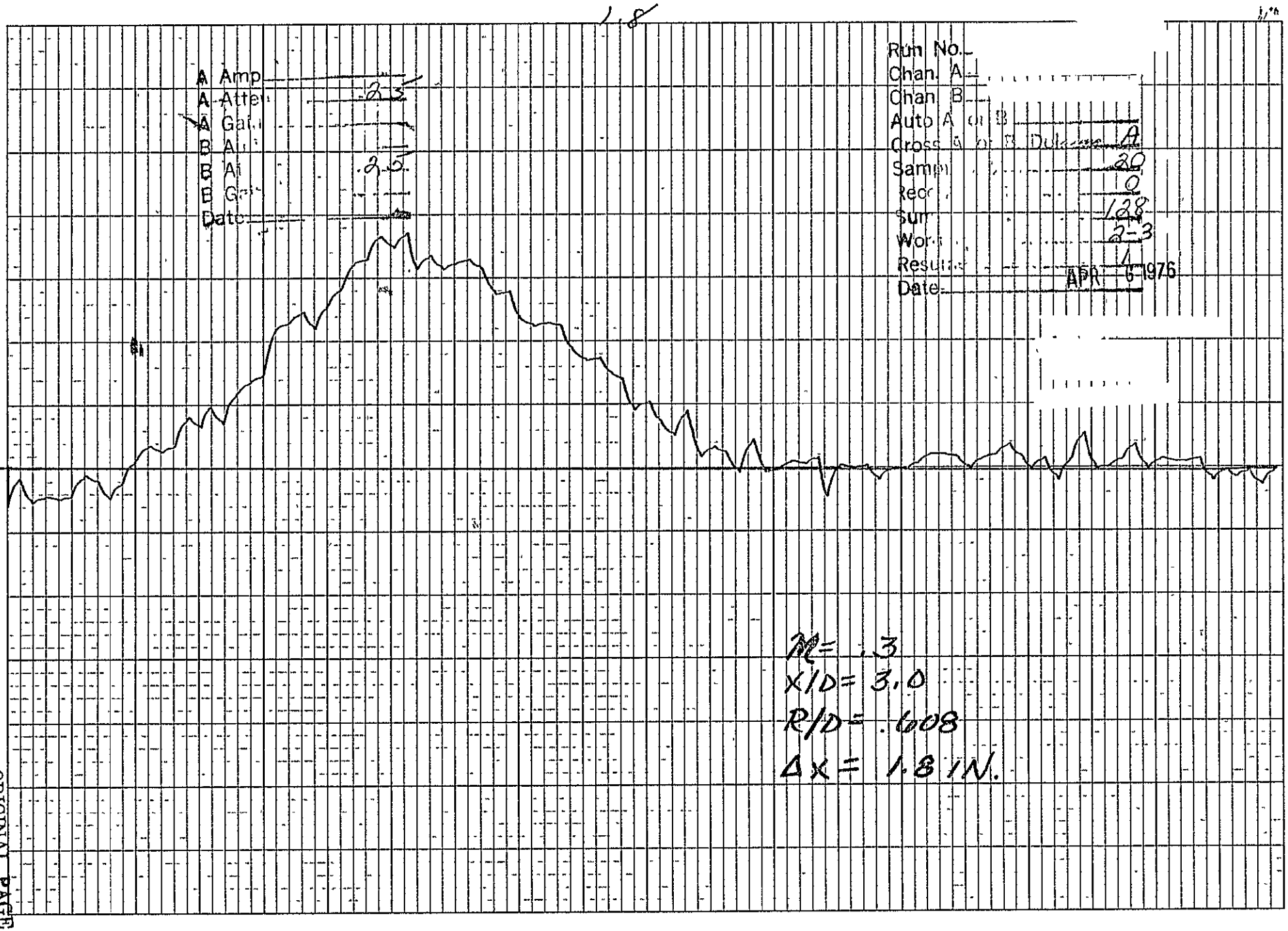

D-107

[redacted] REC[redacted]NG C[redacted]
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BUFFALO NEW YORK
PRINTED IN U.S.A.

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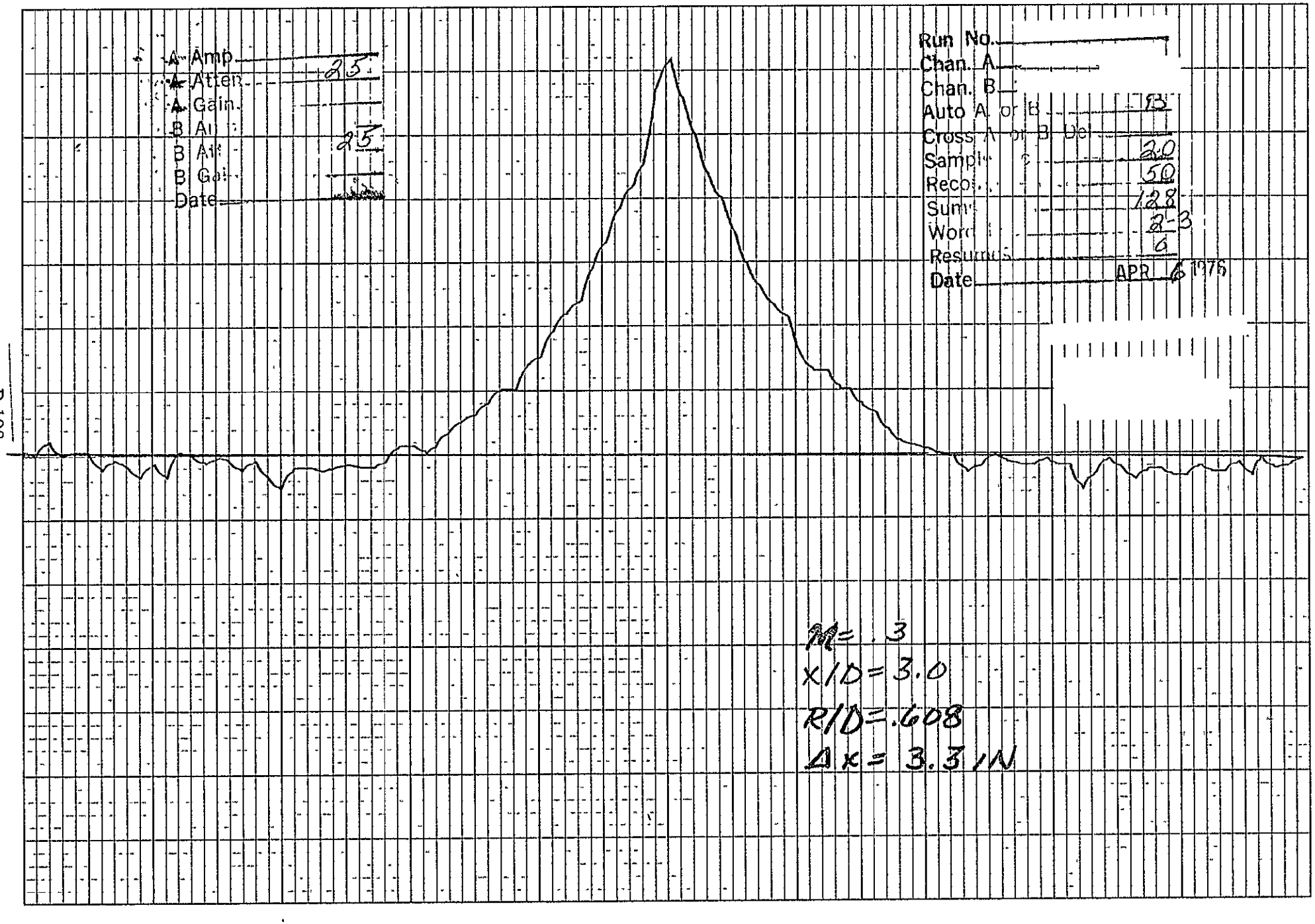
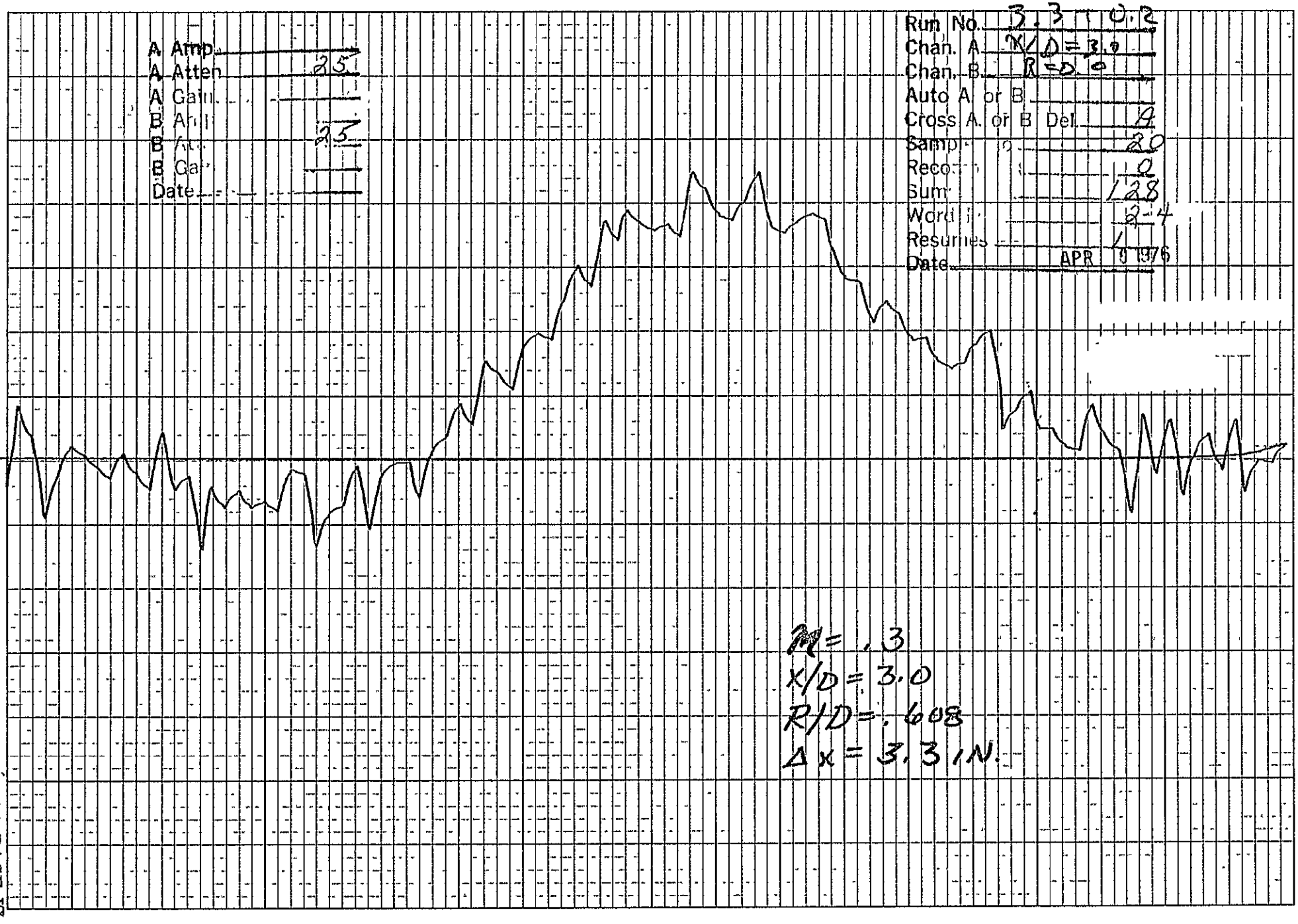


D-108

[redacted] RECORDING [redacted]

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.

[redacted] No XY-1001- SP 1 [redacted]



D-109

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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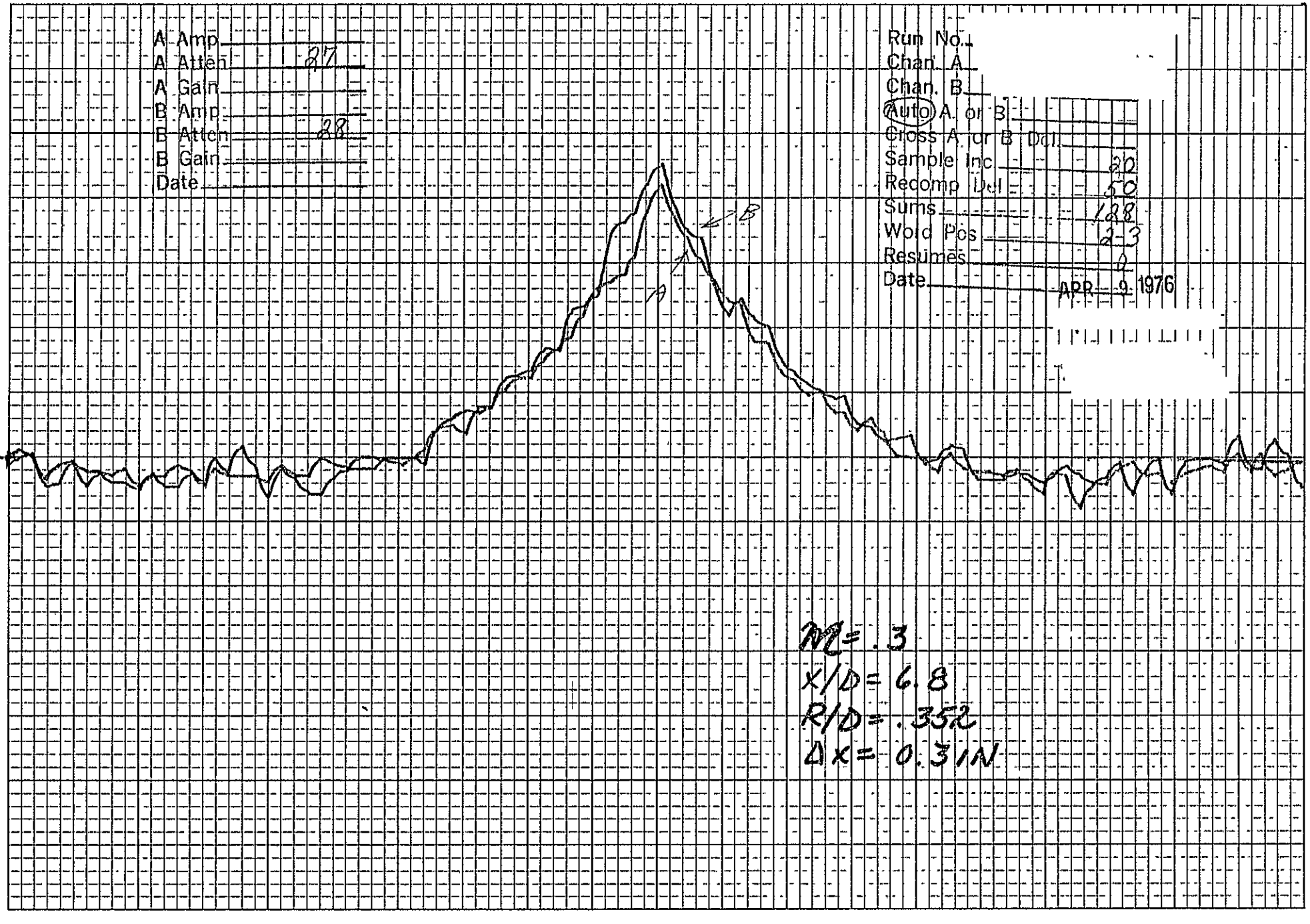
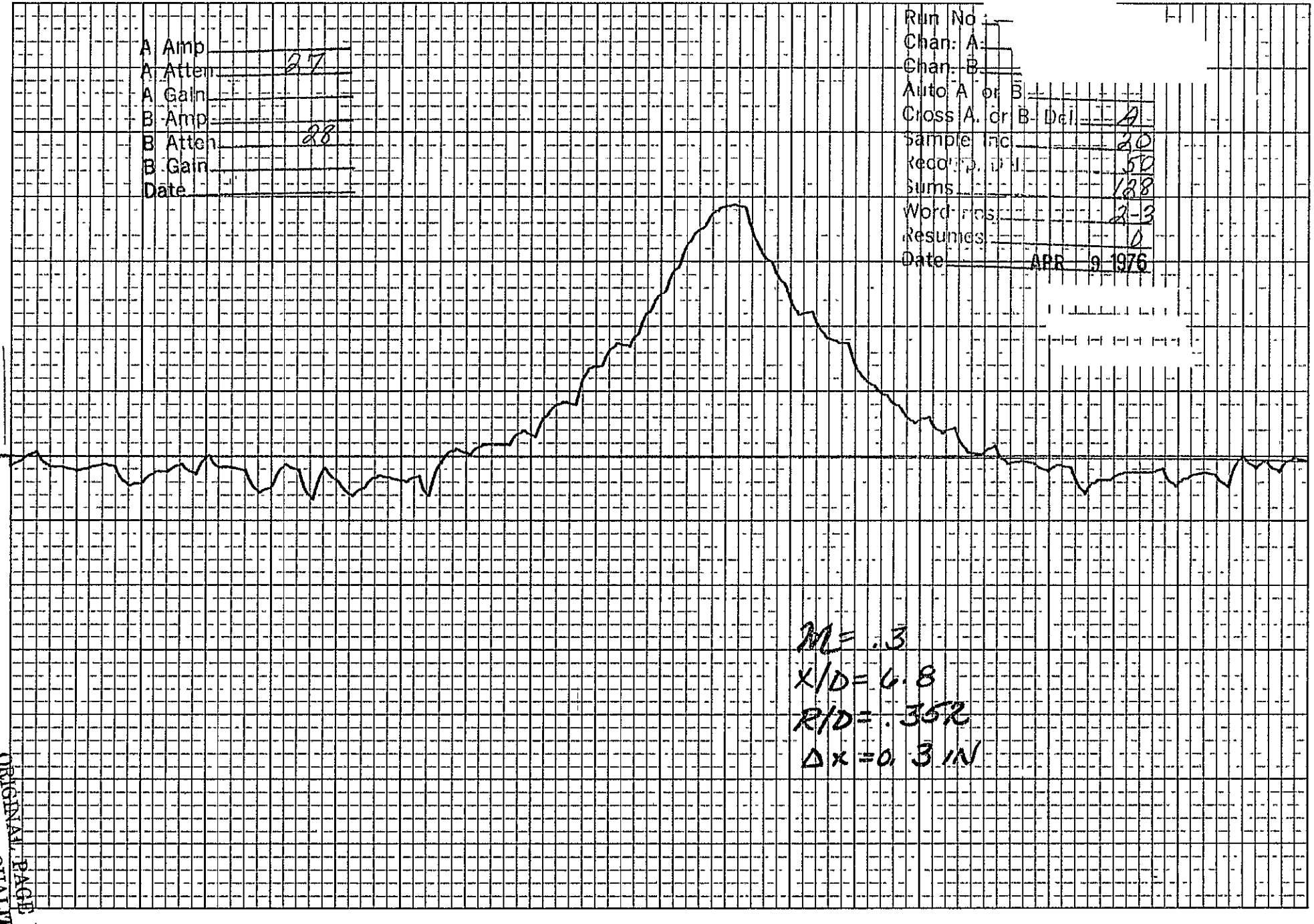
No XY-1001-SP 1



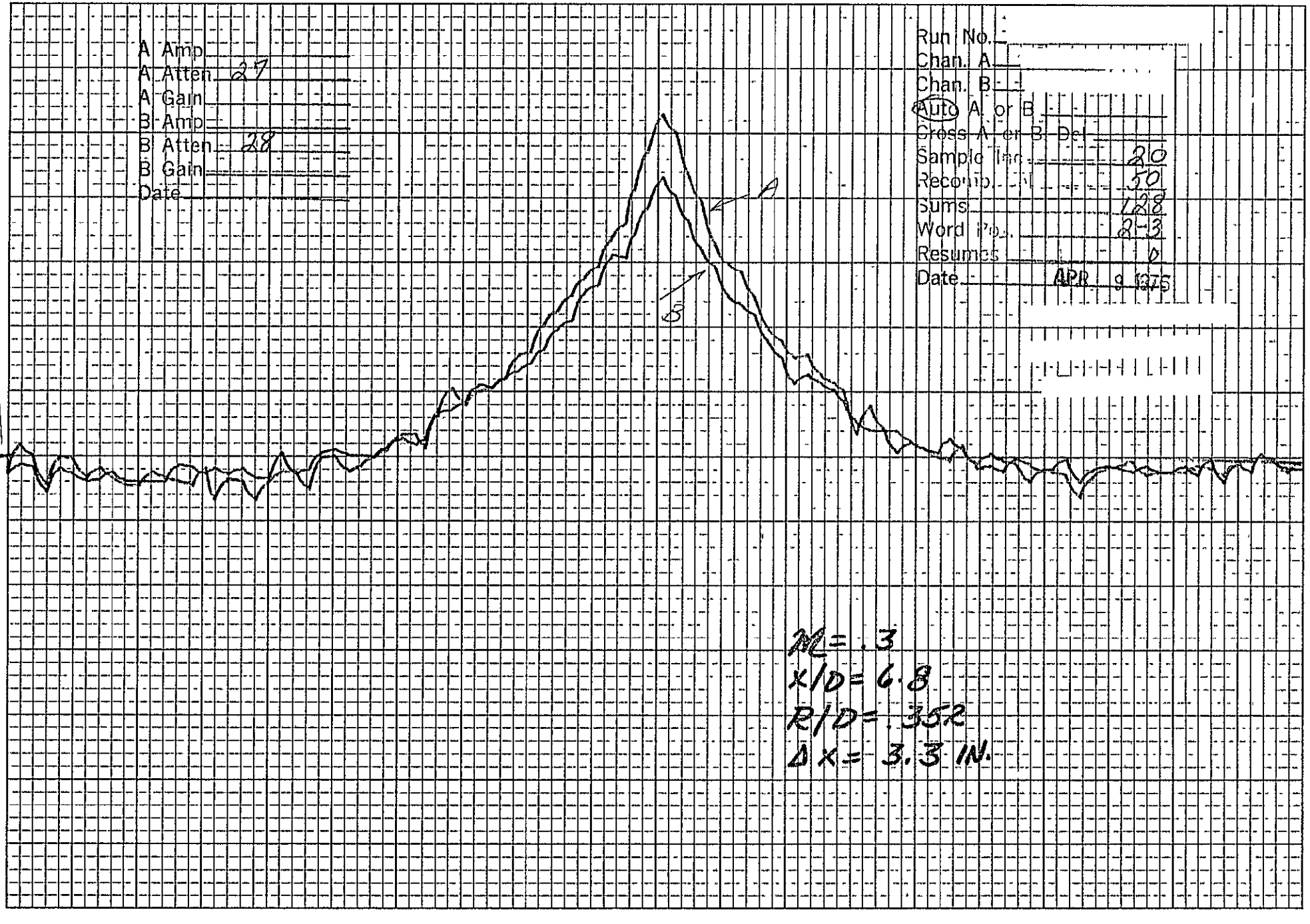
D-110

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-1001-SP 1



D-111


A Amp
A Atten 27
A Gain
B Amp
B Atten 28
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A or B
Cross A or B Del
Sample Inc 20
Recomp 50
Sums 128
Word Pos. 2-13
Resumes 0
Date APR 9 1975
M = .3
X/D = 6.8
R/D = .352
Δx = 3.3 IN.

RECORDING CHARTS
GRAPHIC CONTROLS CORPORATION
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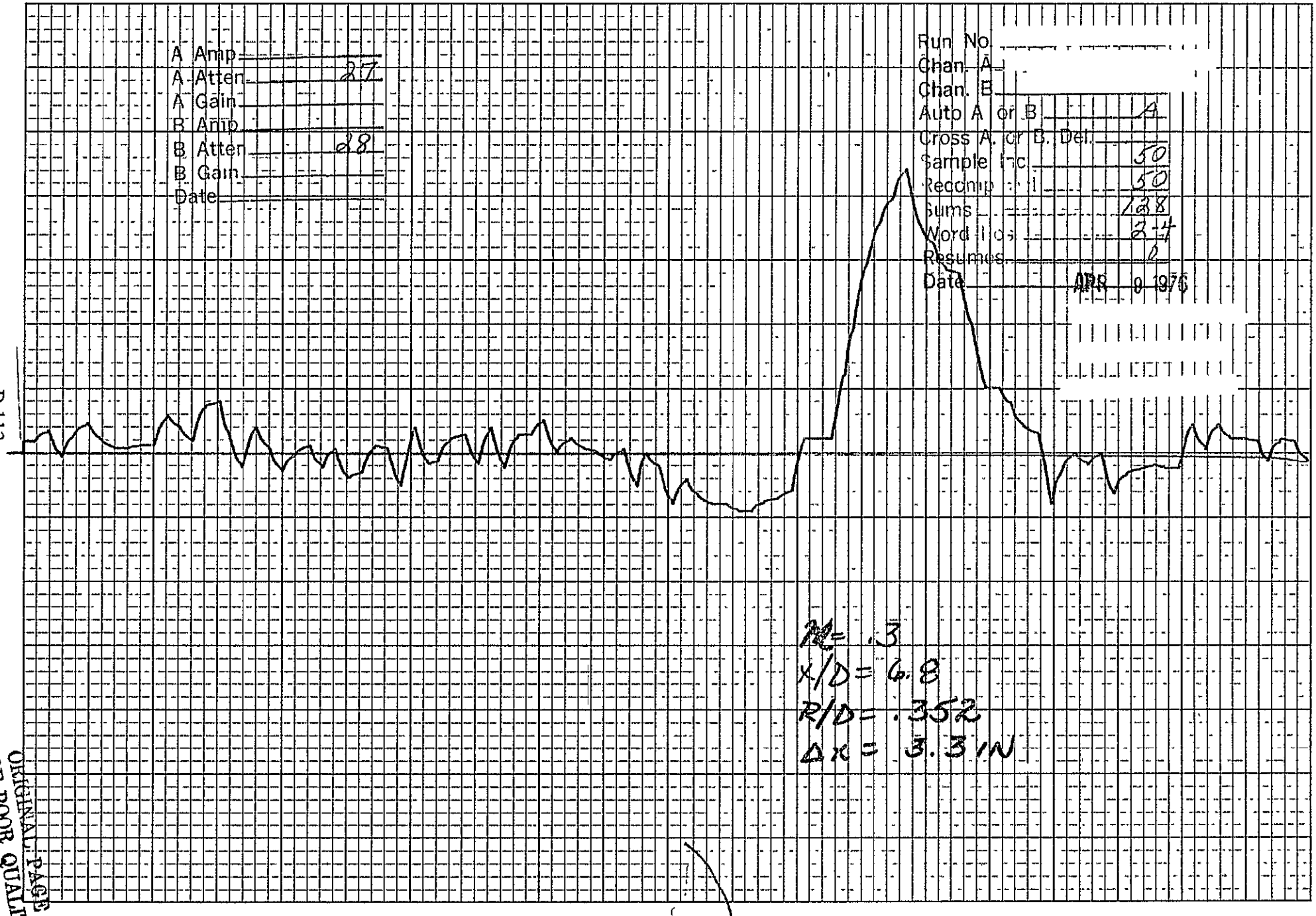
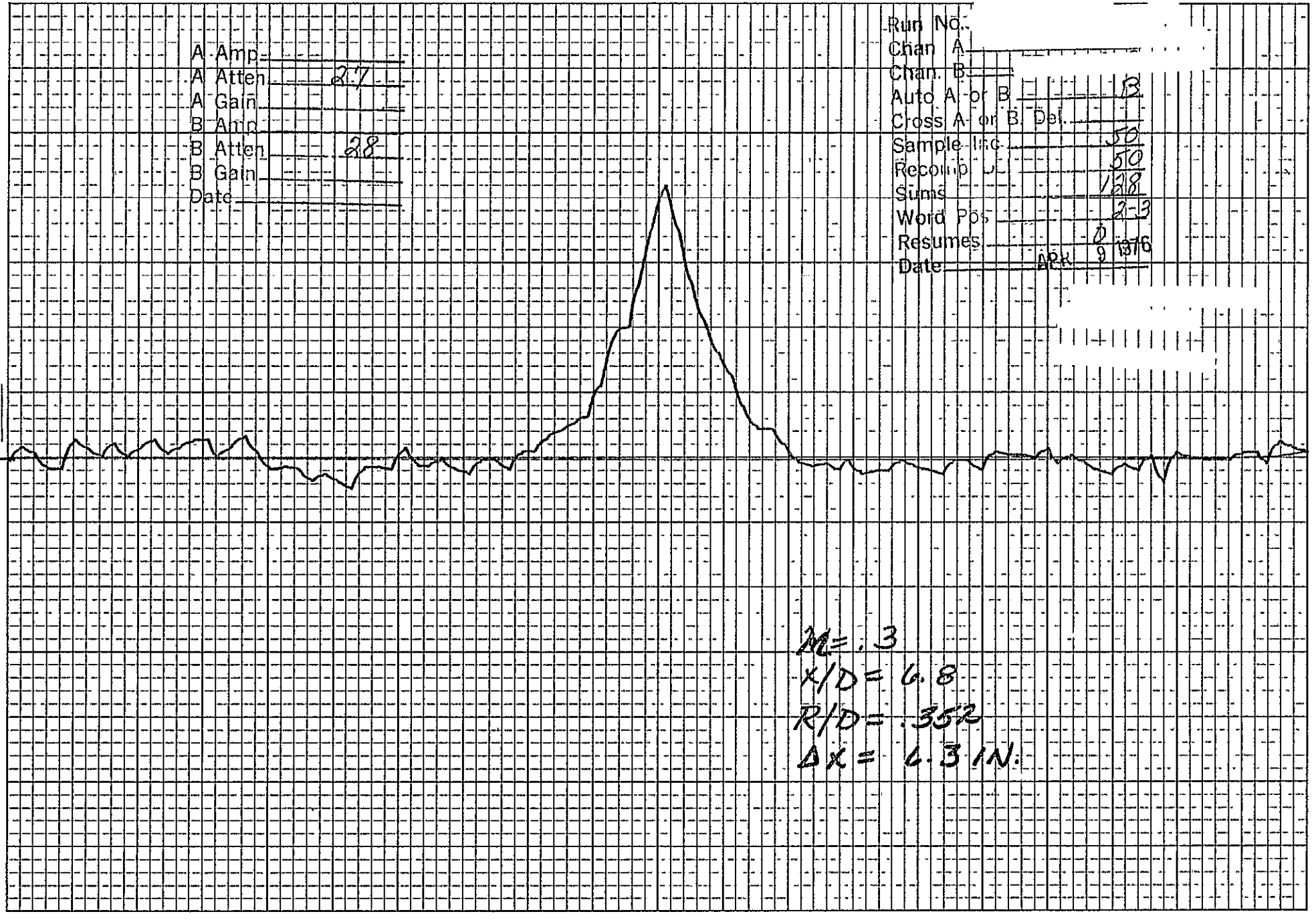
No XY-1001-SP 1



D-113


A Amp
A Atten 27
A Gain
B Amp
B Atten 28
B Gain
Date
Run No.
Chan A
Chan. B
Auto A or B B
Cross A or B Del.
Sample Inc 50
Recomp 50
Sums 128
Word Pos 2-3
Resumes 0
Date APR 9 1976
M= .3
X/D= 6.8
R/D= .352
ΔX= 4.3 IN.

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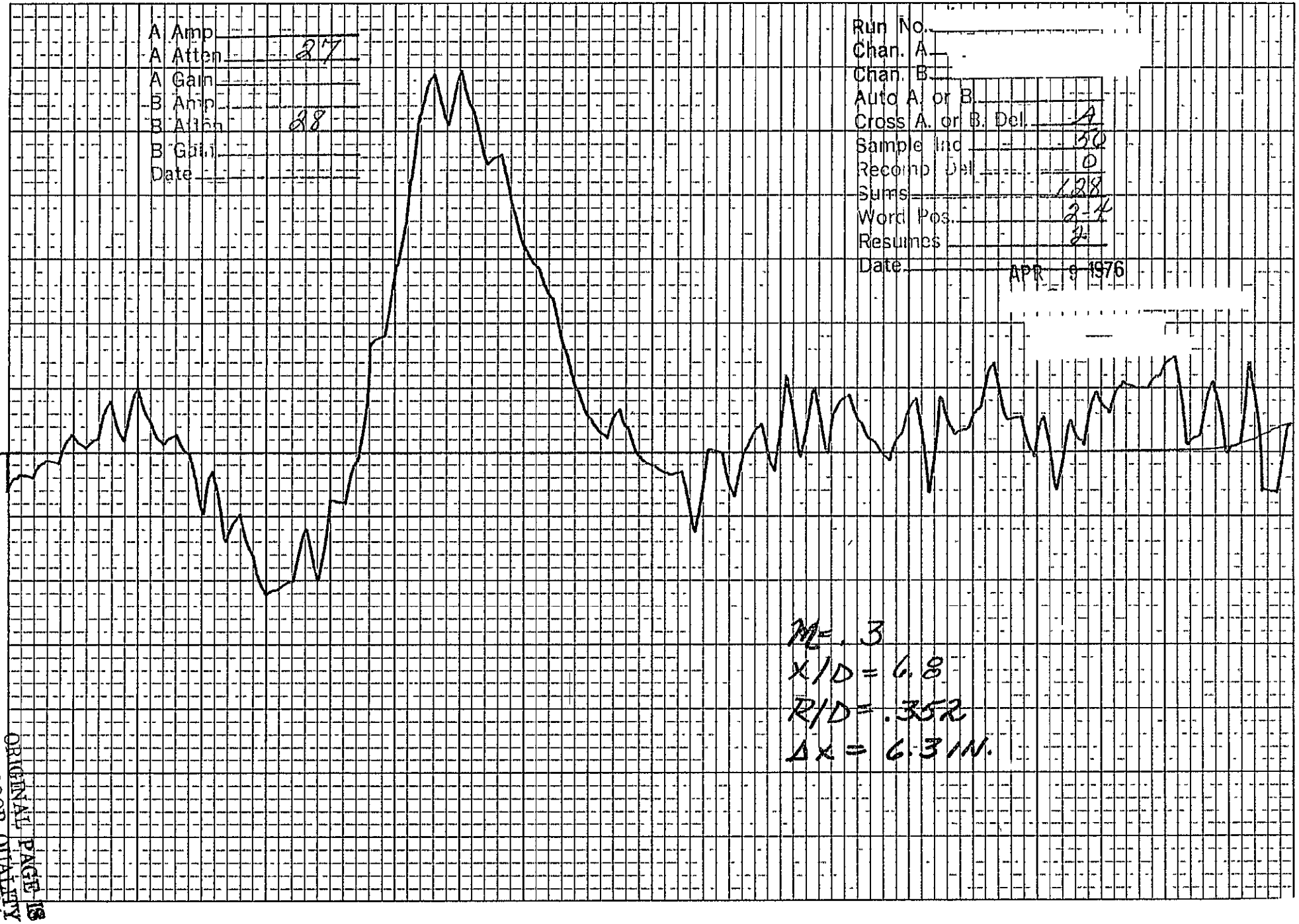
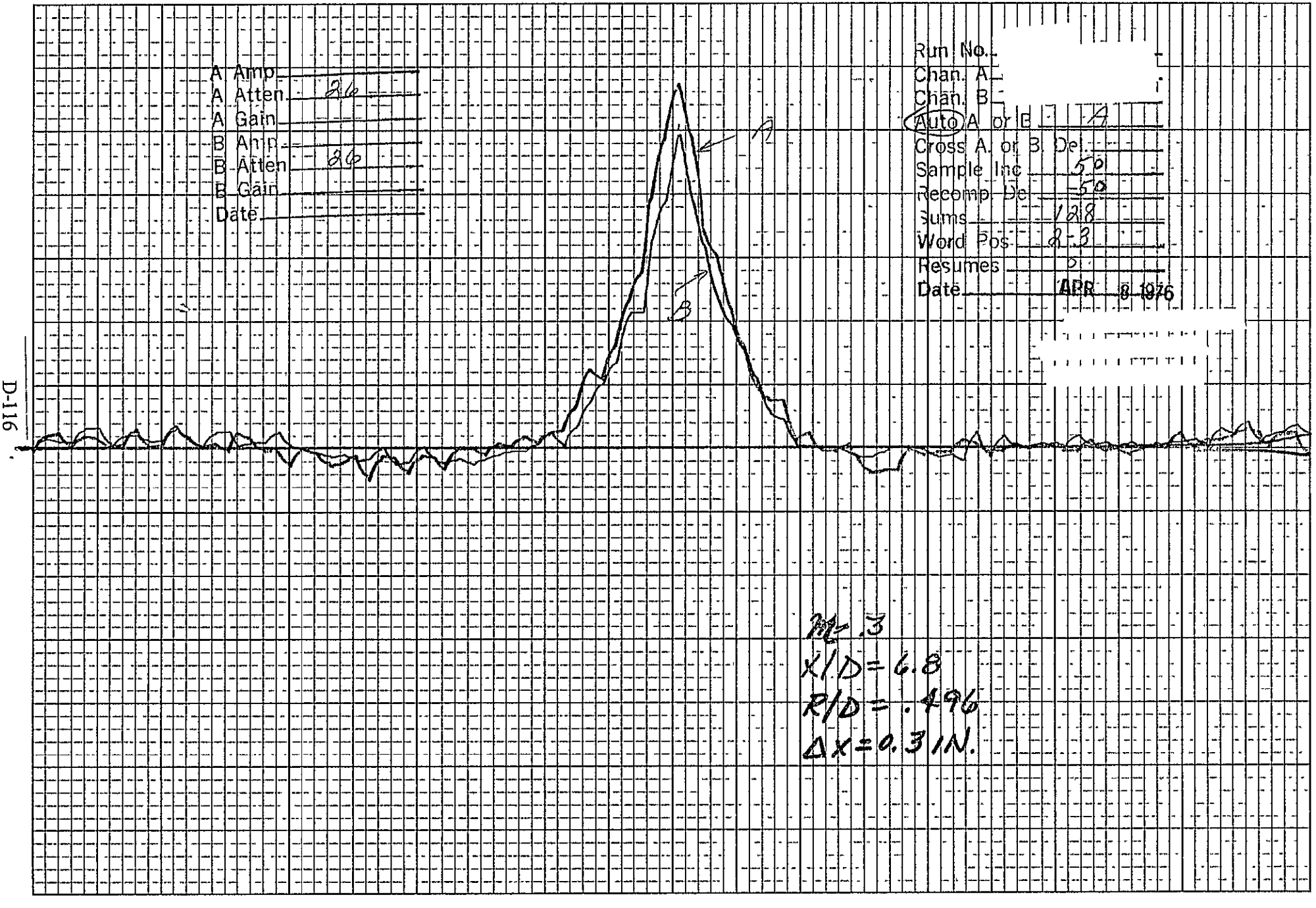
No XY-1001-SP 1



D-115


A Amp
A Atten 26
A Gain
B Amp
B Atten 26
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A or B A
Cross A. or B. De
Sample Inc 50
Recomp De -50
Sums 128
Word Pos 2-3
Resumes 2
Date APR 8 1976
A
B
M .3
X/D = 6.8
R/D = .296
Δx = 0.31 IN.

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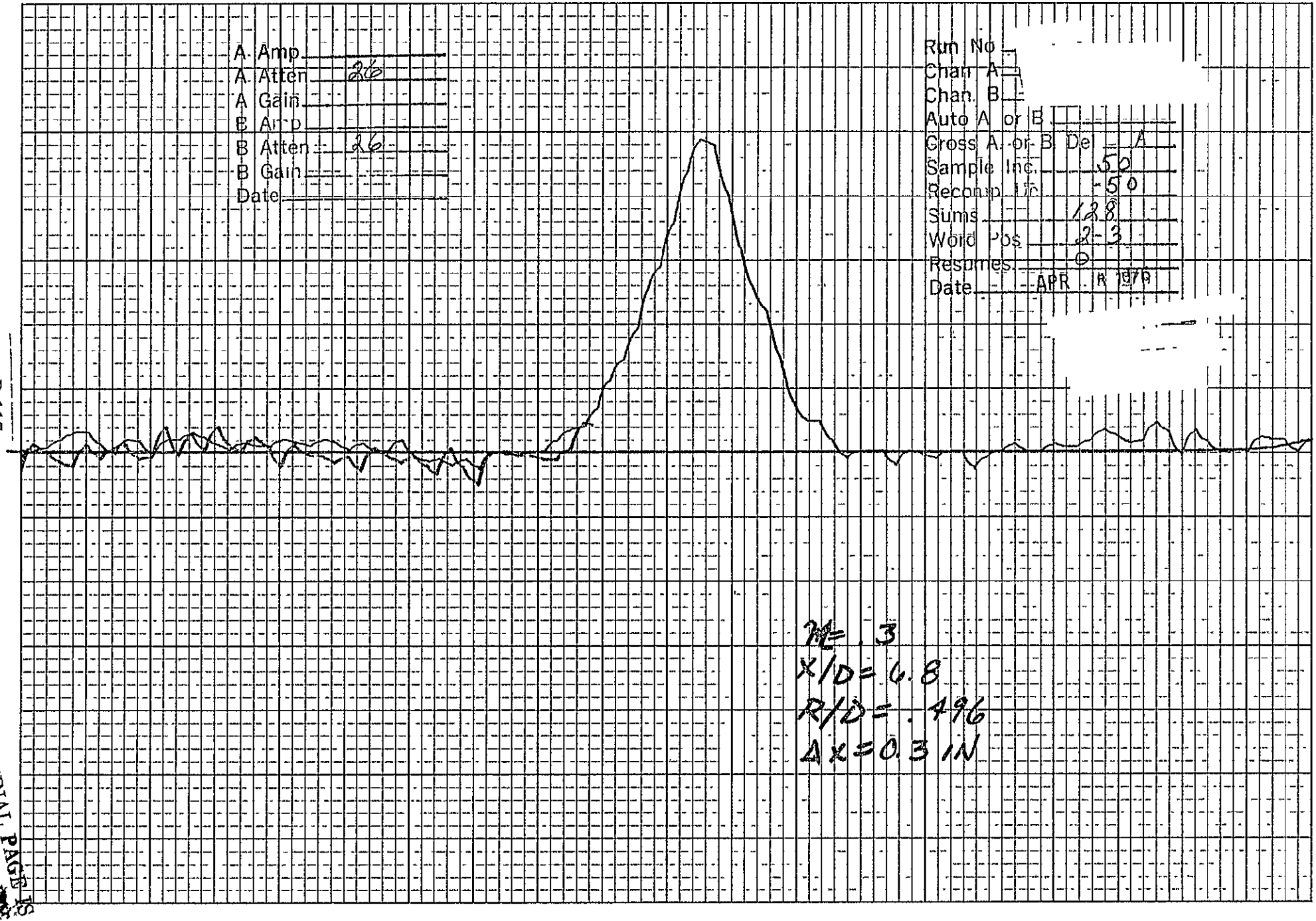
No XY-1001-SP 1



D-117

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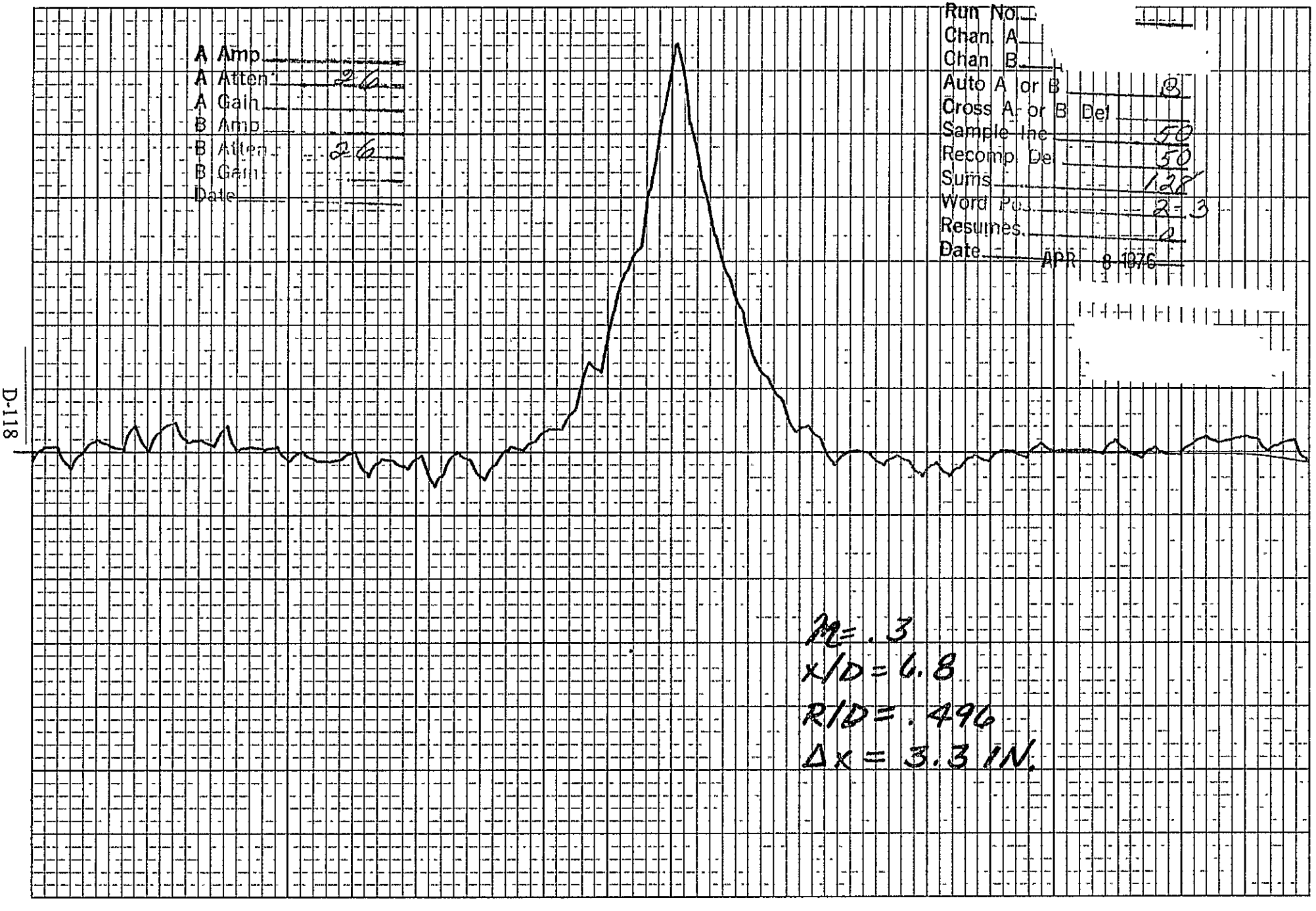
No XY-1001-SP 1



[redacted] REC [redacted] NG C [redacted] S [redacted]

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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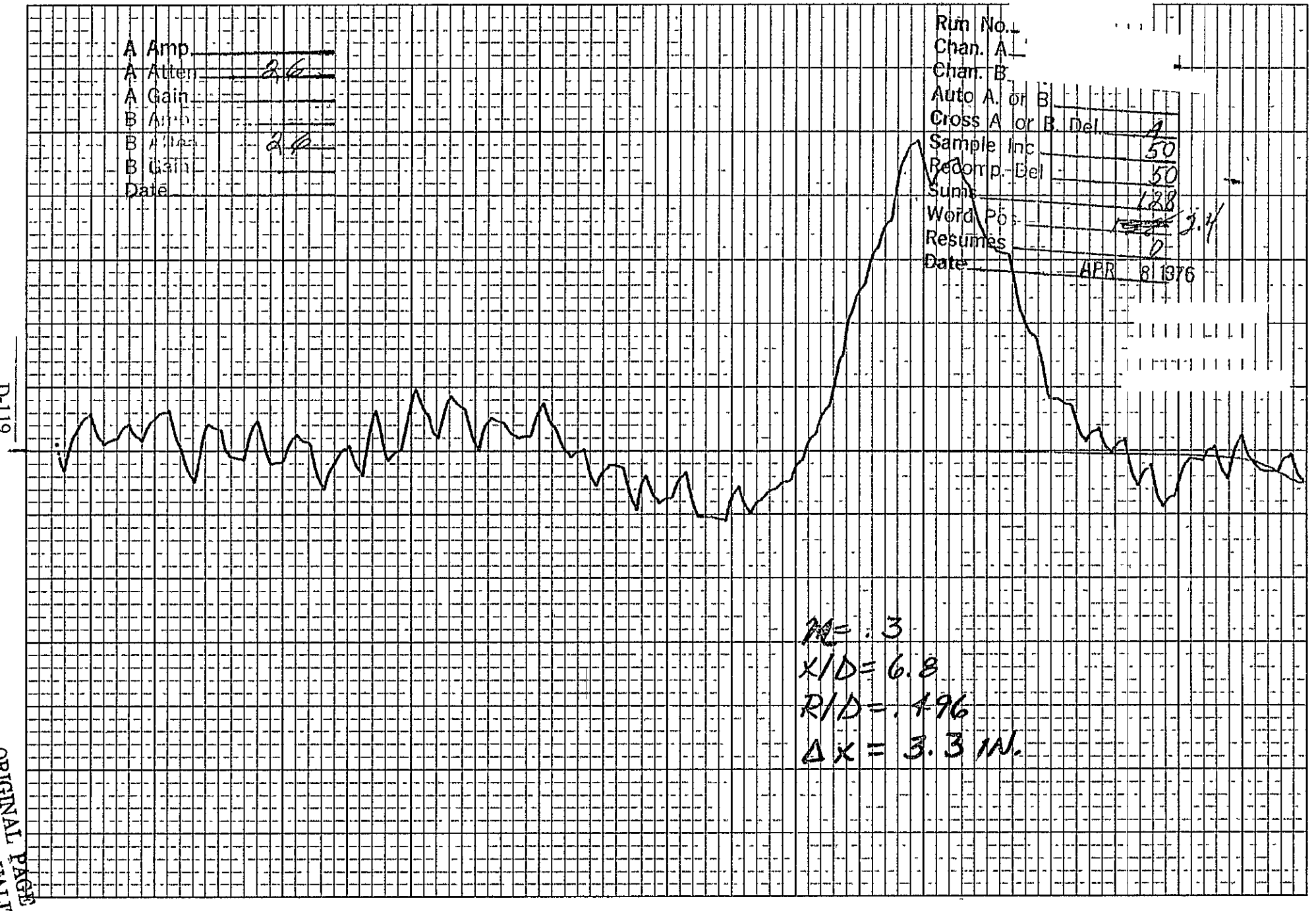
No XY-1001-SP 1



