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PROTOTYPE AIRBORNE ONE-THIRD OCTAVE BAND SPECTRUM ANALYZER FOR ACOUSTIC AND VIBRATION DATA

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by

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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWARD

The research reported herein was conducted by Bolt Beranek and Newman Inc. under Contract NAS1-10165. Acknowledgment is given to Byron E. Blanchard of Bolt Beranek and Newman, who conducted most of the research, and to Mr. Alfred Beswick of Langley Research Center who brought the problem to the forefront and provided careful reviews during the performance of the contract.

PROTOTYPE AIRBORNE ONE-THIRD OCTAVE BAND SPECTRUM ANALYZER FOR ACOUSTIC AND VIBRATION DATA

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SUMMARY

The design of a compact frequency analyzer for measurement and analysis onboard flight vehicles is discussed. By the use of such an analyzer, wideband data can be analyzed onboard, thus substantially reducing the bandwidth requirements on the telemetry links.

The analyzer has been breadboarded in a partial third-octave band configuration with eight filters and detectors spaced by the $\sqrt{10}$ from 100 Hz to 200,000 Hz. The analyzer has been tested over a temperature range of 40 to 120°F, and has demonstrated at least 60 dB of dynamic range.

TABLE OF CONTENTS

LIST OF FIGURES

SECTION I
INTRODUCTION

Acoustic and vibration measurements made on flight vehicles often require wideband data. Such data are usually telemetered or stored on-board for frequency analysis at a later time. However, telemetry and magnetic tape data bandwidths are limited, thus imposing restrictions on the amount of wideband data that can be collected on any one flight. Hence, techniques for obtaining the essential information content of wideband data and converting it into more typical narrow band data that can be commutated and transmitted or stored can be very useful.

In this research program, a breadboard third-octave band analyzer for frequency bands between 100 Hz and 200 kHz was designed and built, using active filters and modern semiconductor circuitry. The analyzer performs a frequency analysis of the wideband data on board the vehicle. Its output is a slowly-varying signal that is compatible with the narrower bandwidths of standard equipment, but which still contains the essential frequency-amplitude information of the original wideband data.

To perform such a spectrum analysis effectively, an analyzer must be capable of handling a very wide range of input signals. The design developed in this program can accept input signals with a range of amplitudes varying by a factor greater than 1000 (i.e., 60 dB), and compress this information into 20 dB/volt at the output (a range of three volts).

The spectrum analyzer system and its circuitry are described in detail in Section II of this report. Section III presents the results of temperature testing of each of eight active filters and associated circuitries which comprise the breadboard analyzer. The tests determined the frequency-amplitude response characteristics at temperatures of 40°F, 70°F, and 120°F.

SECTION II
TECHNICAL DESCRIPTION

The frequency range of interest for the analyzer was specified to extend from 100 Hz to 200 kHz and the amplitude levels of signals within this range were specified to permit a variation of 60 dB. It was necessary to find the best technique for accommodating the wide range of signal characteristics with realizable circuitry compatible with the flight environment. Some potential techniques that were considered include:

a) pre-emphasis,

b) logarithmically converted output, and

c) automatic gain control.

These techniques are discussed below; typical block diagram circuit configurations are shown in Fig. 1.

Pre-emphasis. An input signal level attenuator ahead of each filter circuit is adjusted on the basis of estimates determined prior to the flight experiment. This requires prediction within narrow limits of the behavior of the quantity to be measured, which is often very difficult to do. Further, this method cannot take into account unpredictable variations from expected performance. The advantages of pre-emphasis are that it is very easy to realize and that the inverse attenuation characteristics required for regeneration of the original data can be easily incorporated.

Logarithmically Converted Output. A logarithmic compressor circuit is added to each filter channel to allow a wide range output. The dynamic range of this configuration is limited by the detector, which must operate over the full dynamic range of the input signal. This limitation becomes more severe as frequency increases.

Automatic Gain Control. This configuration does not require the detector to have a wide dynamic range and has the widest potential dynamic range of the three configurations considered. The gain control voltage is used as the system