D-119

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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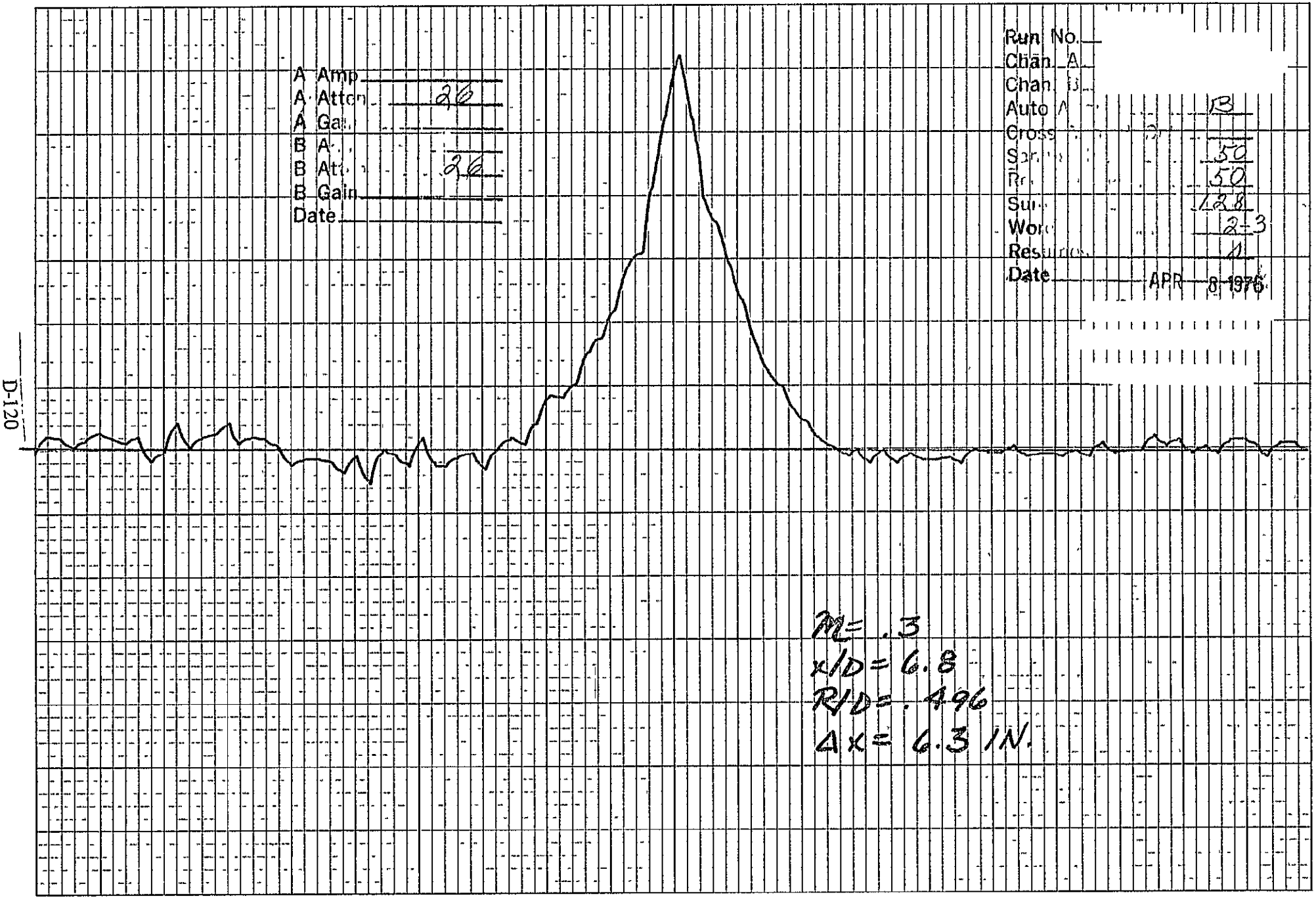
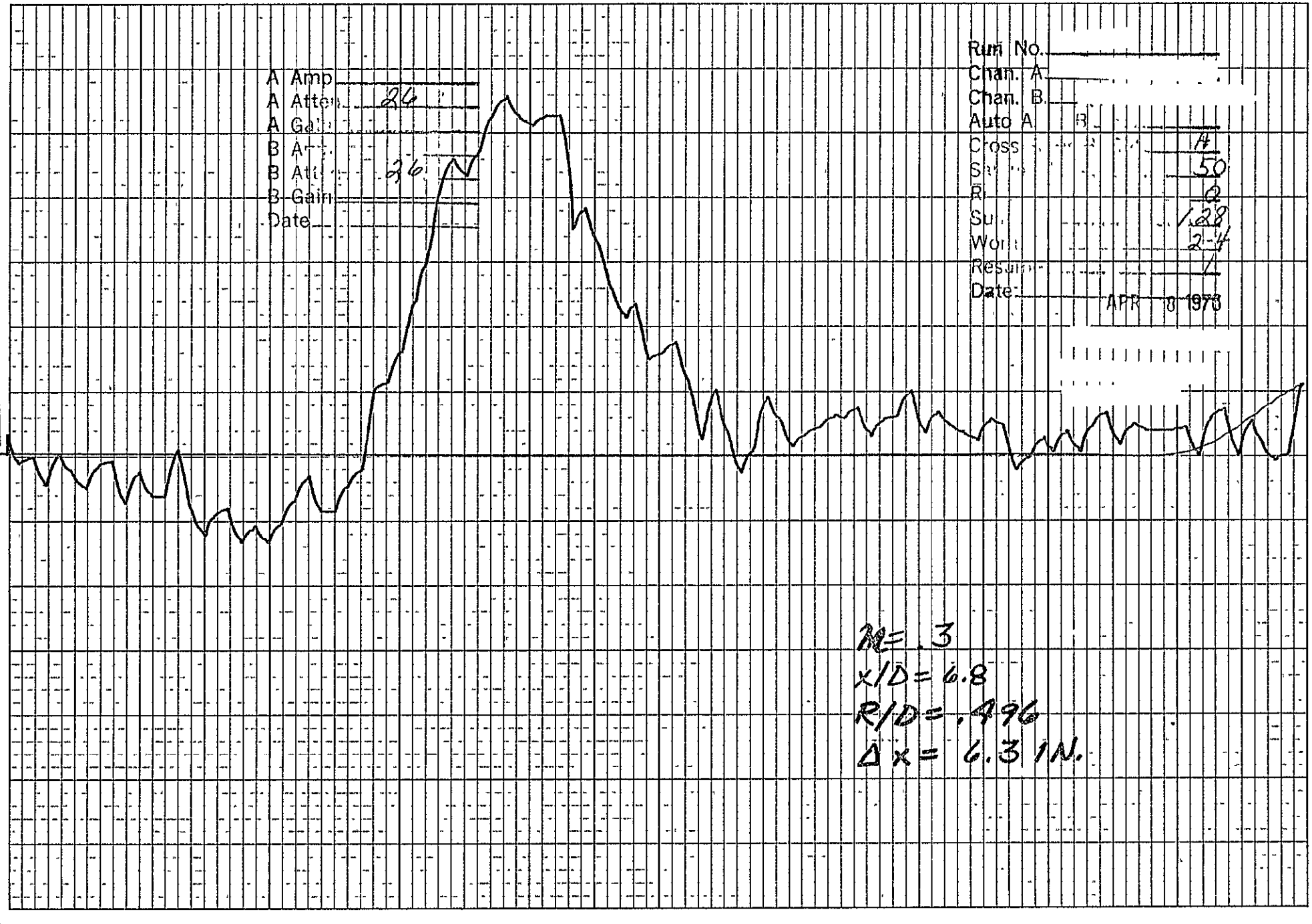
No XY-1001-SP 1



D-120



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BUFFALO NEW YORK
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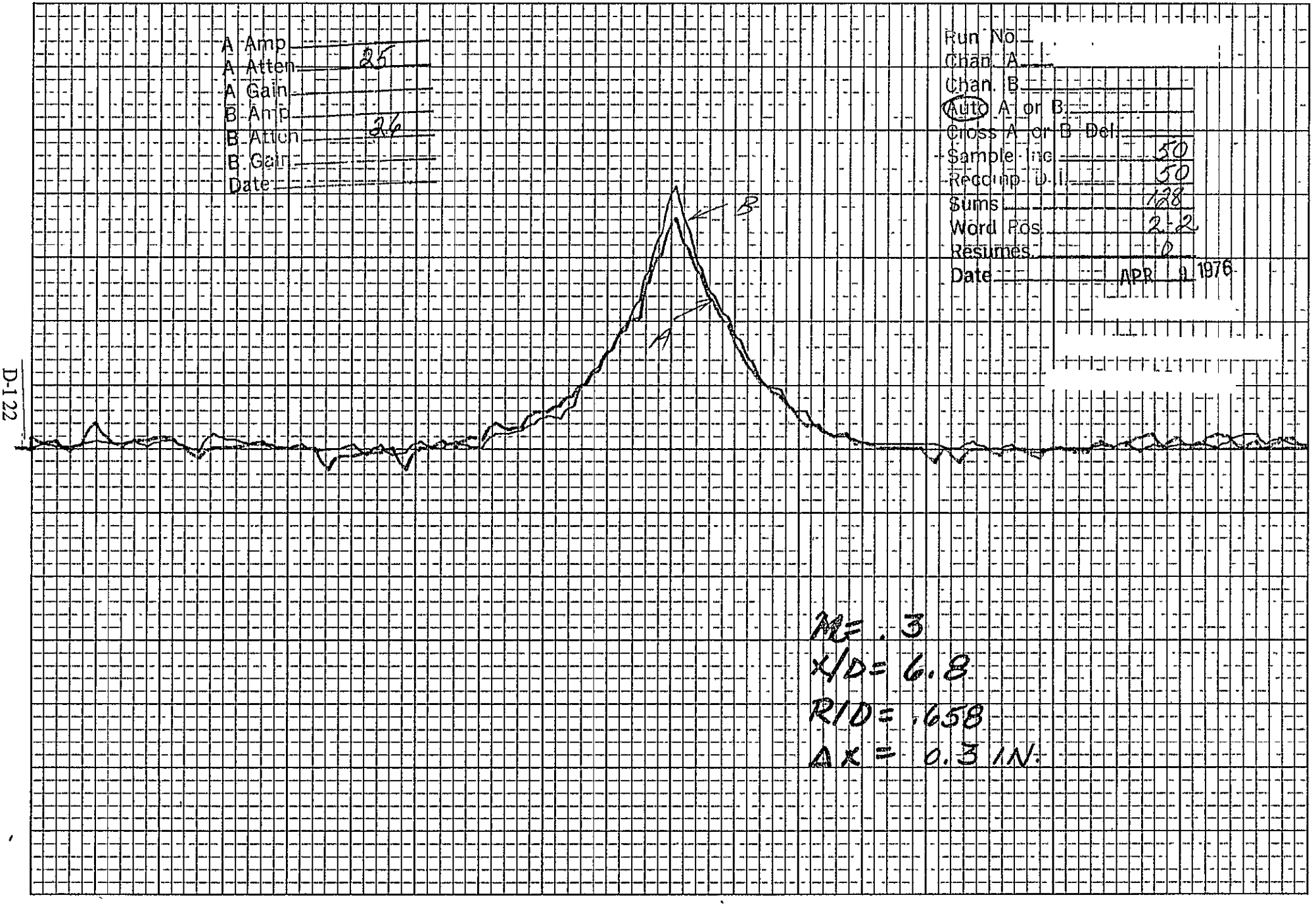
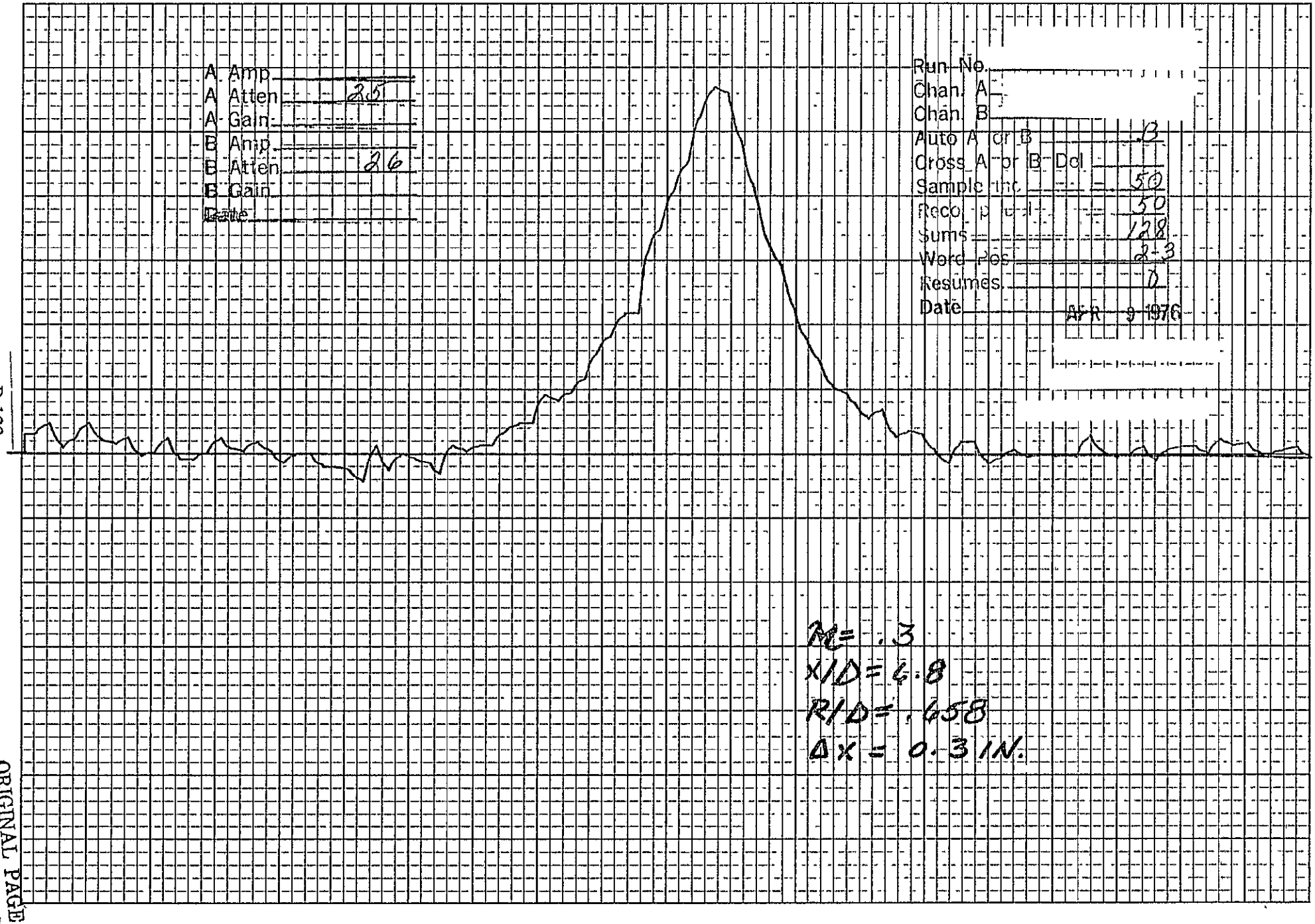
No. XY-1001-SP 1



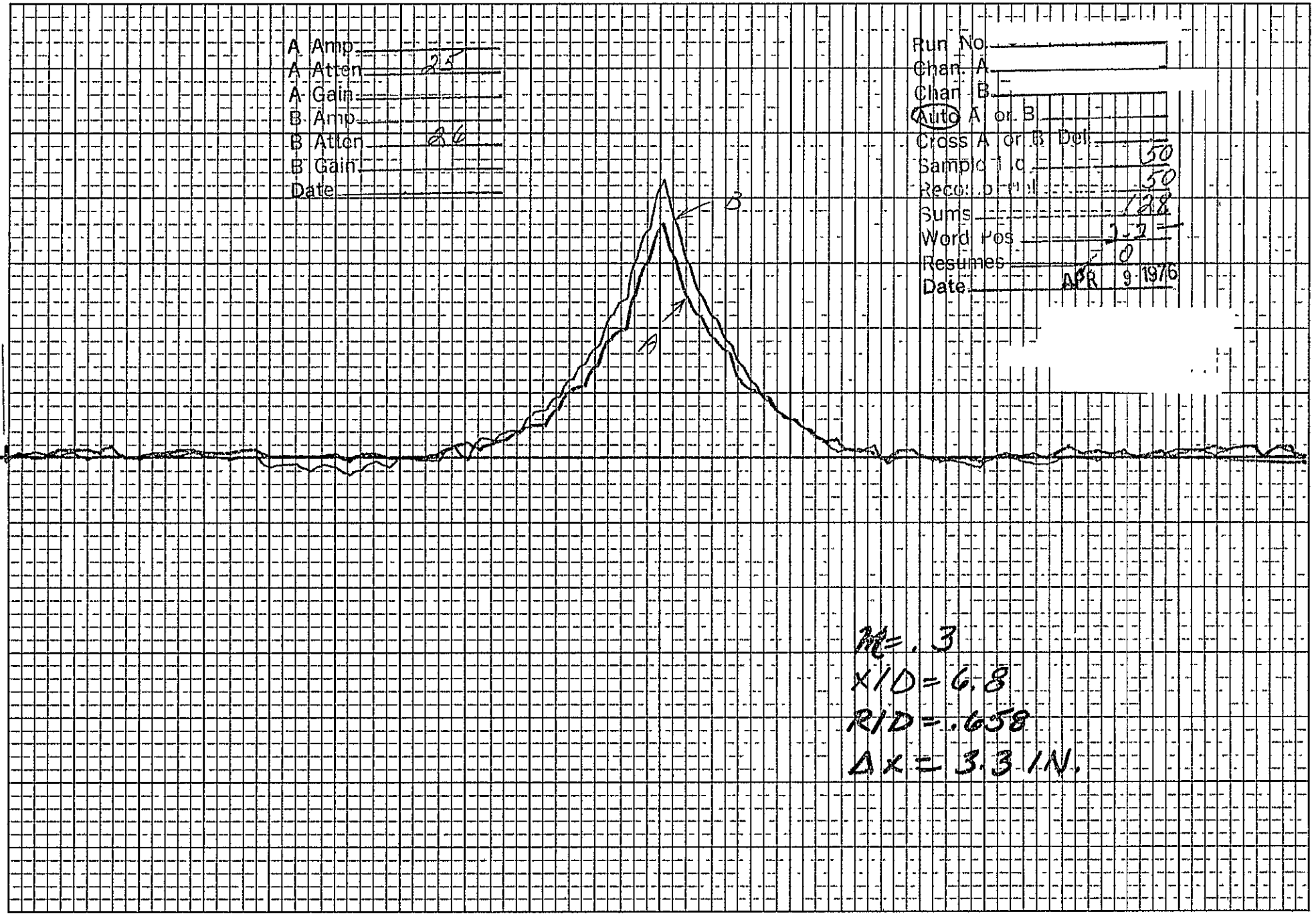
D-122

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U S A

No XY-1001-SP 1



D-123


A Amp
A Atten 25
A Gain
B Amp
B Atten 26
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A or B
Cross A or B Del 50
Sample No 50
Record Length 128
Sums
Word Pos 2-7
Resumes 0
Date APR 9 1976
B
A
M=.3
X/D=6.8
R/D=.658
Δx=3.3 IN.

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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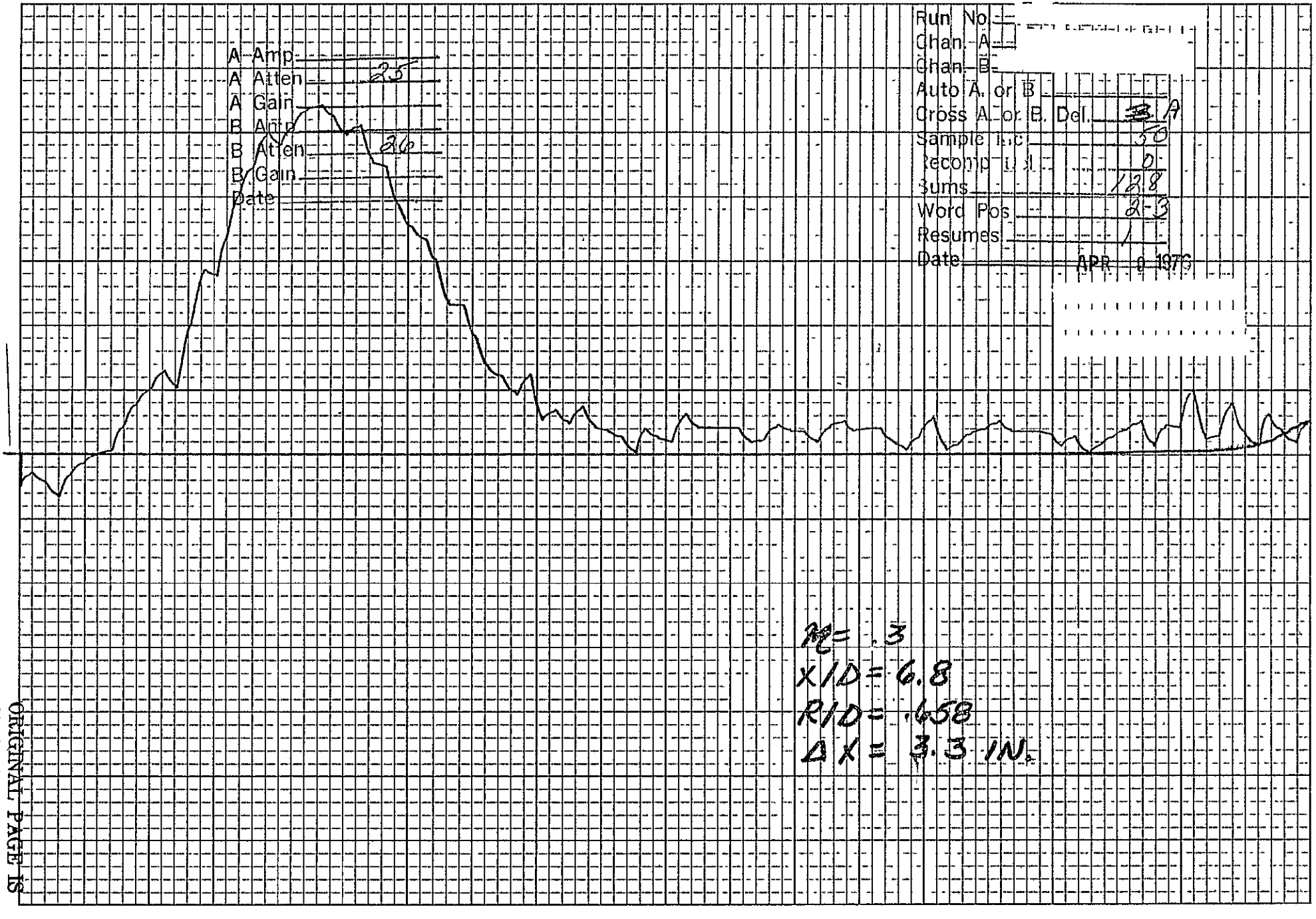
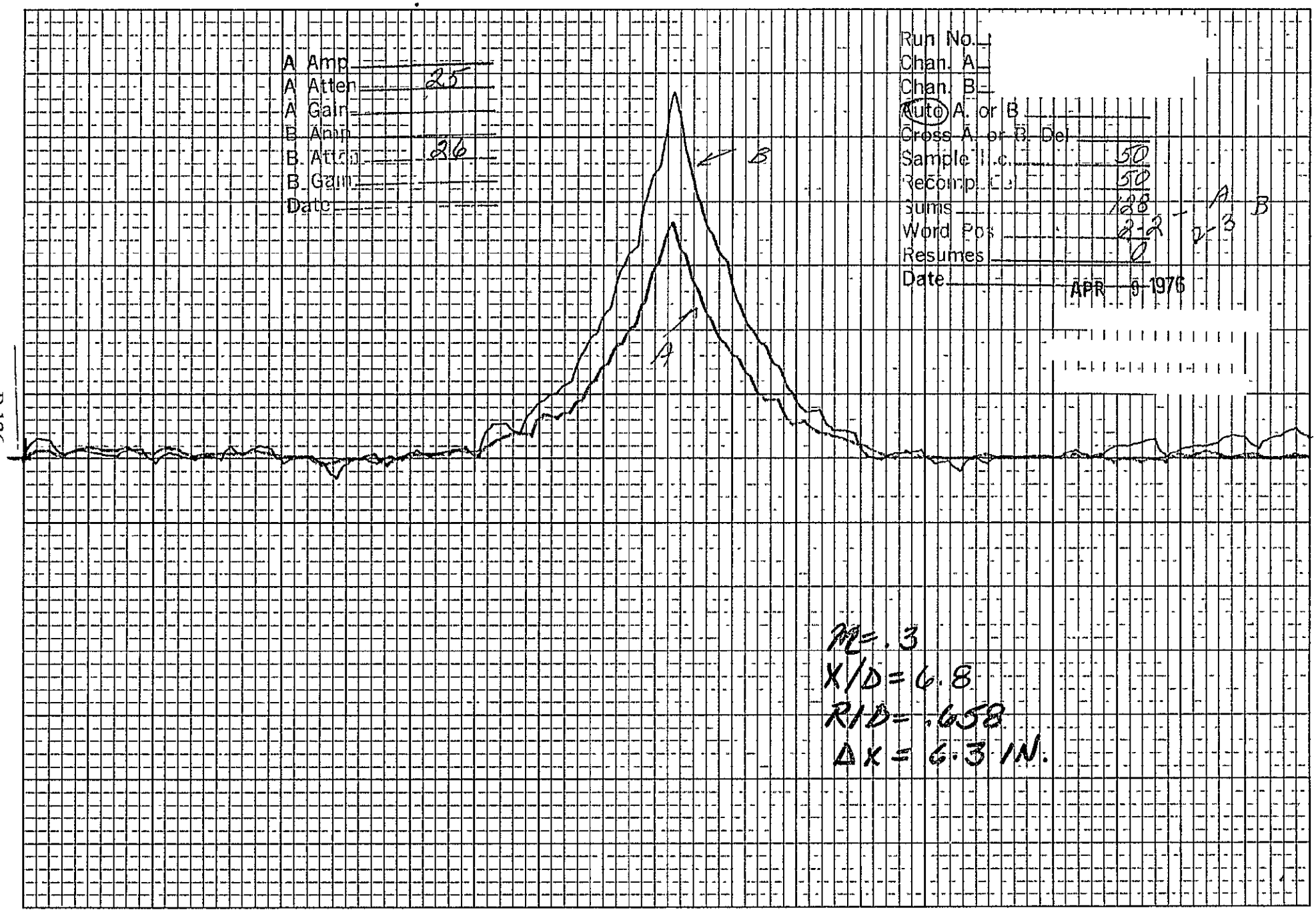
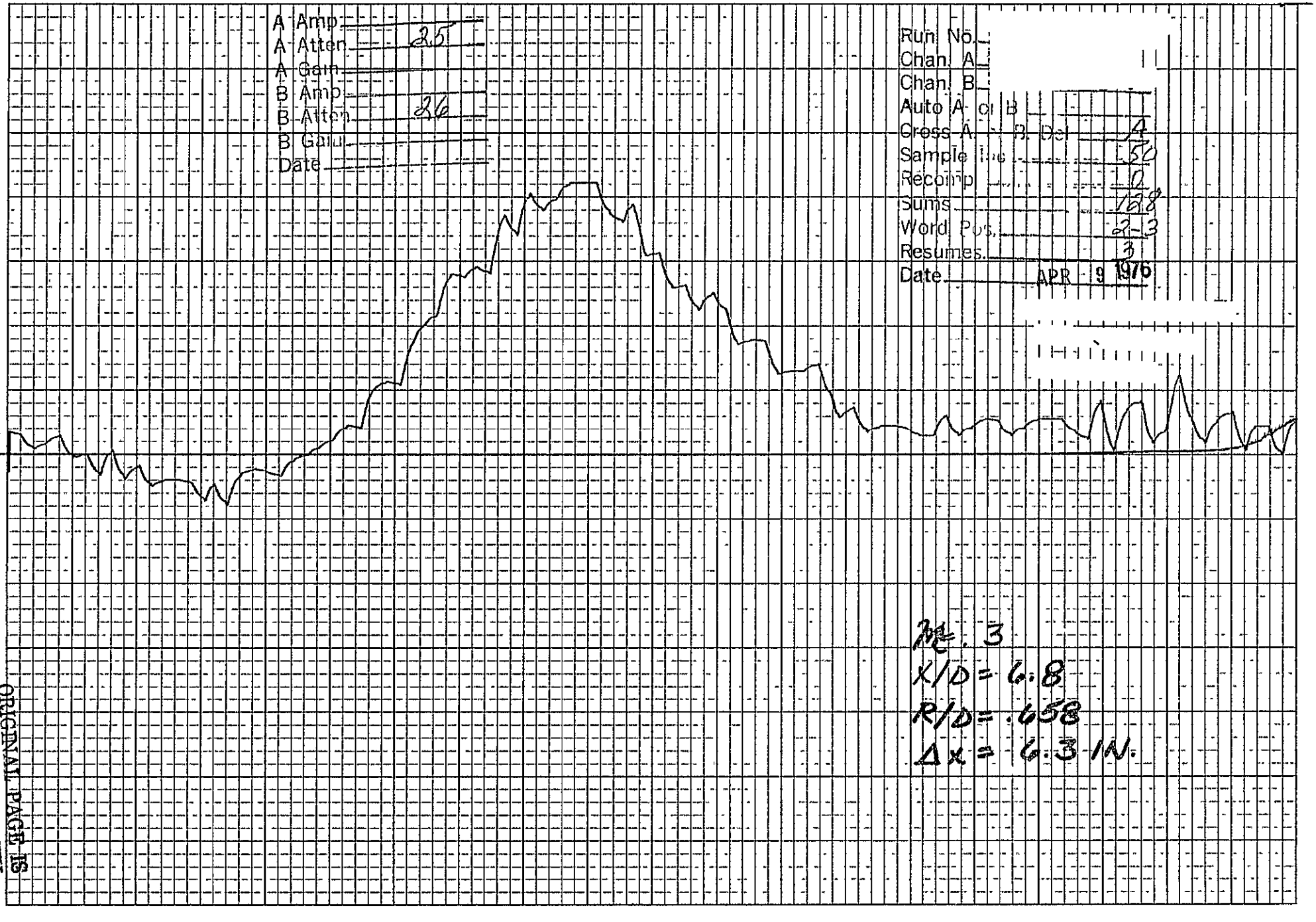
No. XY-1001- SP 1



D-125


A Amp
A Atten 25
A Gain
B Amp
B Atten 26
B Gain
Date
Run No. 1
Chan. A
Chan. B
Auto A. or B
Cross A. or B. Del
Sample I.c. 50
Recomp. 50
Sums 128
Word Pos 2-2
Resumes 0
Date APR 6 1976
B
A
M = .3
X/D = 6.8
R/D = .658
Δx = 6.3 IN.



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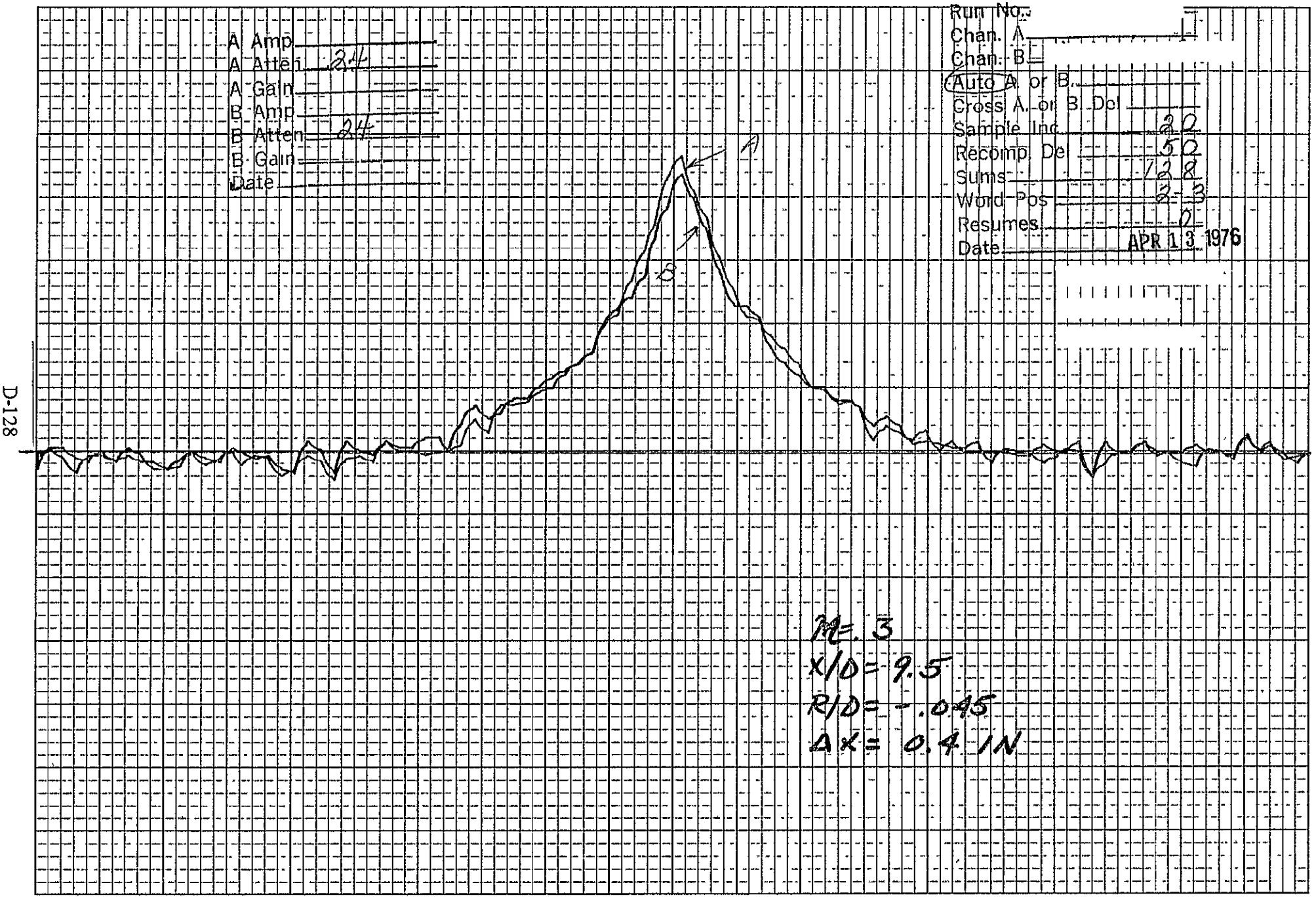
No XY-1001-SP 1



D-128

GRAPHIC CONTROLS CORPORATION
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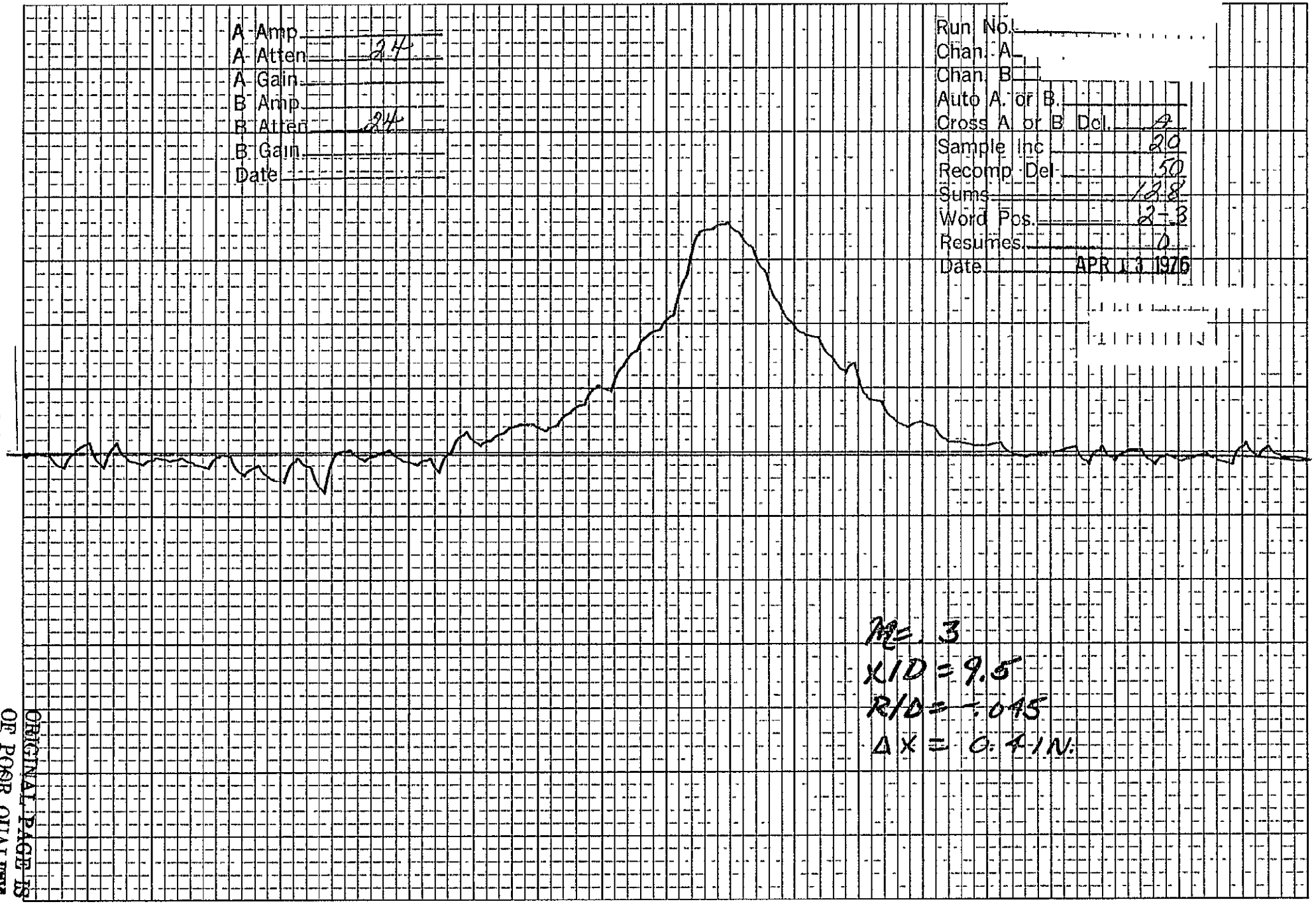
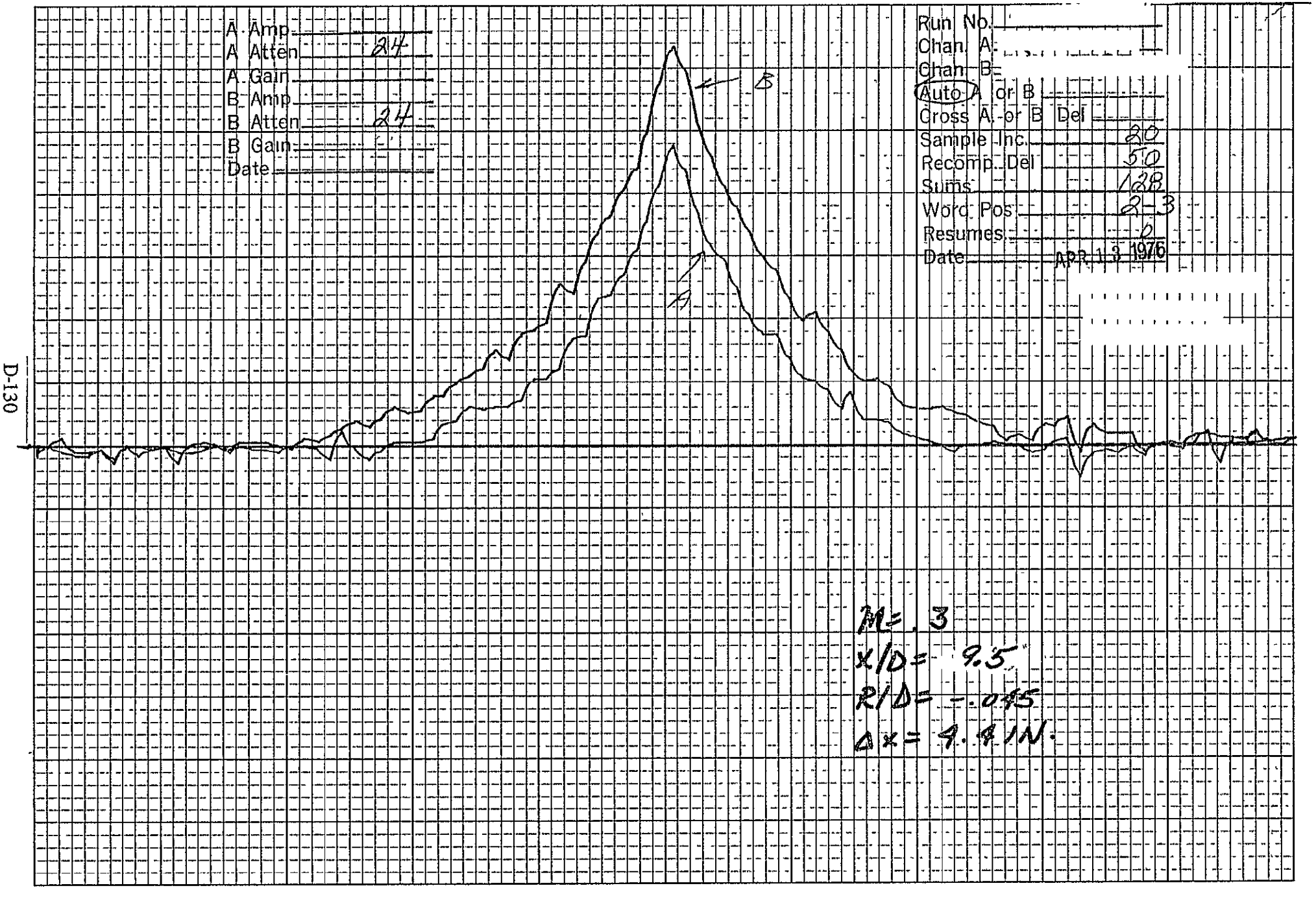
No XY-1001 - SP 1



D-129


A Amp
A Atten 24
A Gain
B Amp
B Atten 24
B Gain
Date
B
A
Run No.
Chan. A:
Chan. B:
Auto A or B
Cross A or B Del
Sample Inc. 20
Recomp. Del 50
Sums 128
Word Pos 2-3
Resumes 2
Date APR 13 1976
M= .3
x/D= 9.5
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GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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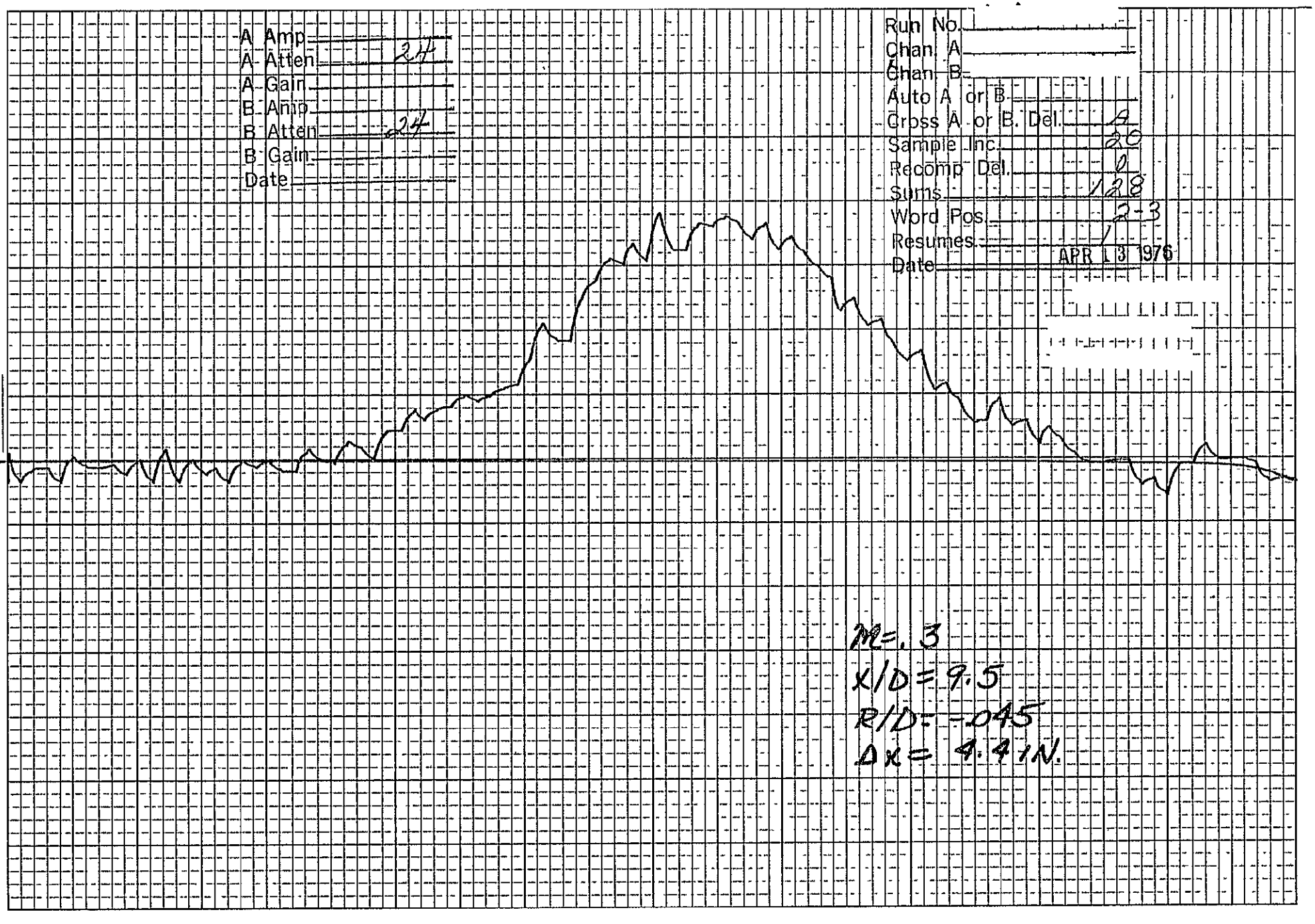
No XY-1001 - SP 1



D-131

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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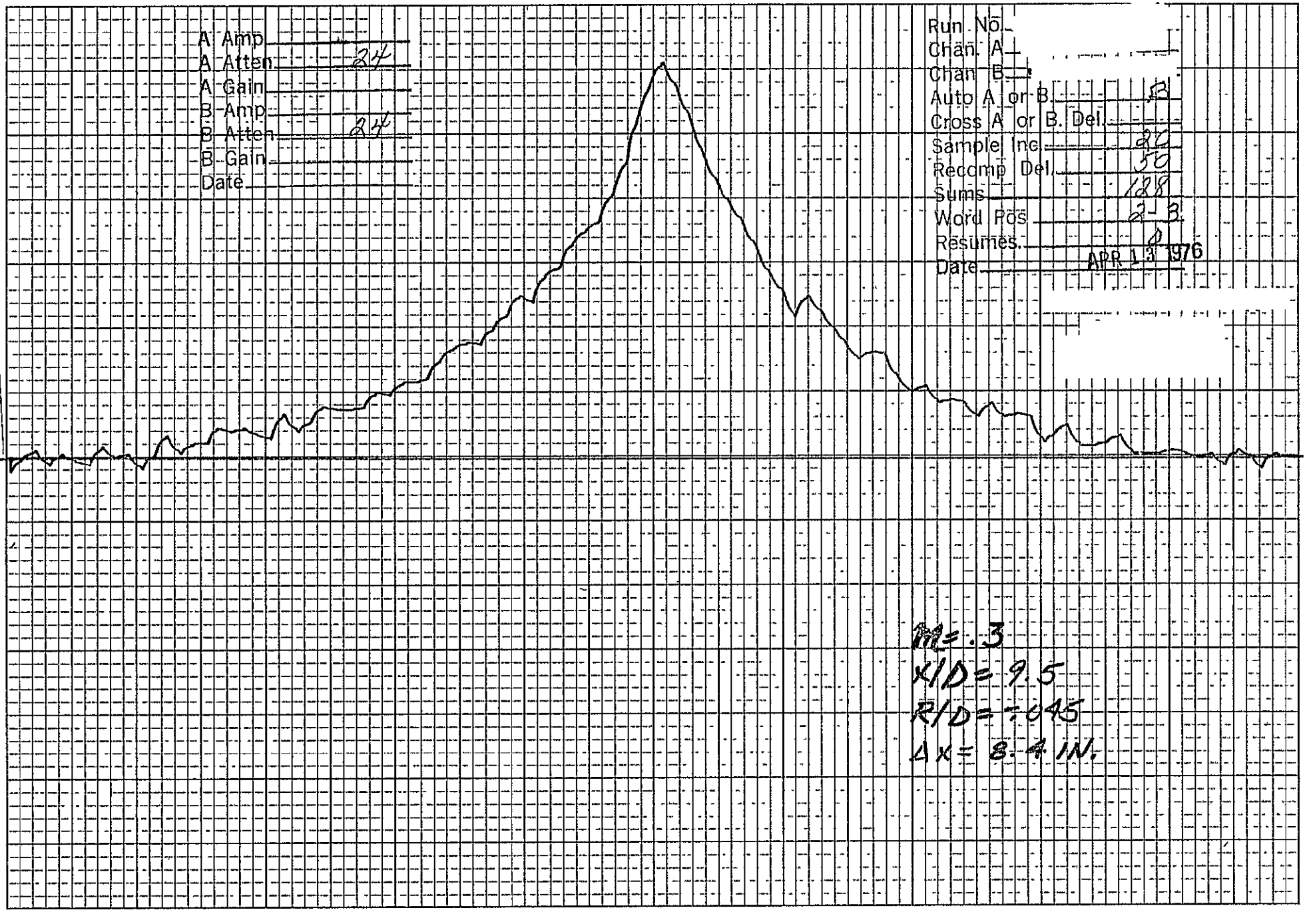
No XY-100T-SP



D-132

[redacted] REC [redacted] G C [redacted] S
GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
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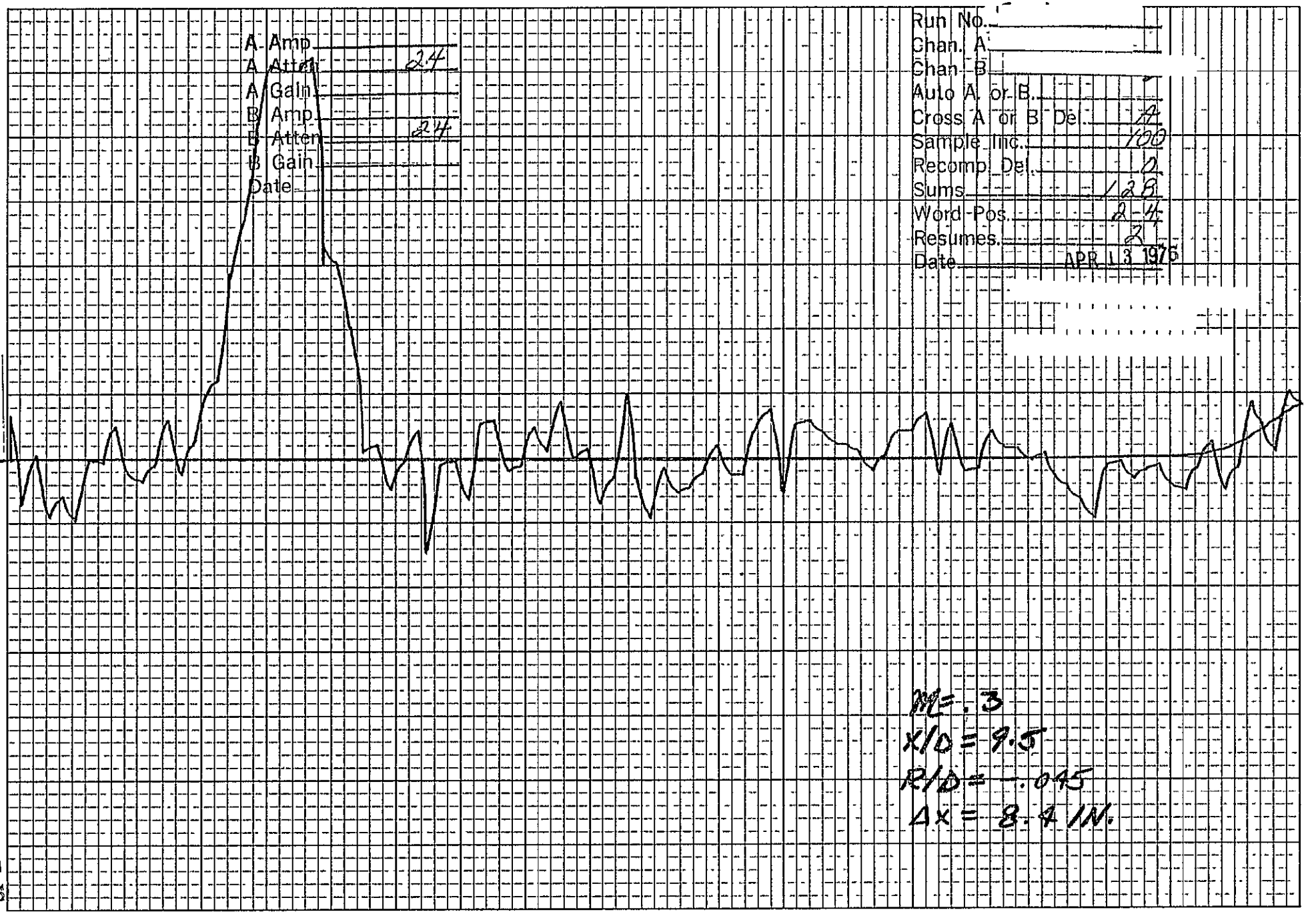
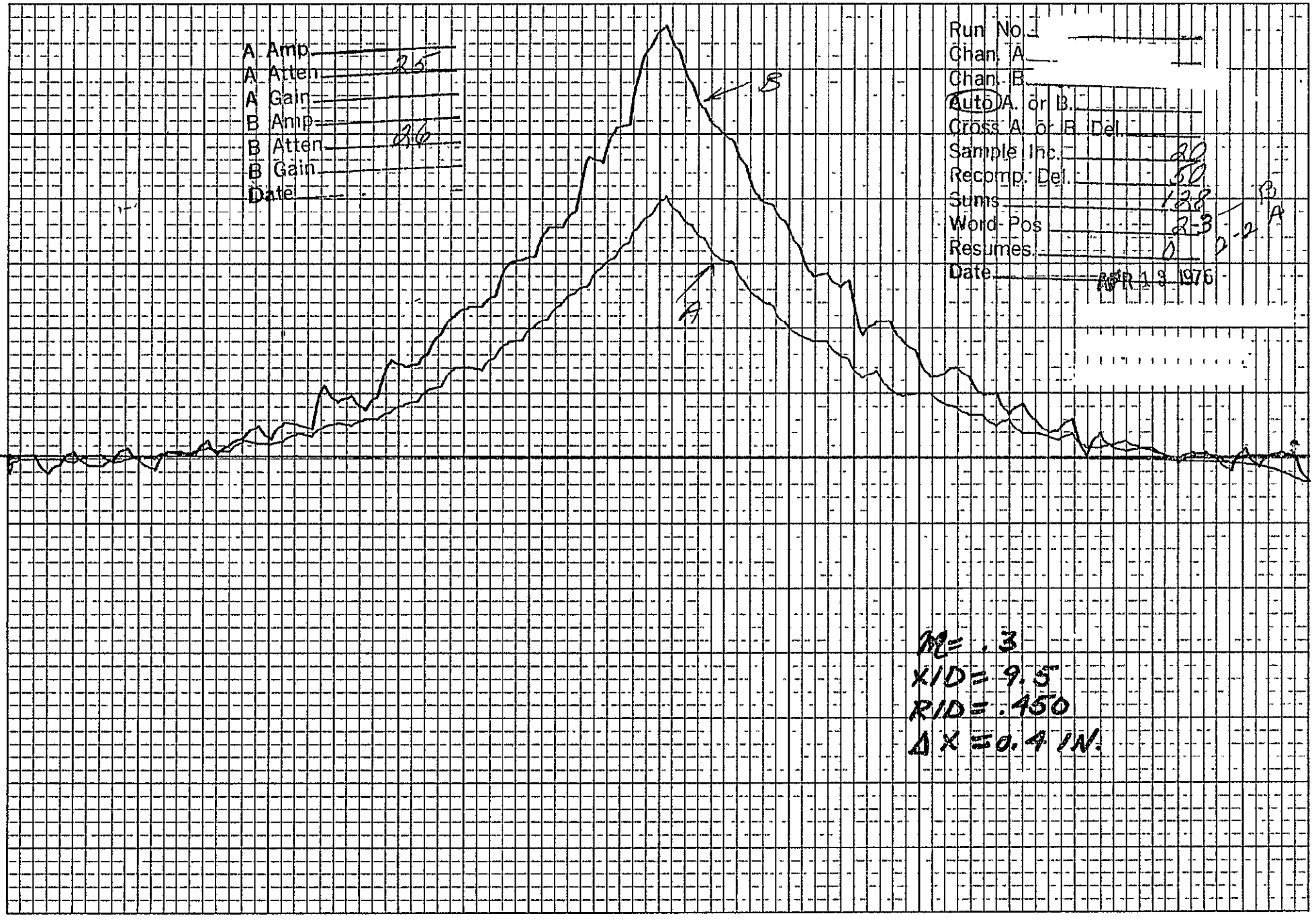


D-133

GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-TOOT-SP 1



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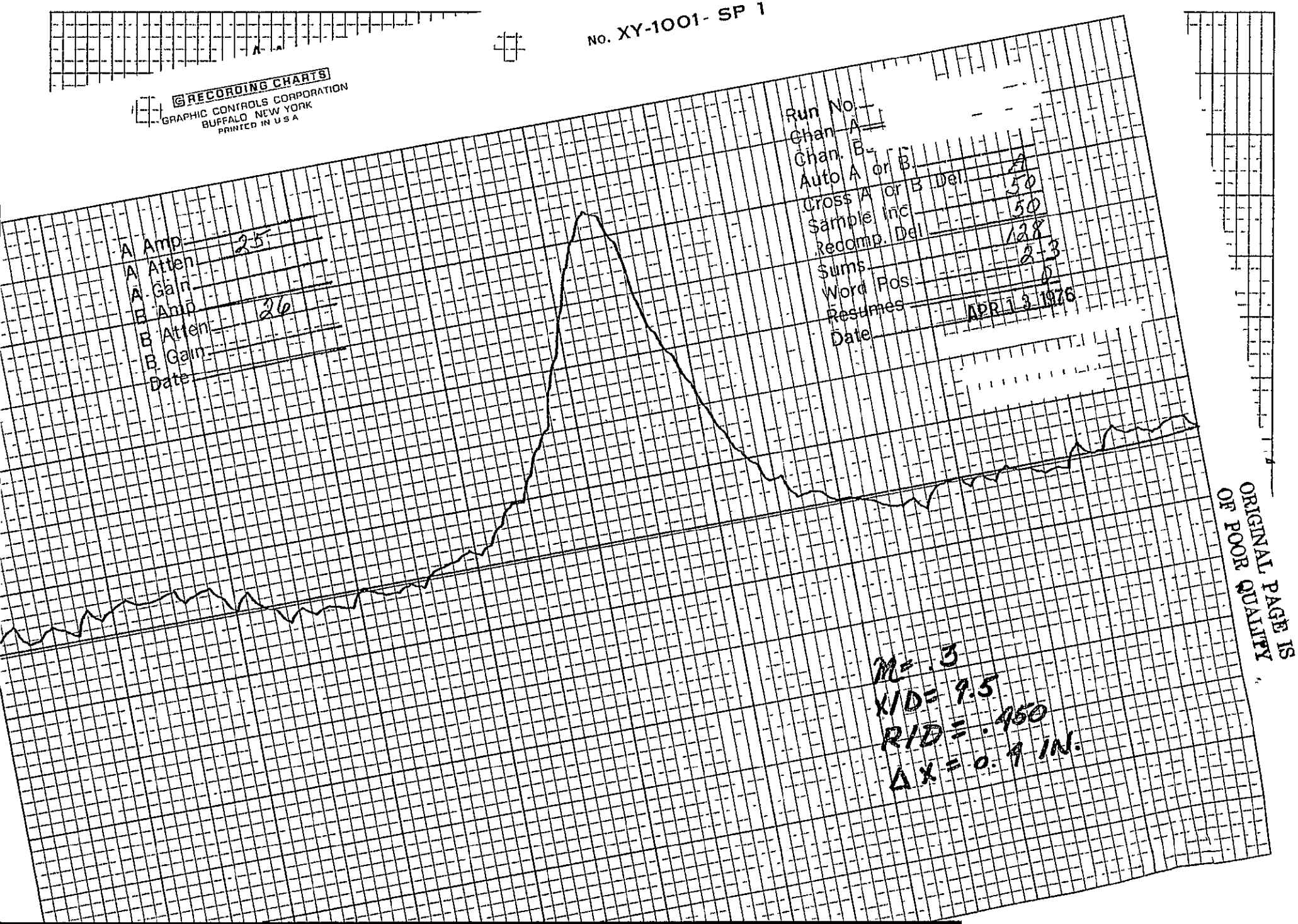
No XY-1001-SP

NO. XY-1001- SP 1

GRECORDING CHARTS
GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U S A



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OF POOR QUALITY

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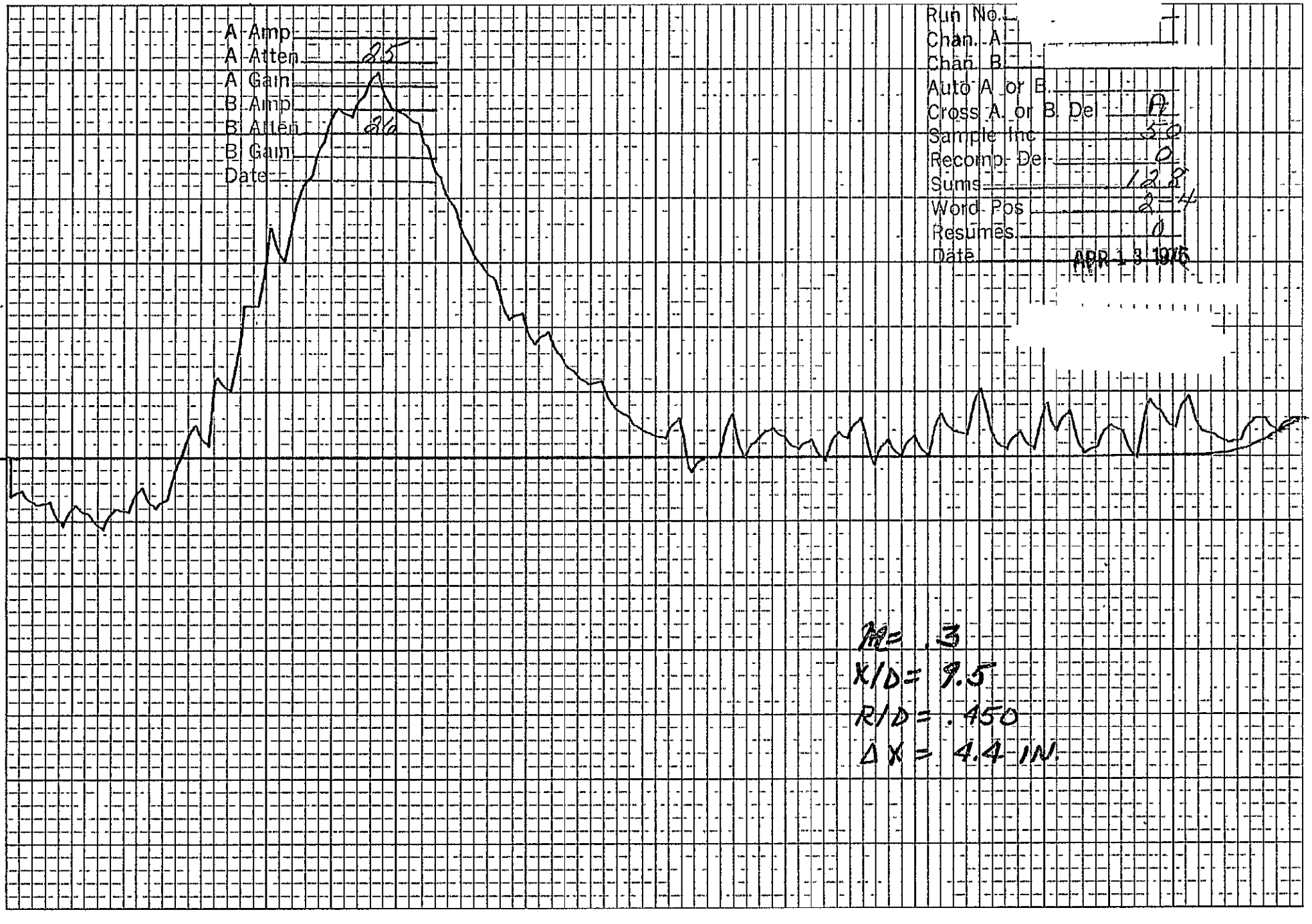
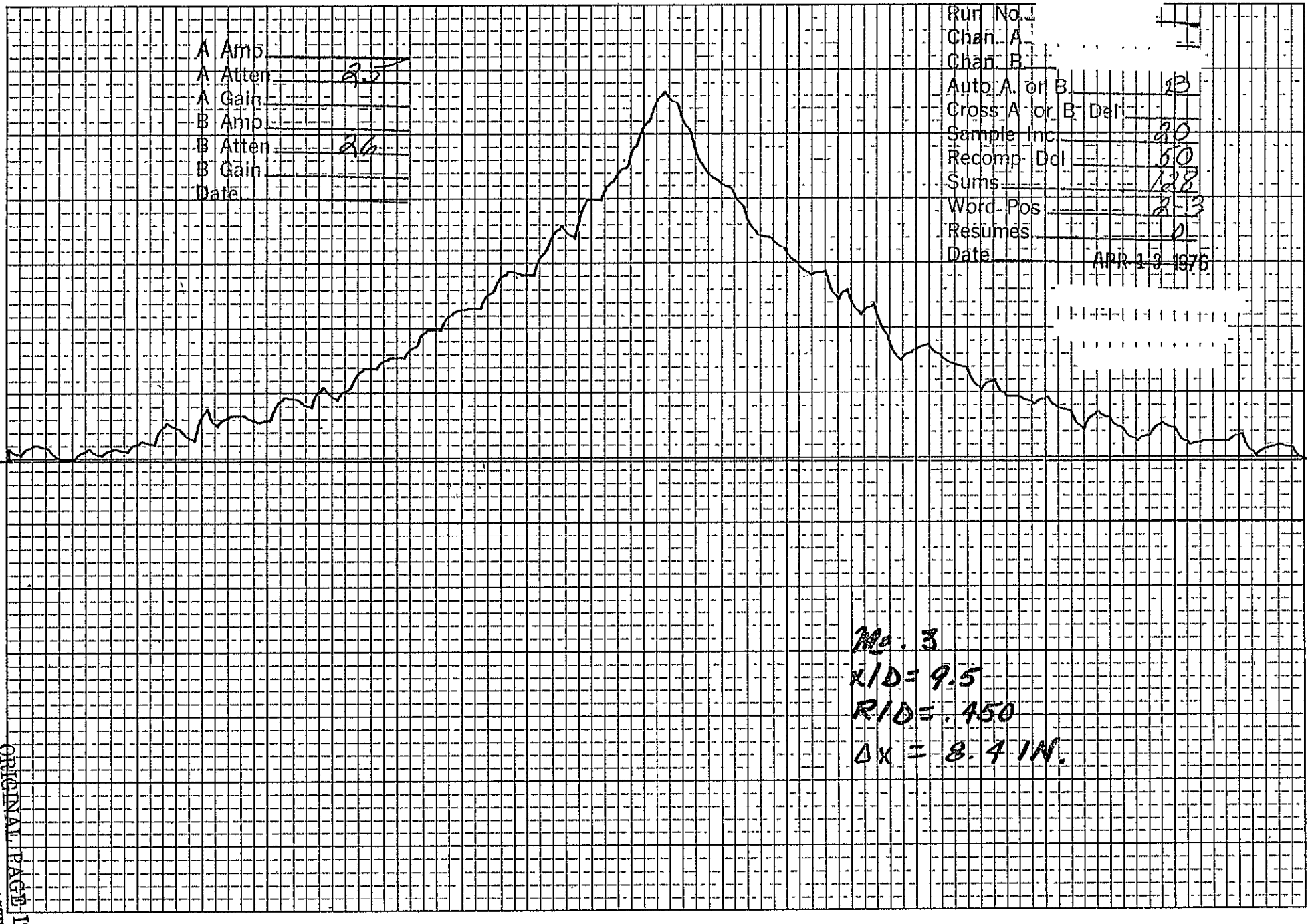
PRINTED IN U.S.A.

NO XY-1001 - SP 1





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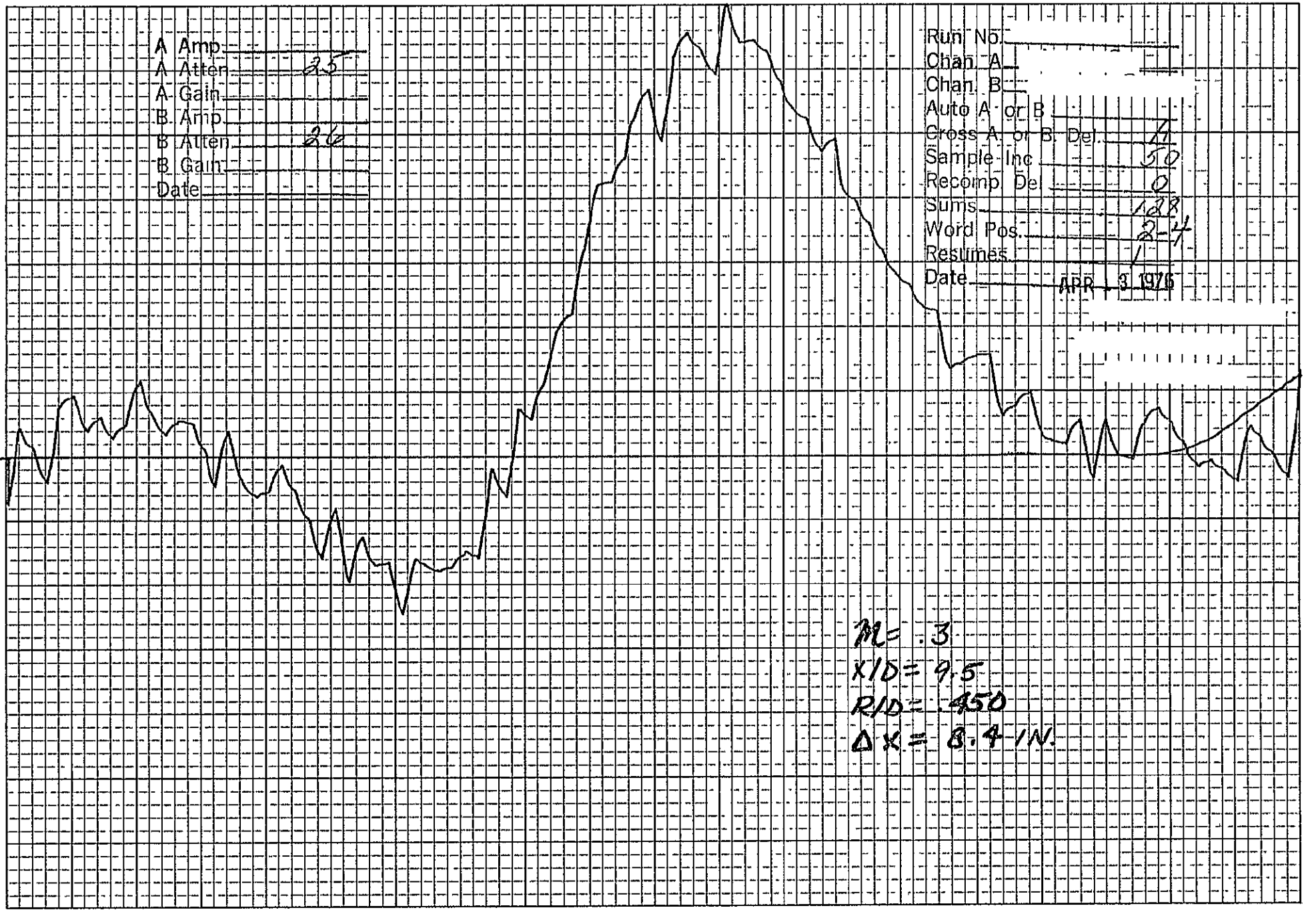

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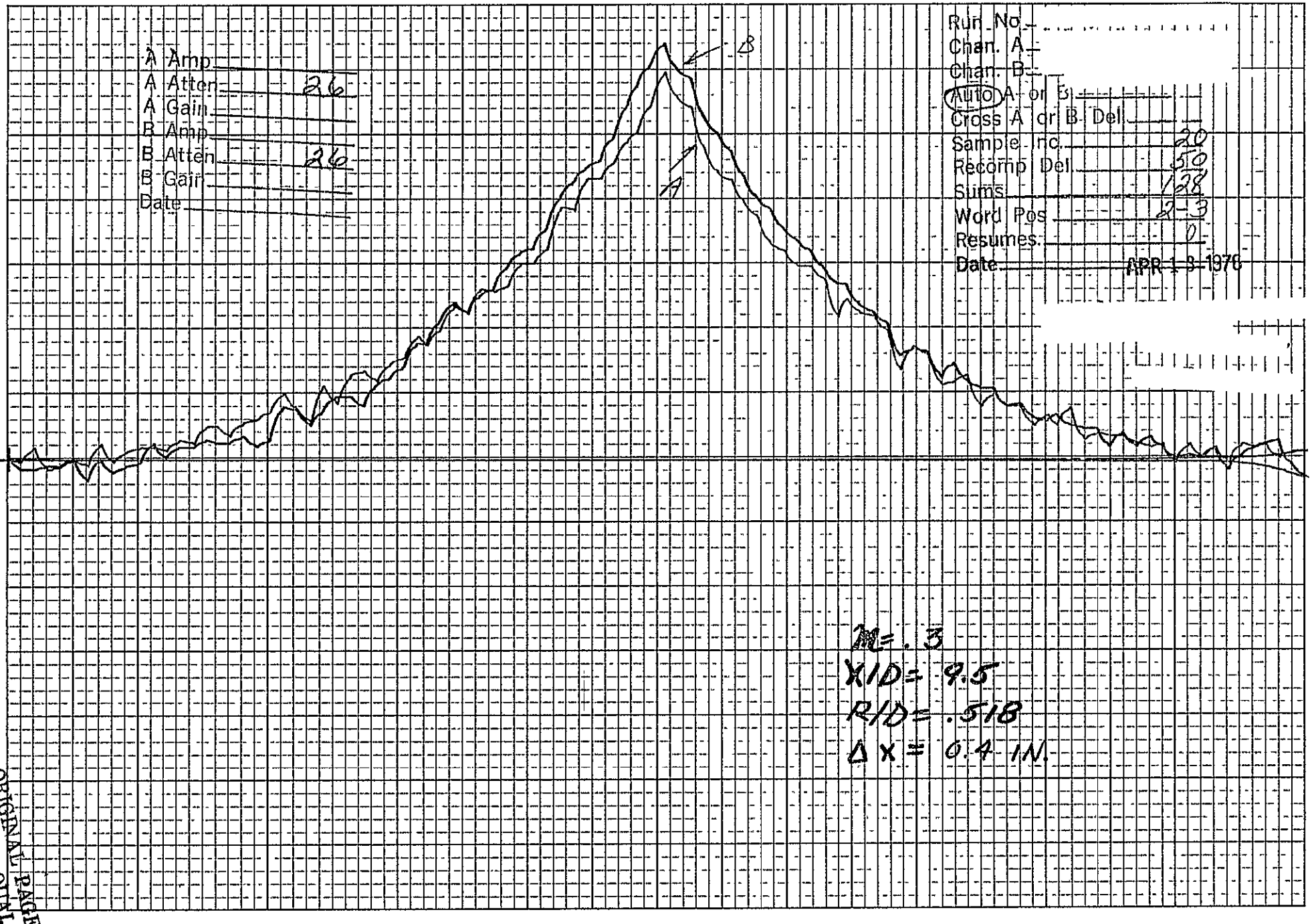
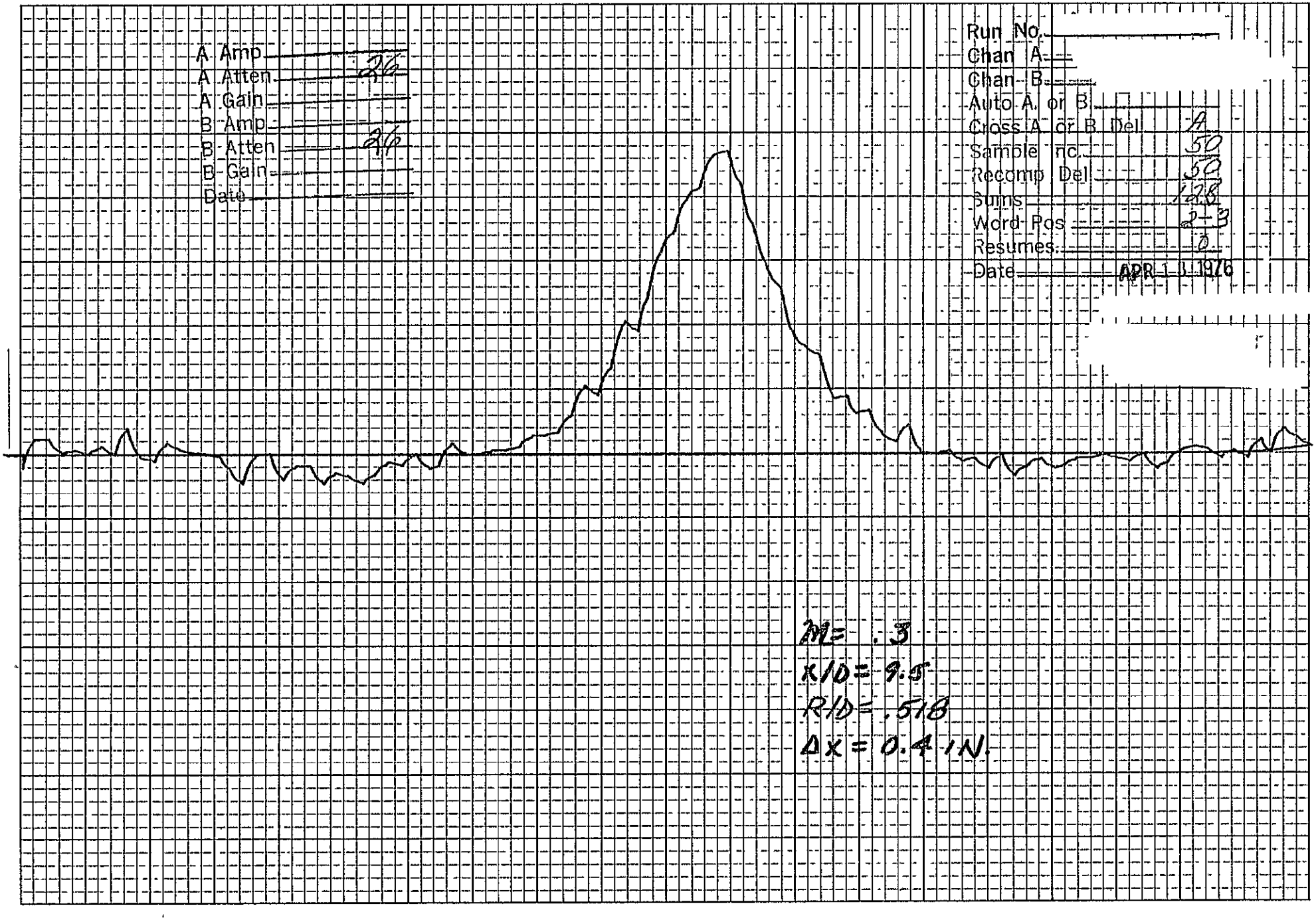


D-140

[redacted] REC[redacted]NG C[redacted]S
GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-1001-SP 1



D-141

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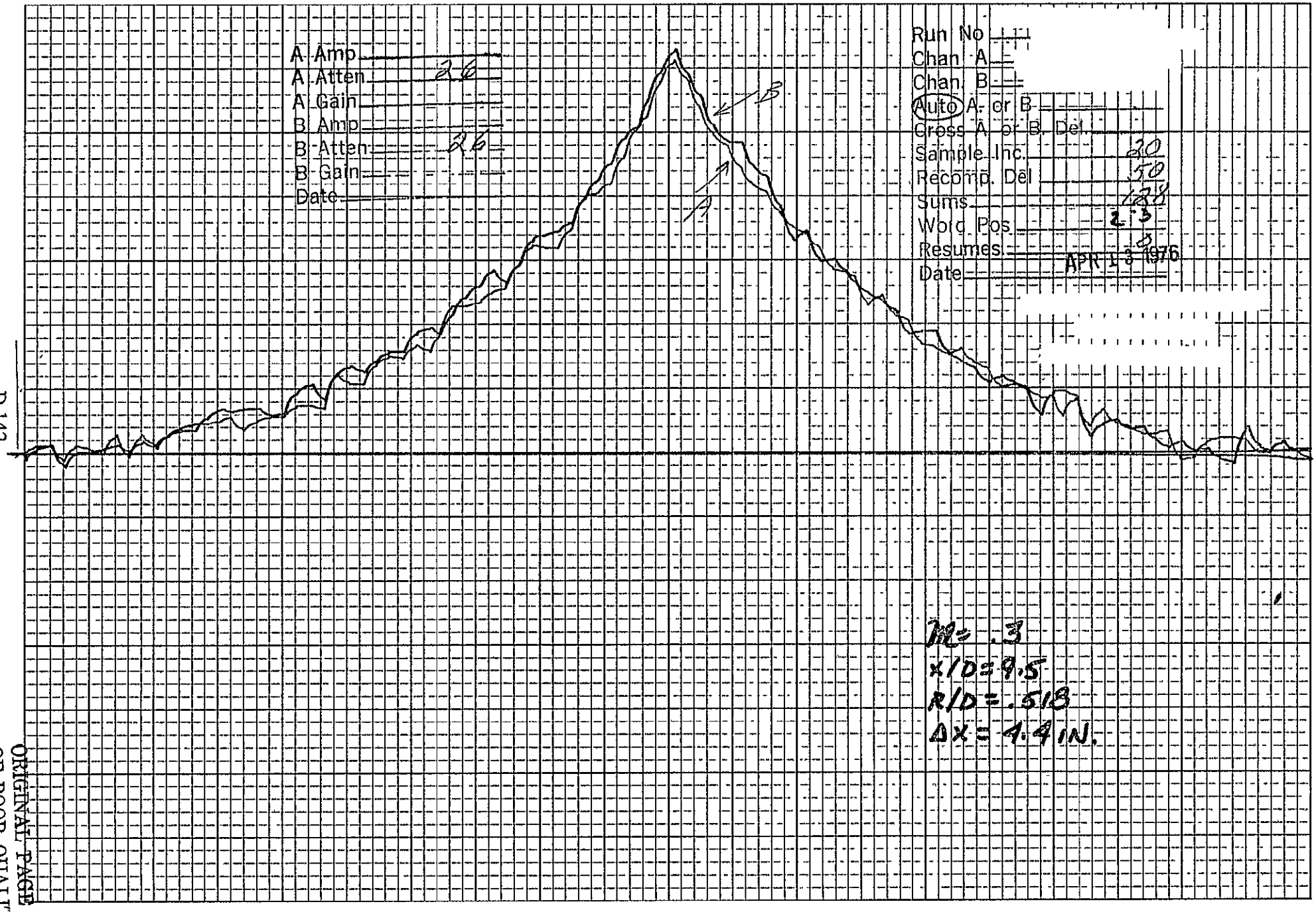
BUFFALO NEW YORK
PRINTED IN U.S.A.

No XY-1001-SP



D-142

[redacted] REC [redacted] NG C[redacted] S [redacted]
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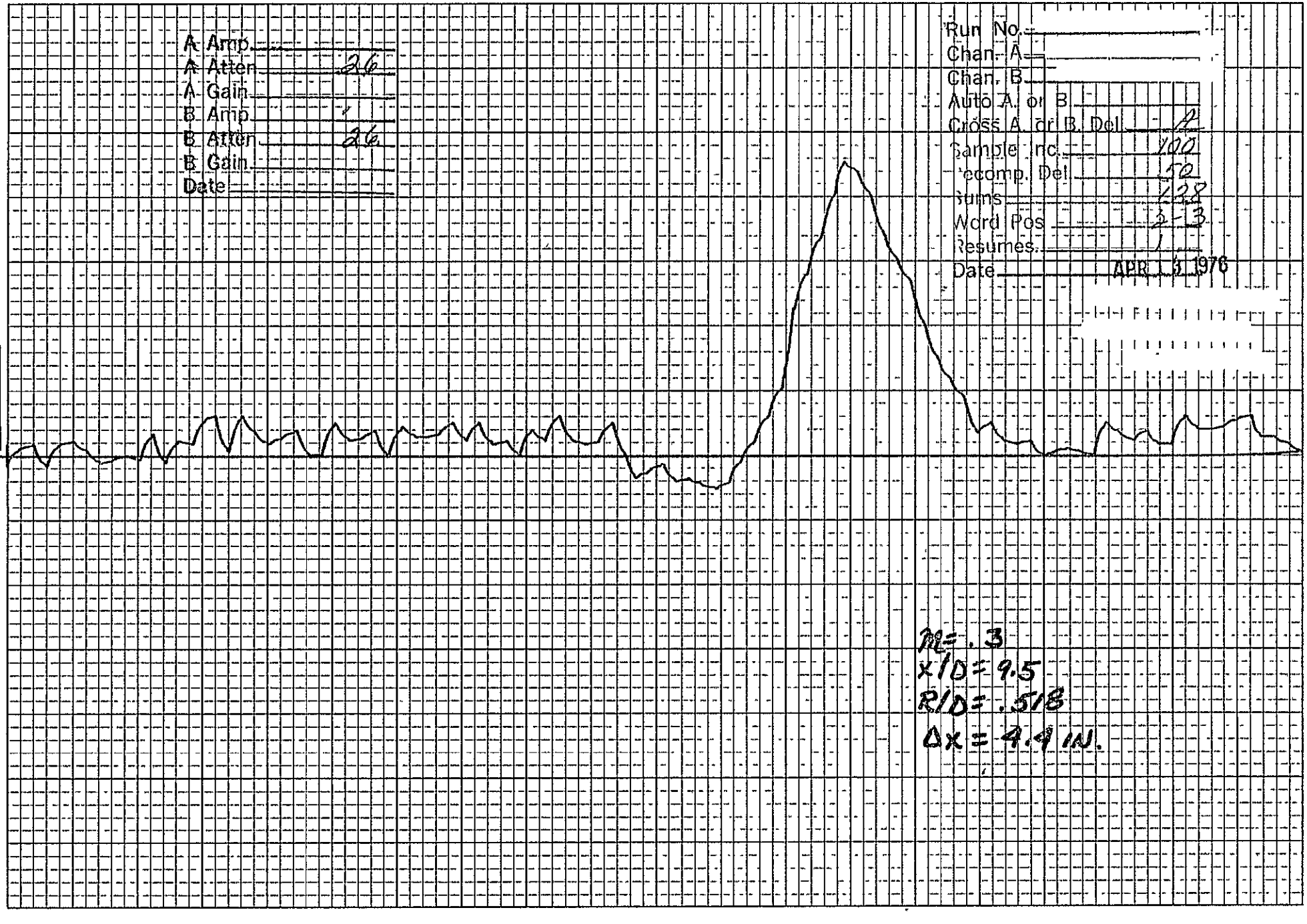
No XY-1001 - SP 1



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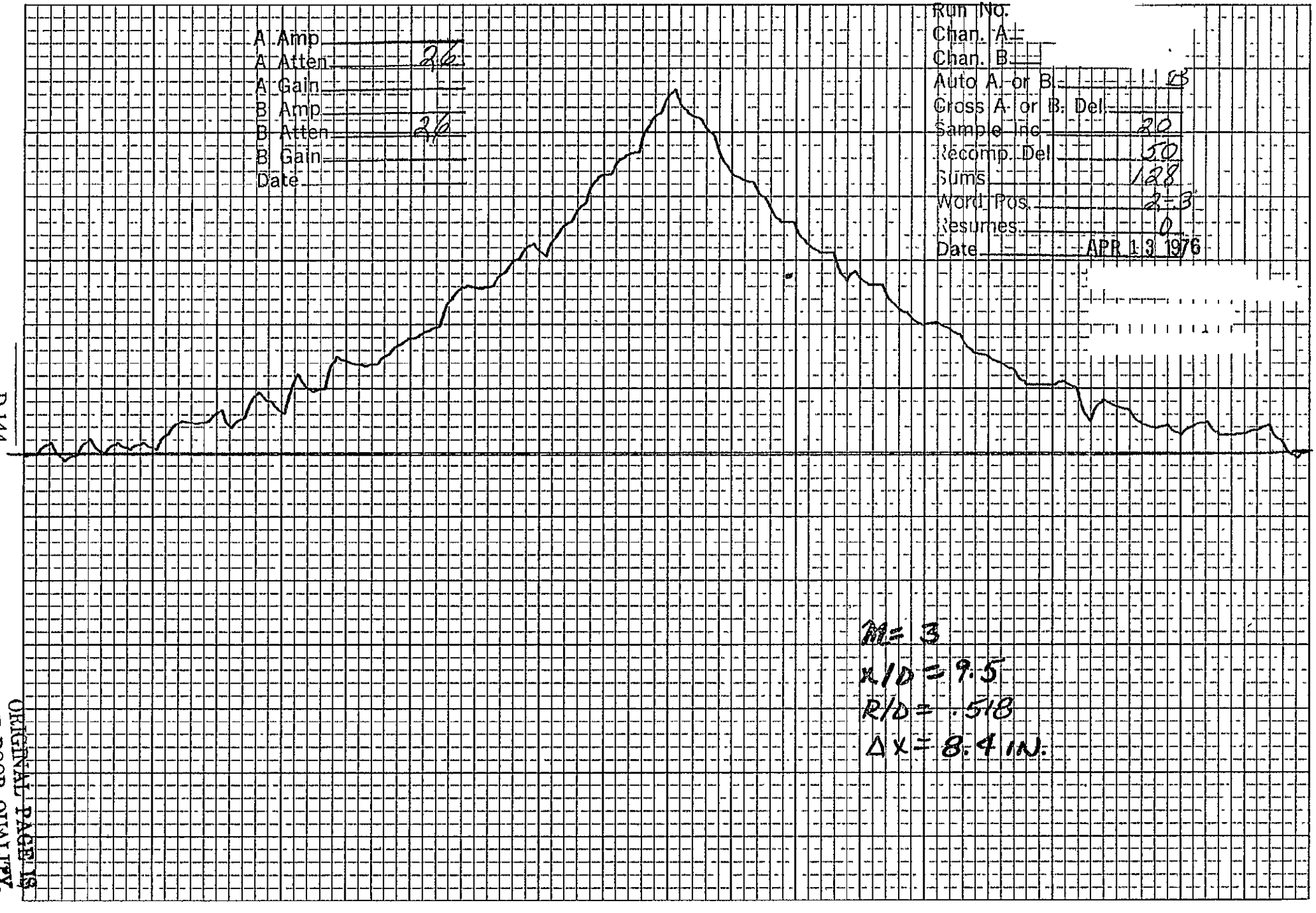

D-144

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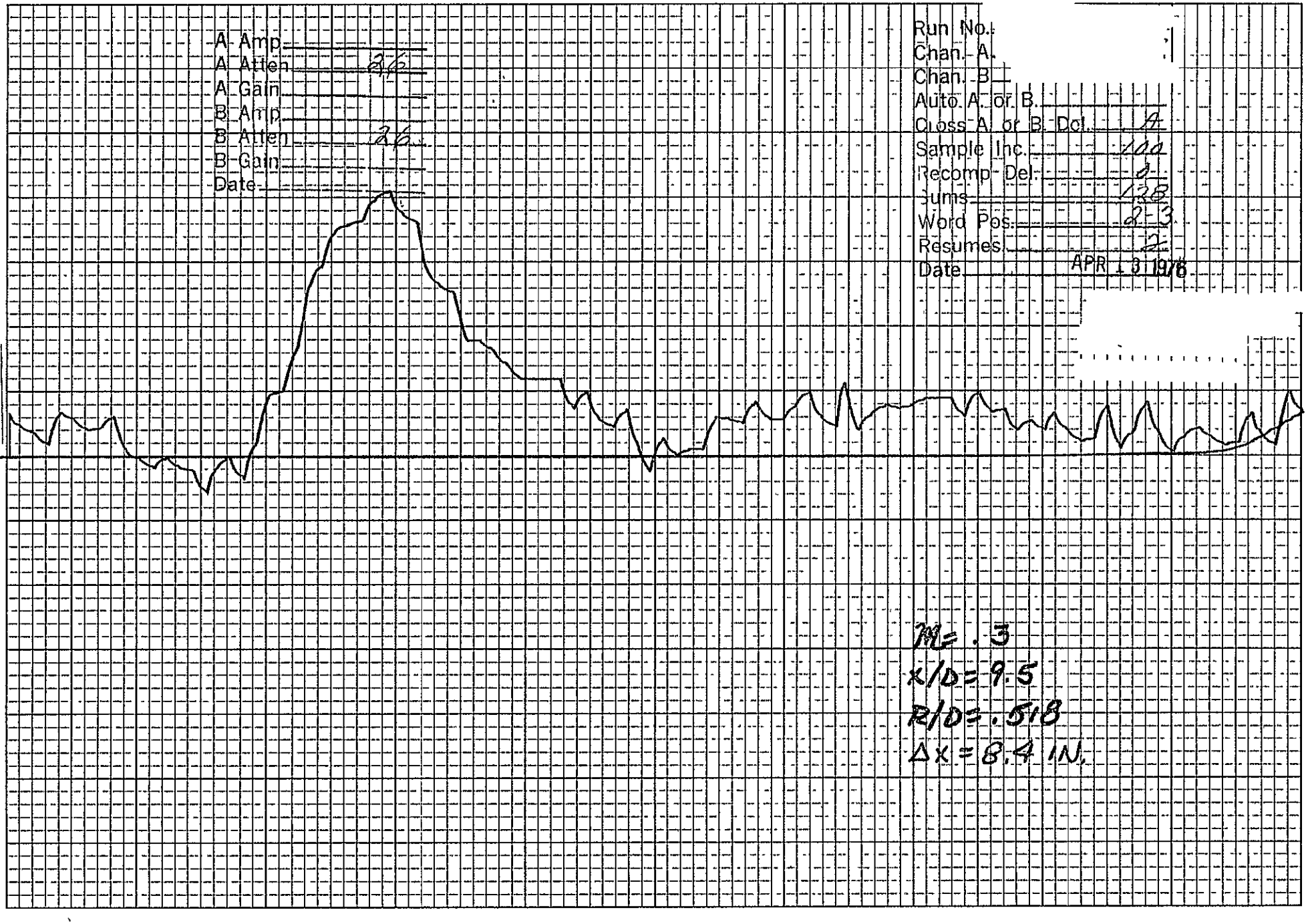

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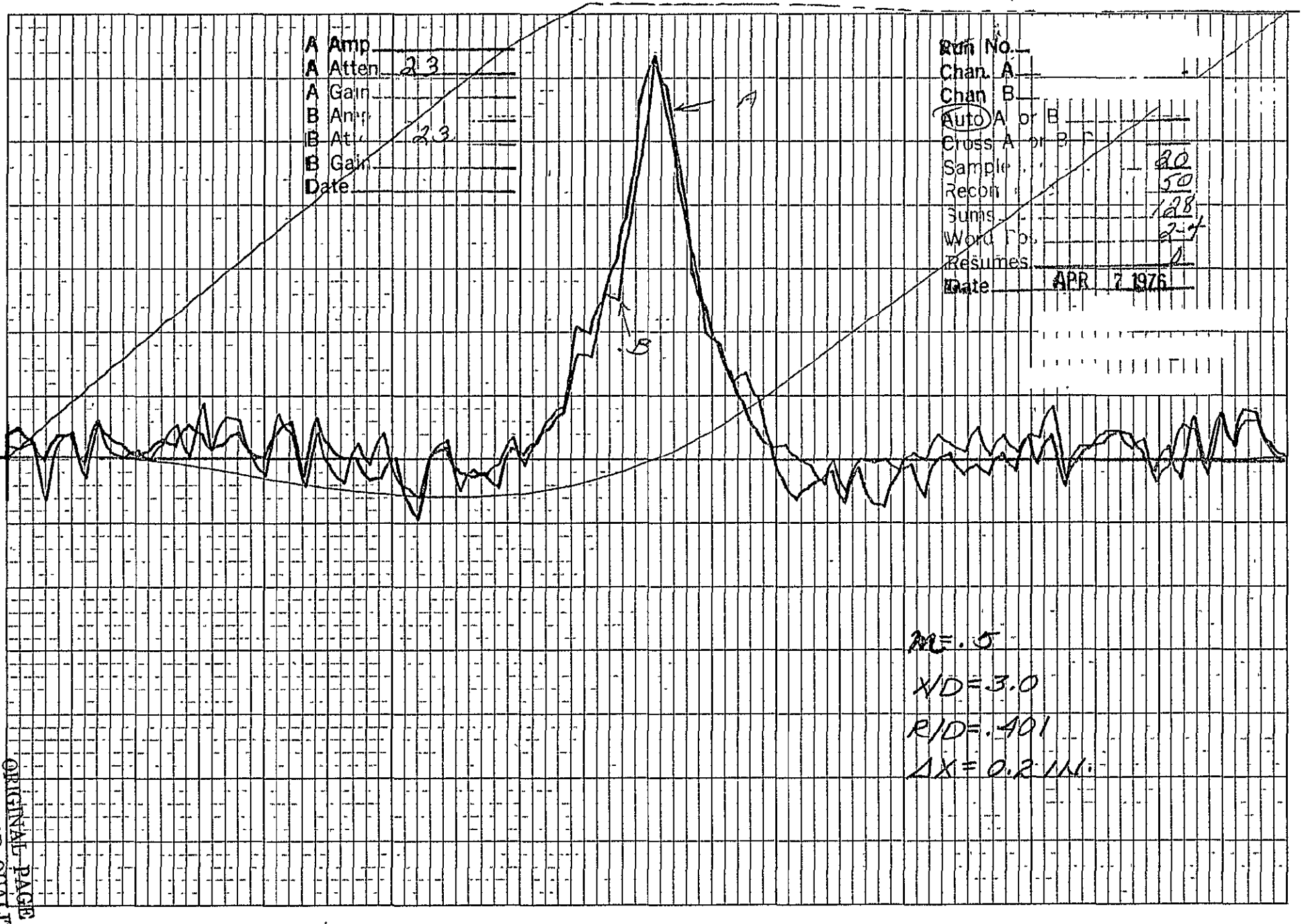

D-146

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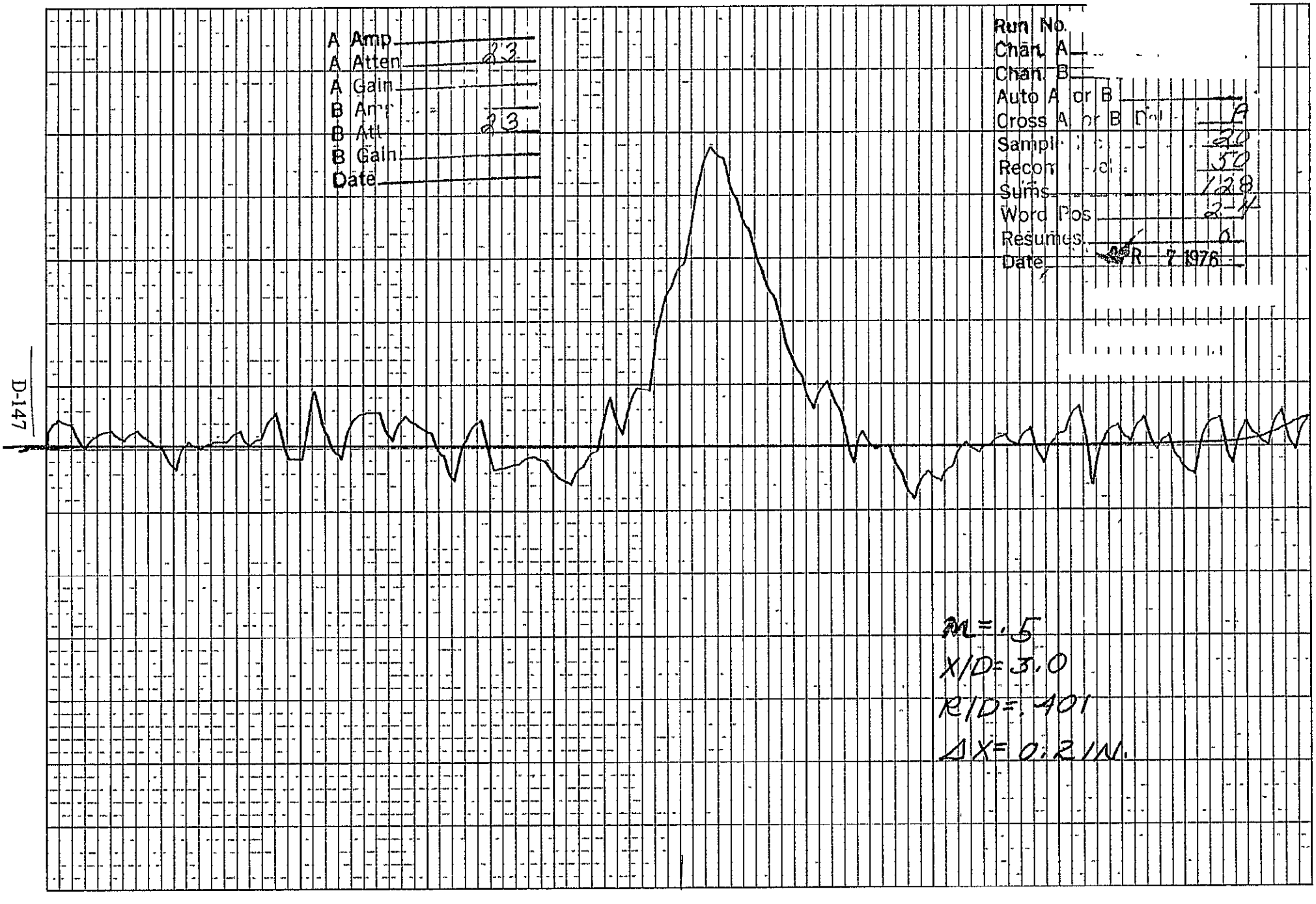

NO XY-1001 - SP 1

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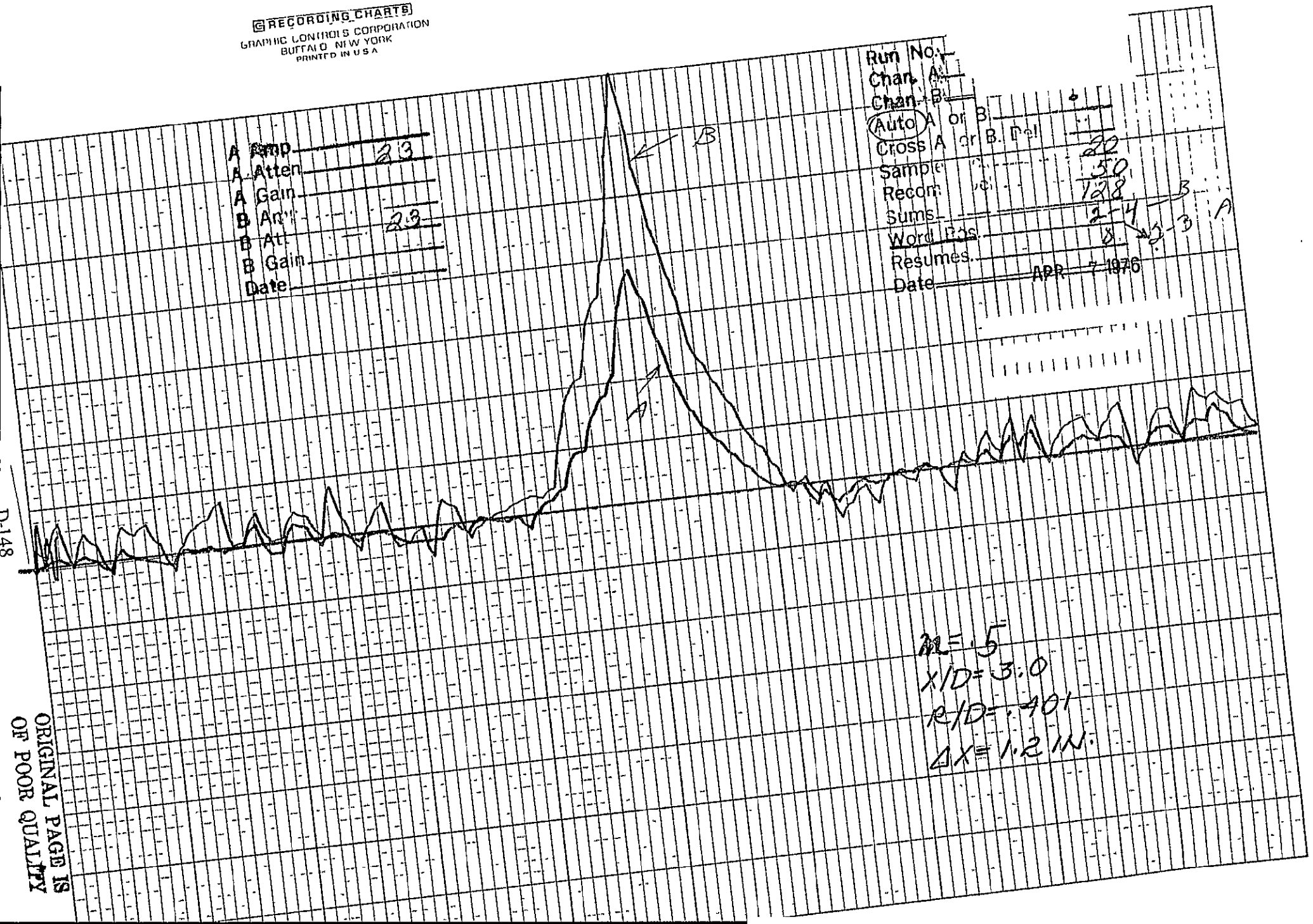

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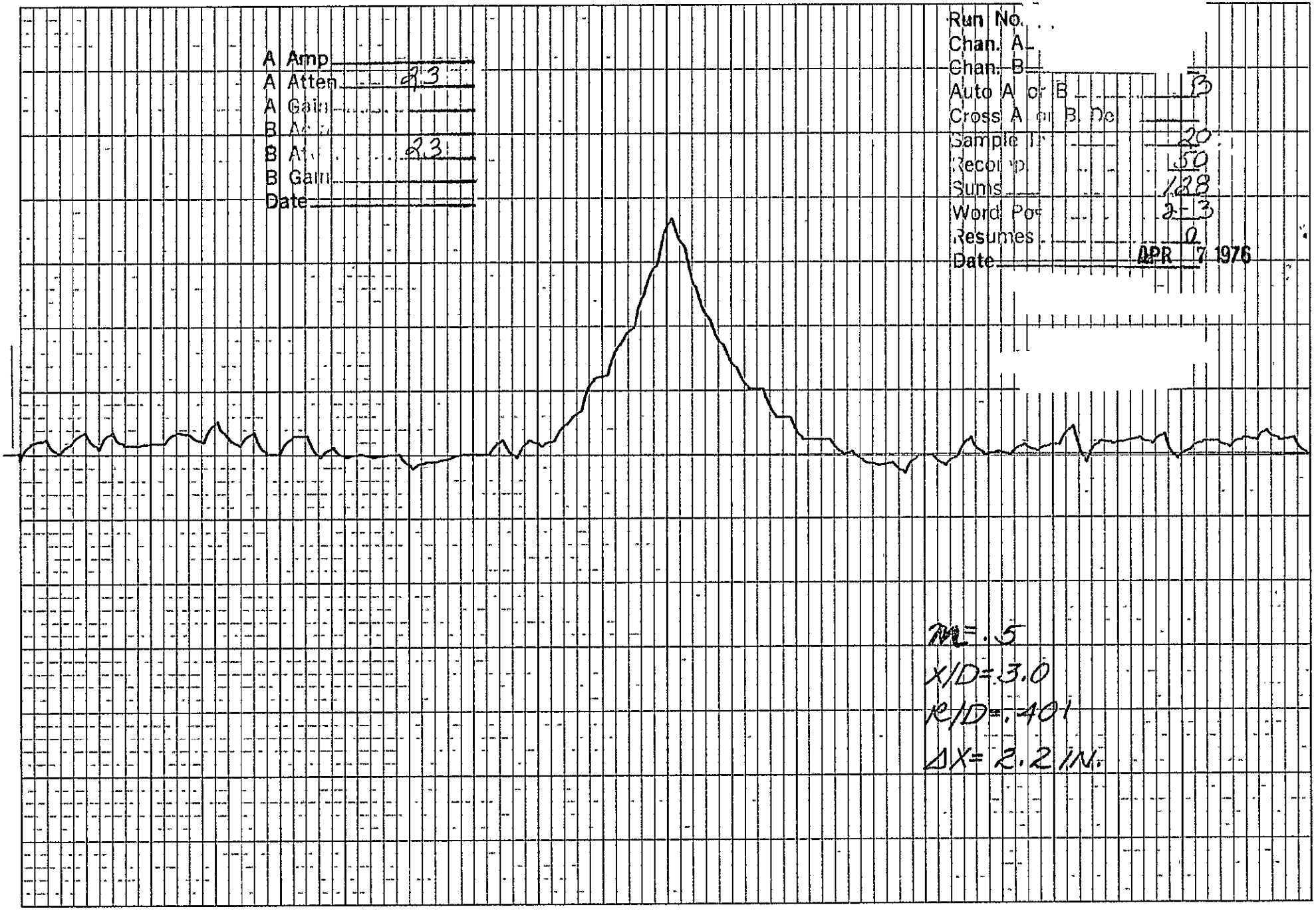

D-150

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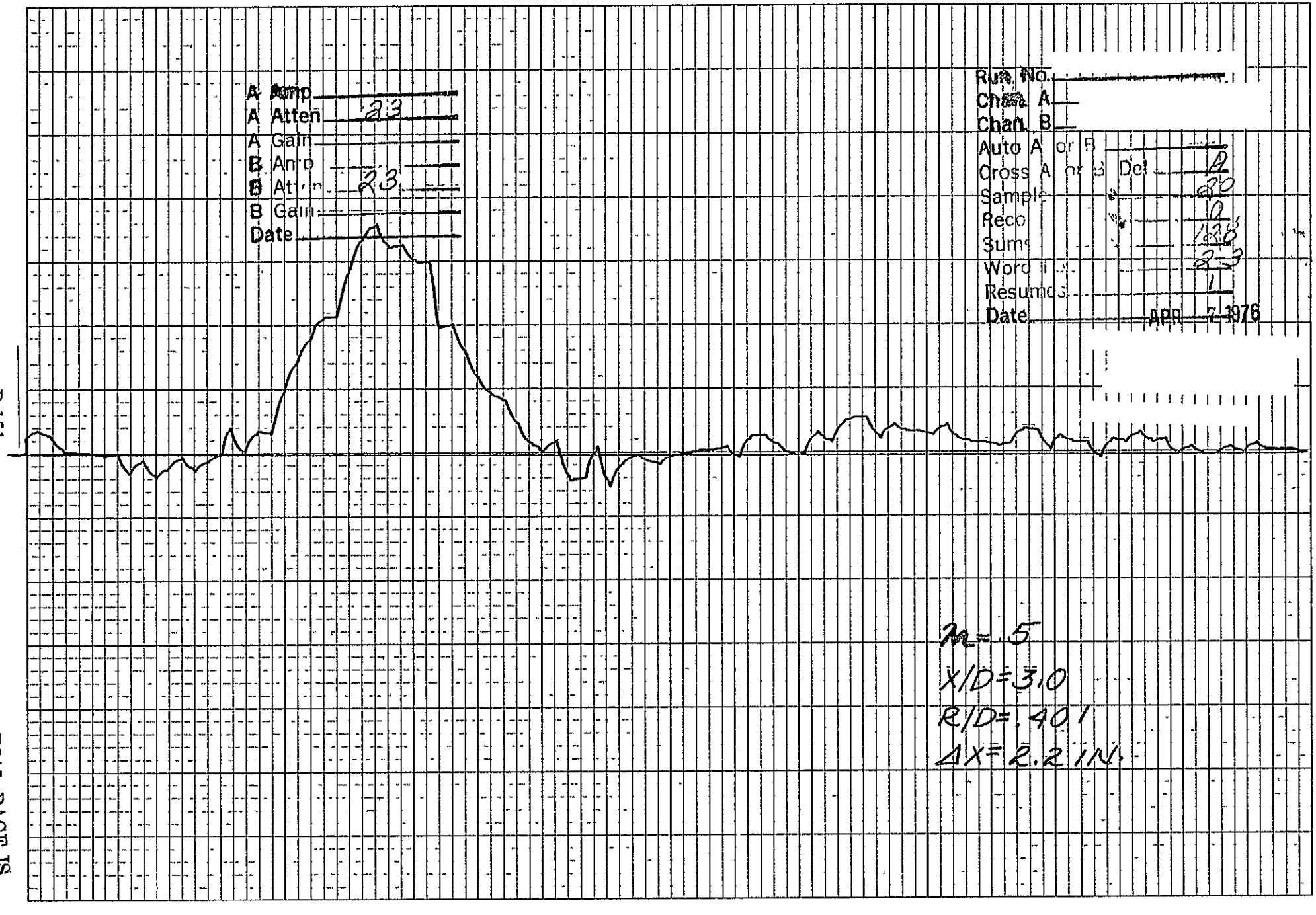

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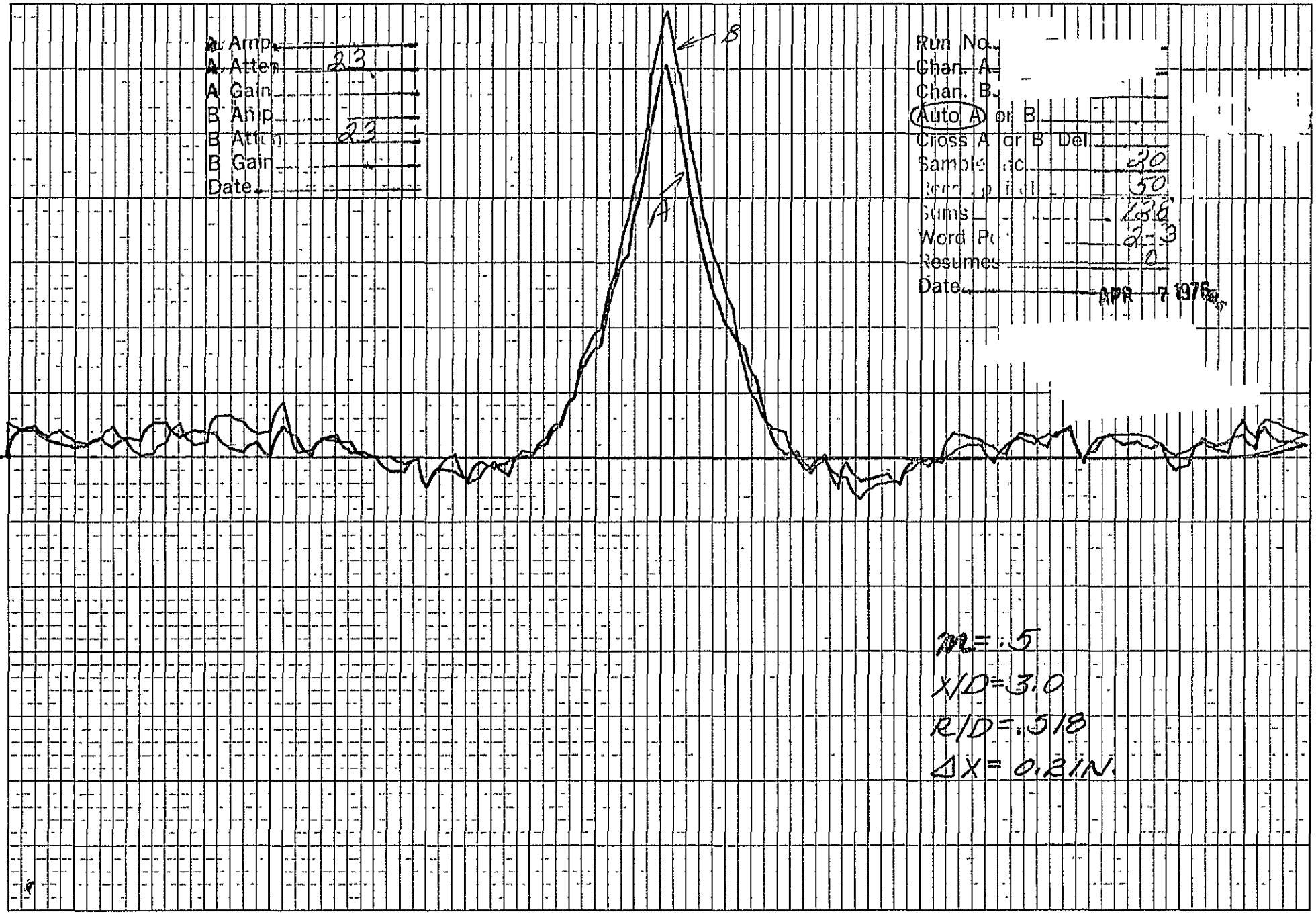

D-152

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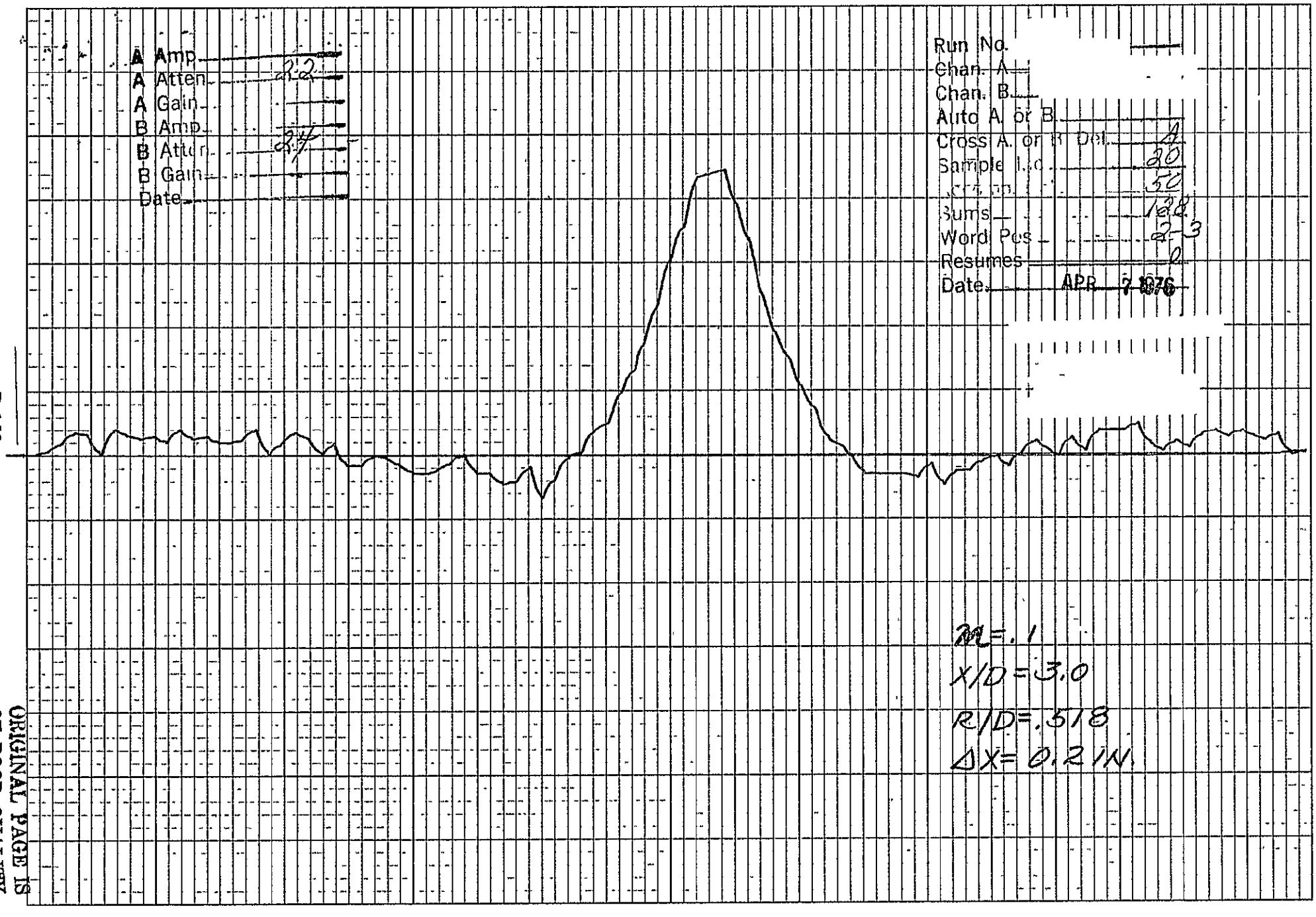

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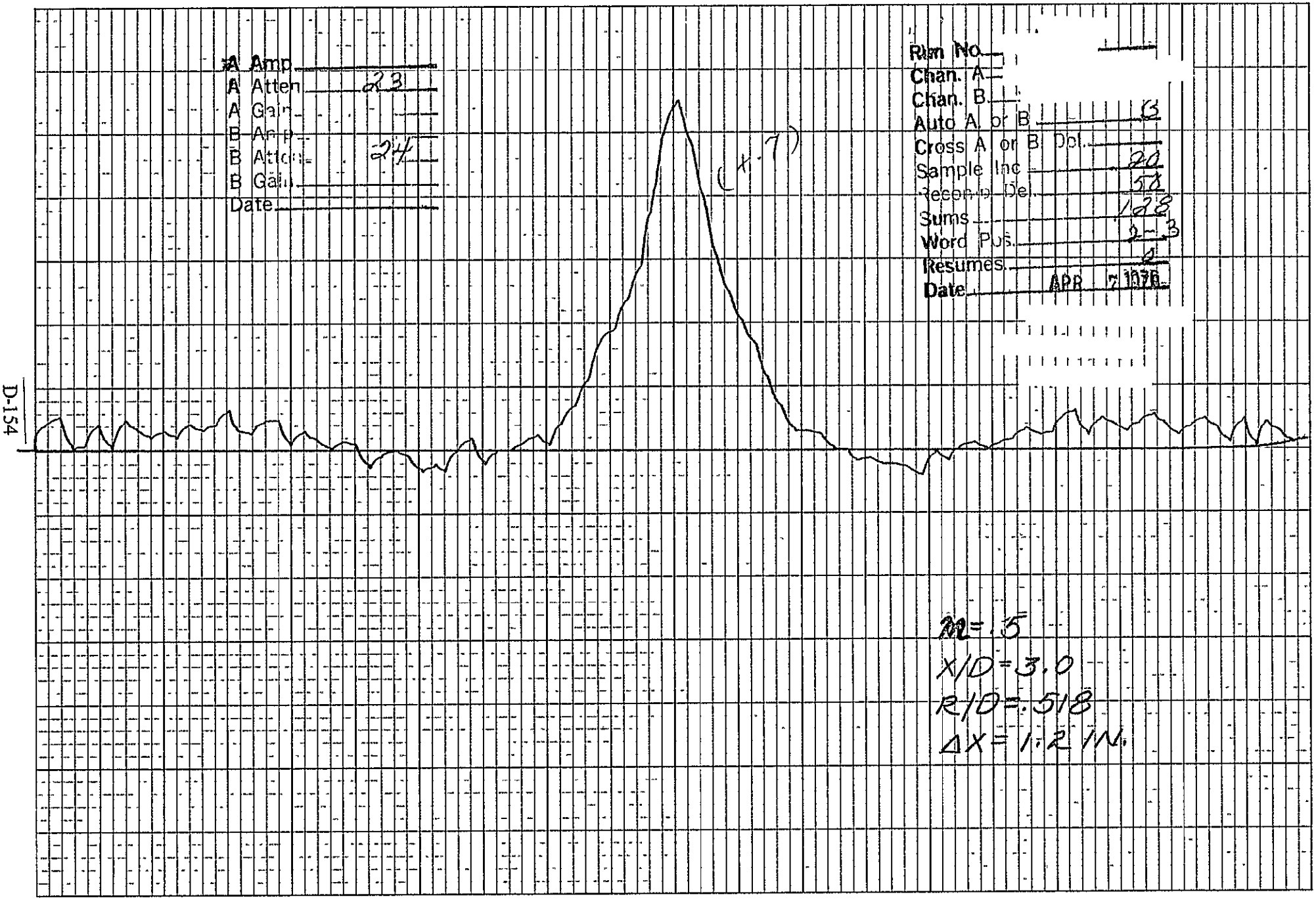

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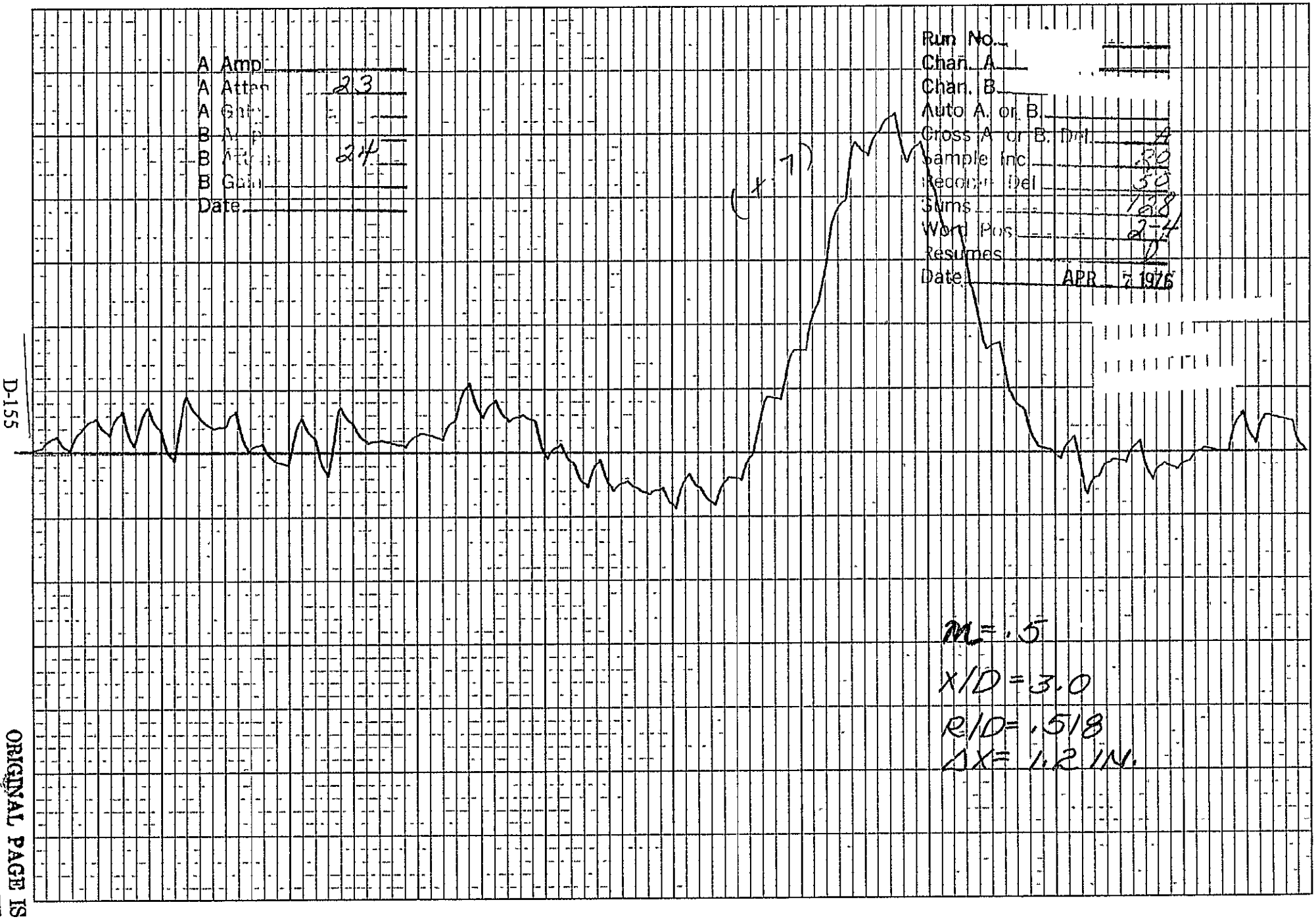

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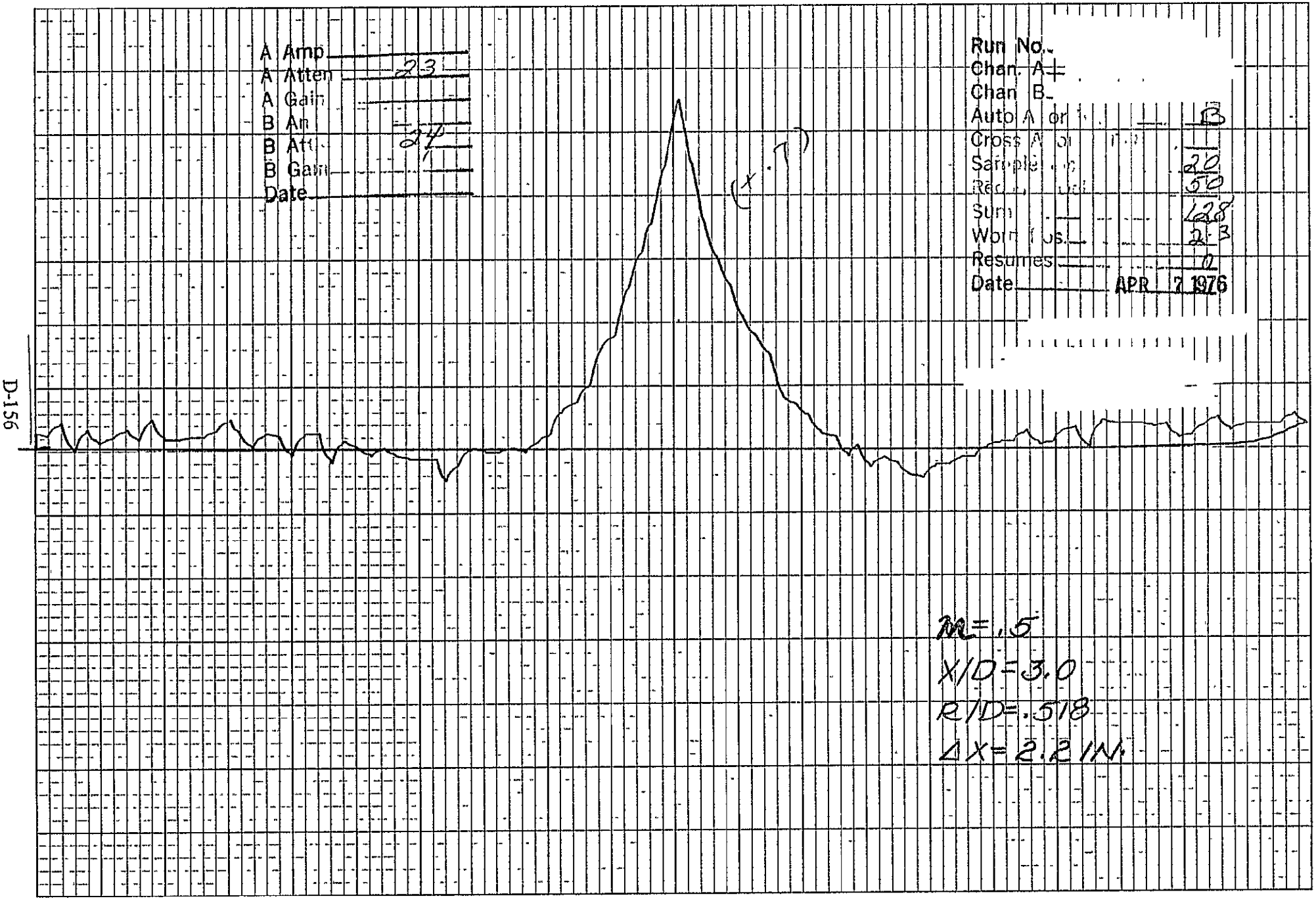

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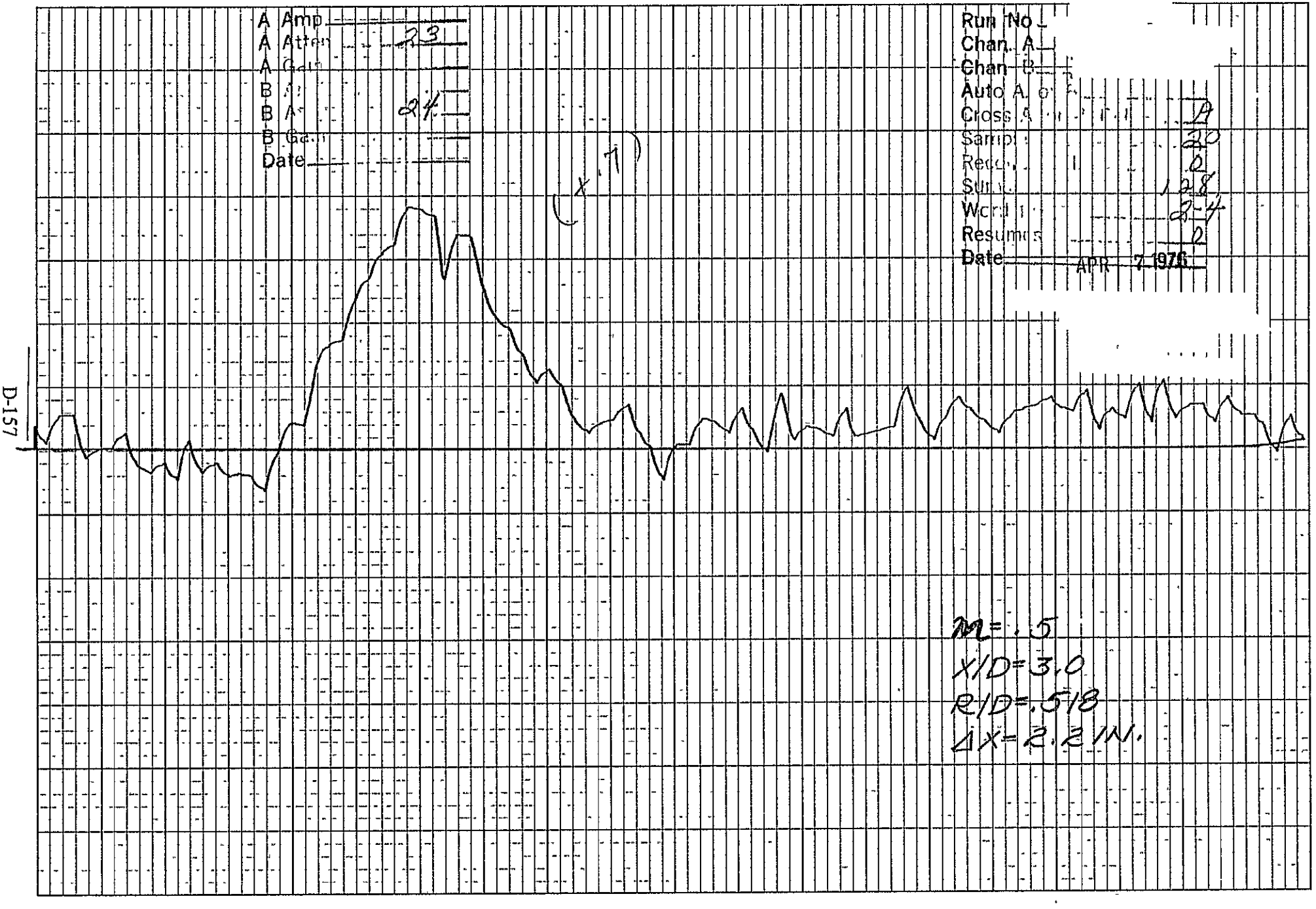

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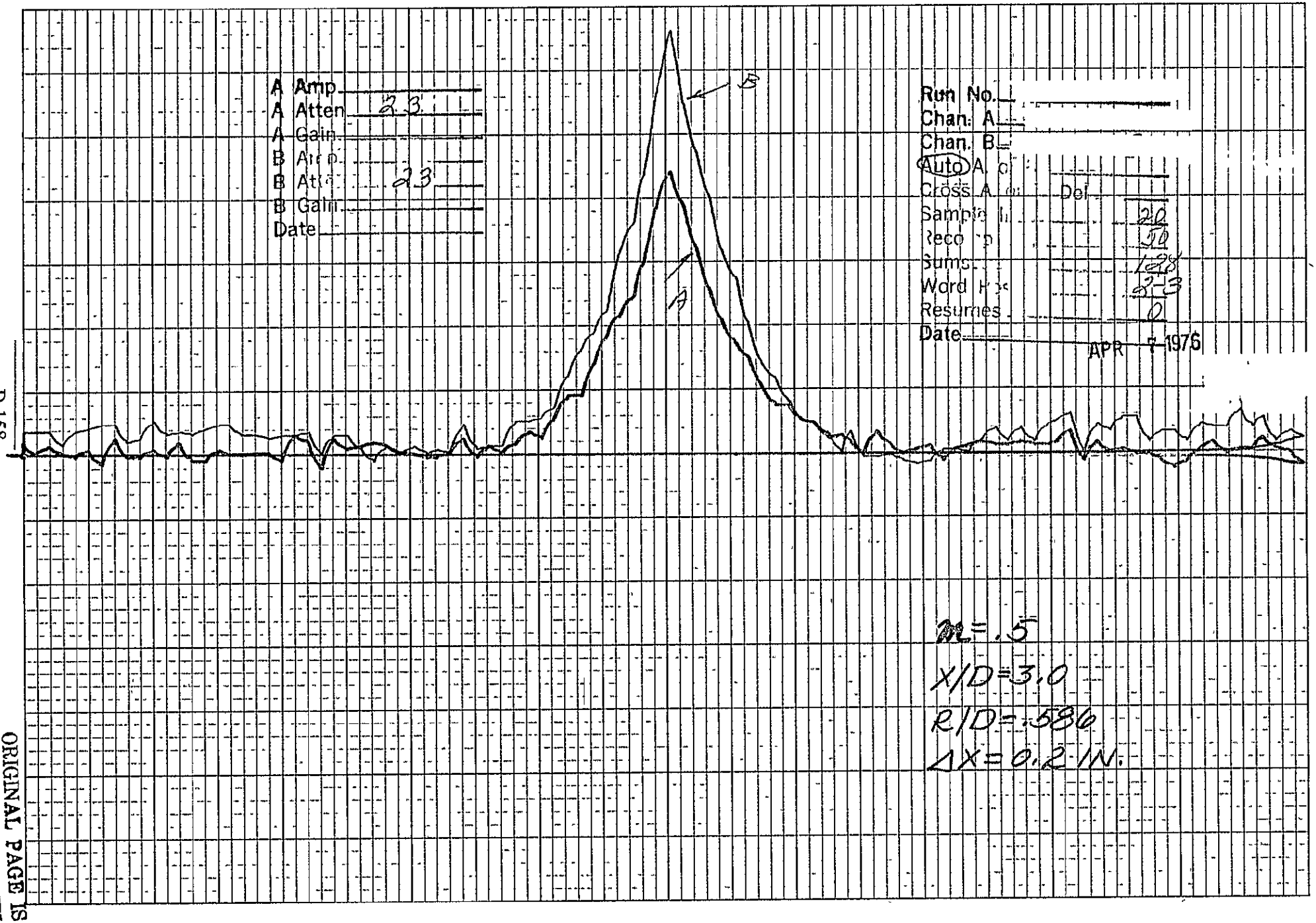

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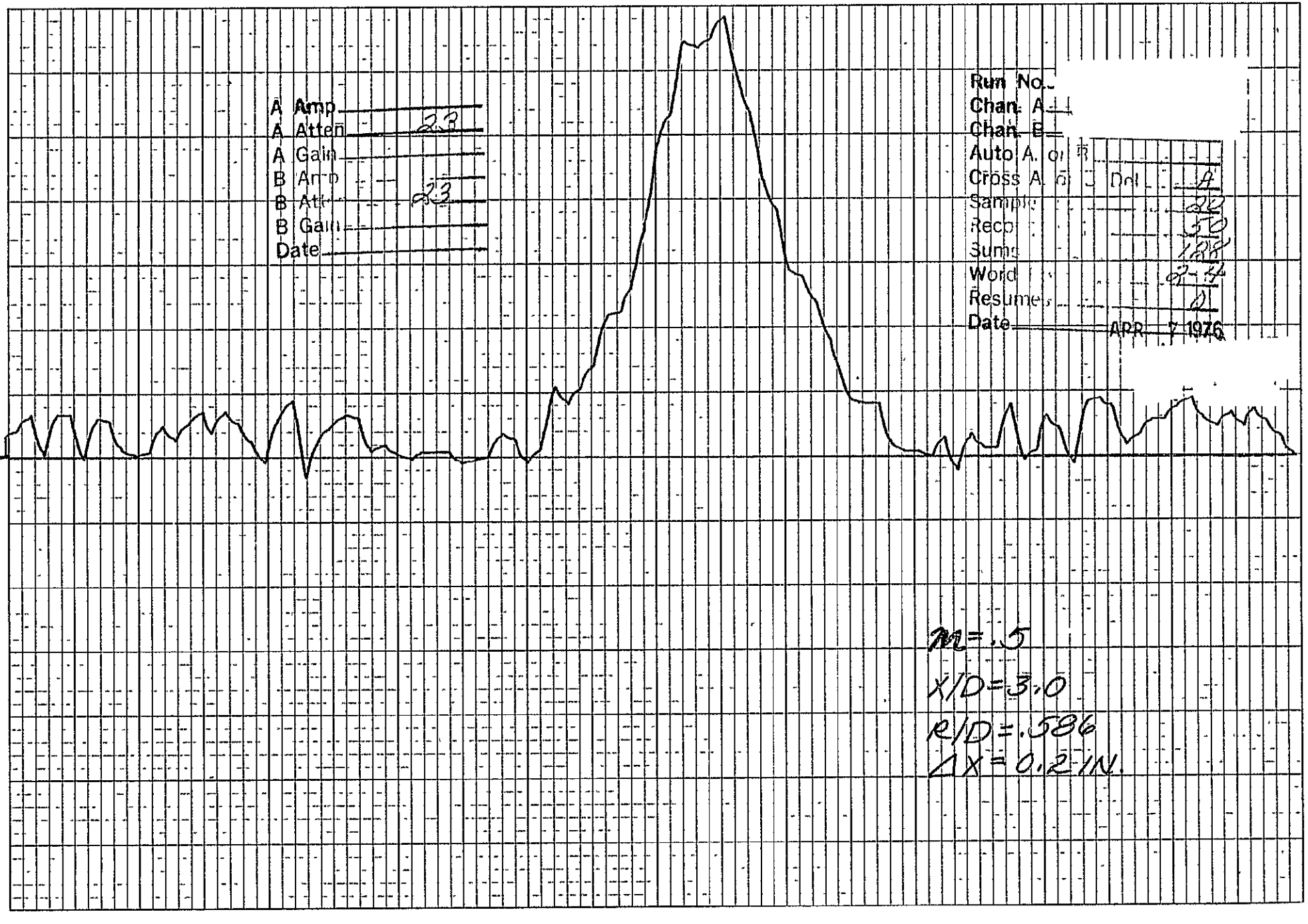

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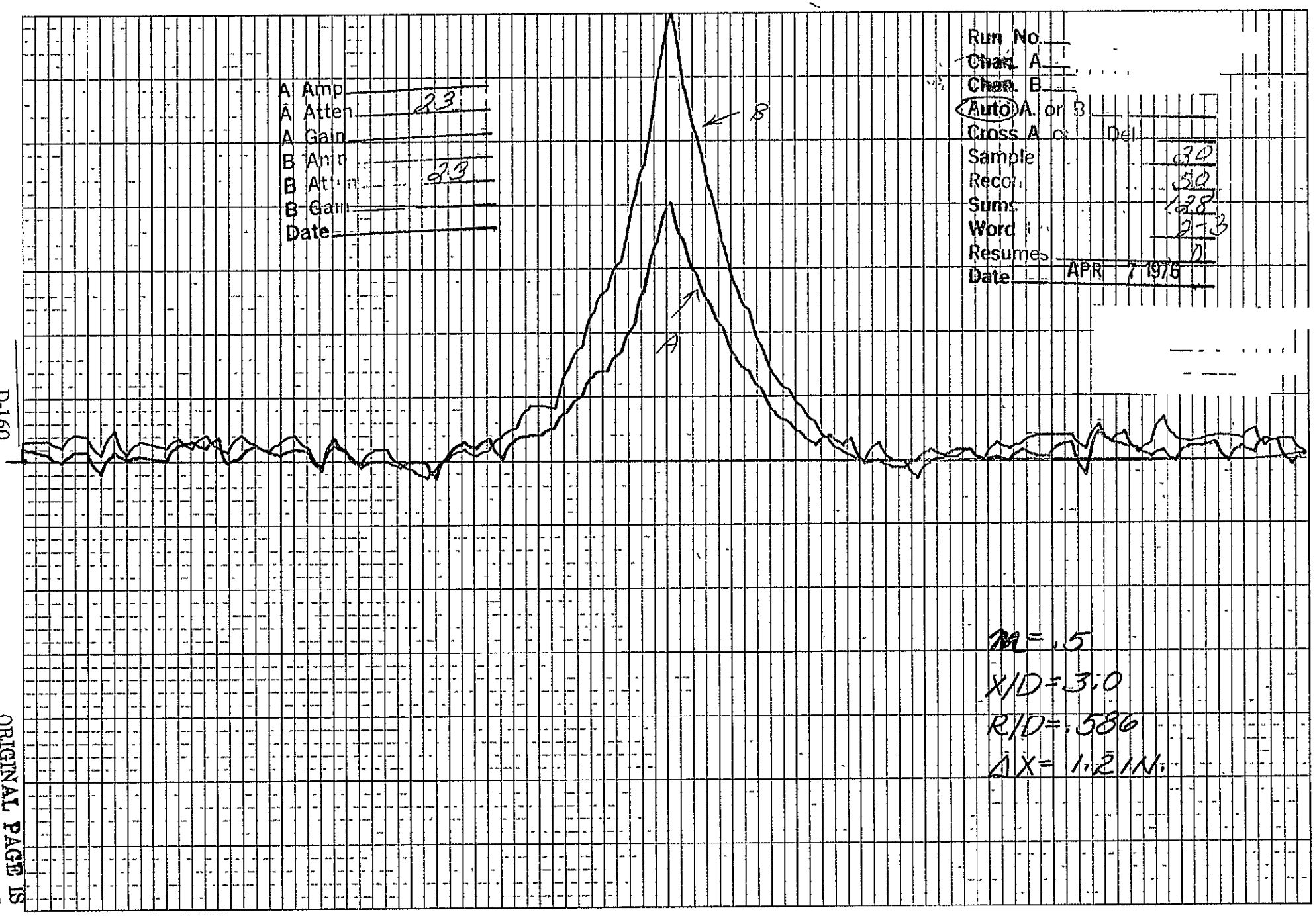

D-160

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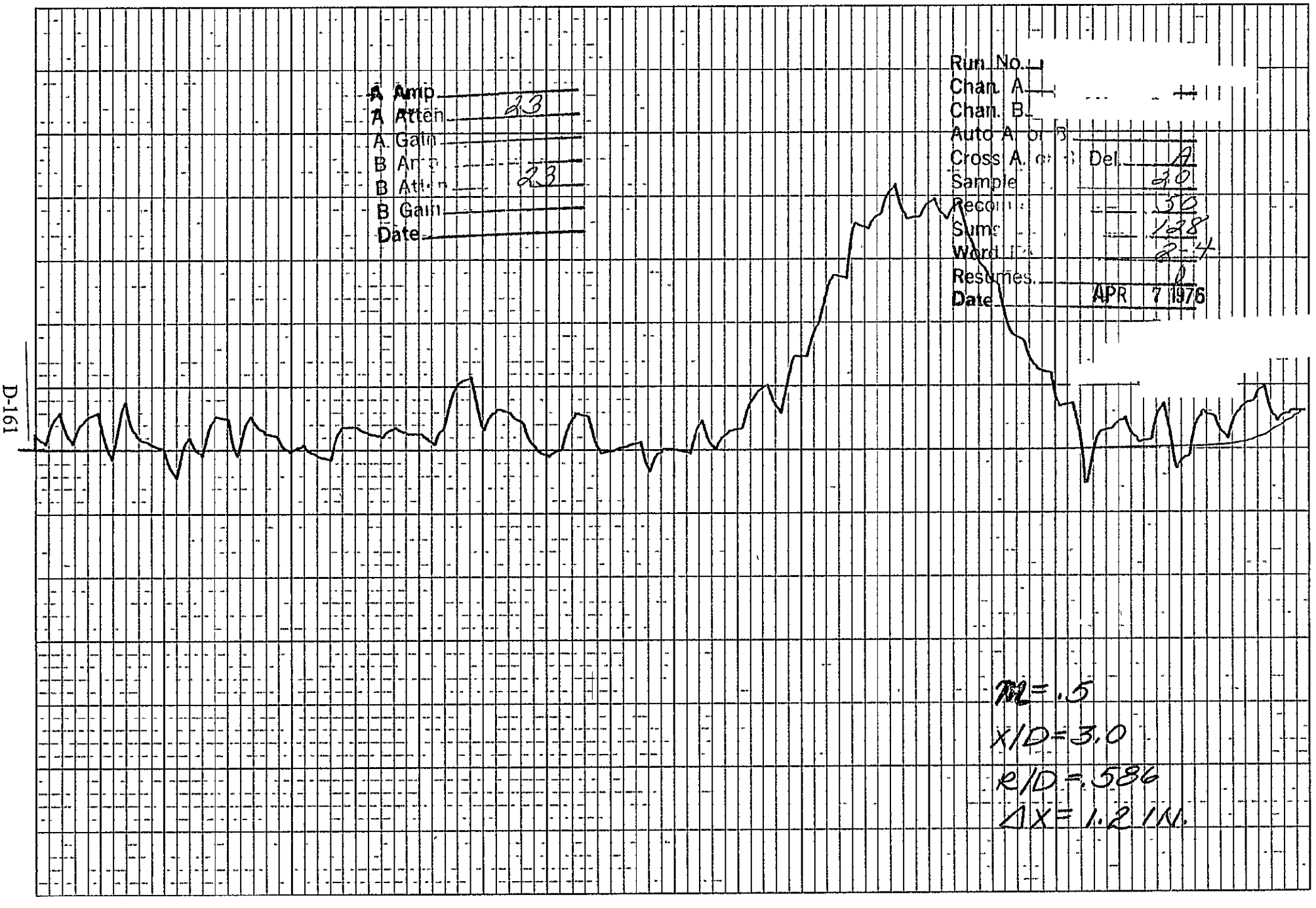
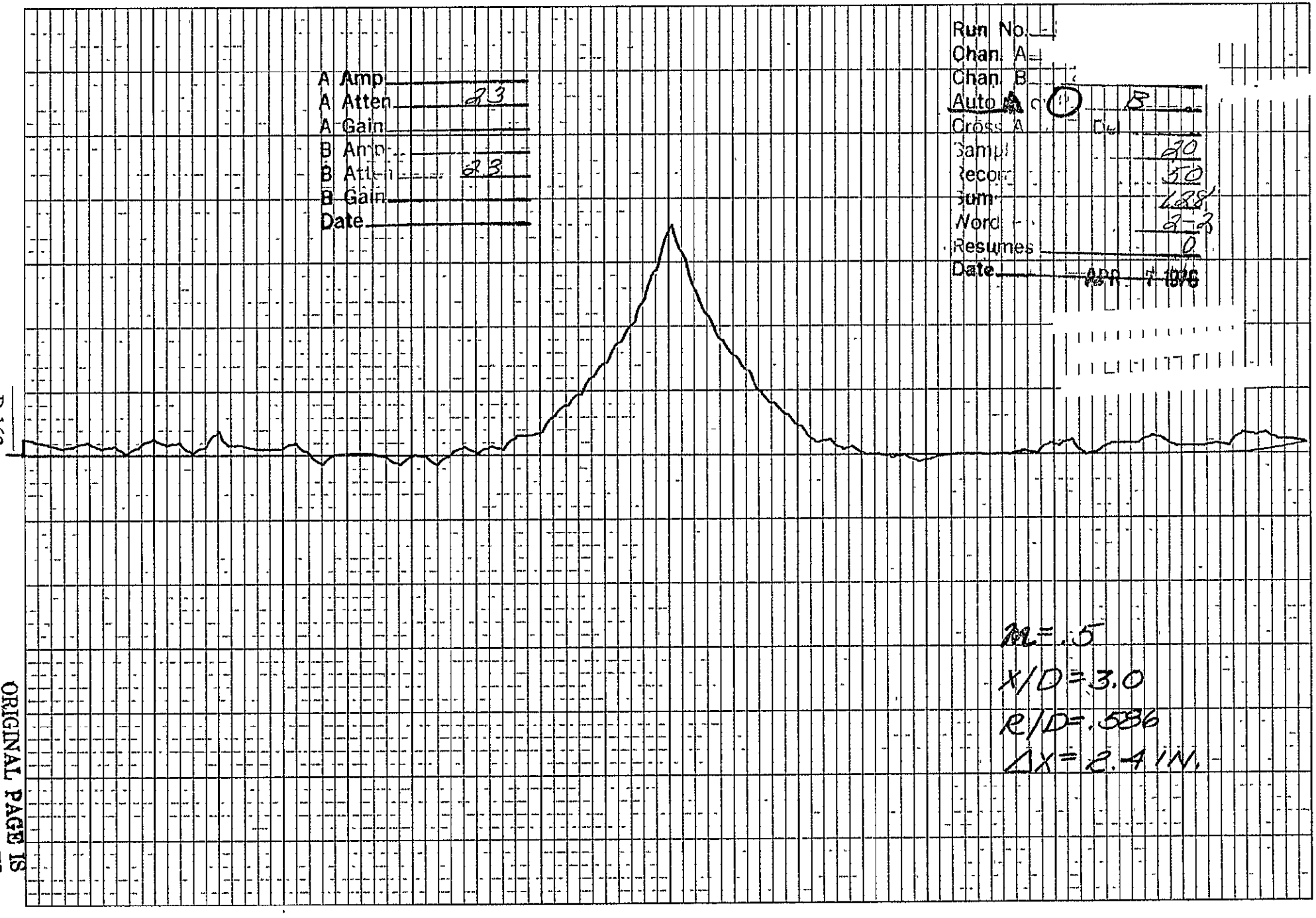


D-161



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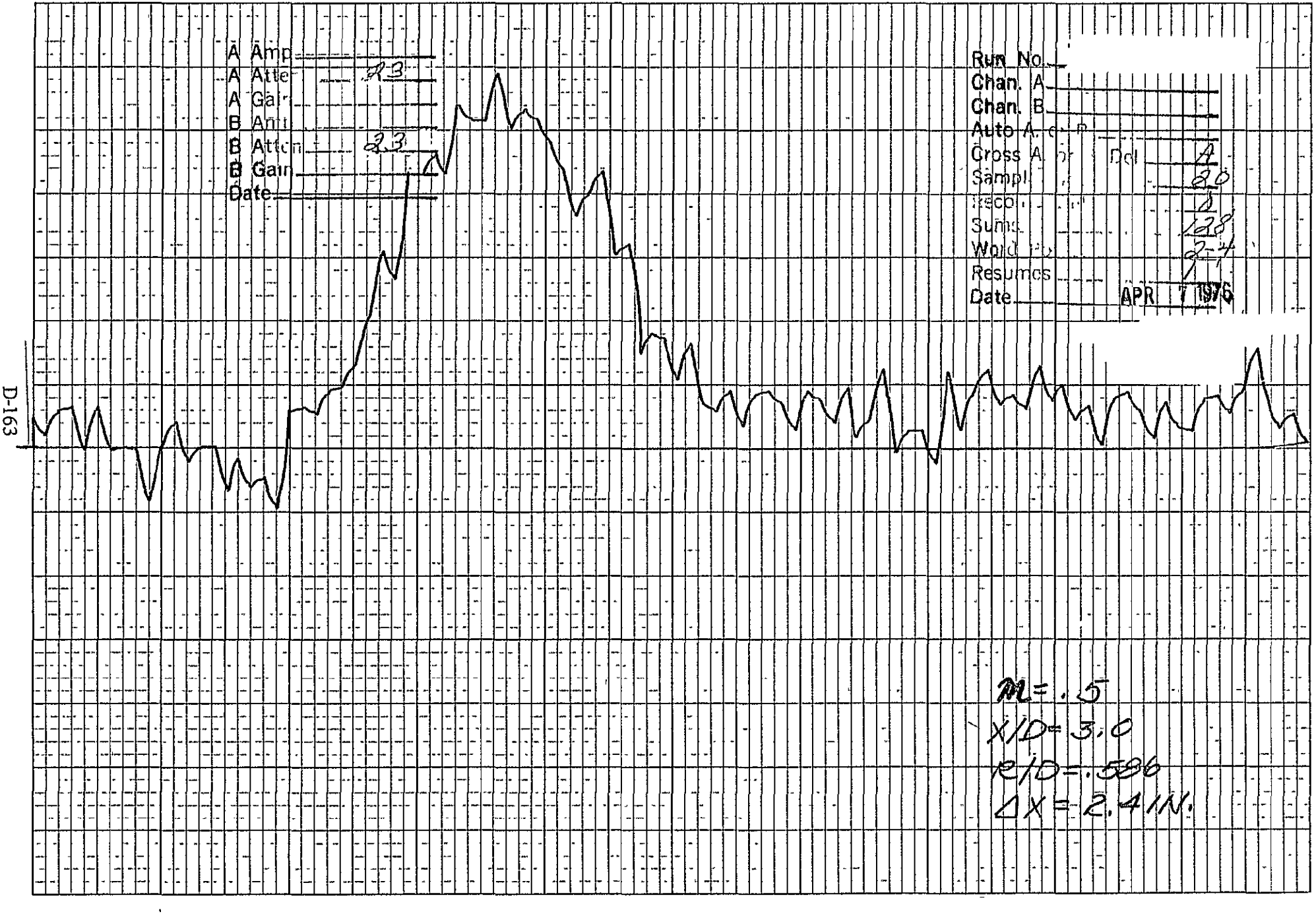

D-163

$M = .5$
$X/D = 3.0$
$R/D = .586$
$\Delta X = 2.41$ IN.

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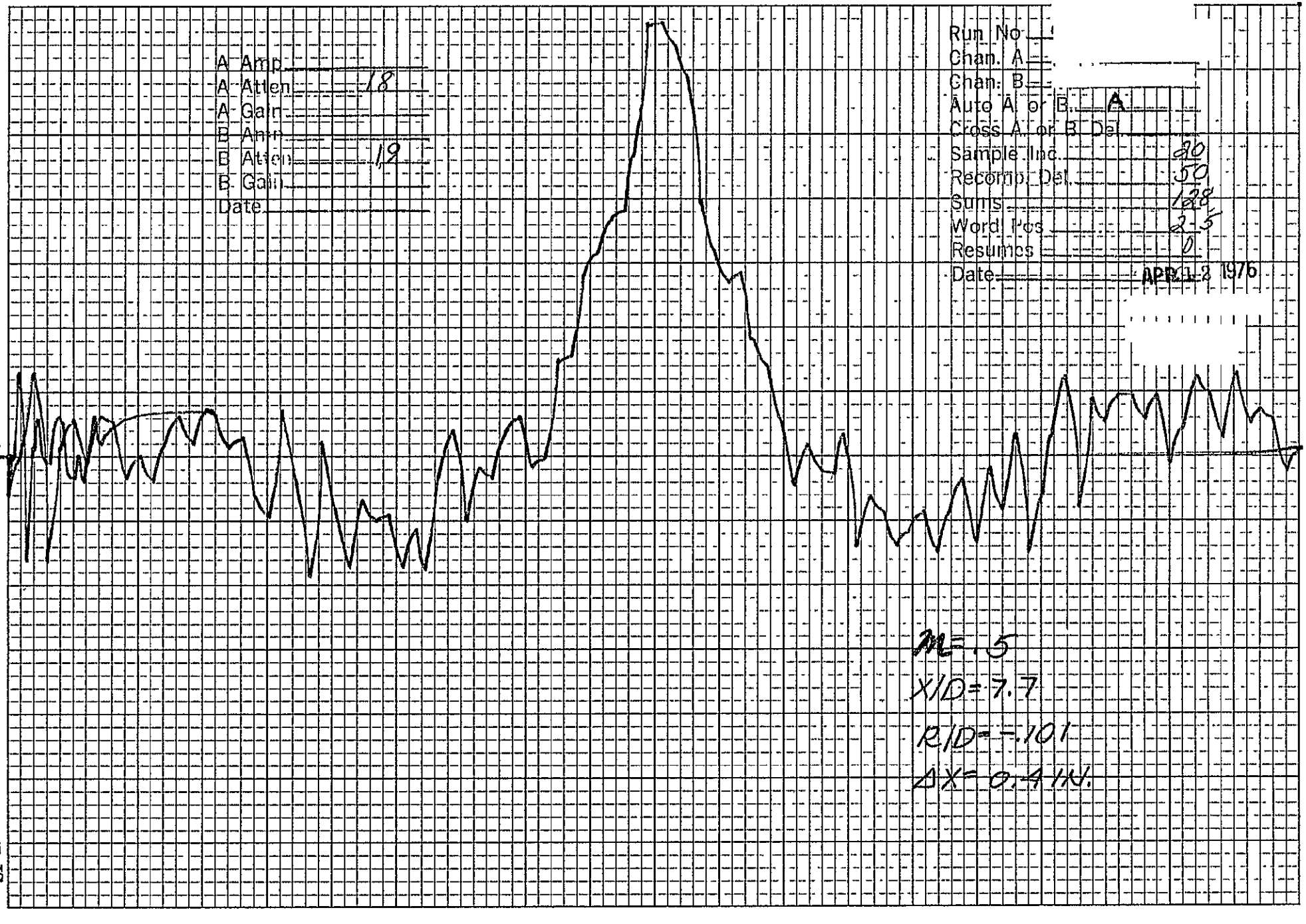
No. XY-1001- SP 1

C-3



D-164

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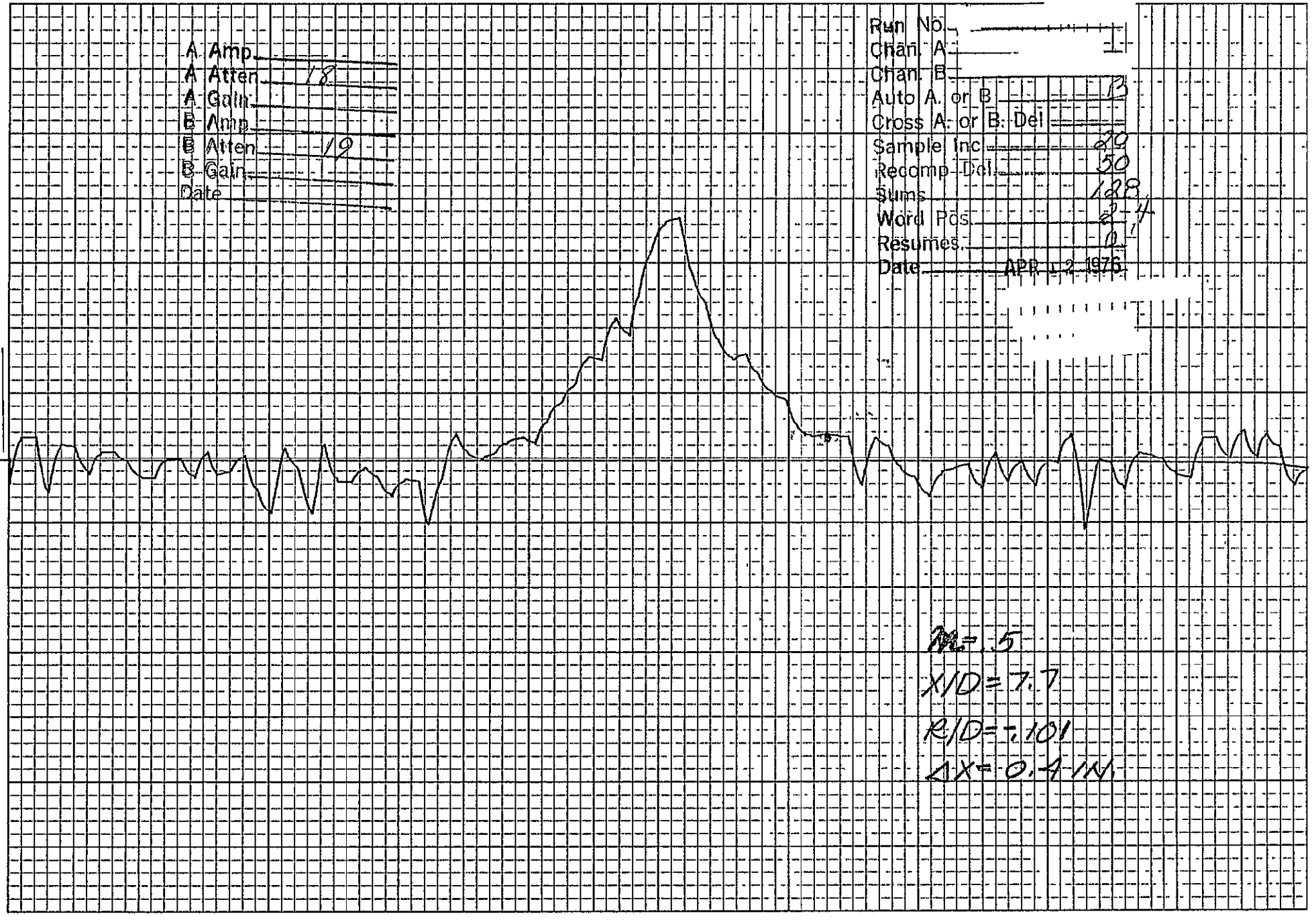

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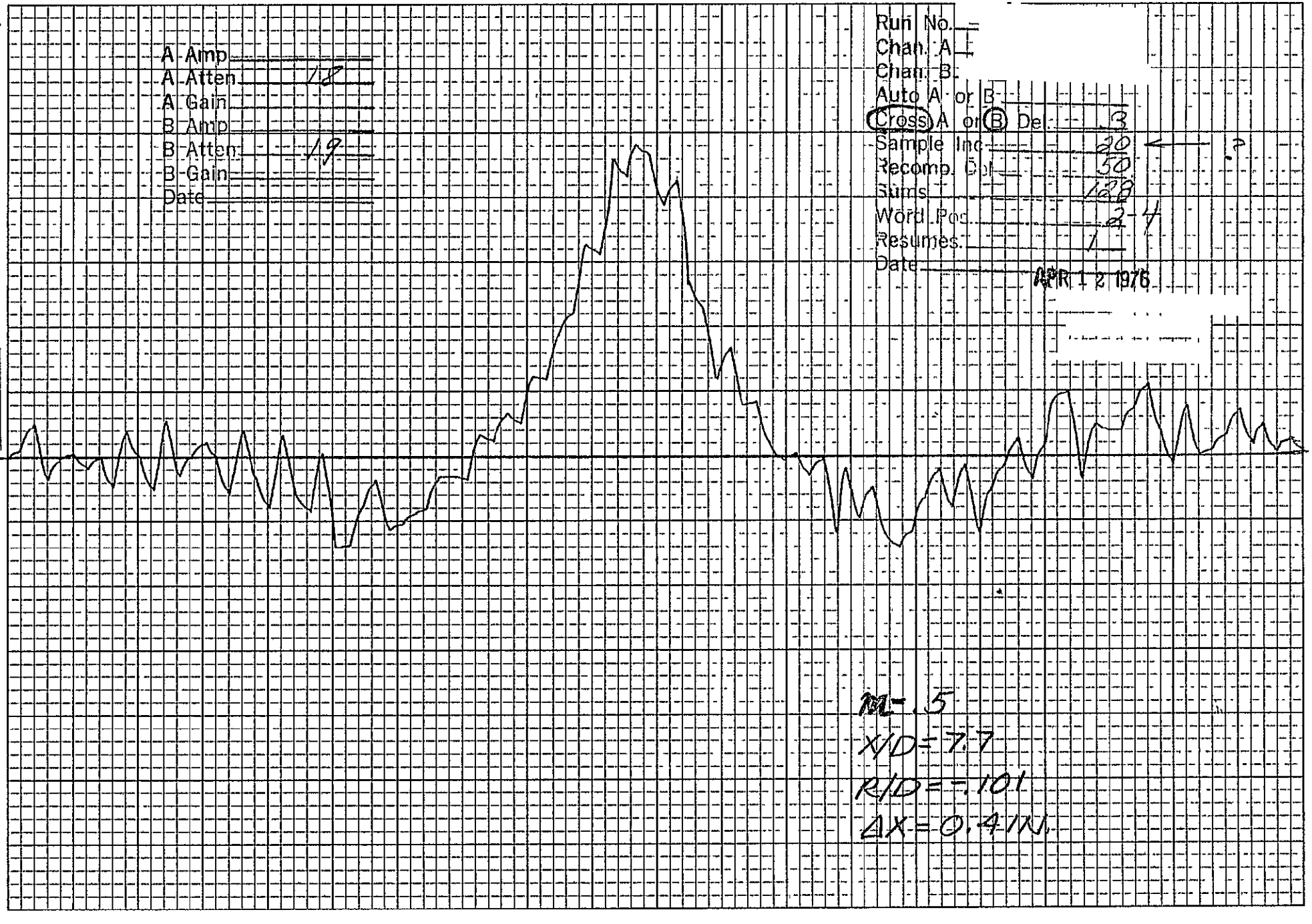

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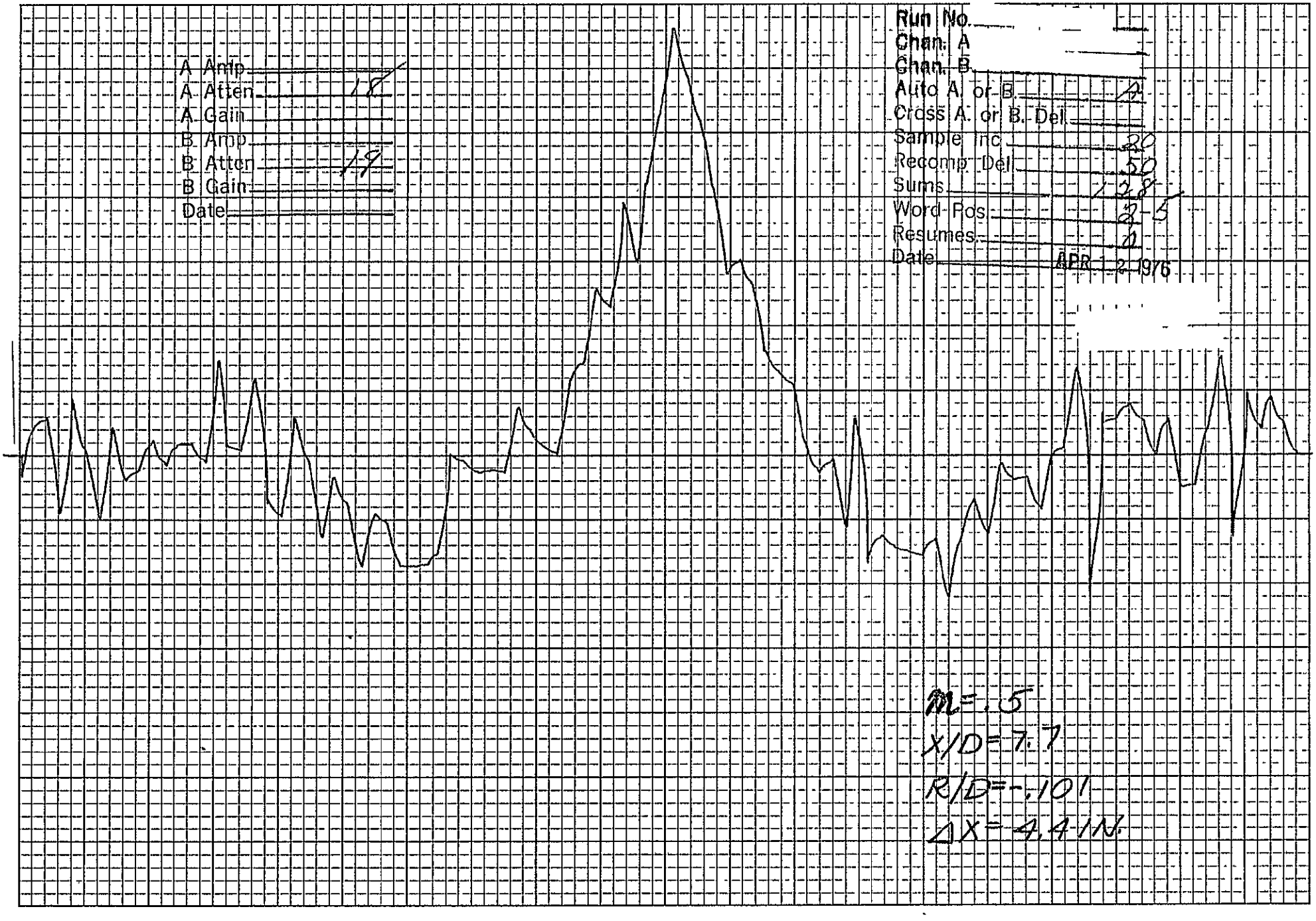

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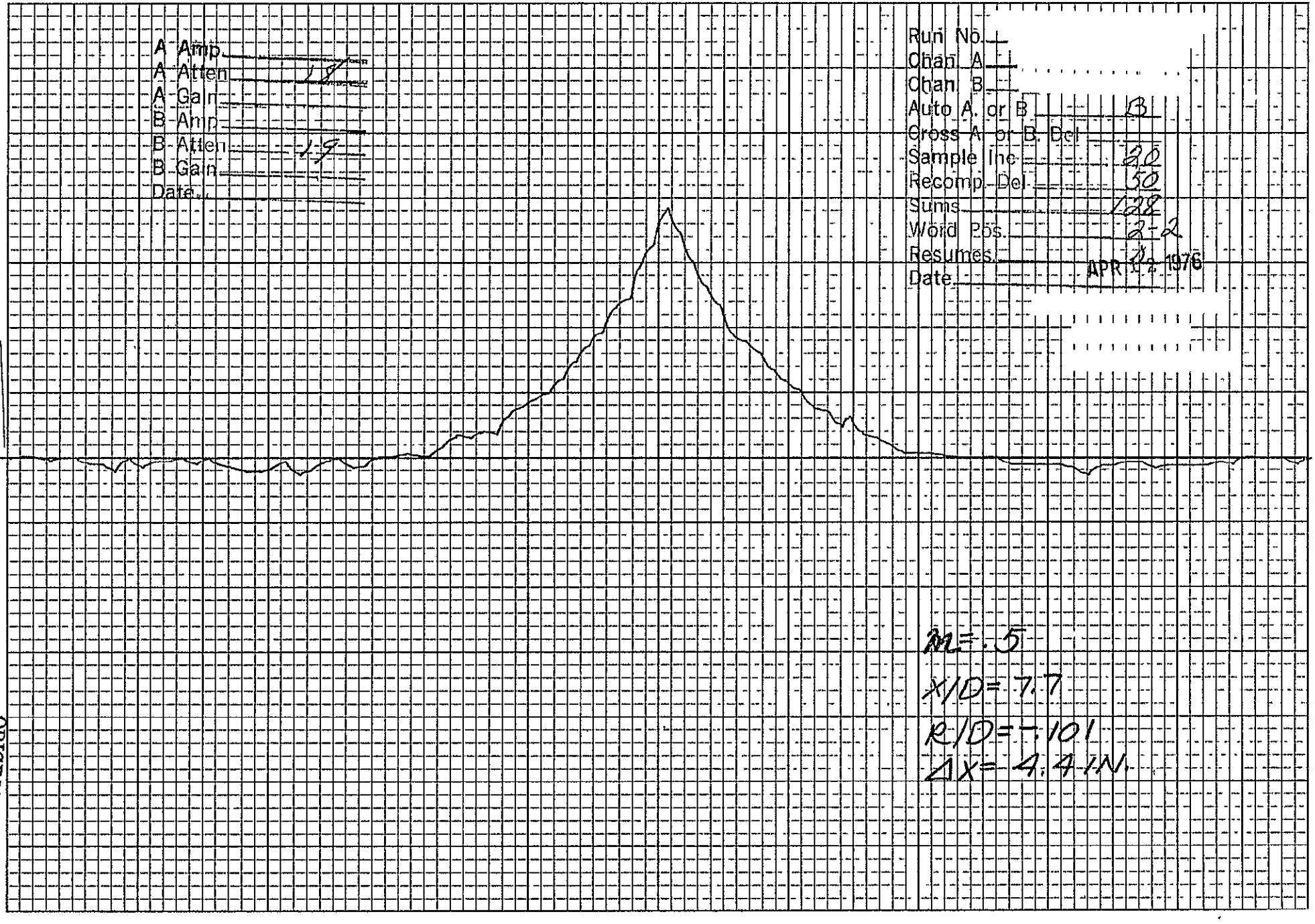

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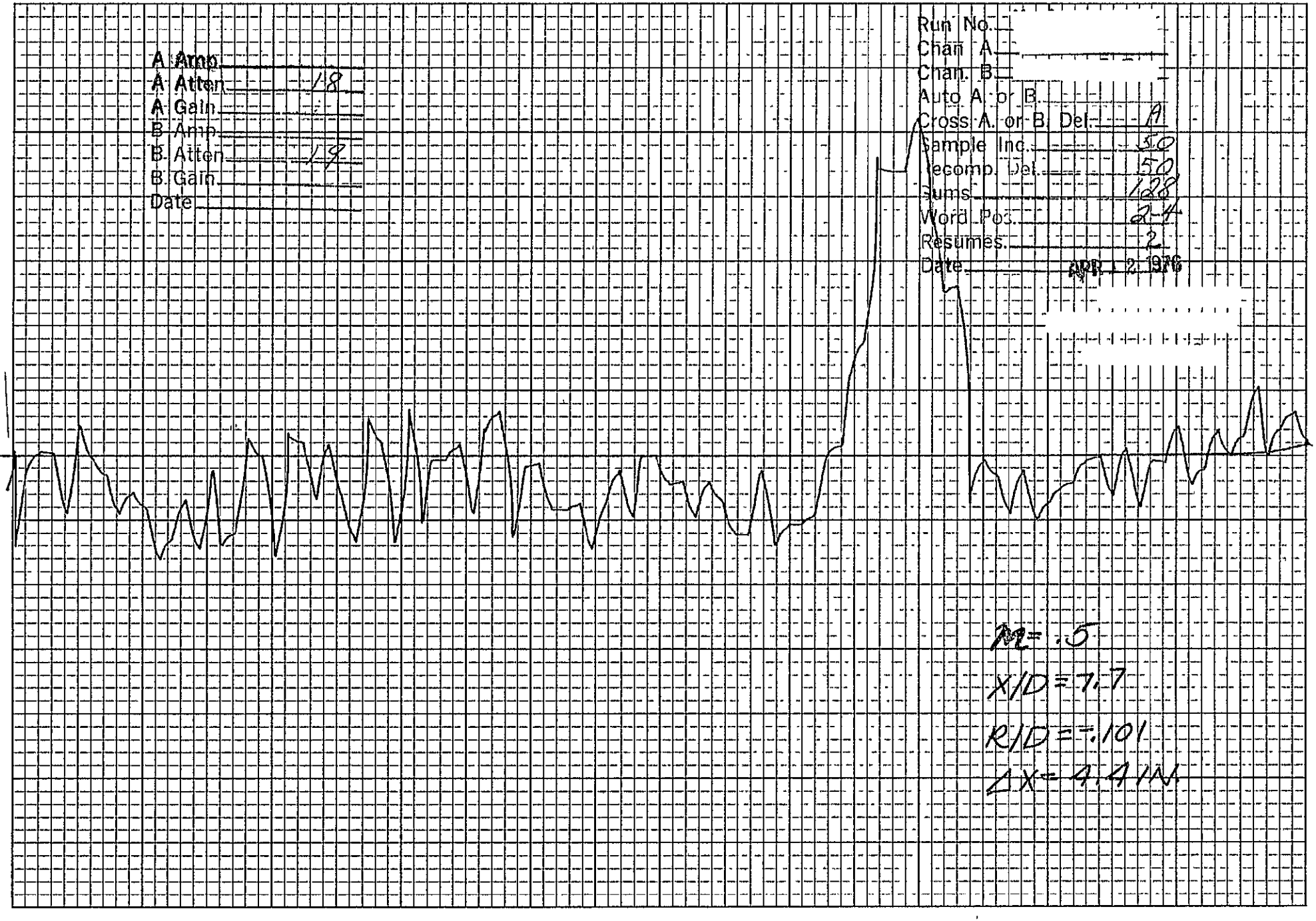

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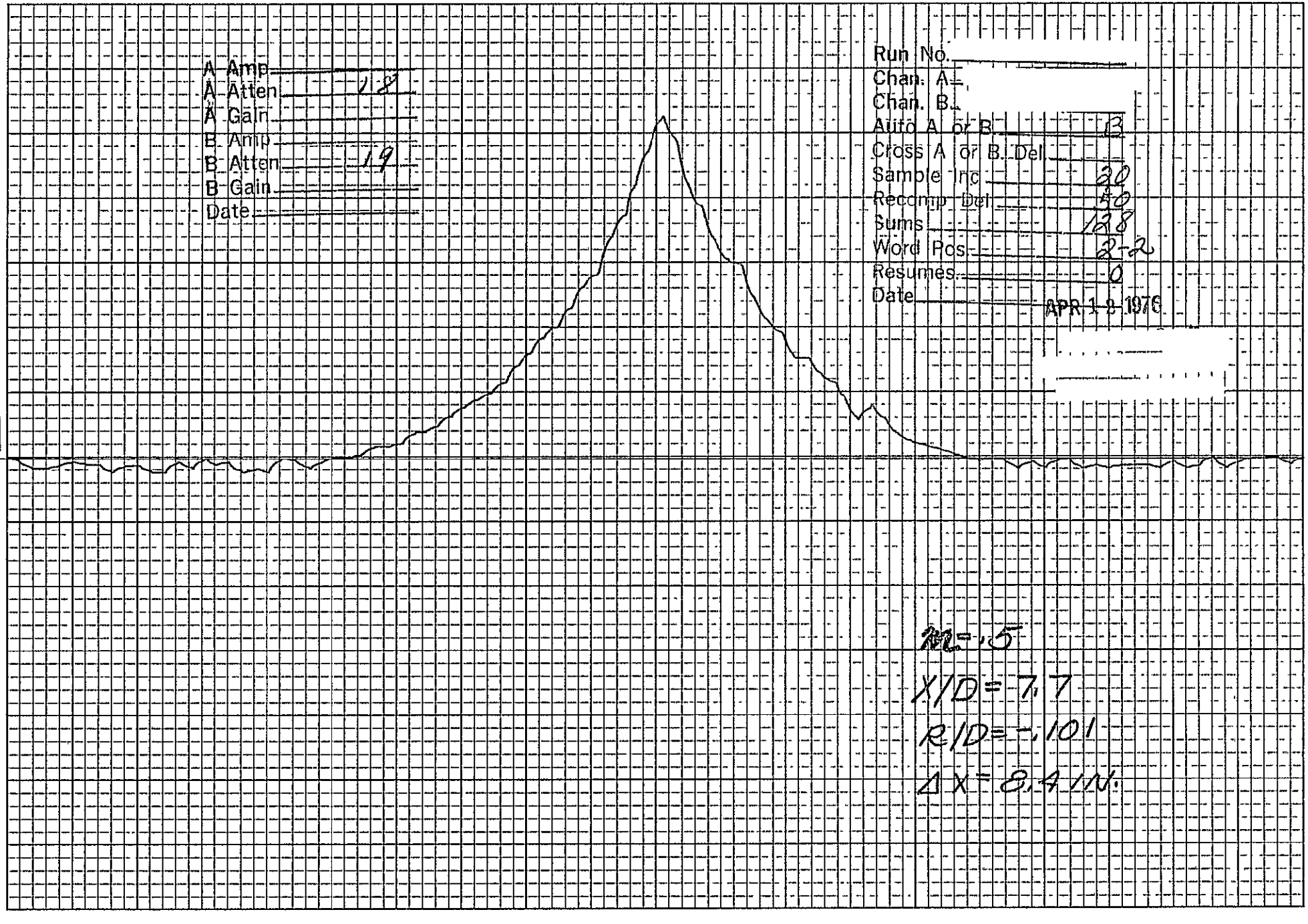

D-170

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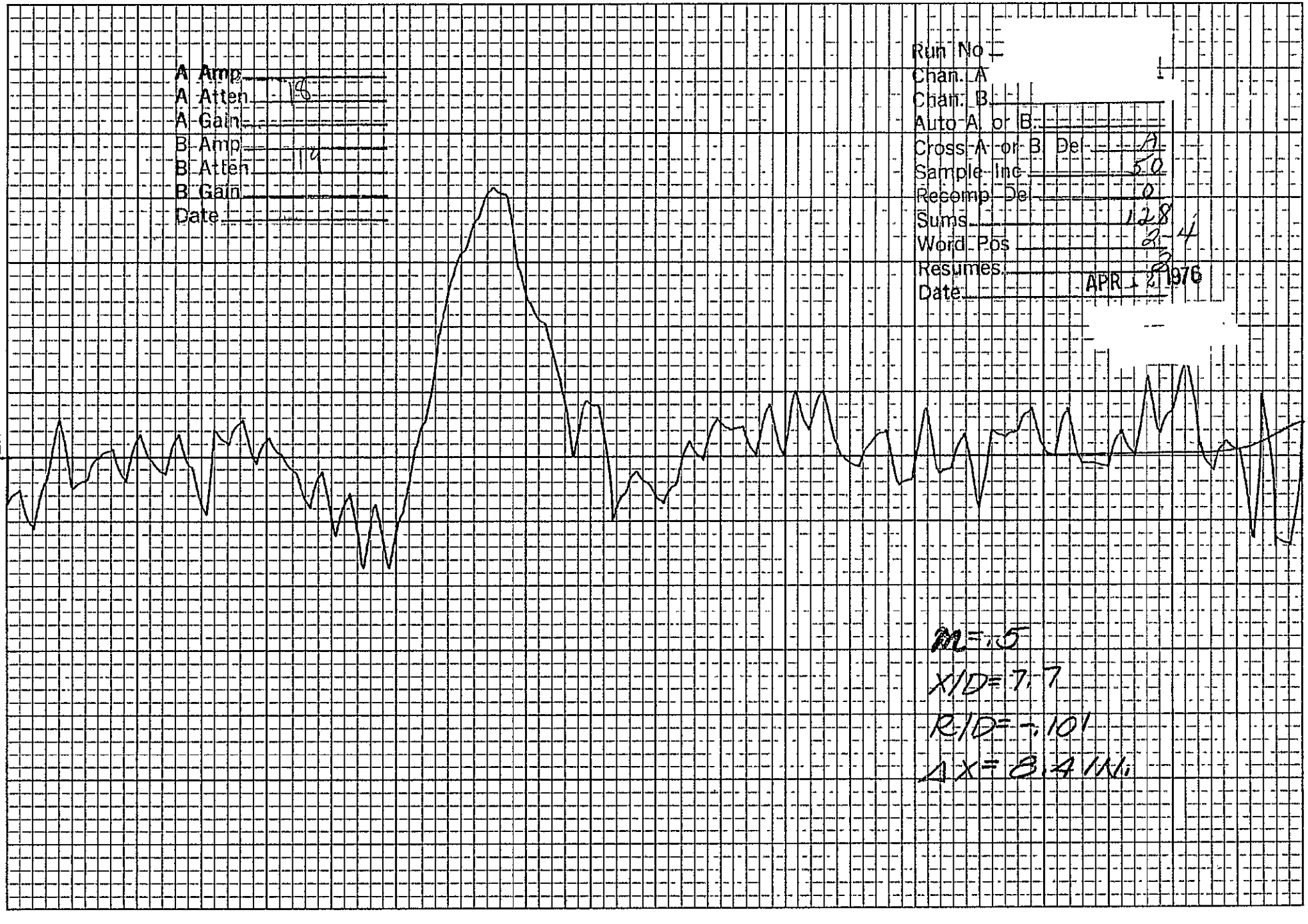

D-171

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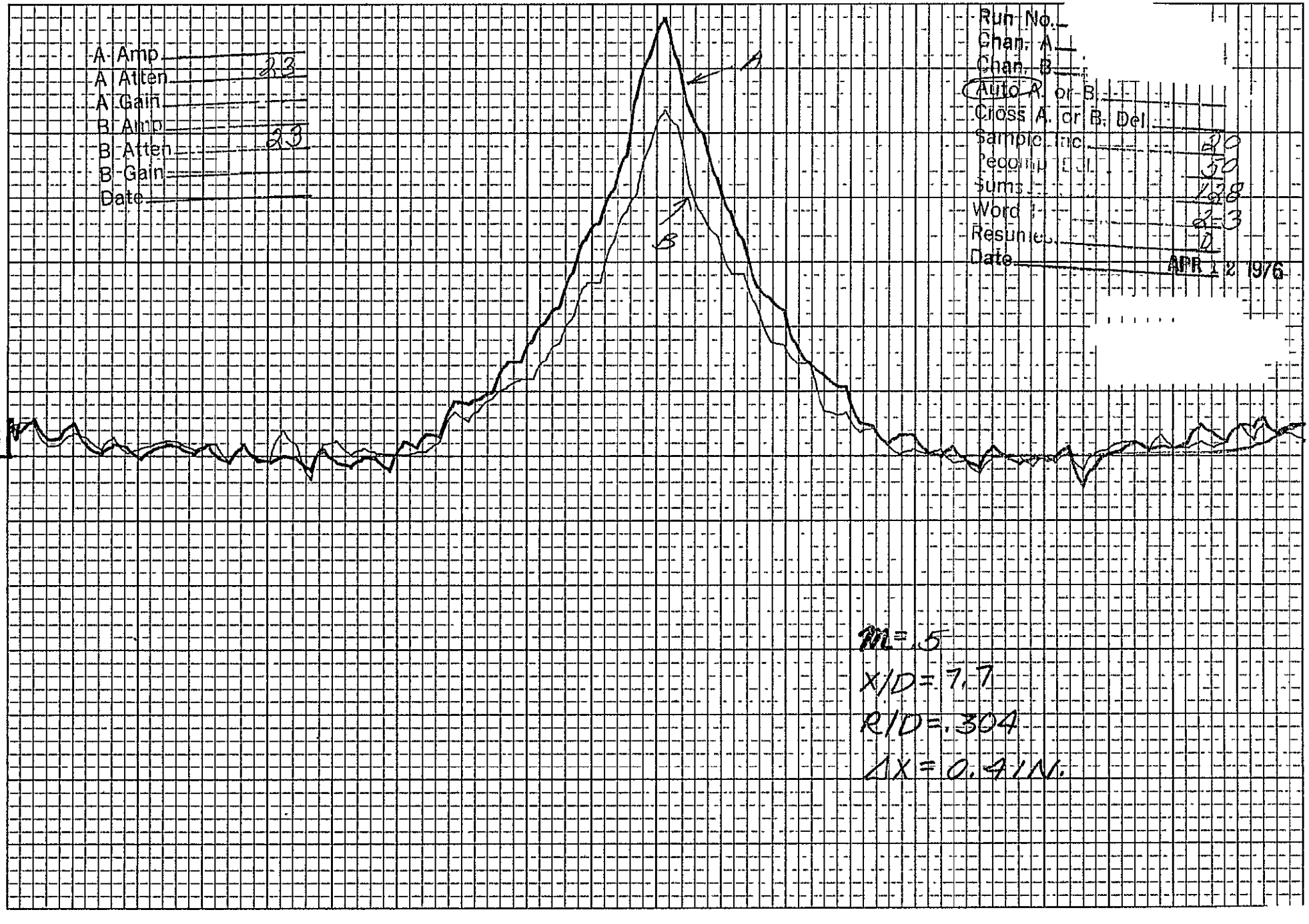

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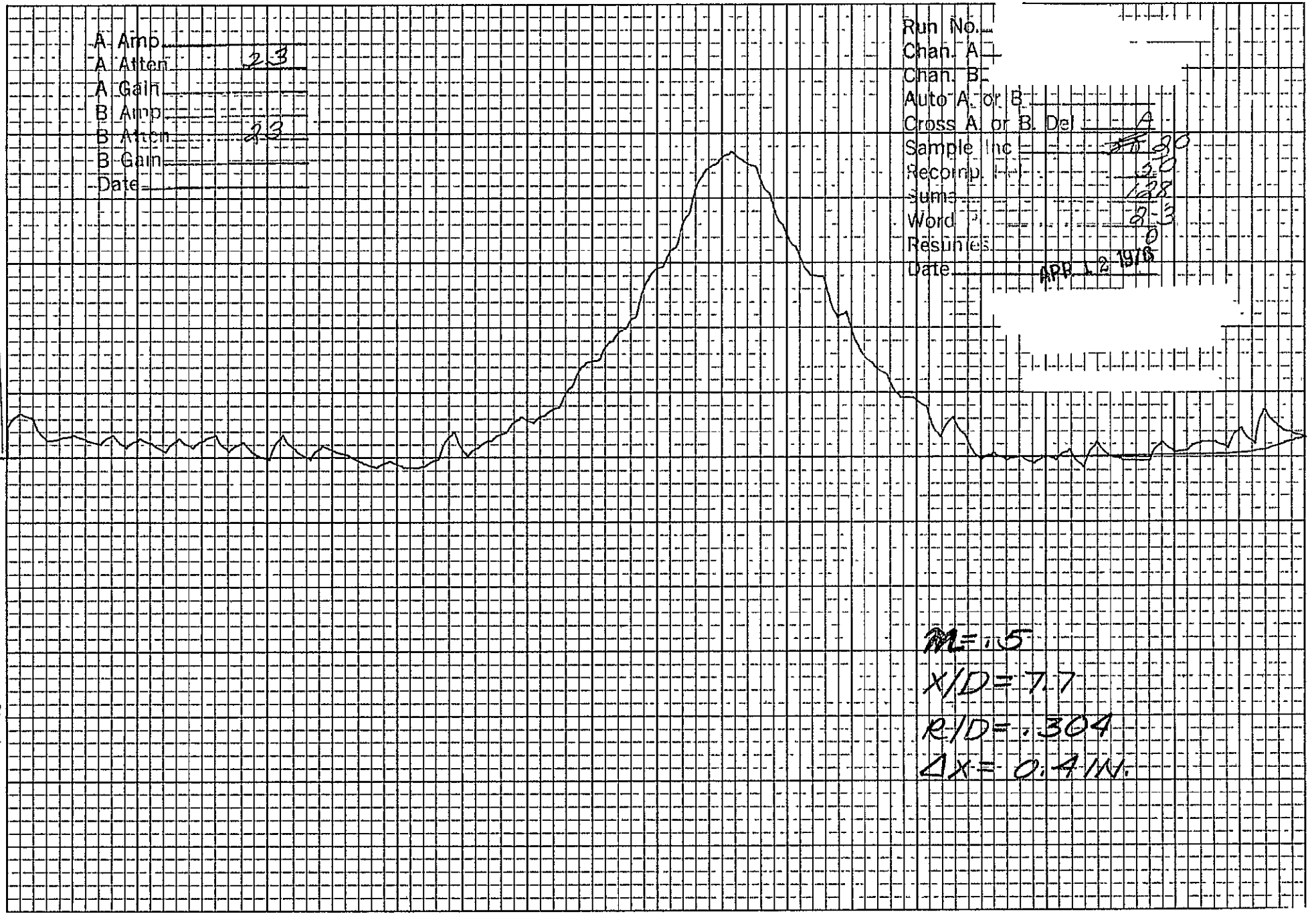

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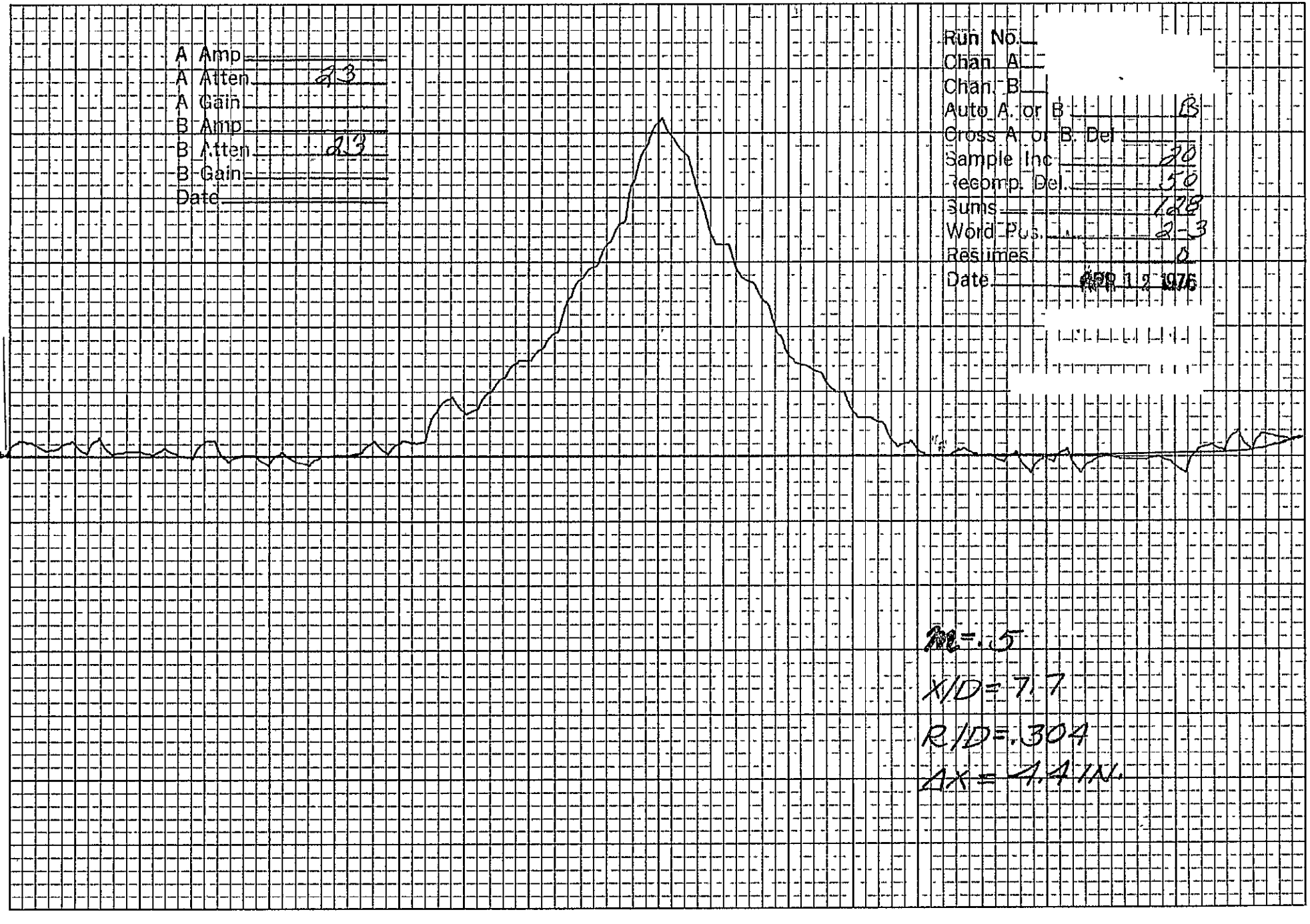

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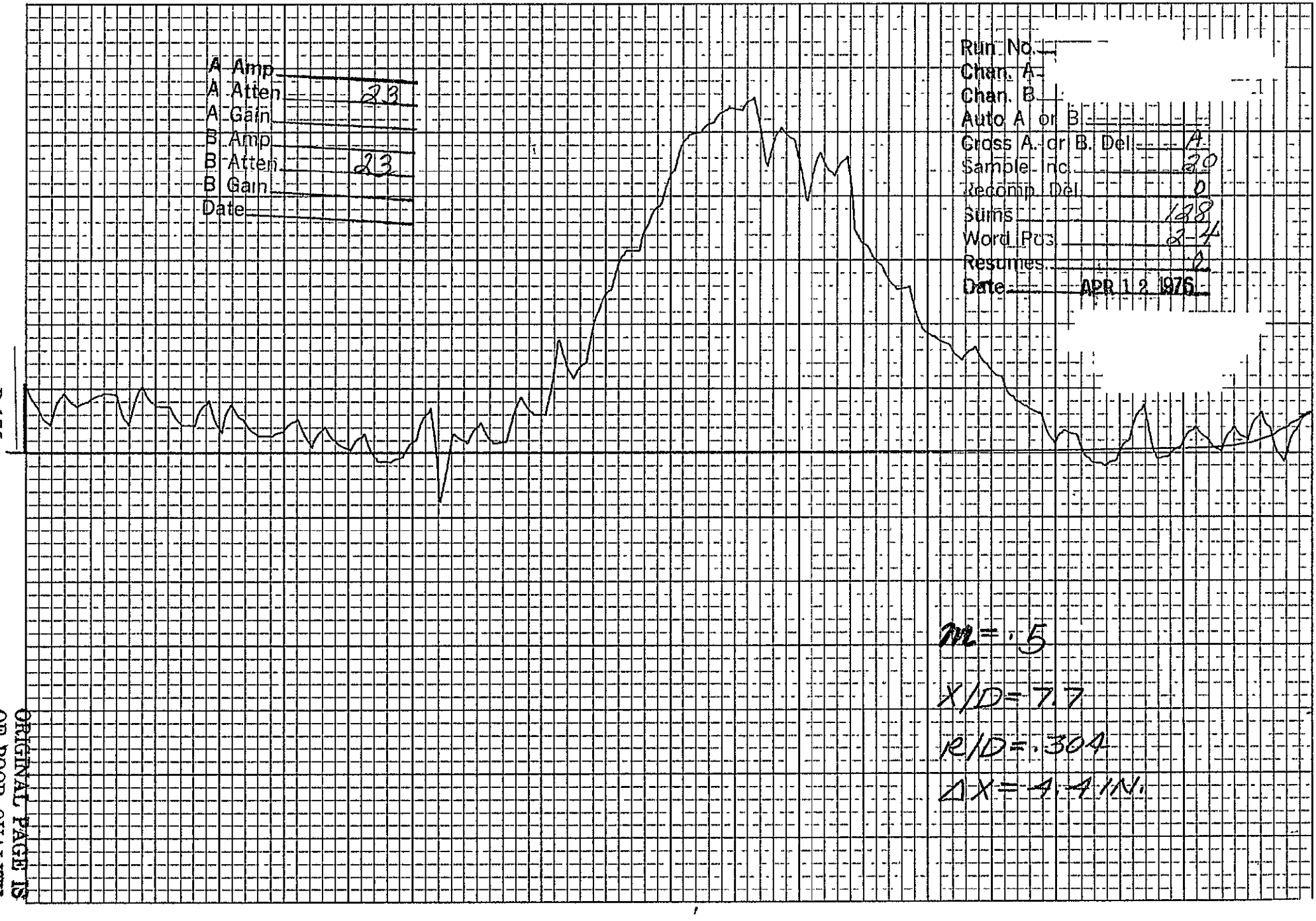

D-175

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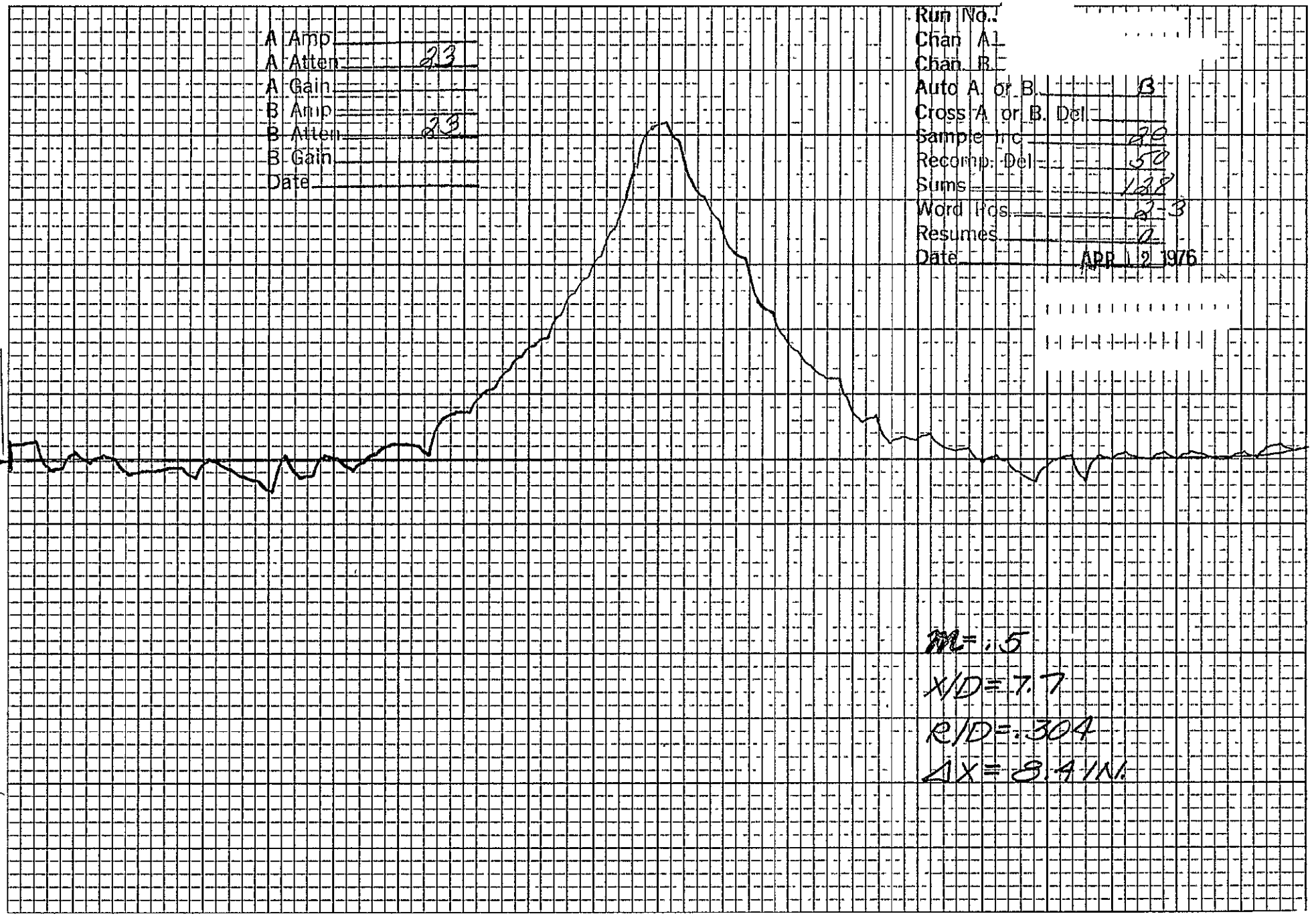

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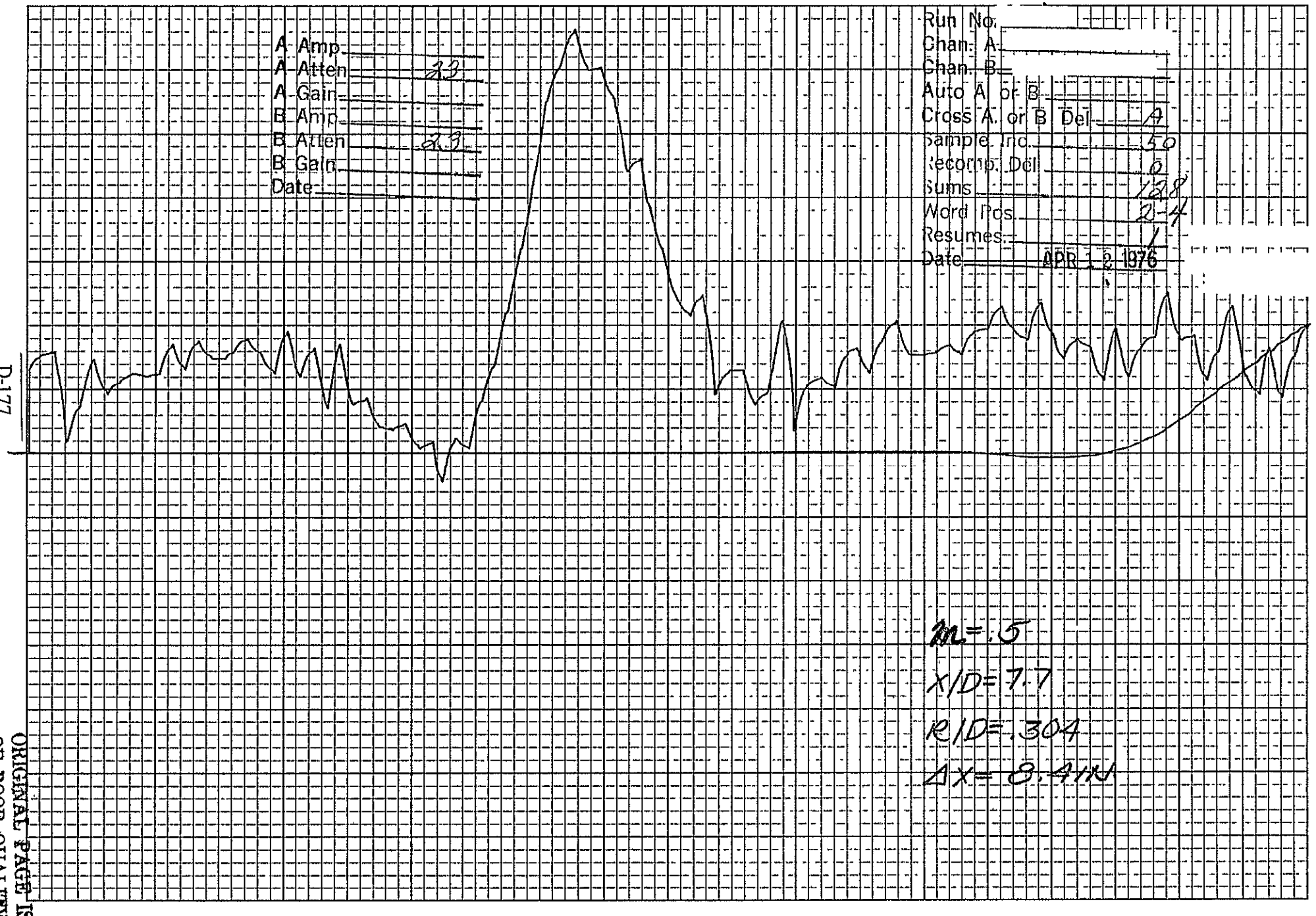

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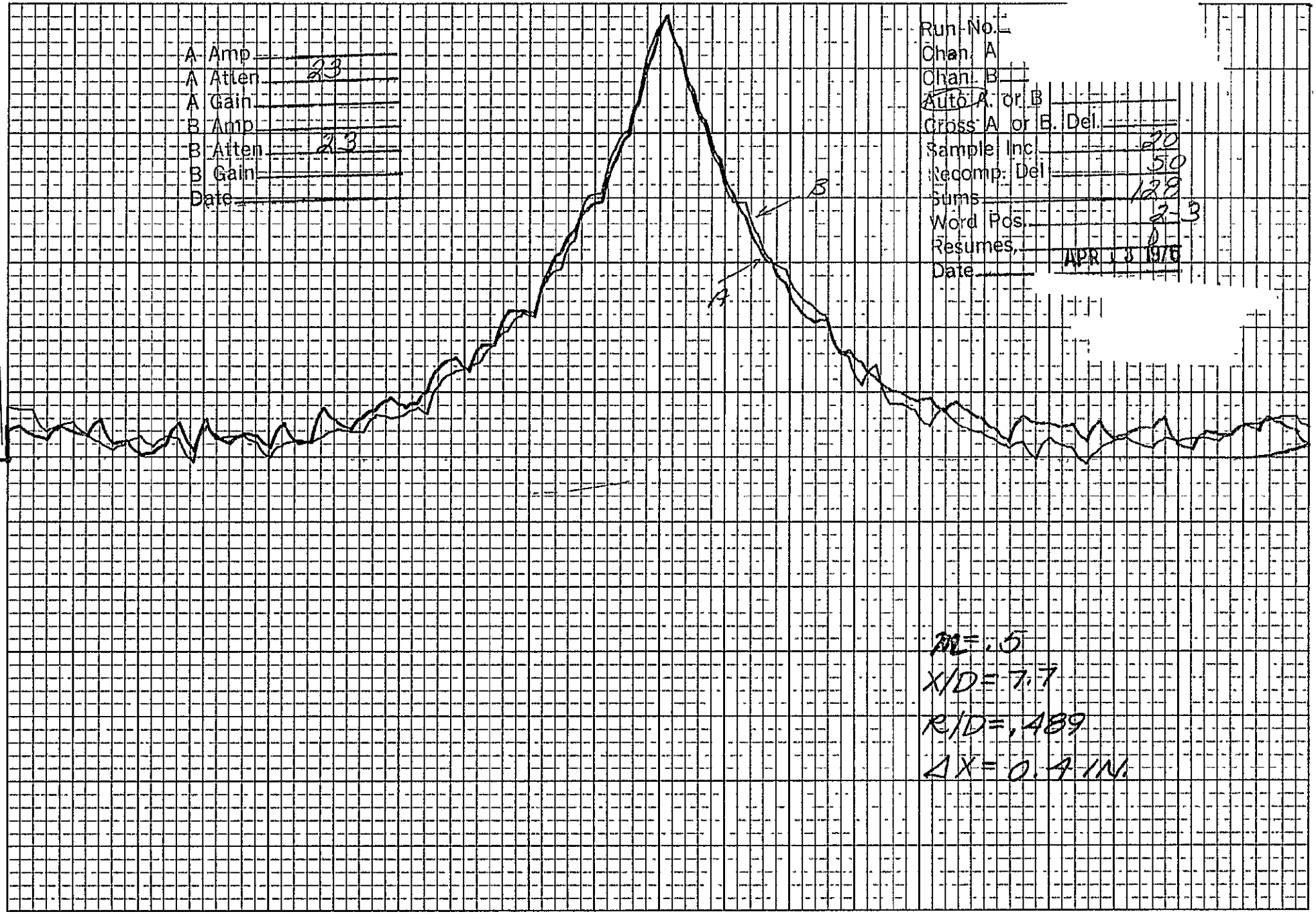

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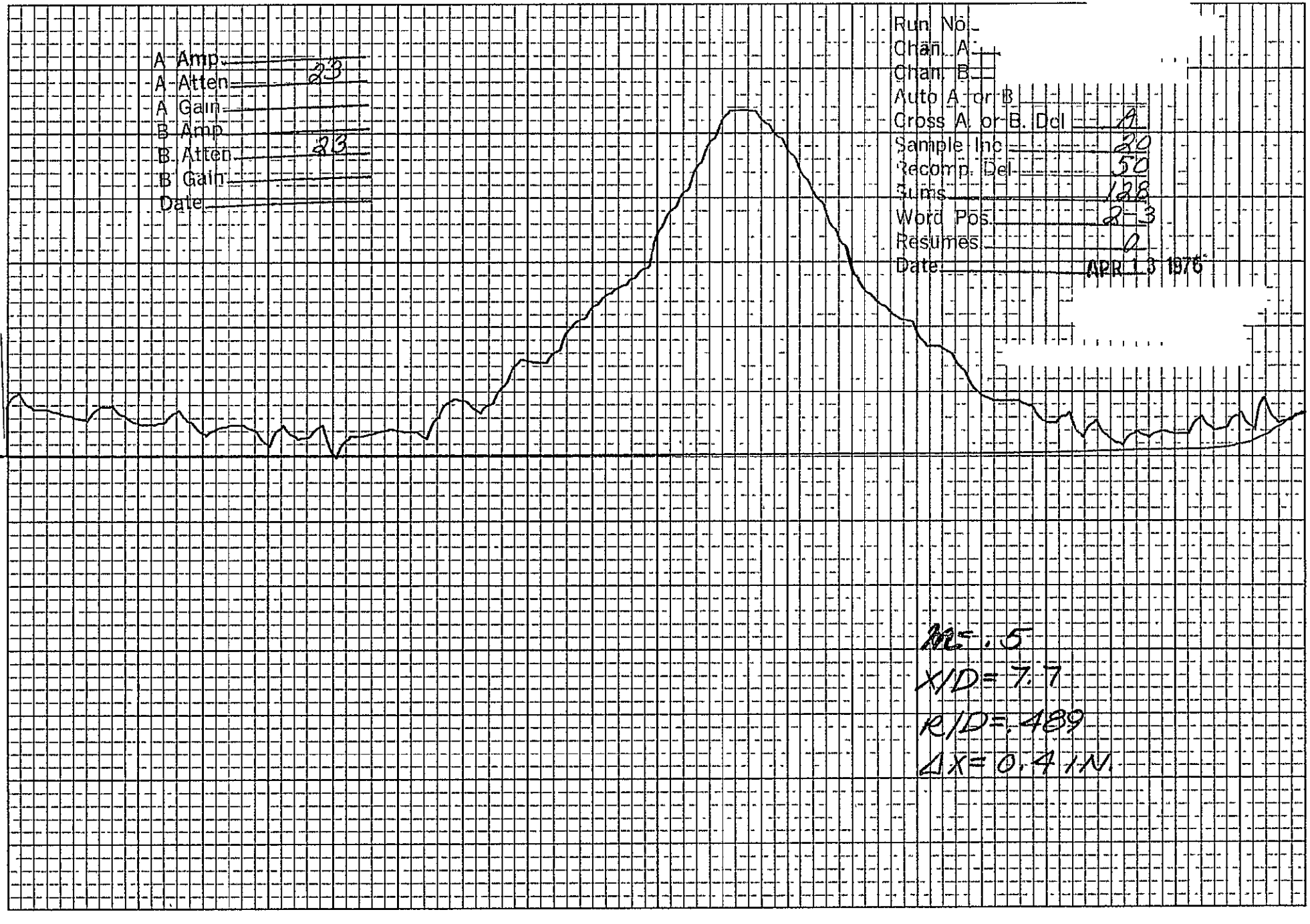

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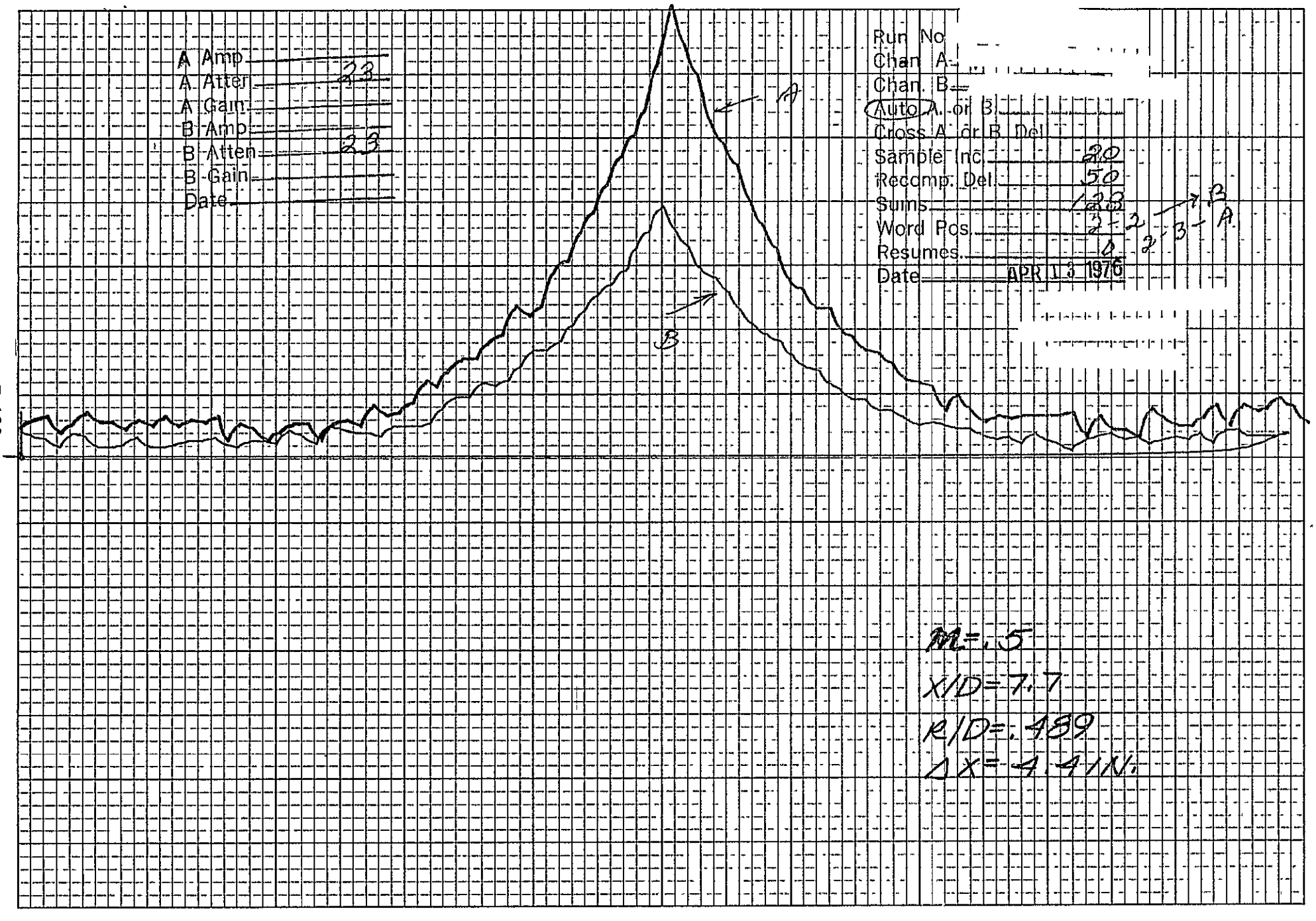

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GRAPHIC CONTROLS CORPORATION
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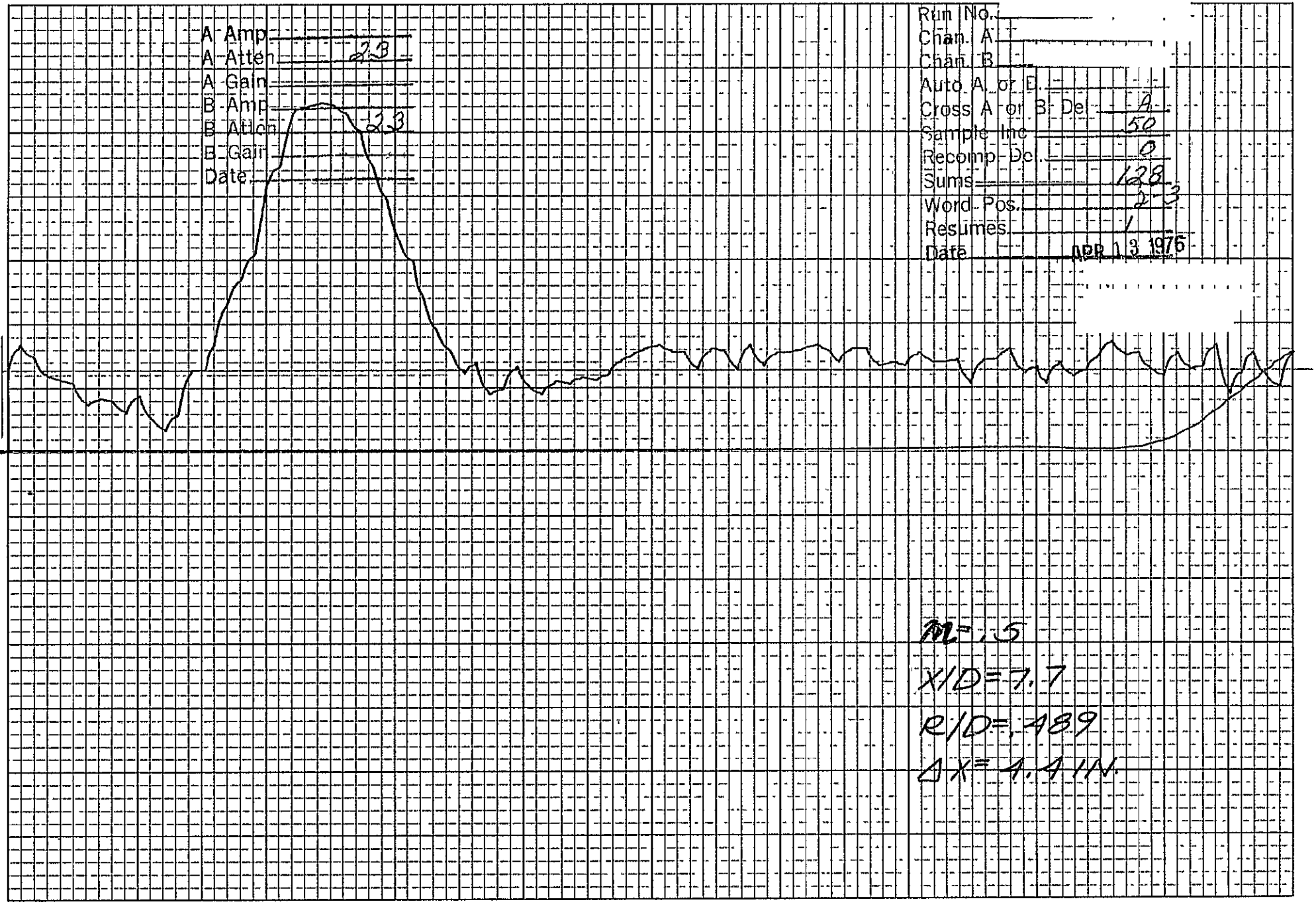

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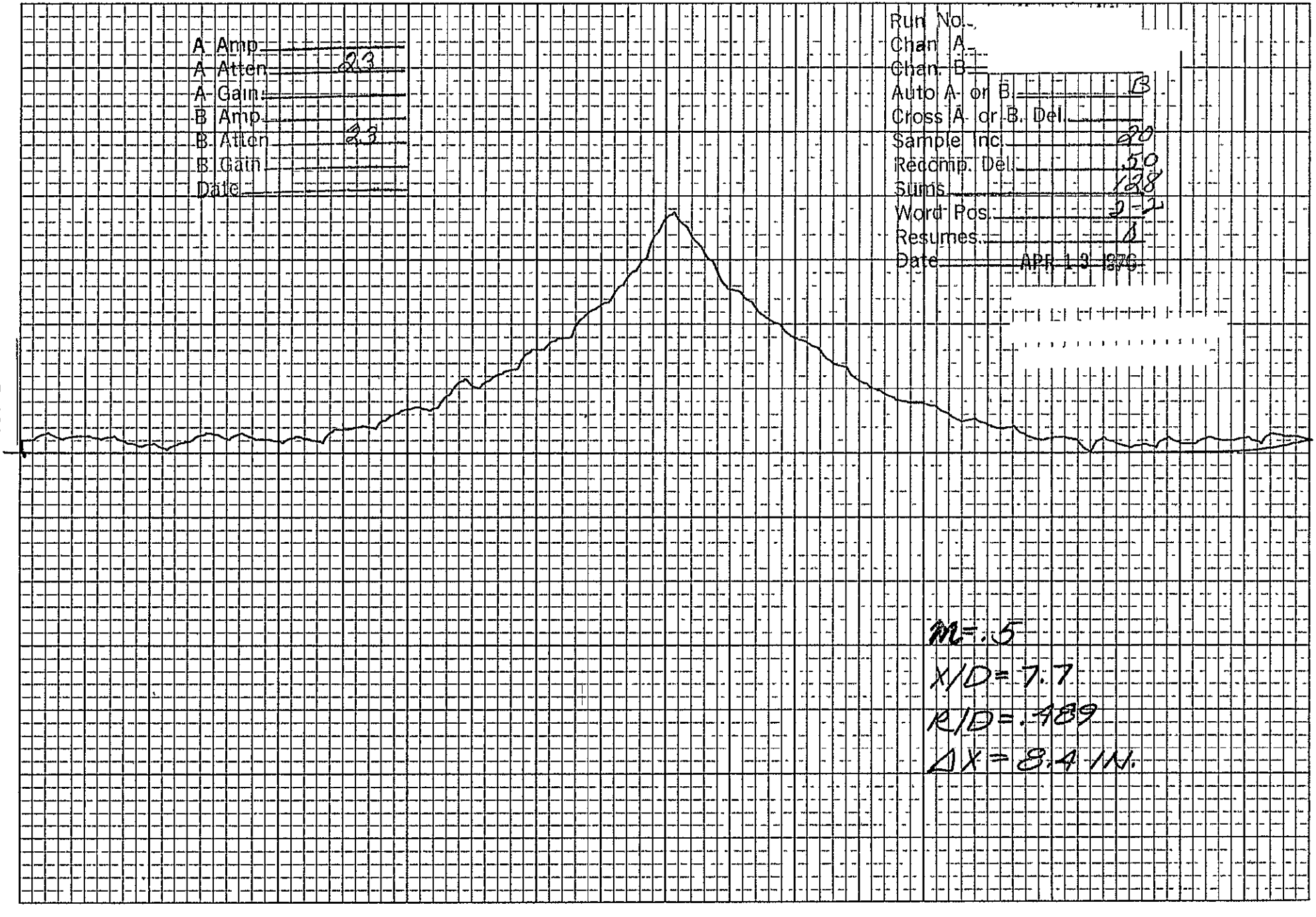

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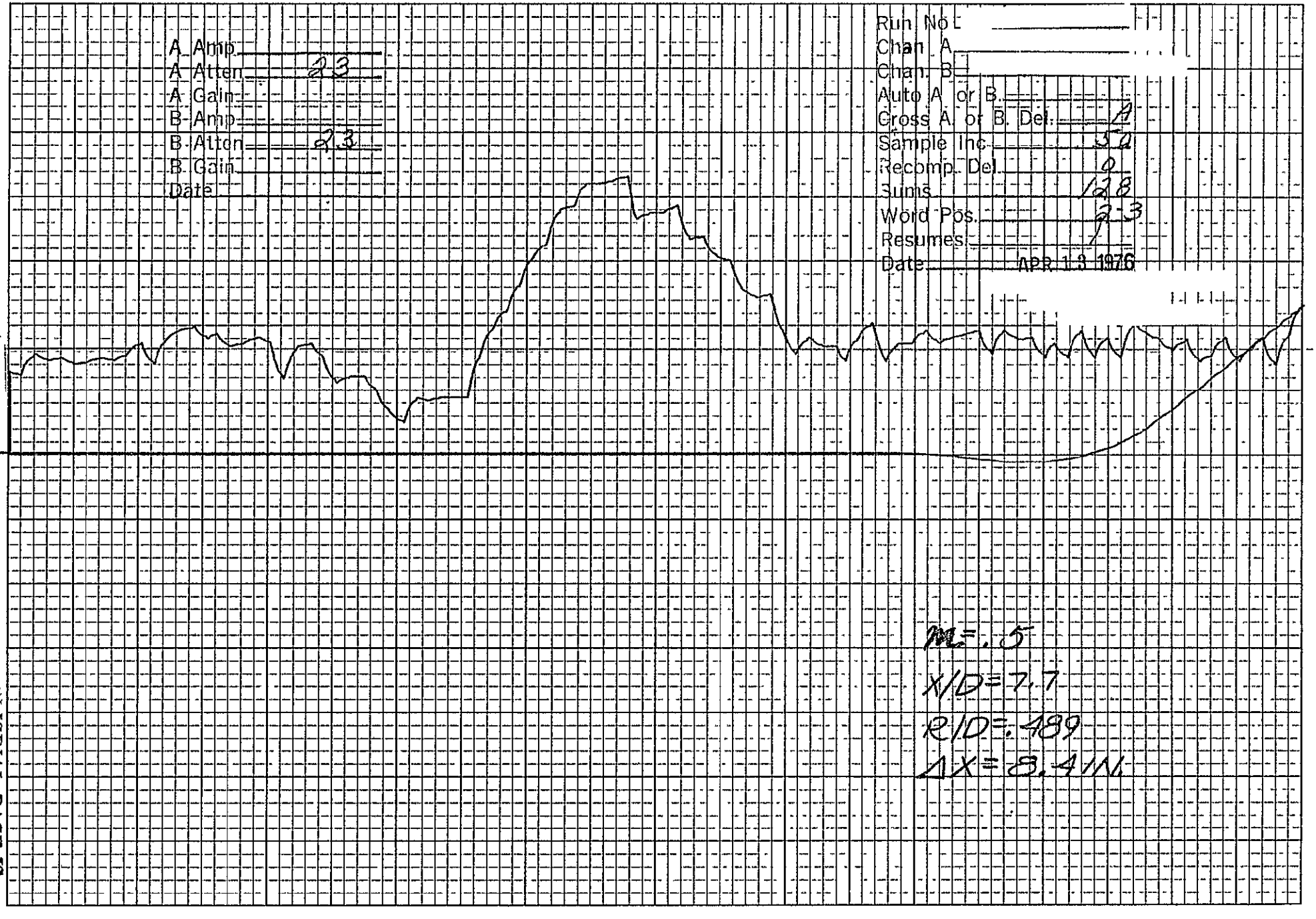

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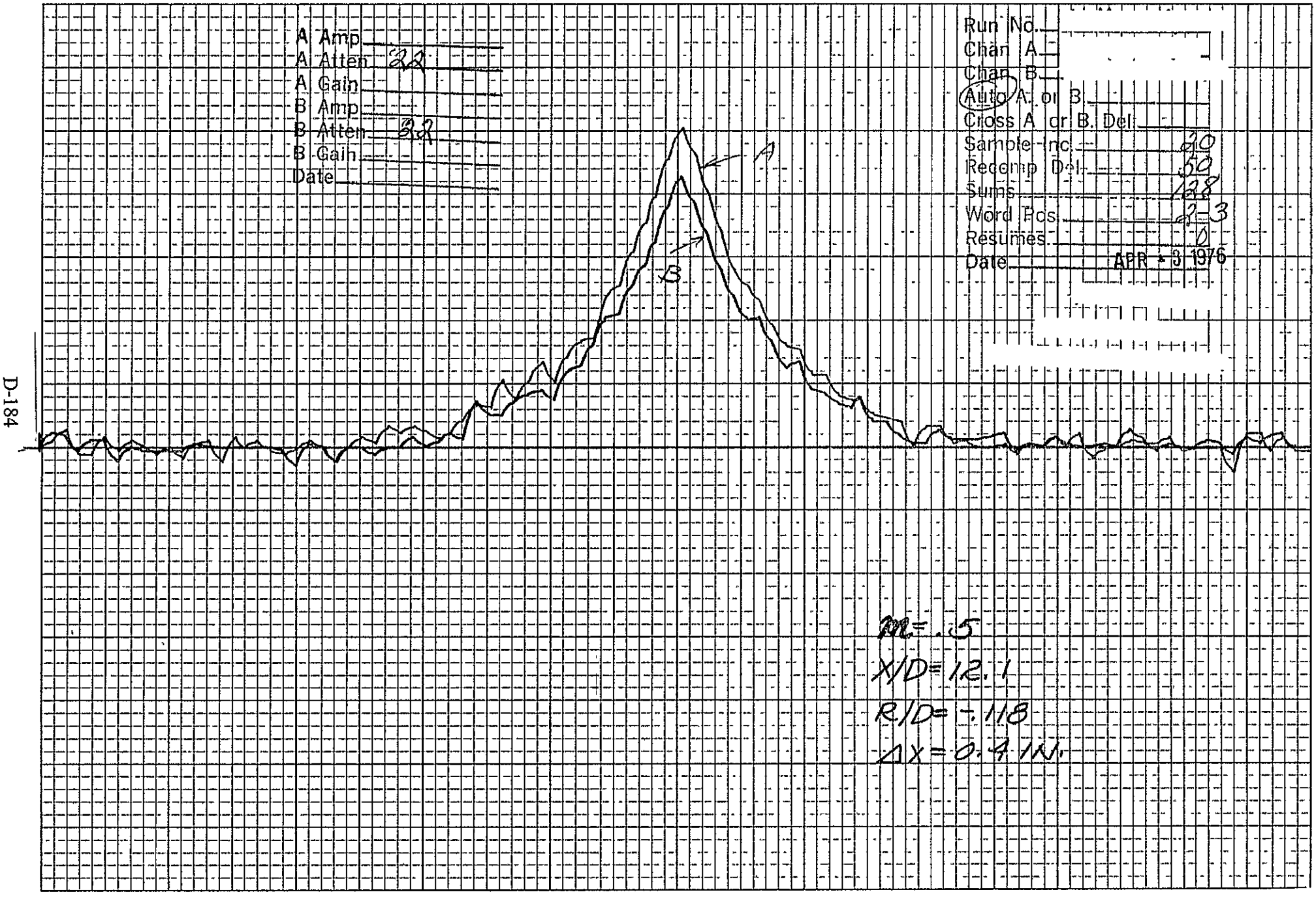

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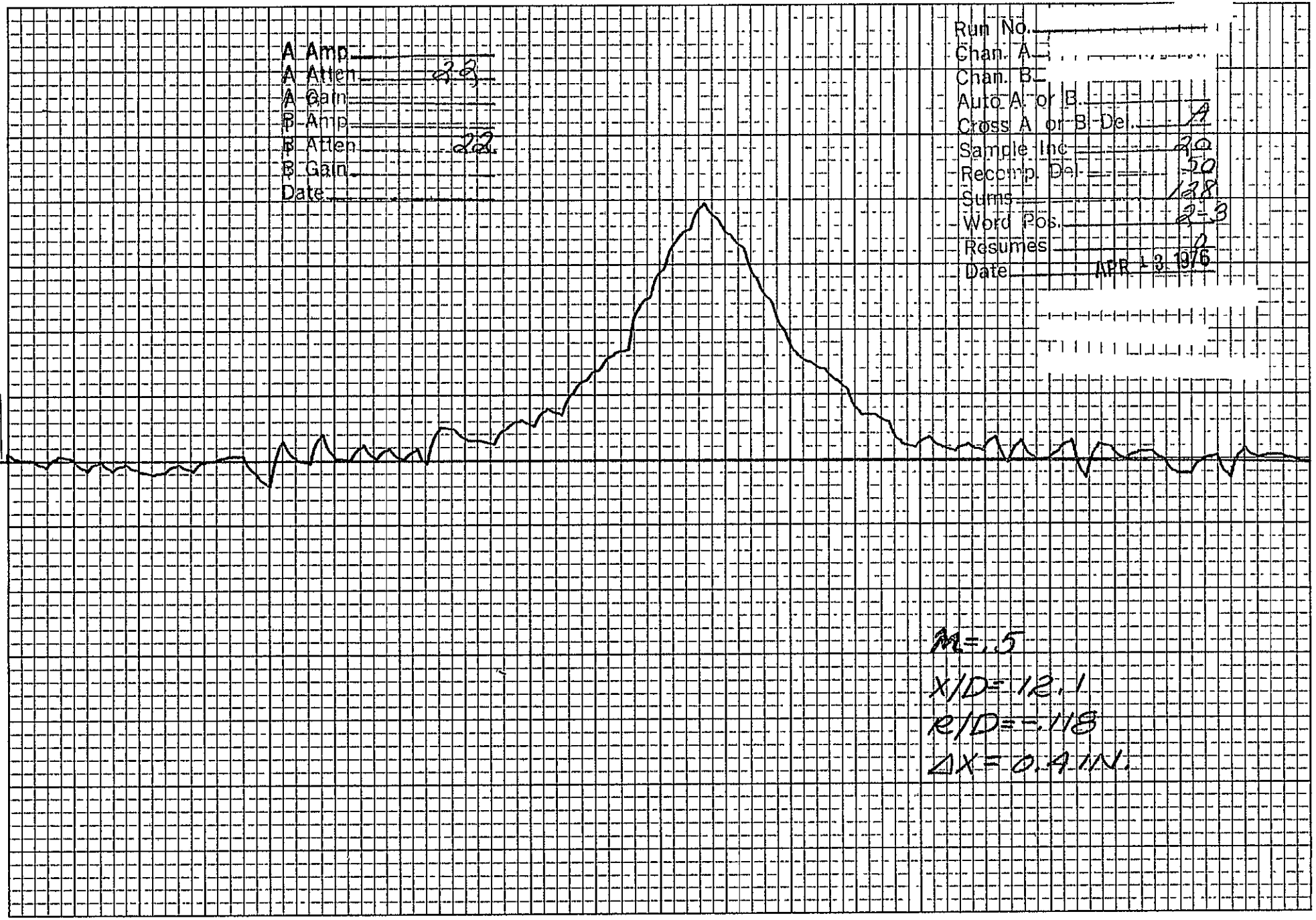

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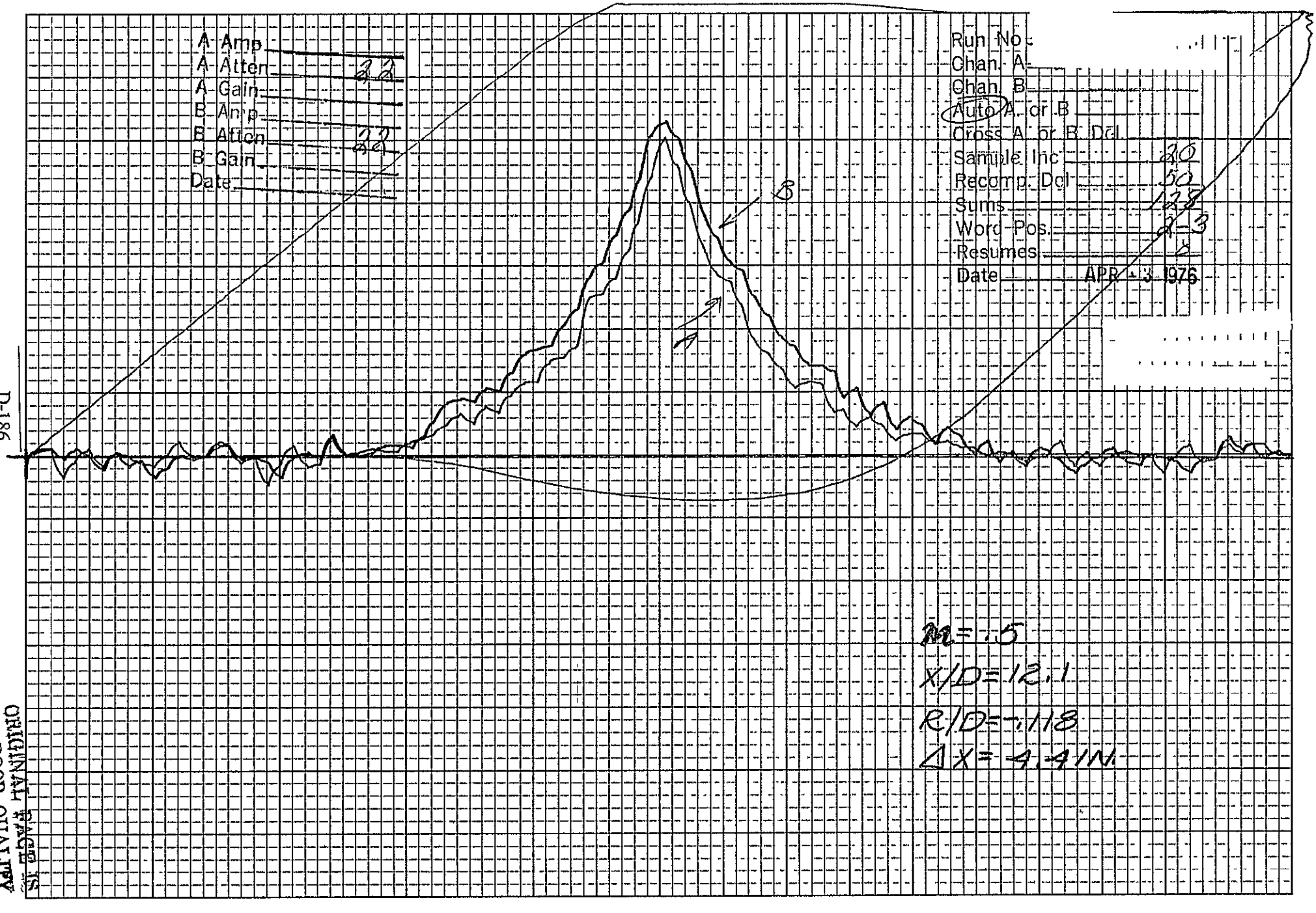

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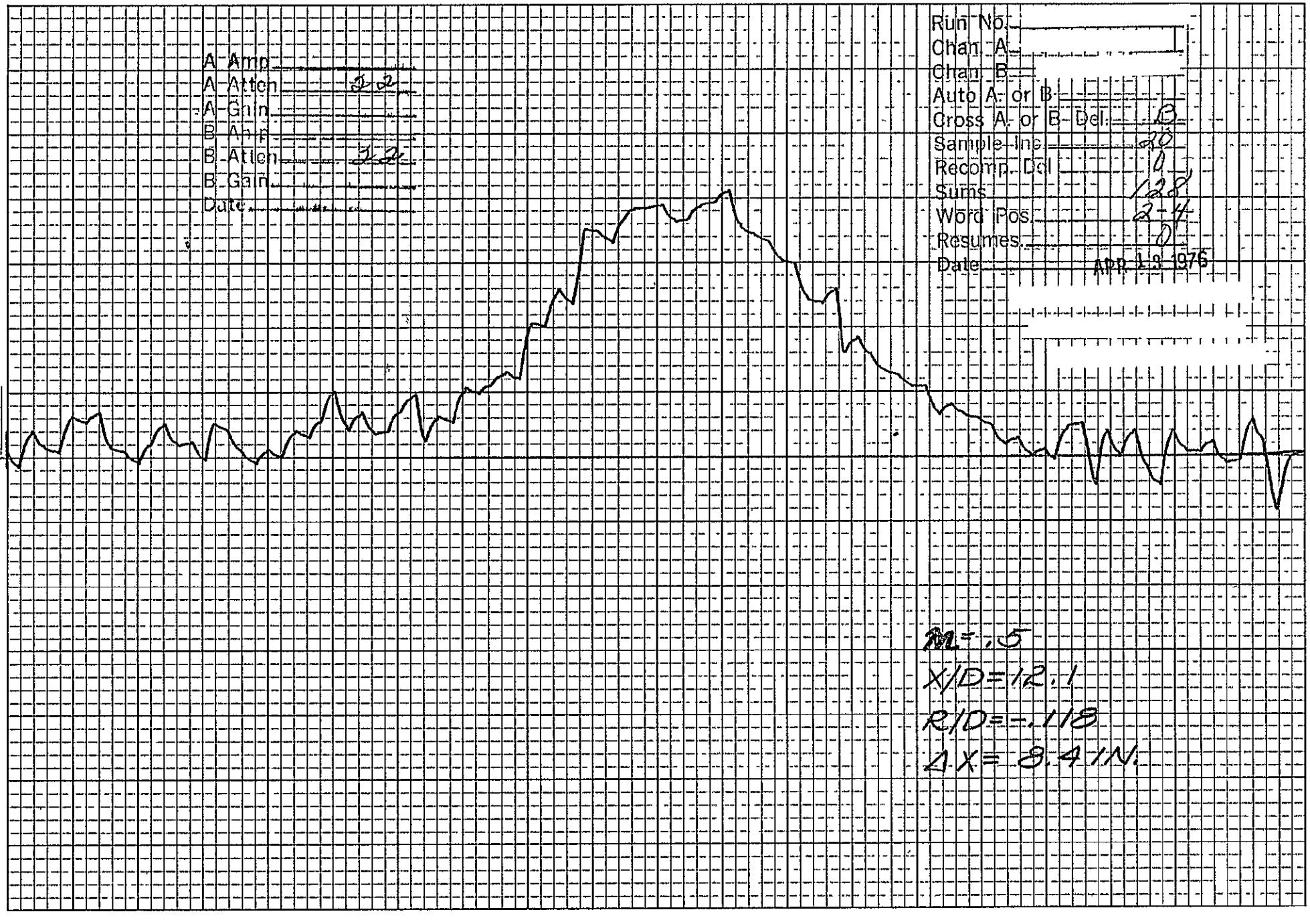

D-187

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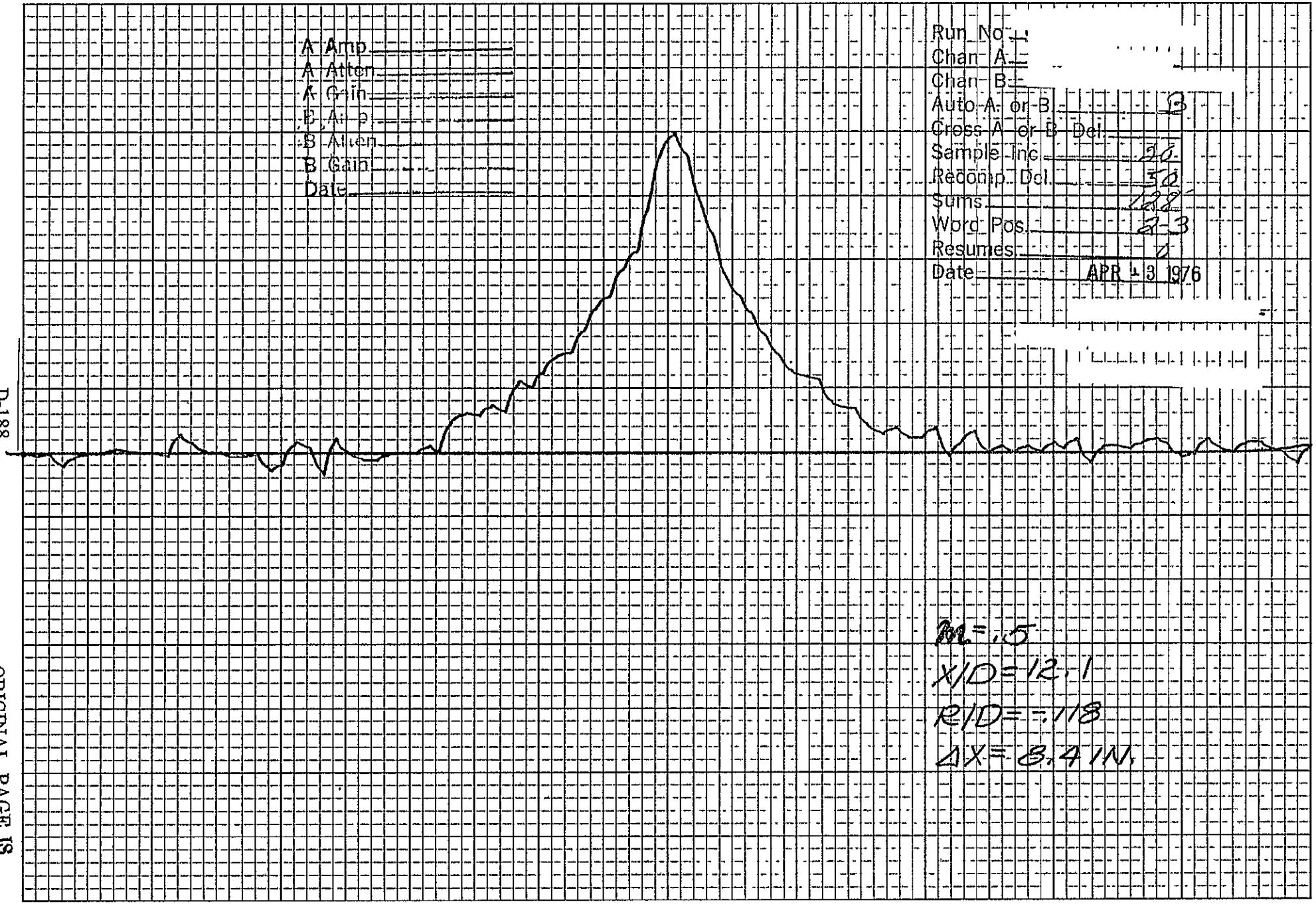

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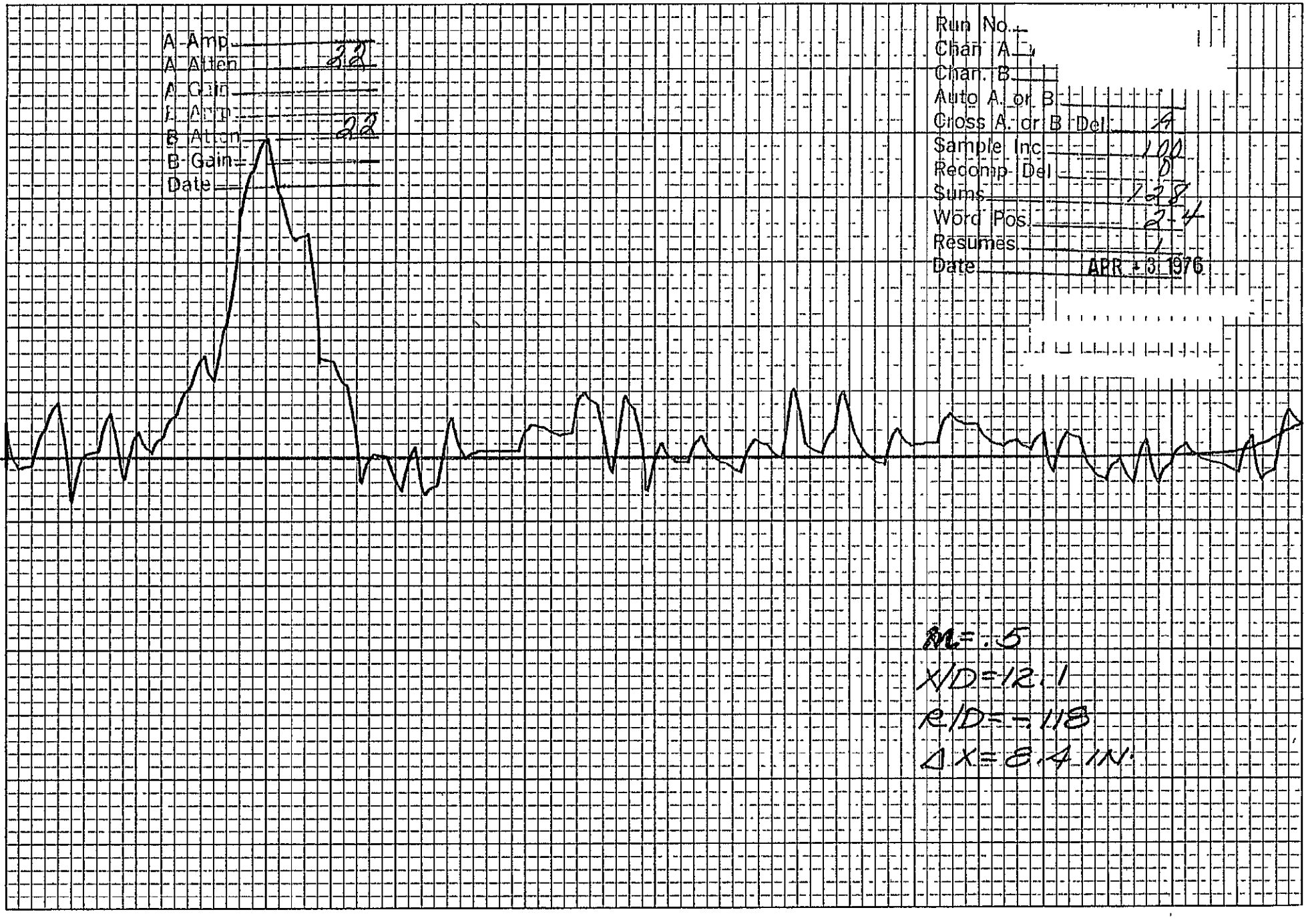

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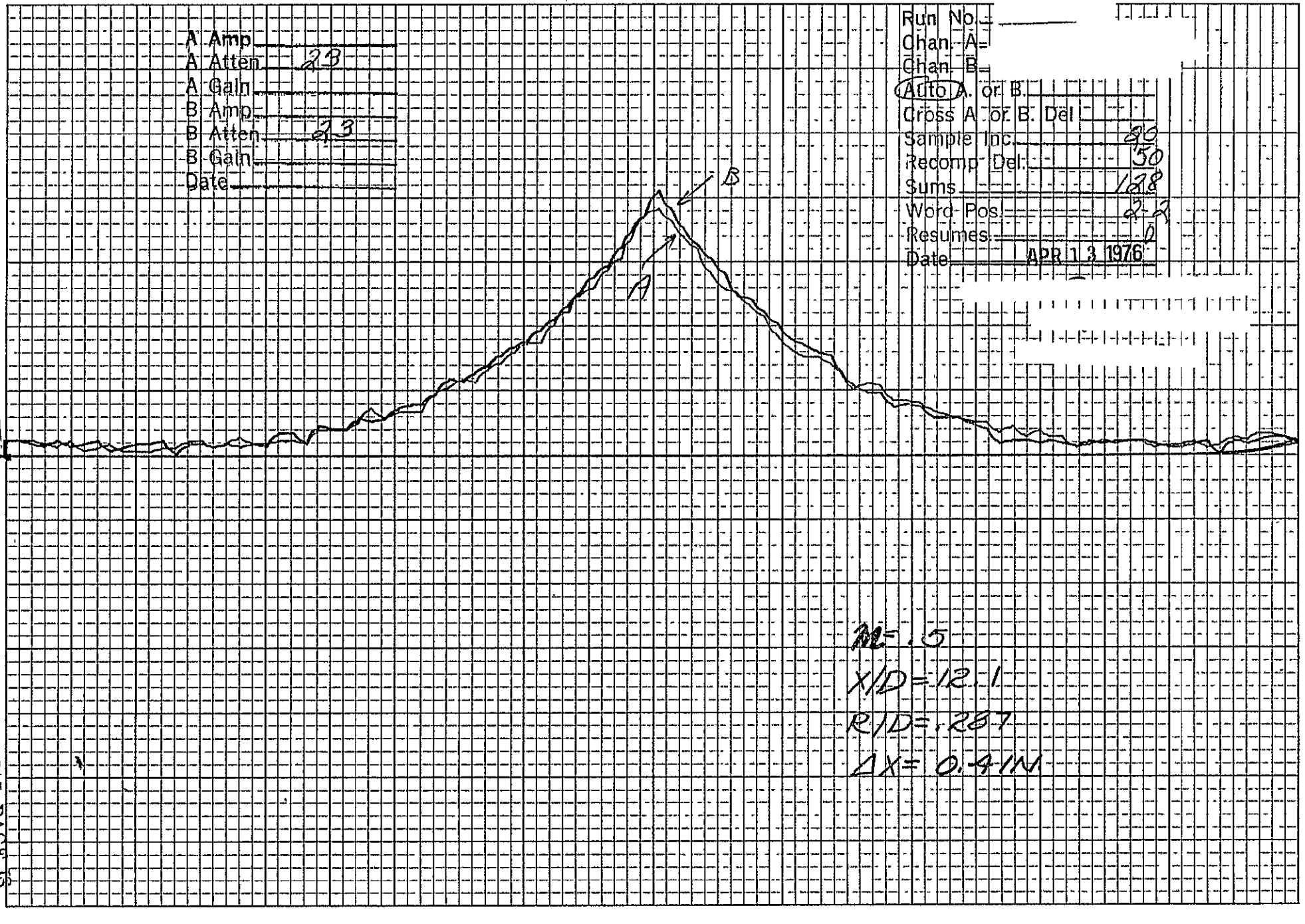

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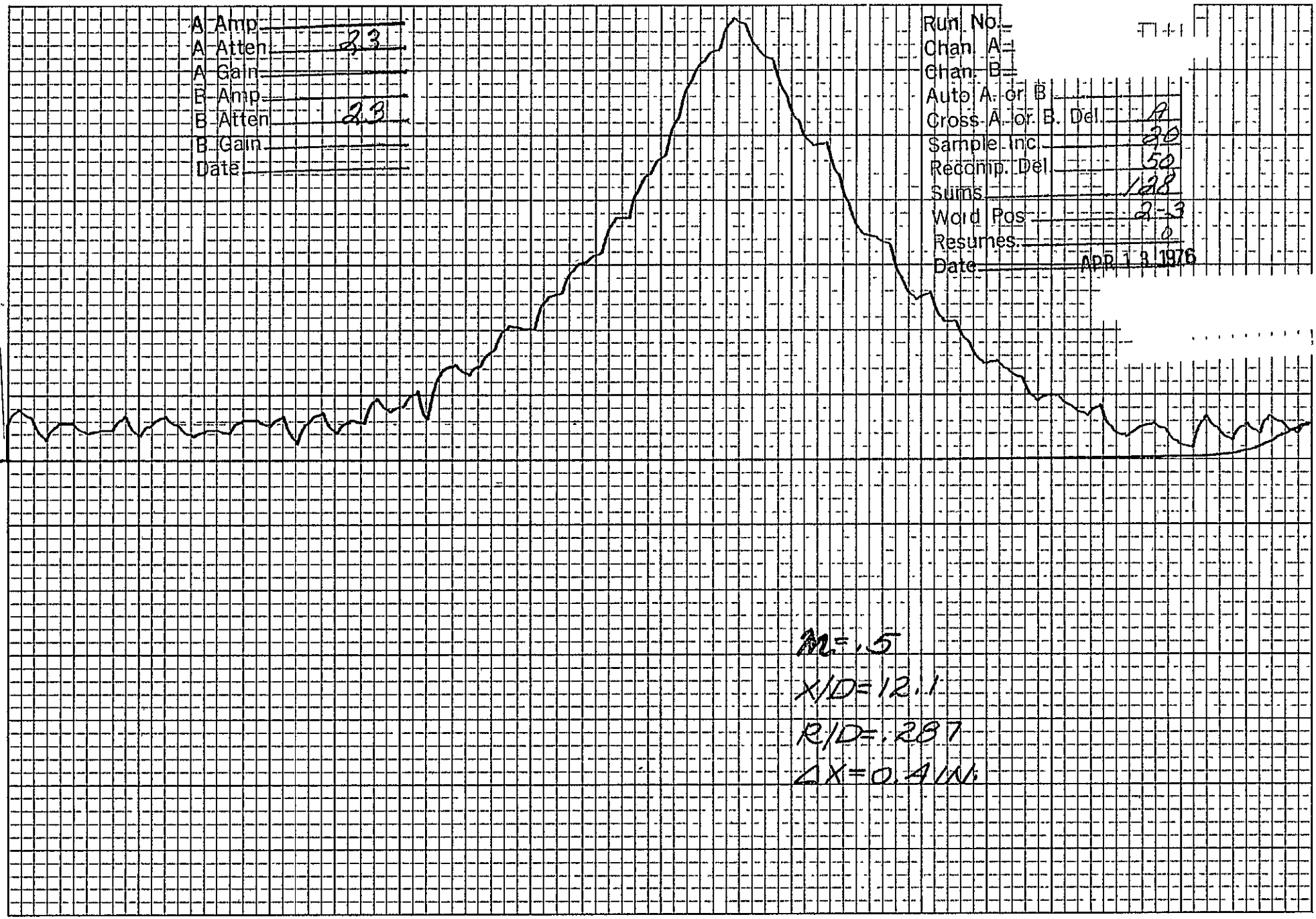
No XY-1001 - SP 1



D-191

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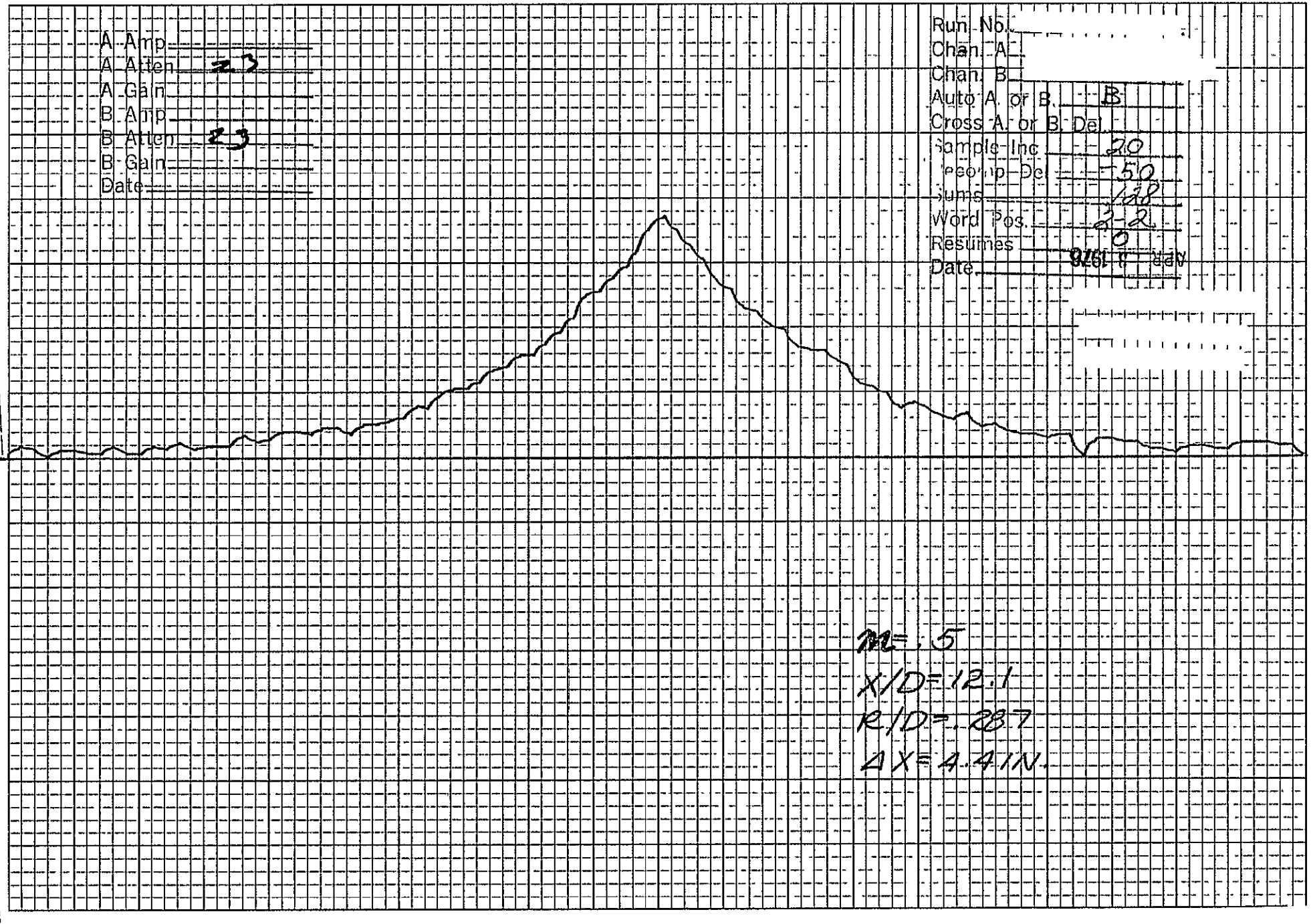
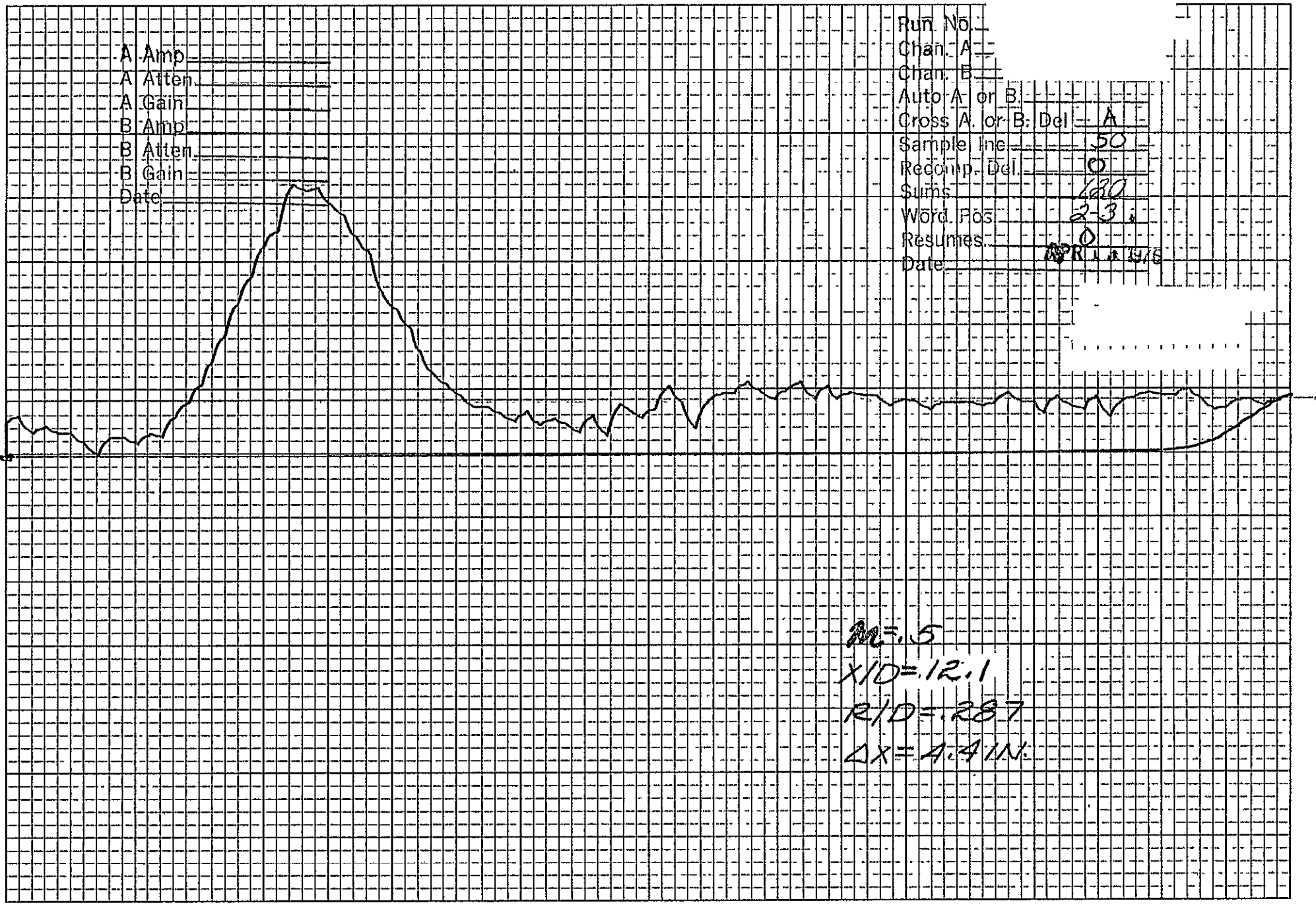
No XY-1001 - SP 1




A Amp
A Atten
A Gain
B Amp
B Atten
B Gain
Date
Run No.
Chan. A
Chan. B
Auto A or B
Cross A. or B. Del A
Sample Inc 50
Recomp. Del 0
Sums 400
Word. Pos 2-3
Resumes 0
Date APR 1 1976
M=.5
X10=12.1
R10=.287
ΔX=4.4 IN.

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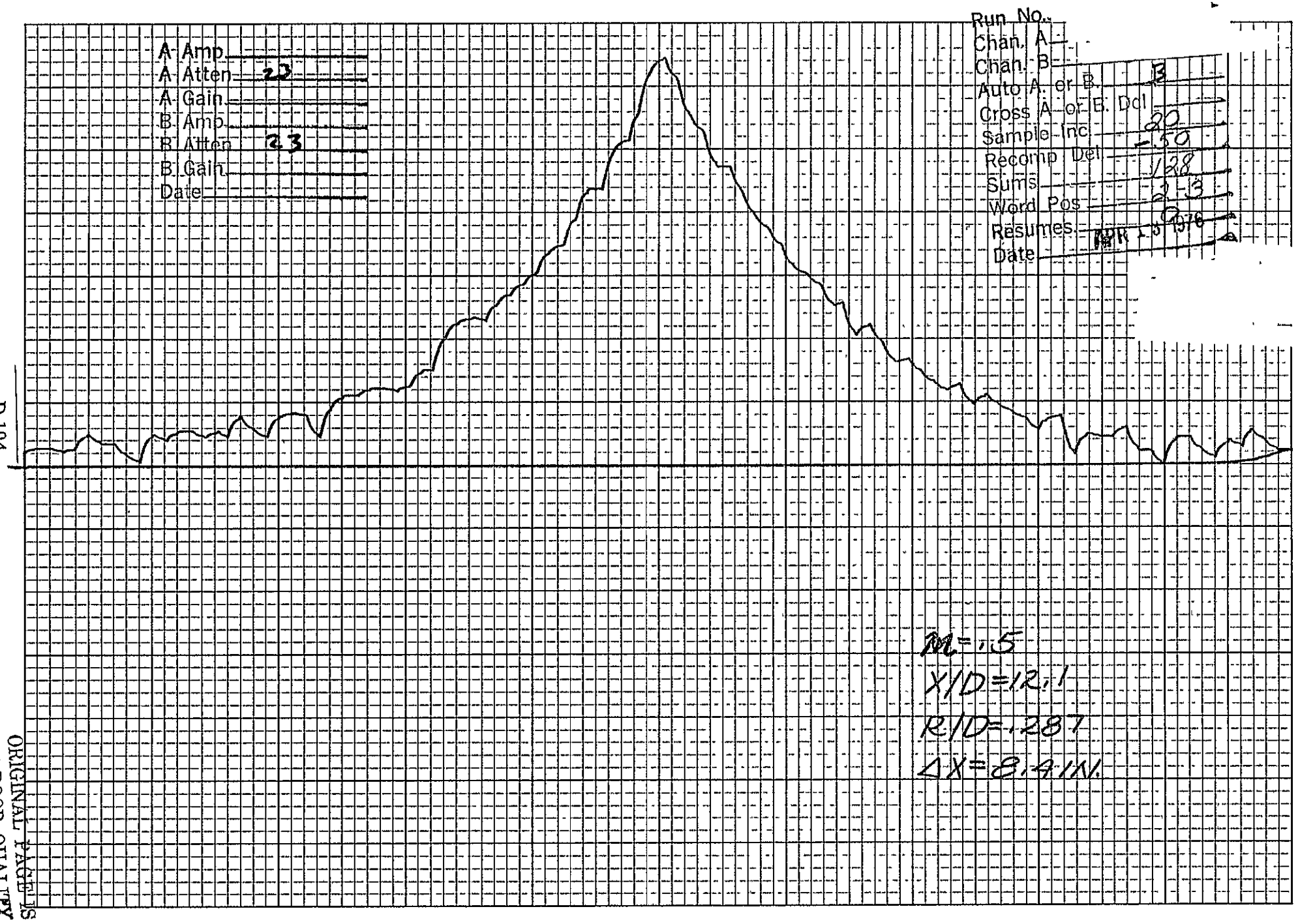
No XY-1001-SP 1



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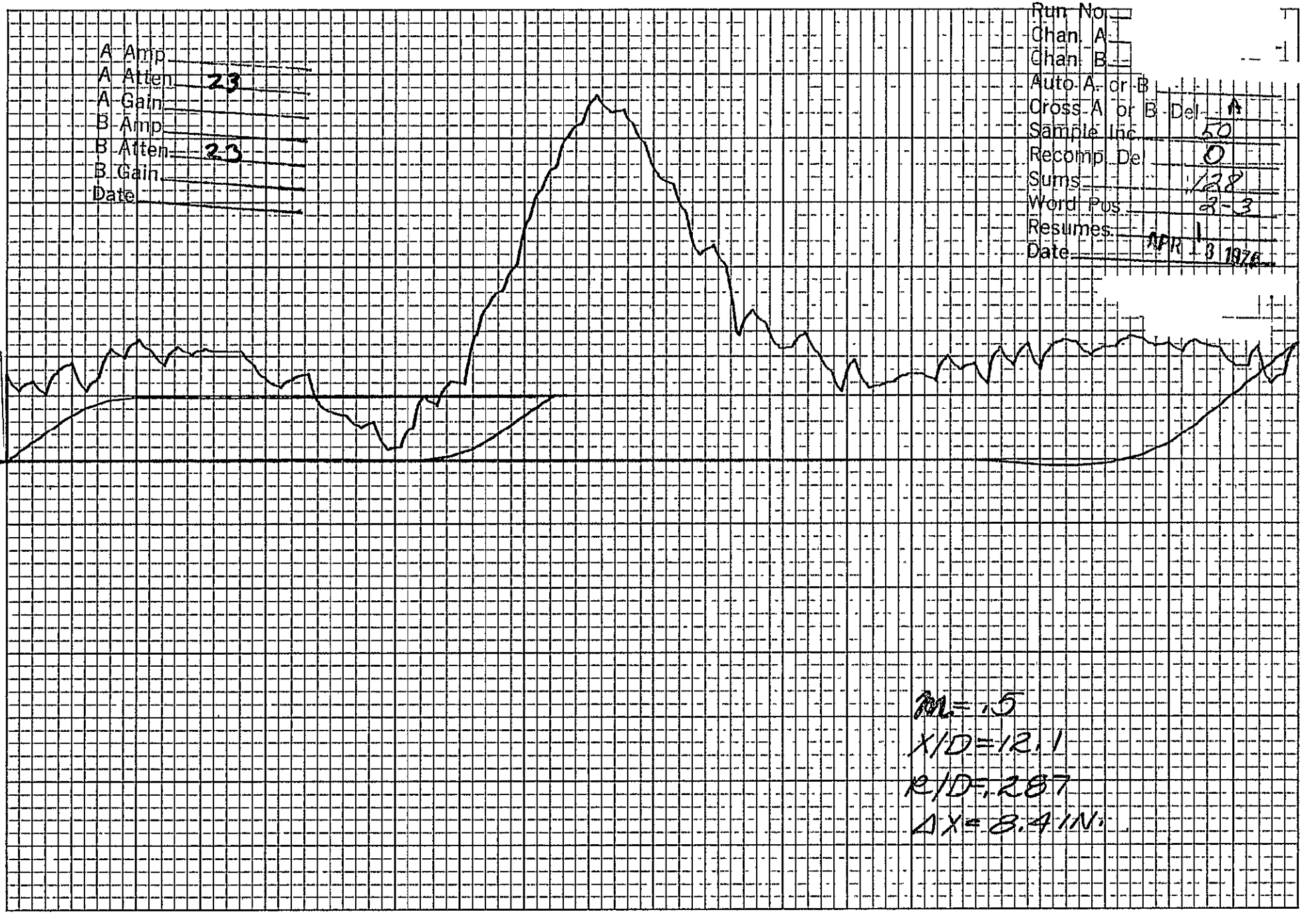
No XY-1001-SP 1



[redacted] REC [redacted] IG C [redacted] E]
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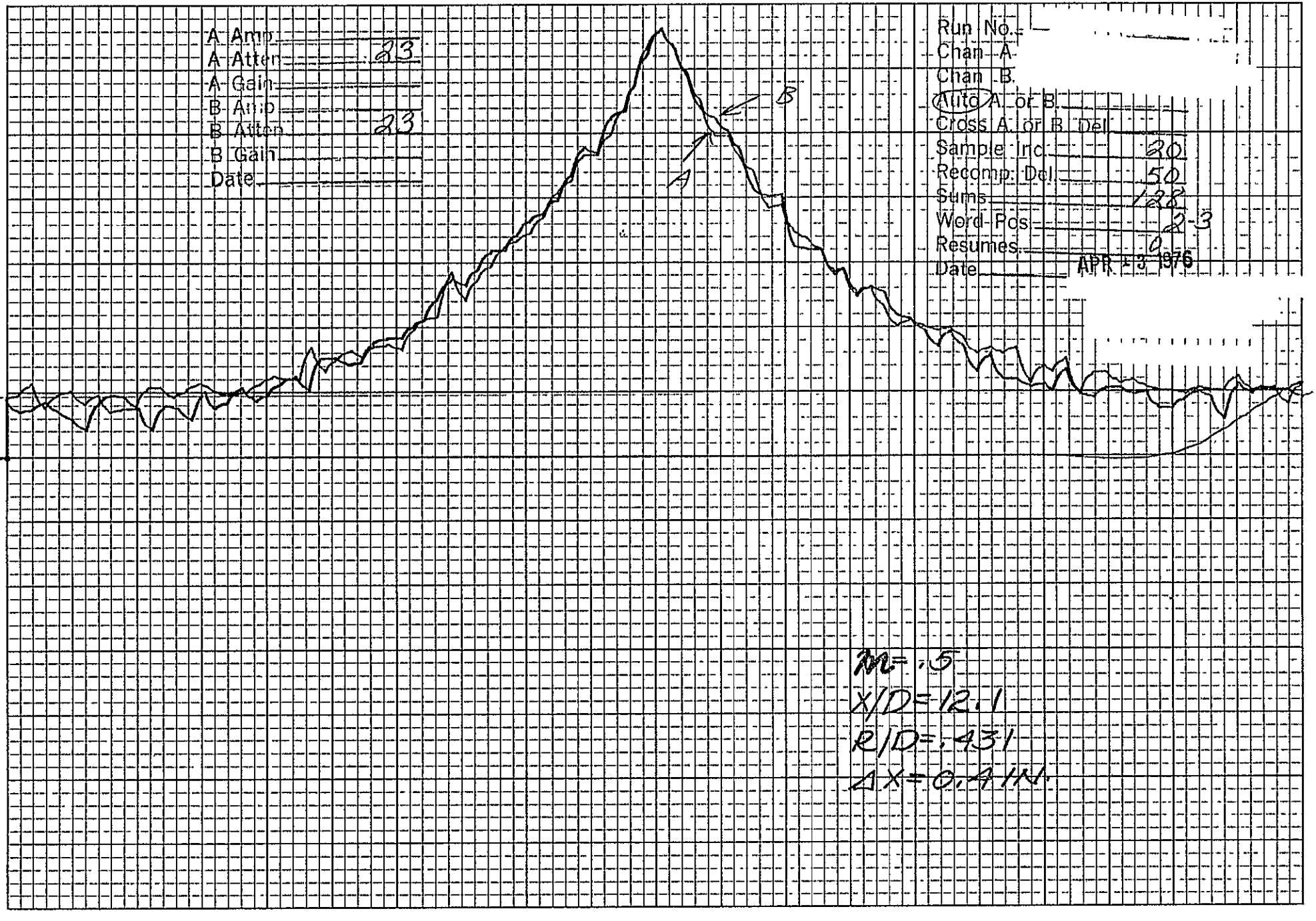
No XY-1001 - SP 1



REC[illegible]NG C[illegible]S
GRAPHIC CONTROLS CORPORATION
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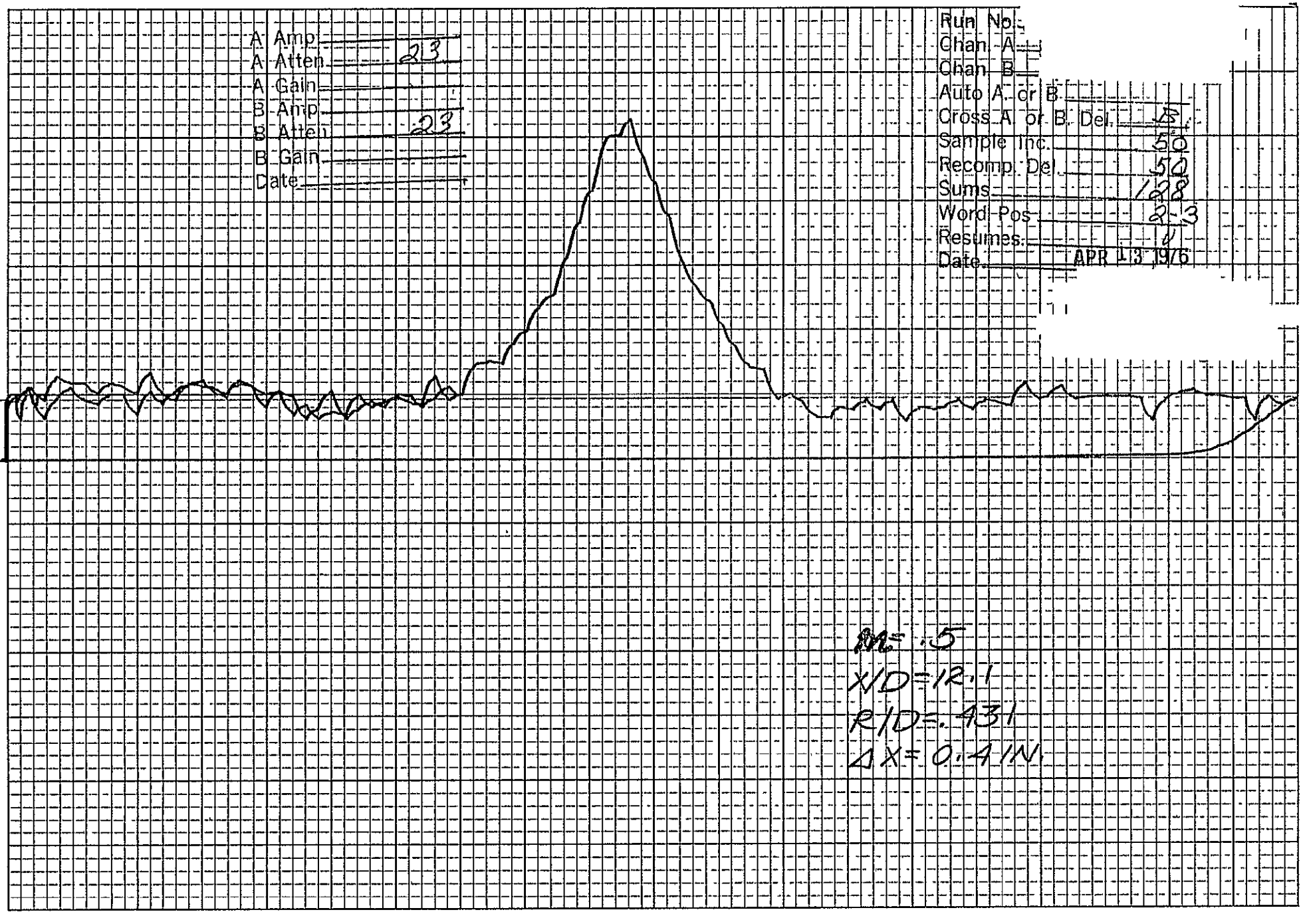
[illegible] No XY-1001-SP



[redacted] RECORDING [redacted]

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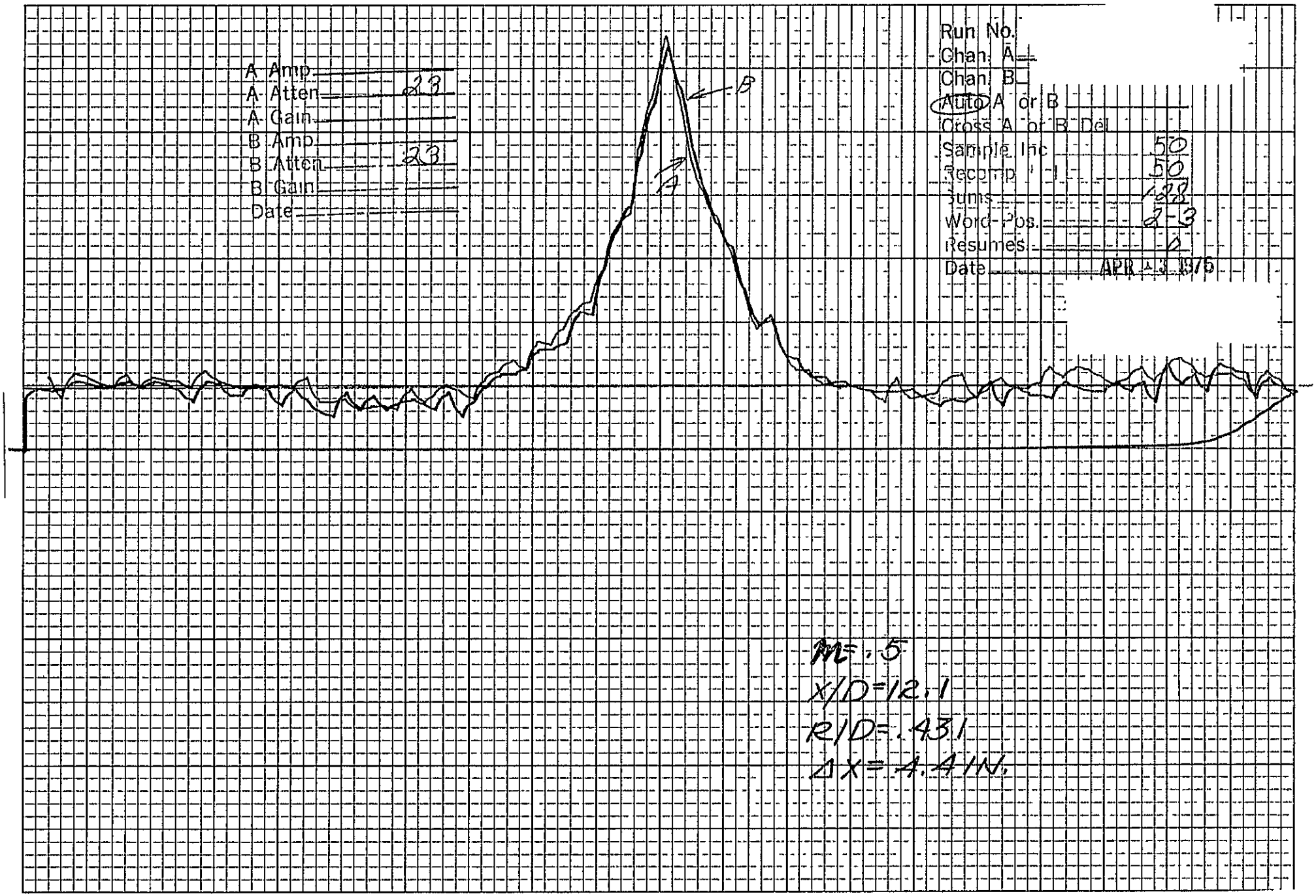
[redacted] [redacted]

No XY-1001-SP 1



[redacted] REC [redacted] G C [redacted]
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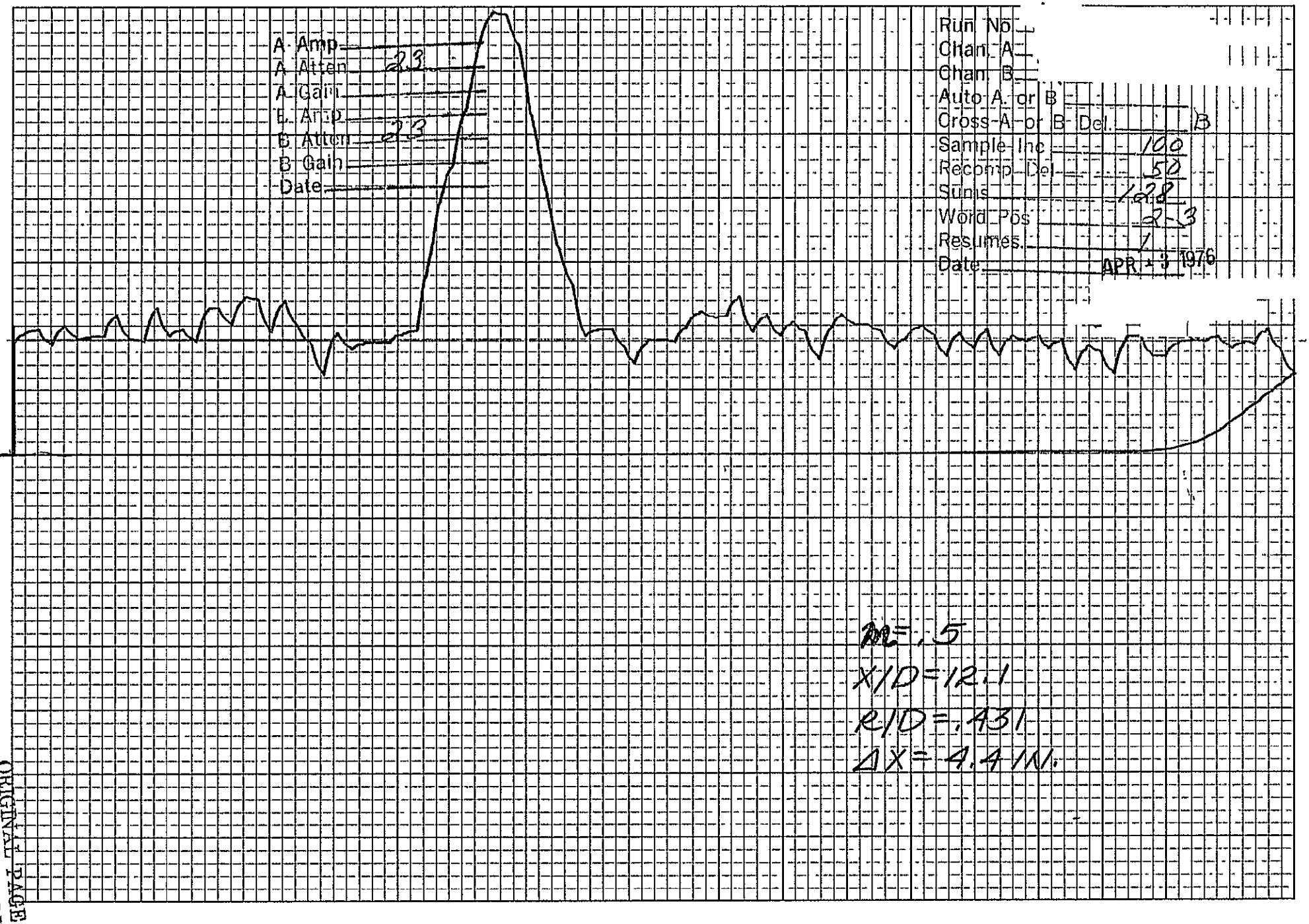
[redacted] [redacted]
No XY-1001 - SP



M = .5
X/D = 12.1
R/D = .431
ΔX = 4.4 in.

[redacted] REC [redacted] G C [redacted]
GRAPHIC CONTROLS CORPORATION
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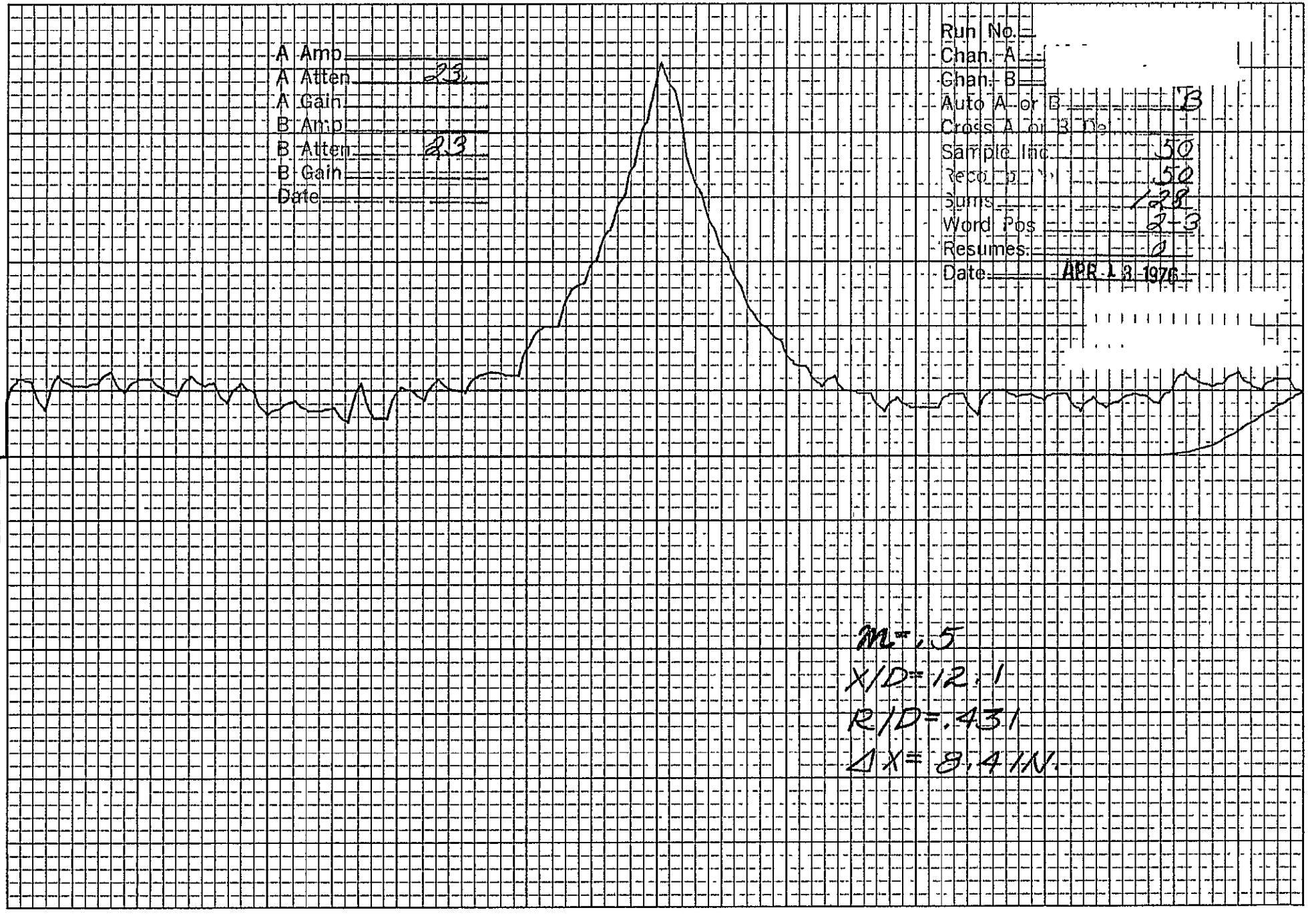
[redacted] [redacted] No XY-1001 - SP



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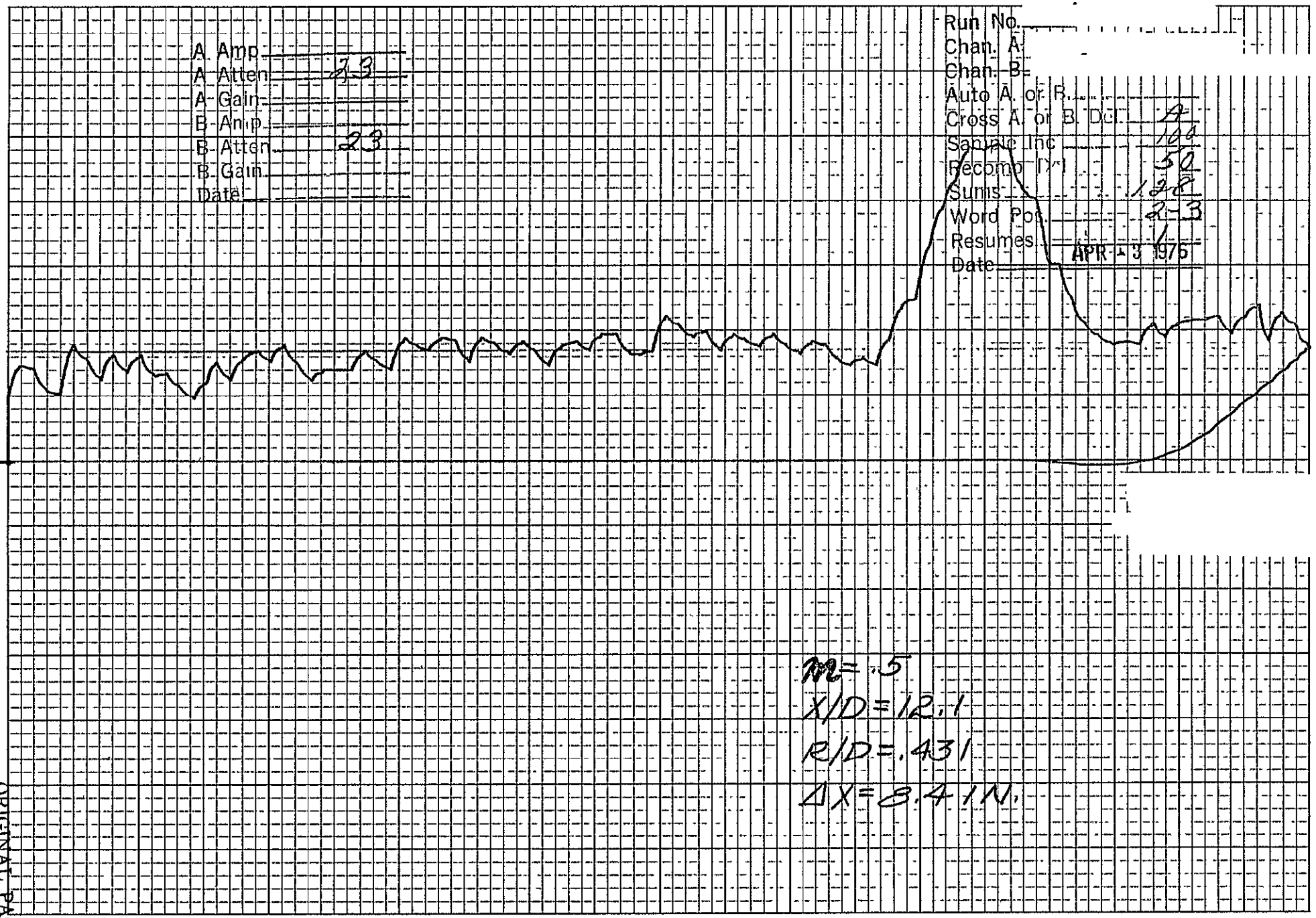
No XY-1001-SP

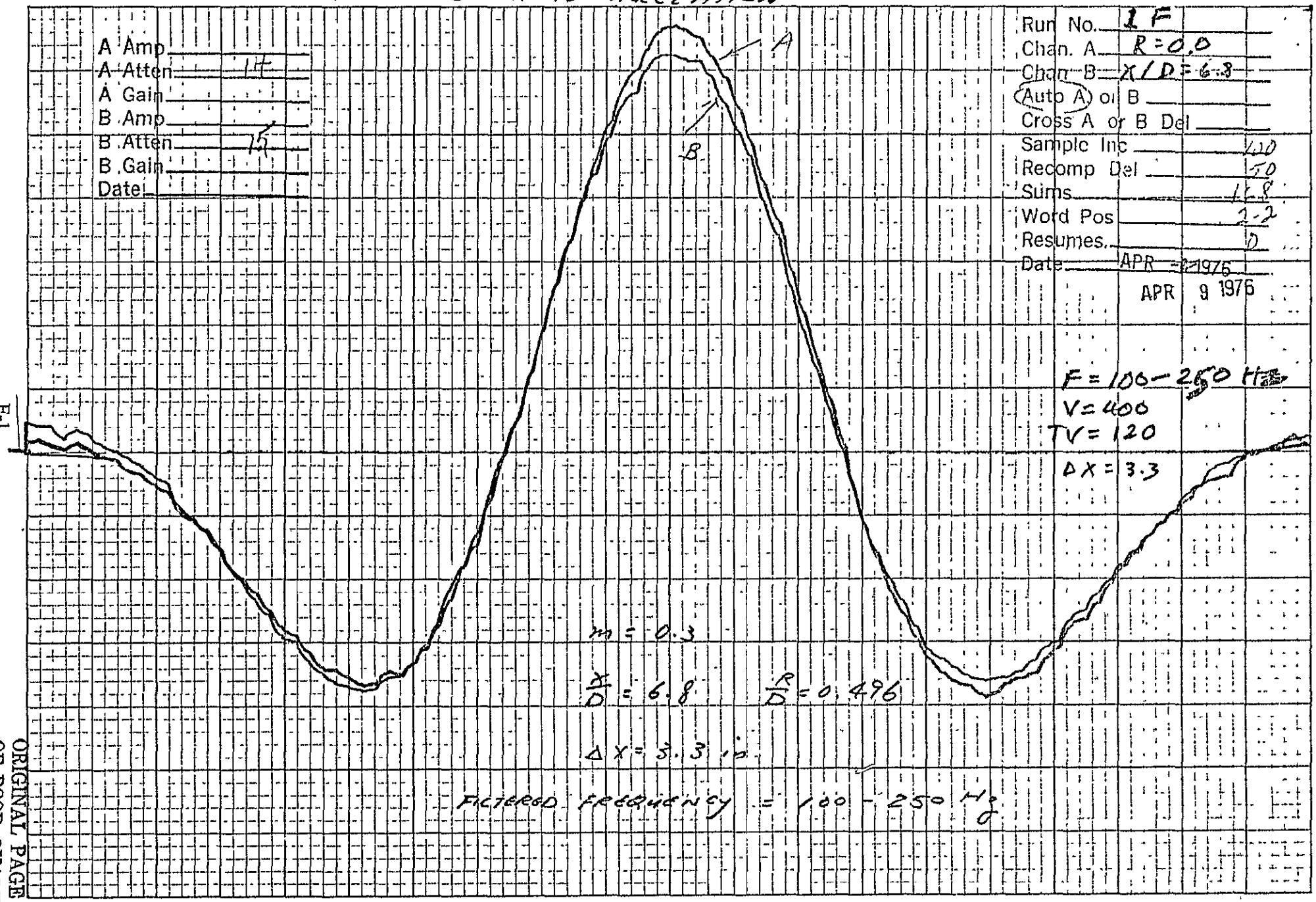


D-201

E. Filtered Auto and Cross Correlations

This section contains the filtered auto and cross correlations. In section D, all the signals were band-pass filtered from 0-20 KHz. In this section the signals were band-pass filtered at the various selected frequency ranges as listed on the bottom center of the plots.

FILTERED AUTO CORRELATION



E-1

RECORDING CHART
[redacted] GRAPHIC [redacted] CORPORATION
BUFFALO NEW YORK
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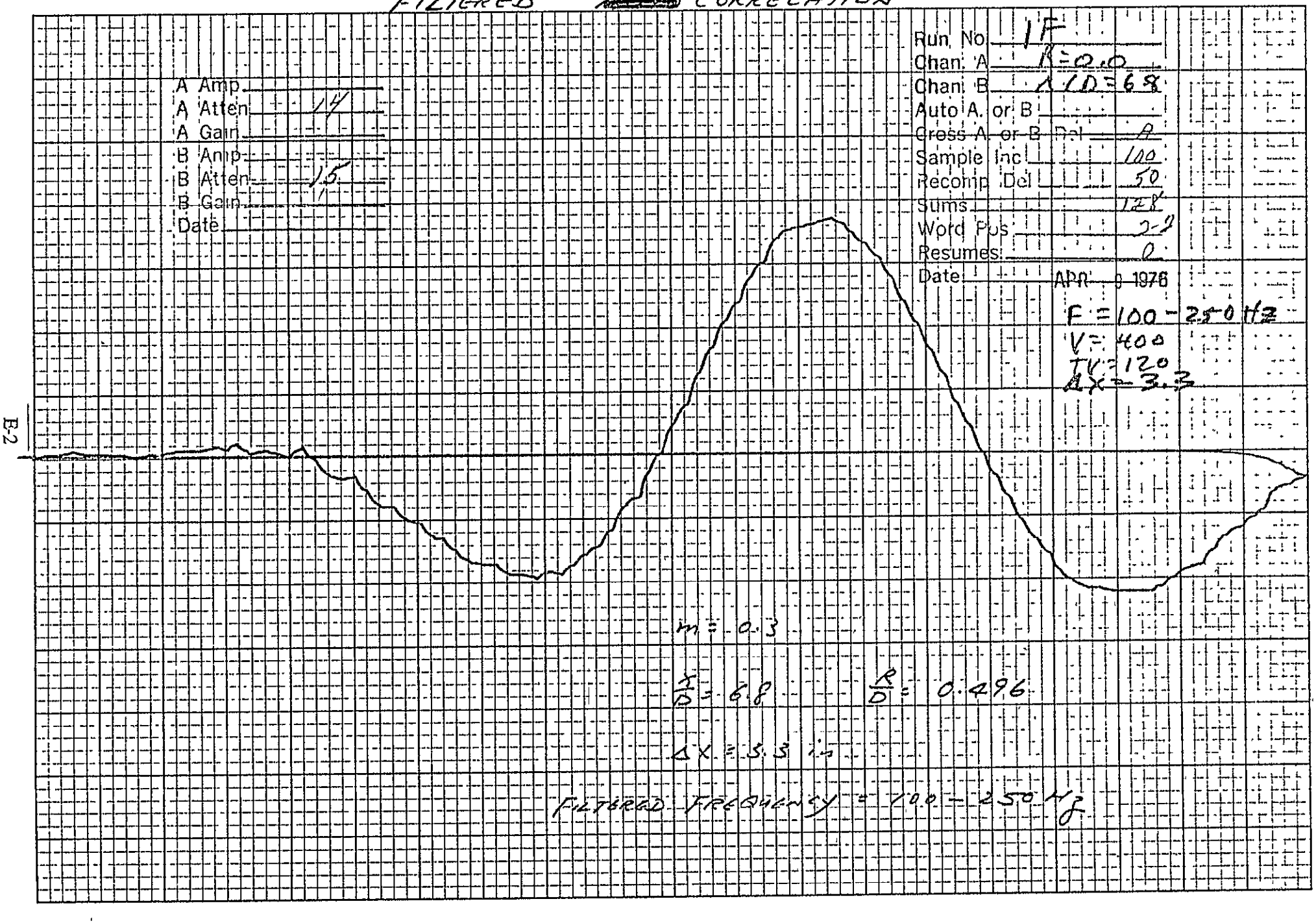
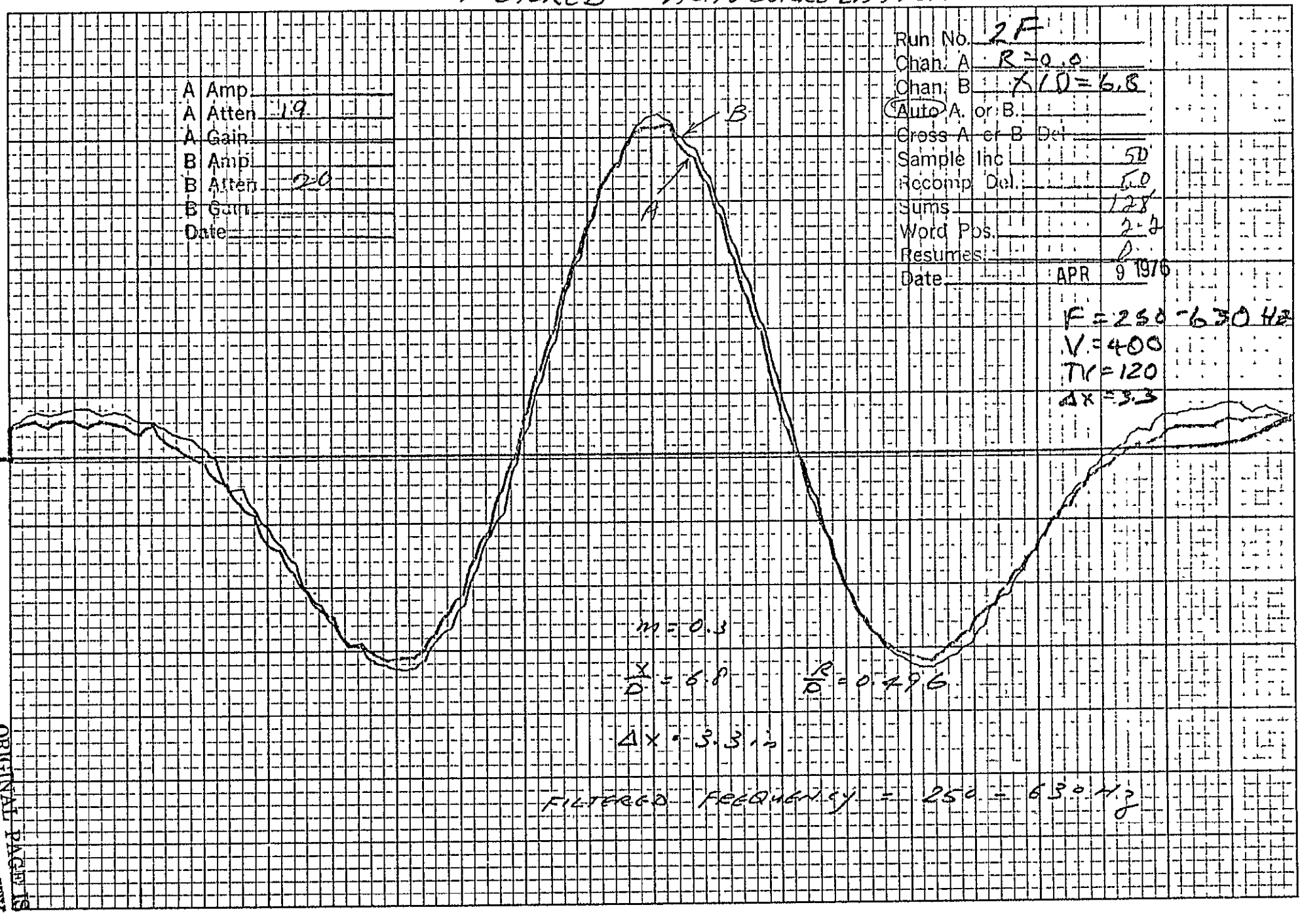
CROSS

FILTERED [redacted] CORRELATION



E-2

FILTERED AUTO CORRELATION



E-3

[RECORDING CHARTS]
[redacted] GRAPHIC CONTROLS [redacted] CORPORATION
BUFFALO NEW YORK
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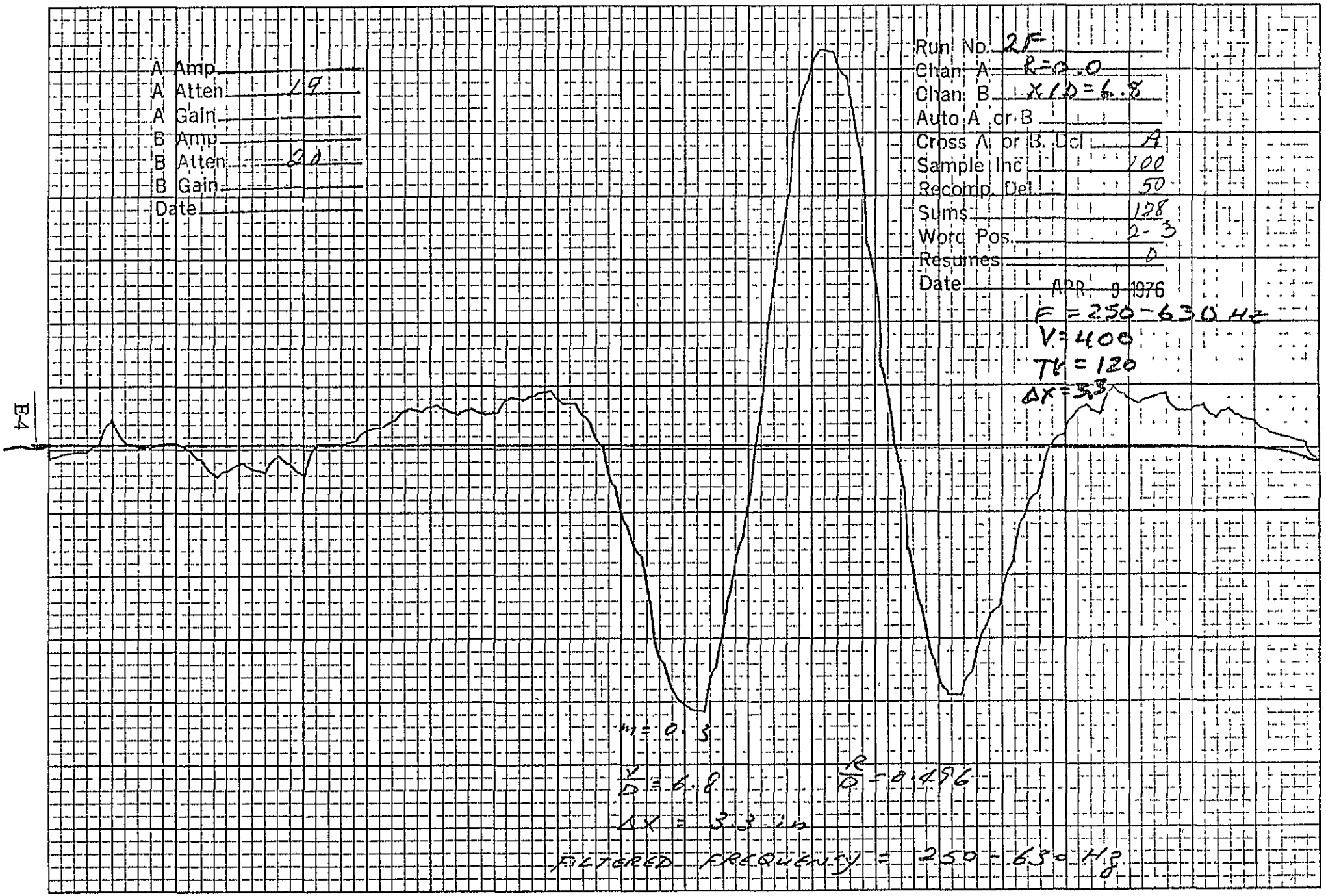
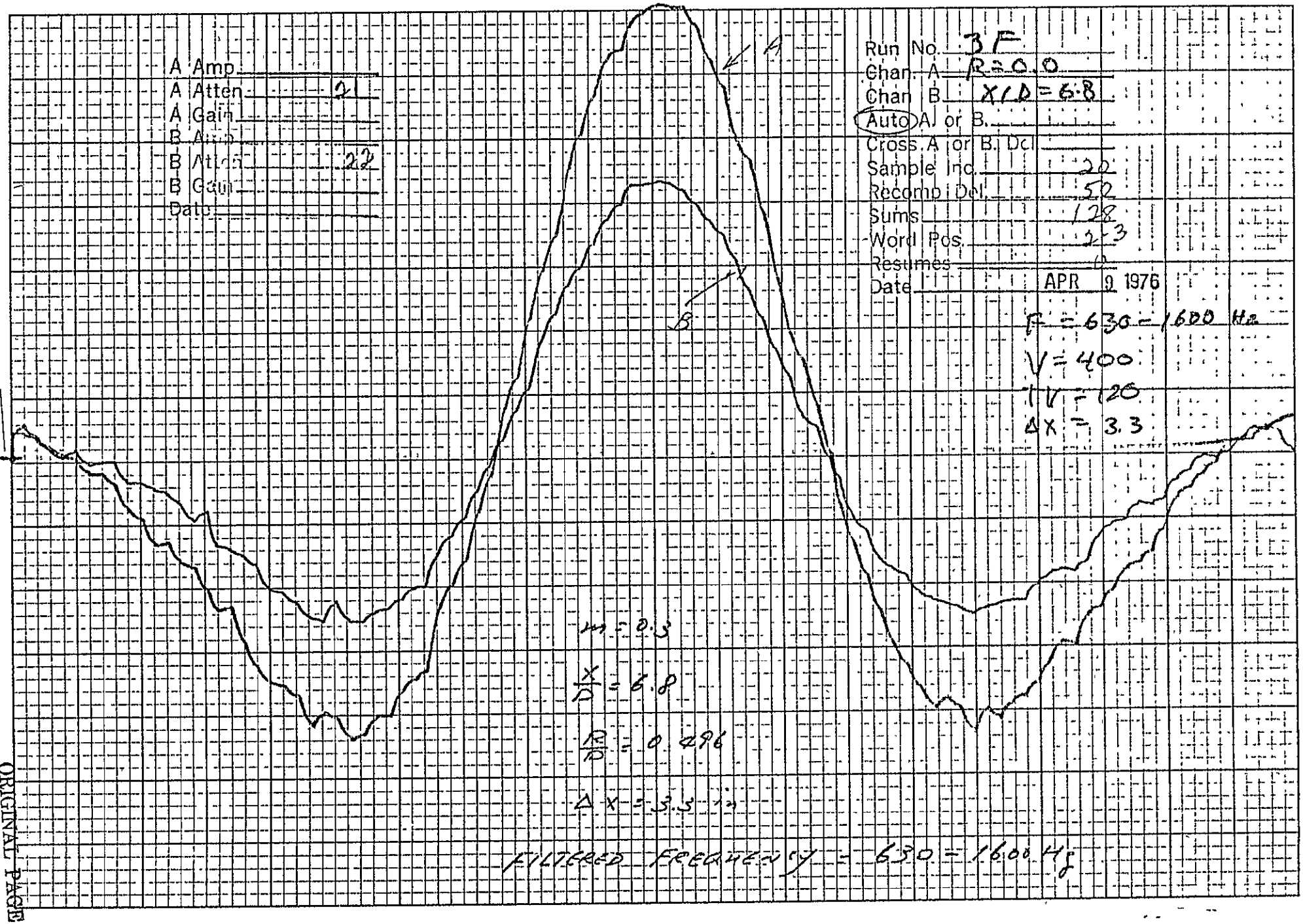
FILTERED CROSS CORRELATION

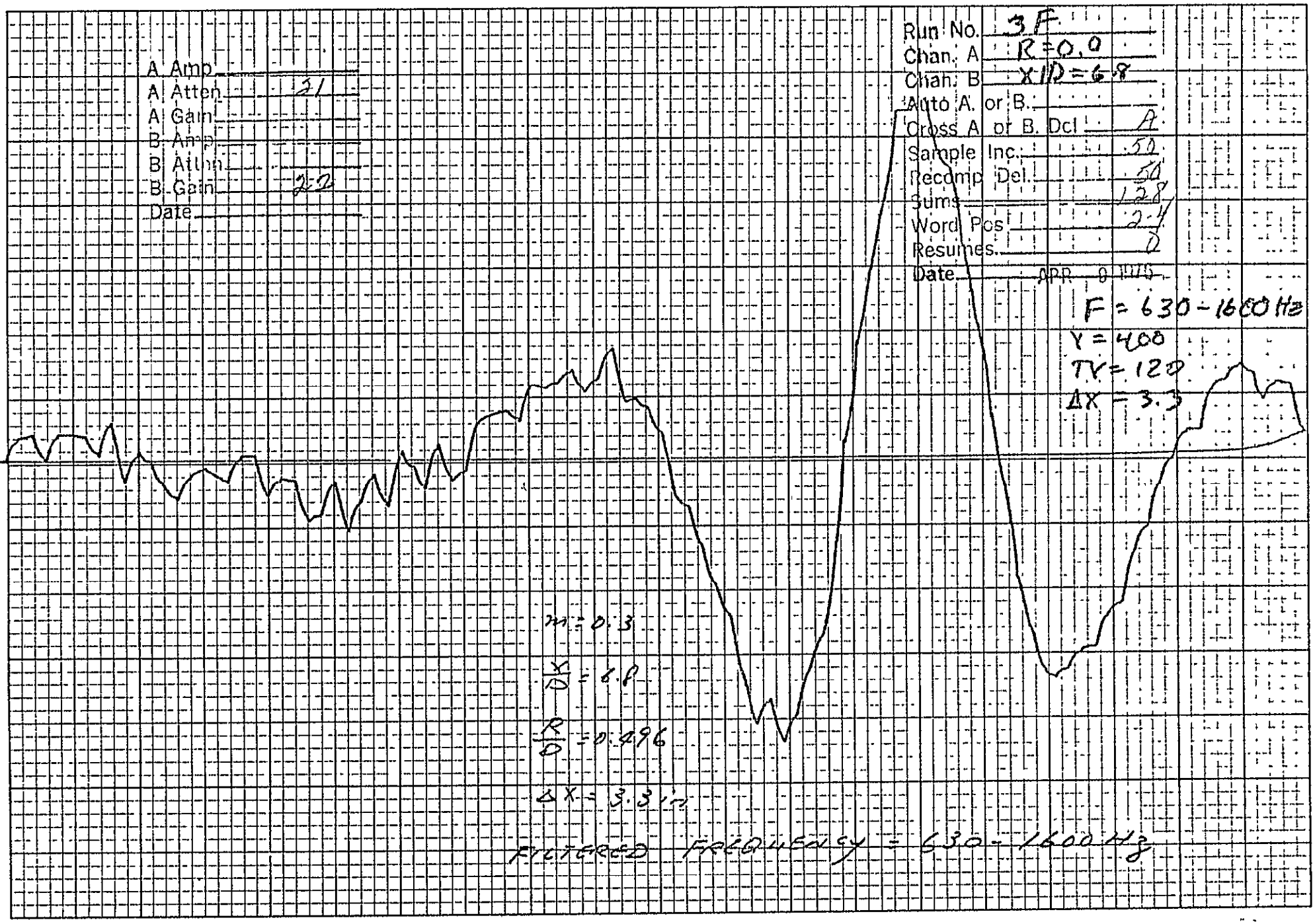


FILTERED AUTO CORRELATION

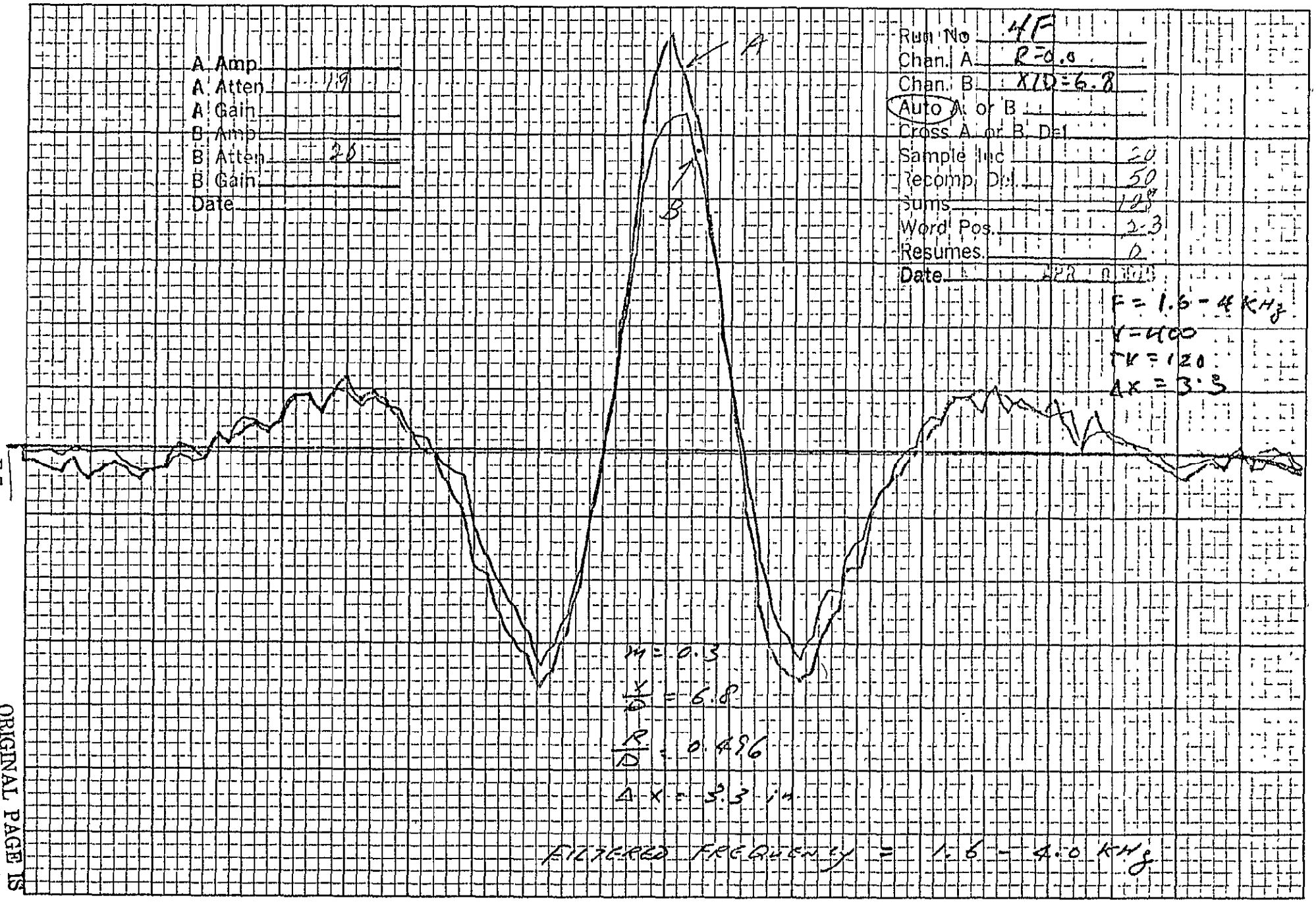


E-5

FILTERED CROSS CORRELATION

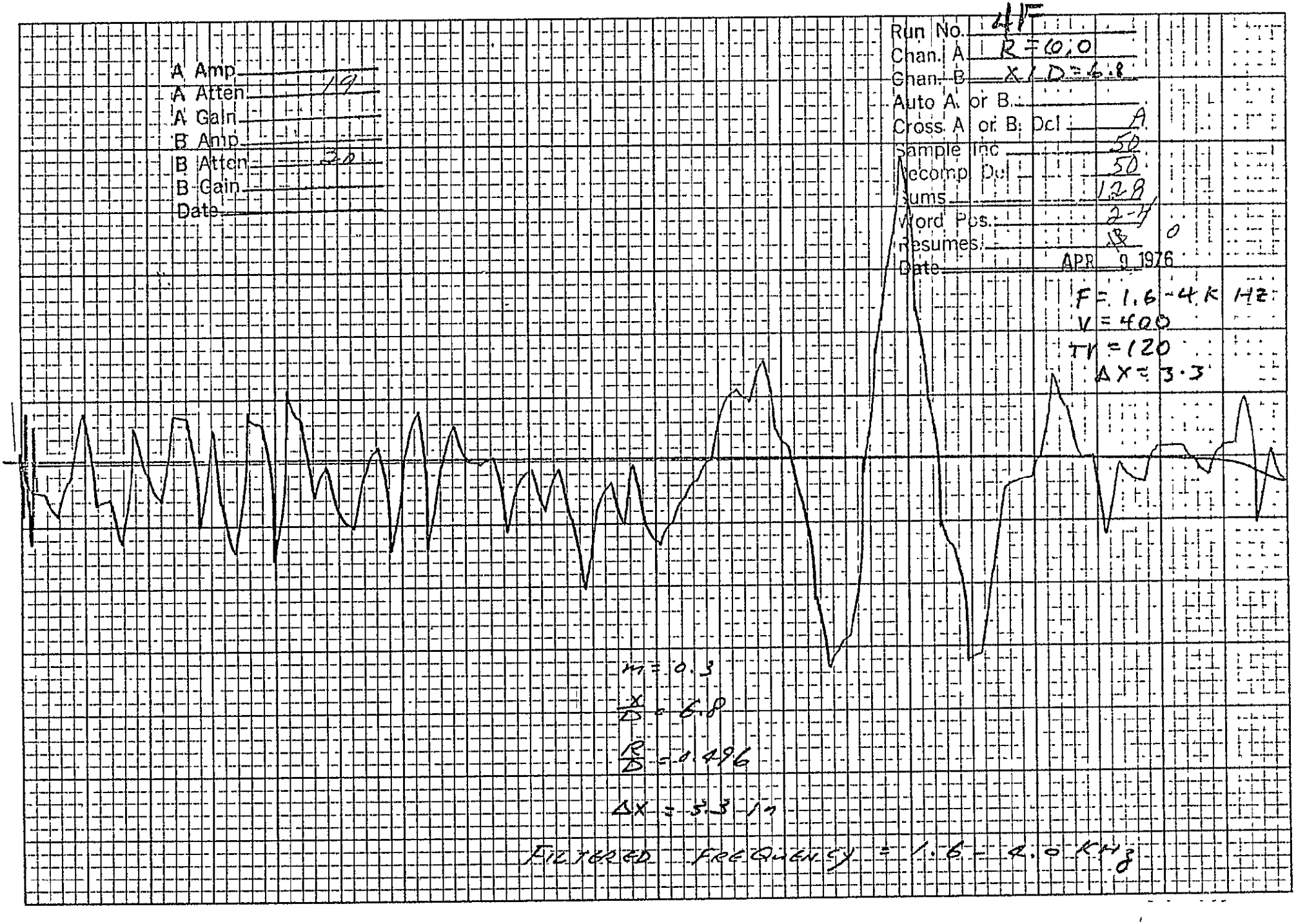


FILTERED AUTOCORRELATION



E-7

FILTERED CROSS CORRELATION



F. Normalized Cross Correlation Coefficients

With the following definitions:

A_A = Channel A attenuation for cross correlation

A_B = Channel B attenuation for cross correlation

A_A' = Channel A attenuation for auto correlation

A_B' = Channel B attenuation for auto correlation

R_{AB} = peak cross correlation read from raw data chart

R_{AA} = peak autocorrelation read from raw data chart

R_{BB} = peak autocorrelation read from raw data chart

W_A, W_B, W_{AB} = word position appropriate for autocorrelation A. autocorrelation B, or cross correlation AB

γ_A, γ_B, γ_{AB} = resumes factor appropriate for autocorrelation A, autocorrelation B, or cross correlation AB

The normalized cross correlation coefficient $\hat{R}_{AB}$ is given by

$$\hat{R}_{AB} = \frac{10^{-A_A/10}\ 10^{-A_B/10}\ R_{AB}\ W_{AB}\ \gamma_{AB}}{\sqrt{10^{-2A_A'/10}\ R_{AA}\ W_A\ \gamma_A\ 10^{-2A_B'/10}\ R_{BB}\ W_B\ \gamma_B}}$$

The factor γ may be determined from Table F.1.

Table F.1

Relation of γ to Number of Resumes

Resume	γ
0	1
1	$\frac{1}{2}$
2	$\frac{1}{3}$
3	$\frac{1}{4}$

Resume	γ
4	$\frac{1}{5}$

Normalized cross correlation coefficients are plotted for fixed velocity ratio, in axial position X/D, and radial position R/D as a function of probe axial separation.

Sample Calculation

The following caluclation was made for the first set of data in Section D; m = 0, X/D = 3, R/D = 0.363. ΔX = 0.6 in. The data are contained on pages D1 (Autocorrelation A), D2 (Autocorrelation B), and D3 (Cross Correlation).

$A_A = 27$

$A_B = 27$

$A'_A = 27$

$A'_B = 27$

$R_{AB} = 27.8$

$R_{AA} = 20.0$

$R_{BB} = 18.0$

$W_A = 2\text{-}3$

$W_B = 2\text{-}3$

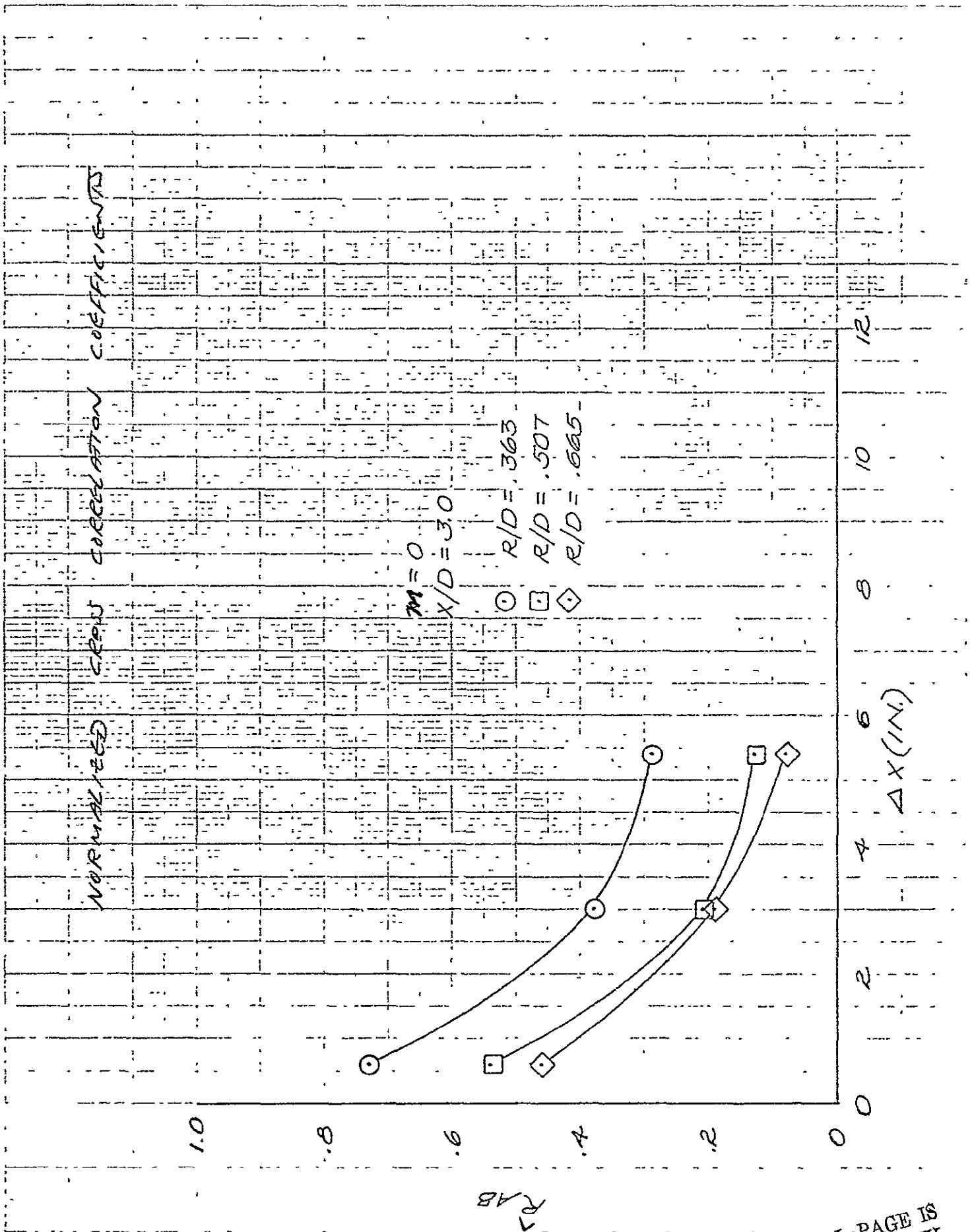
$W_{AB} = 2\text{-}4$

$r_A = 1$

$r_B = 1$

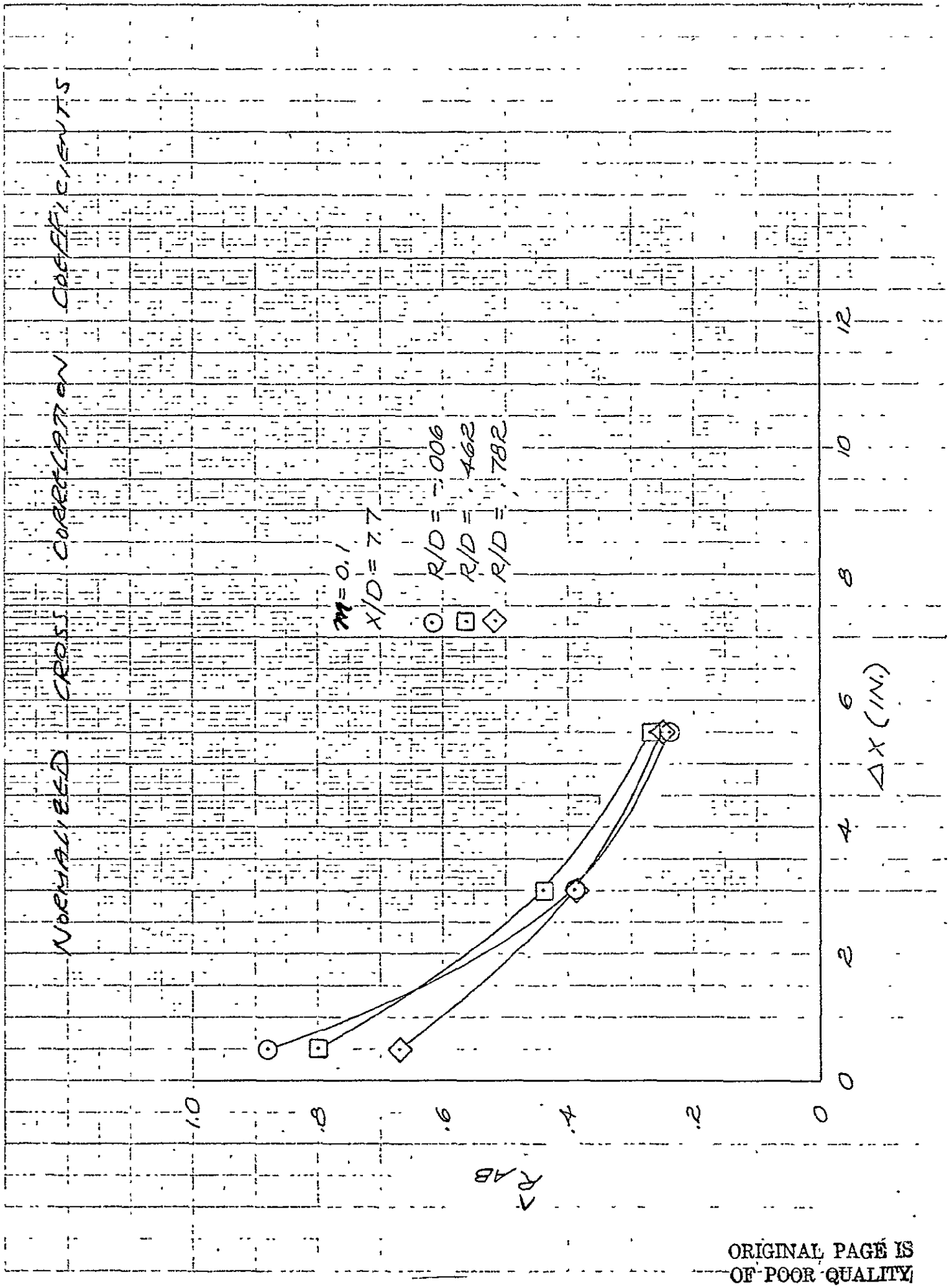
$r_{AB} = 1$

$$\text{Then } \hat{R}_{AB} = \frac{10^{-2.7} \times 10^{-2.7} \times 27.8 \times 2^{-4} \times 1}{\sqrt{10^{-5.4} \times 20 \times 2^{-3} \times 1 \times 10^{-5.4} \times 18 \times 2^{-3} \times 1}} = 0.73$$

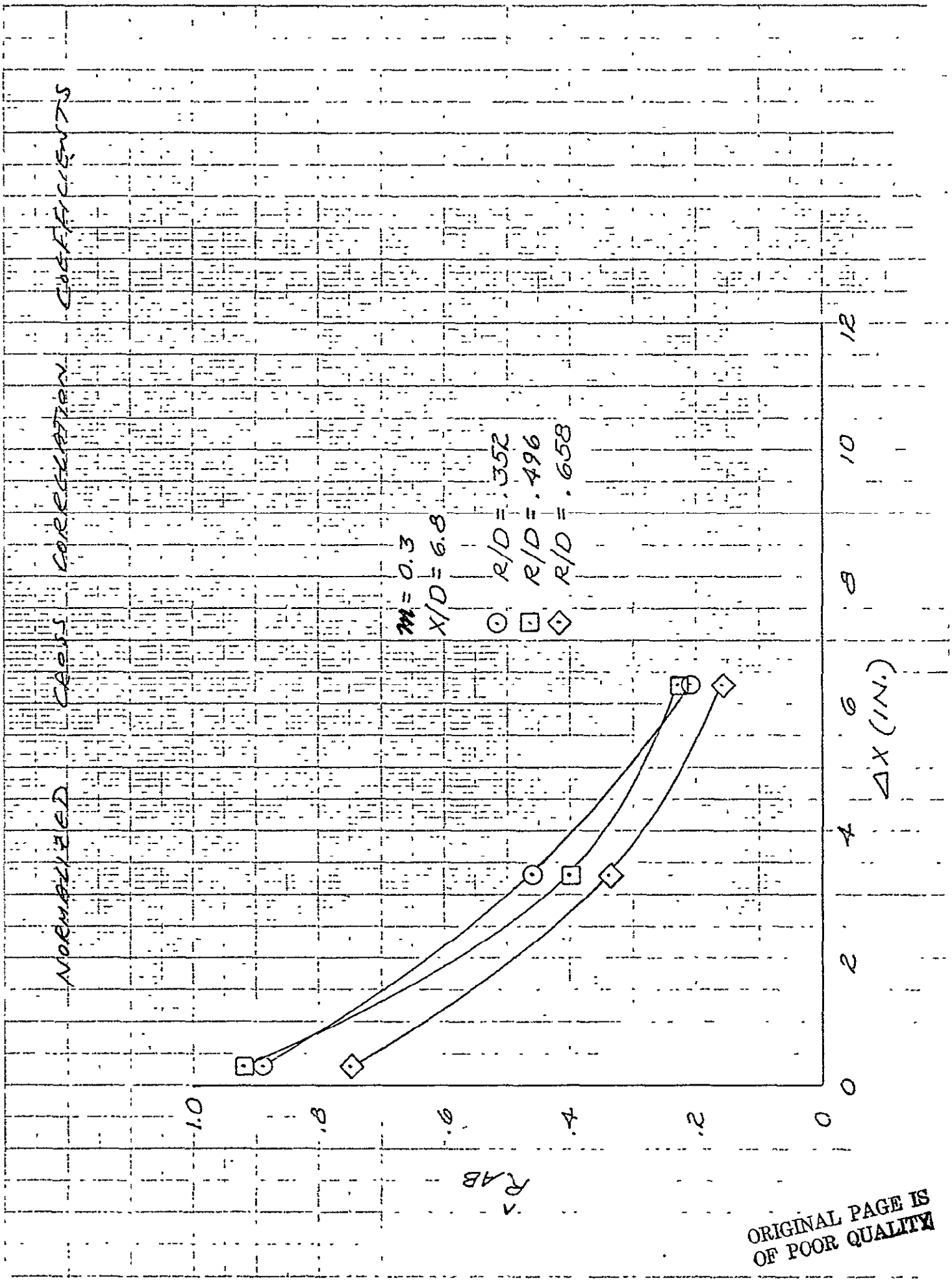


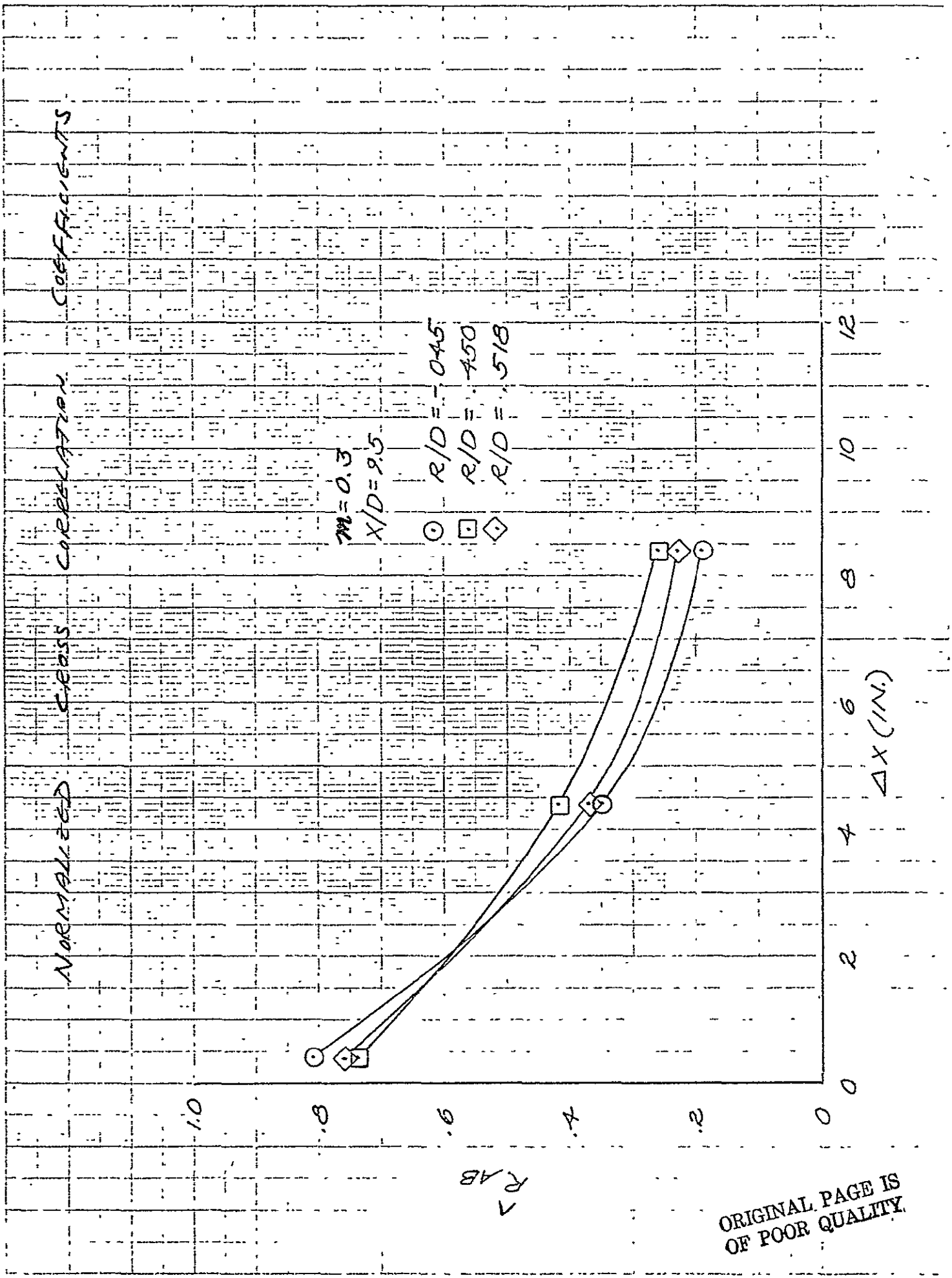
NORMALIZED CROSS CORRELATION COEFFICIENTS
M = 0
X/D = 5.0
R/D = .304
R/D = .462
R/D = .665
R_{AB}
1.0
.8
.6
.4
.2
0
0
2
4
6
8
10
12
ΔX (IN.)

NORMALIZED CROSS CORRELATION COEFFICIENTS
M = 0.1
X/D = 5.5
R/D = .290
R/D = .484
R/D = .700
R_{AB}
1.0
.8
.6
.4
.2
0
0
2
4
6
8
10
12
Δ X (IN.)

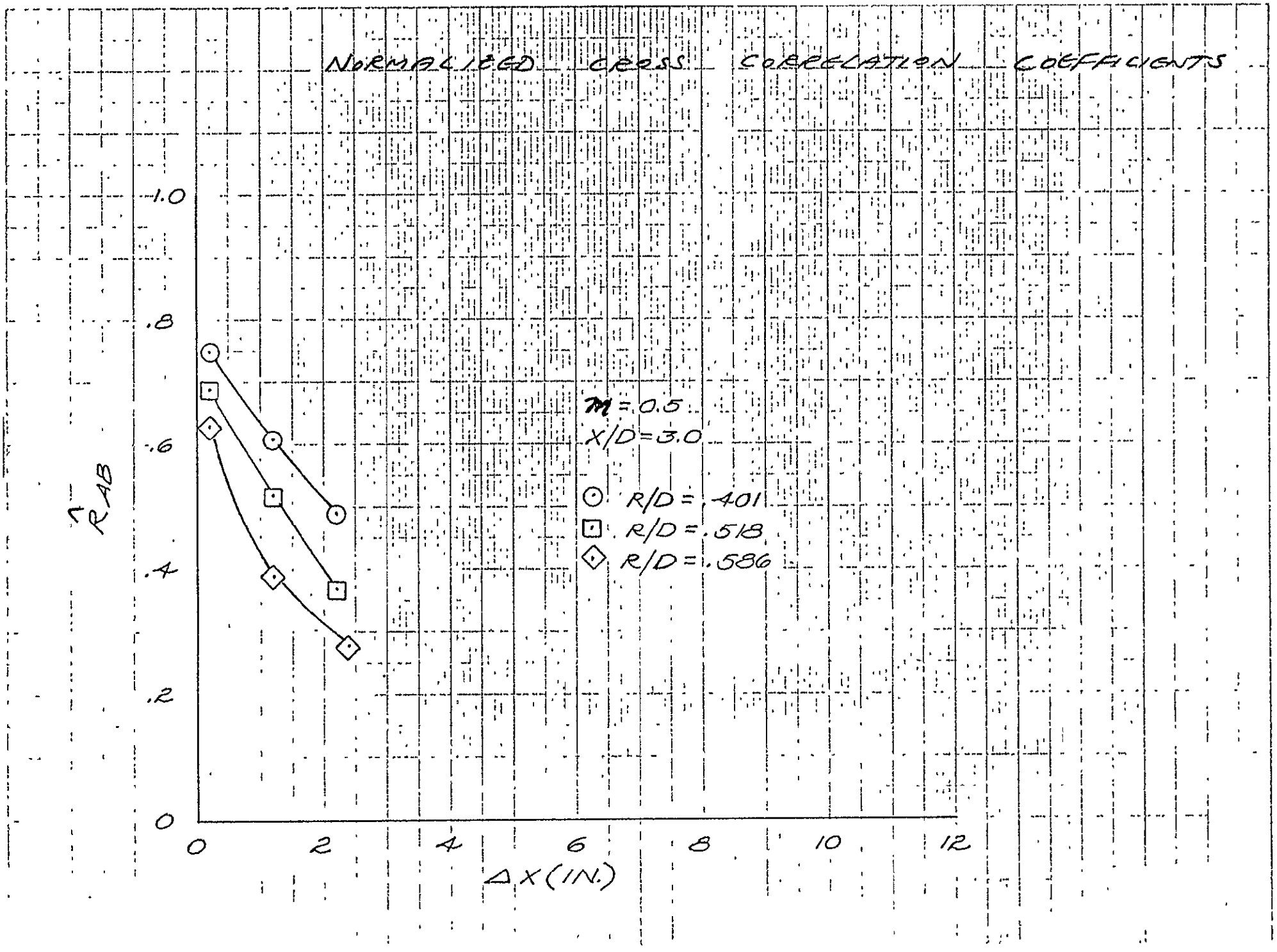


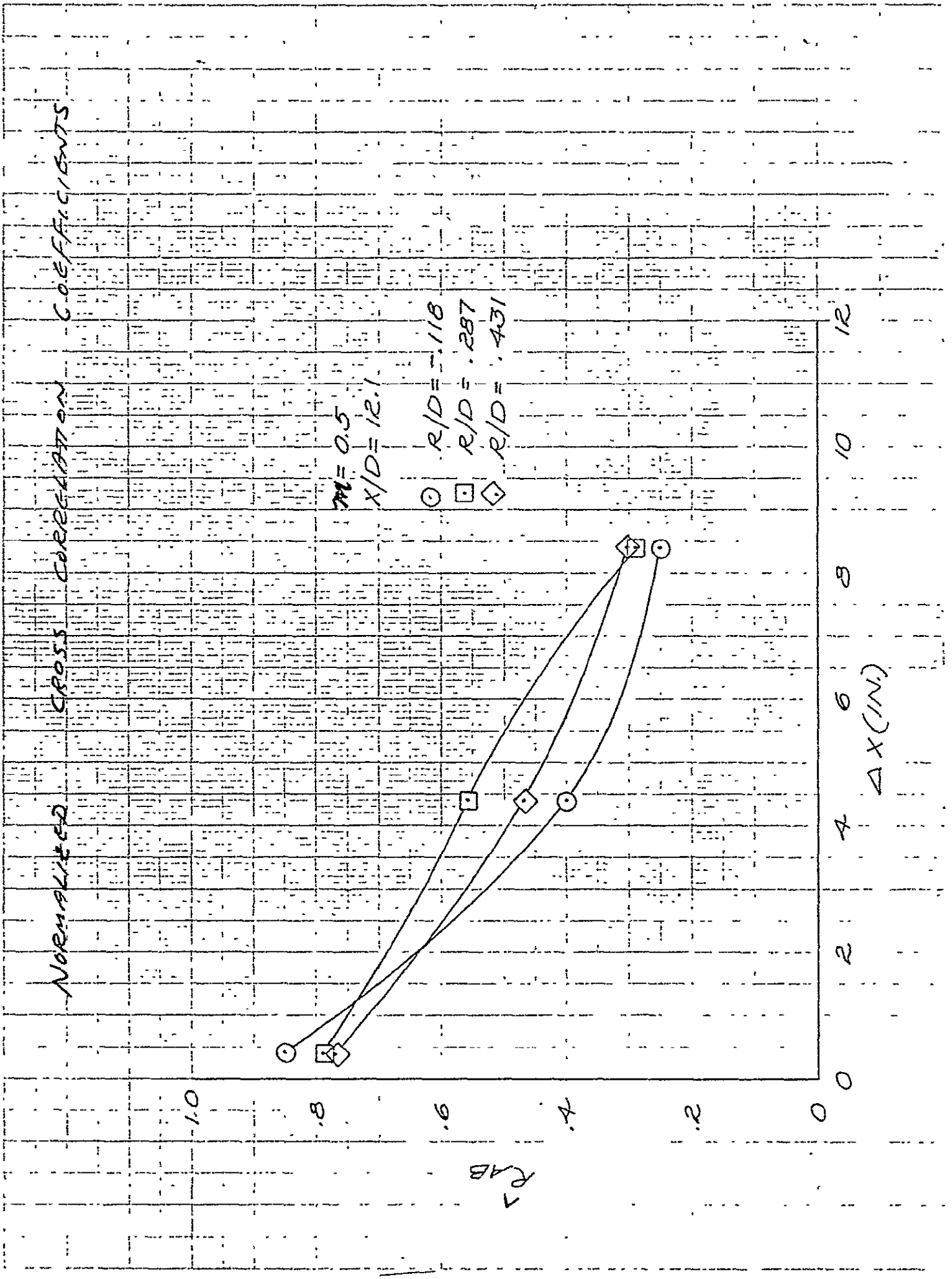
NORMALIZED CROSS CORRELATION COEFFICIENTS
R_{AB}
1.0
.8
.6
.4
.2
0
0
2
4
6
8
10
12
ΔX (IN.)
M = 0.3
X/D = 3.0
R/D = .410
R/D = .518
R/D = .608





ORIGINAL PAGE IS
OF POOR QUALITY


NORMALIZED CROSS CORRELATION COEFFICIENTS
M = 0.5
X/D = 3.0
R/D = .401
R/D = .518
R/D = .586
R_AB
ΔX (IN.)
0
.2
.4
.6
.8
1.0
0
2
4
6
8
10
12


NORMALIZED CROSS CORRELATION COEFFICIENTS
M = 0.5
X/D = 12.1
R/D = .118
R/D = .287
R/D = .431
R_AB
1.0
.8
.6
.4
.2
0
0
2
4
6
8
10
12
ΔX (IN.)

G. Tabulation of Convection Velocity

The convection velocity is determined by cross correlating the fluctuating signals of two hot wires which are separated axially by a distance ΔX. Convection velocities are calculated by dividing the separation ΔX by the time delay for the maximum cross correlation coefficient. A tabulation of the calculated convected velocities is contained in this section.

CONVECTION VELOCITY

$m=\frac{U_e}{U_j}$	$\frac{X}{D}$	$\frac{R}{D}$	ΔX (in)	U_c (fps)	$m=\frac{U_e}{U_j}$	$\frac{X}{D}$	$\frac{R}{D}$	ΔX (in)	U_c (fps)
0	3.0	0.363	0.6	200	0.1	3.0	0.381	0.5	278
		0.363	3.0	281			0.381	3.0	278
		0.363	5.4	282			0.381	5.5	296
		0.507	0.6	213			0.471	0.5	189
		0.507	3.0	230			0.471	3.0	263
		0.507	5.4	254			0.471	5.5	270
		0.665	0.6	106			0.687	0.5	194
		0.665	3.0	181			0.687	3.0	199
		0.665	5.4	190			0.687	5.5	202
	5.0	0.304	1.0	278		5.5	0.290	0.3	196
		0.304	6.0	297			0.290	3.3	289
		0.304	11.0	278			0.290	6.3	282
		0.462	1.0	220			0.484	0.3	147
		0.462	6.0	250			0.484	3.3	239
		0.462	11.0	237			0.484	6.3	239
		0.665	1.0	167			0.700	0.3	86
		0.665	6.0	217			0.700	3.3	198
		0.665	11.0	207			0.700	6.3	202
						7.7	-.006	0.5	306
							-.006	3.0	301
							-.006	5.5	337
							0.462	0.5	177
							0.462	3.0	238
							0.462	5.5	239
							0.782	0.5	123
							0.782	3.0	160
							0.782	5.5	189

CONVECTION VELOCITY

$m=\frac{U_e}{U_j}$	$\frac{x}{D}$	$\frac{R}{D}$	Δx (in)	U_c (fps)	$m=\frac{U_e}{U_j}$	$\frac{x}{D}$	$\frac{R}{D}$	Δx (in)	U_c (fps)
0.3	3.0	0.410	0.3	240	0.5	3.0	0.401	0.2	333
		0.410	1.8	319			0.401	1.2	333
		0.410	3.3	299			0.401	2.2	340
		0.518	0.3	216			0.518	0.2	269
		0.518	1.8	259			0.518	1.2	286
		0.518	3.3	263			0.518	2.2	306
		0.608	0.3	174			0.586	0.2	157
		0.608	1.8	246			0.556	1.2	286
		0.608	3.3	246			0.586	2.4	276
	6.8	0.352	0.3	219		7.7	-.101	0.4	980
		0.352	3.3	299			-.101	4.4	367
		0.352	6.3	309			-.101	8.4	375
		0.496	0.3	179			0.304	0.4	292
		0.496	3.3	262			0.304	4.4	324
		0.496	6.3	269			0.304	8.4	328
		0.658	0.3	132			0.489	0.4	256
		0.658	3.3	237			0.489	4.4	302
		0.658	6.3	236			0.489	8.4	295
	9.5	-.045	0.4	347		12.1	-.118	0.4	483
		-.045	4.4	327			-.118	4.4	353
		-.045	8.4	318			-.118	8.4	350
		0.450	0.4	185			0.287	0.4	298
		0.450	4.4	256			0.287	4.4	319
		0.450	8.4	252			0.287	8.4	306
		0.518	0.4	139			0.431	0.4	300
		0.518	4.4	255			0.431	4.4	286
		0.518	8.4	238			0.431	8.4	269

CONVECTION VELOCITY

$\frac{R}{D} = 0.496$

$m = \frac{U_e}{U_j}$	$\frac{X}{D}$	Δx (in)	FILTERED FREQUENCY (KHz)		U_c (fps)
0.3	6.8	3.3	.1	.25	217
↓	↓	↓	.25	.63	250
↓	↓	↓	.63	1.60	275
↓	↓	↓	1.60	4.00	285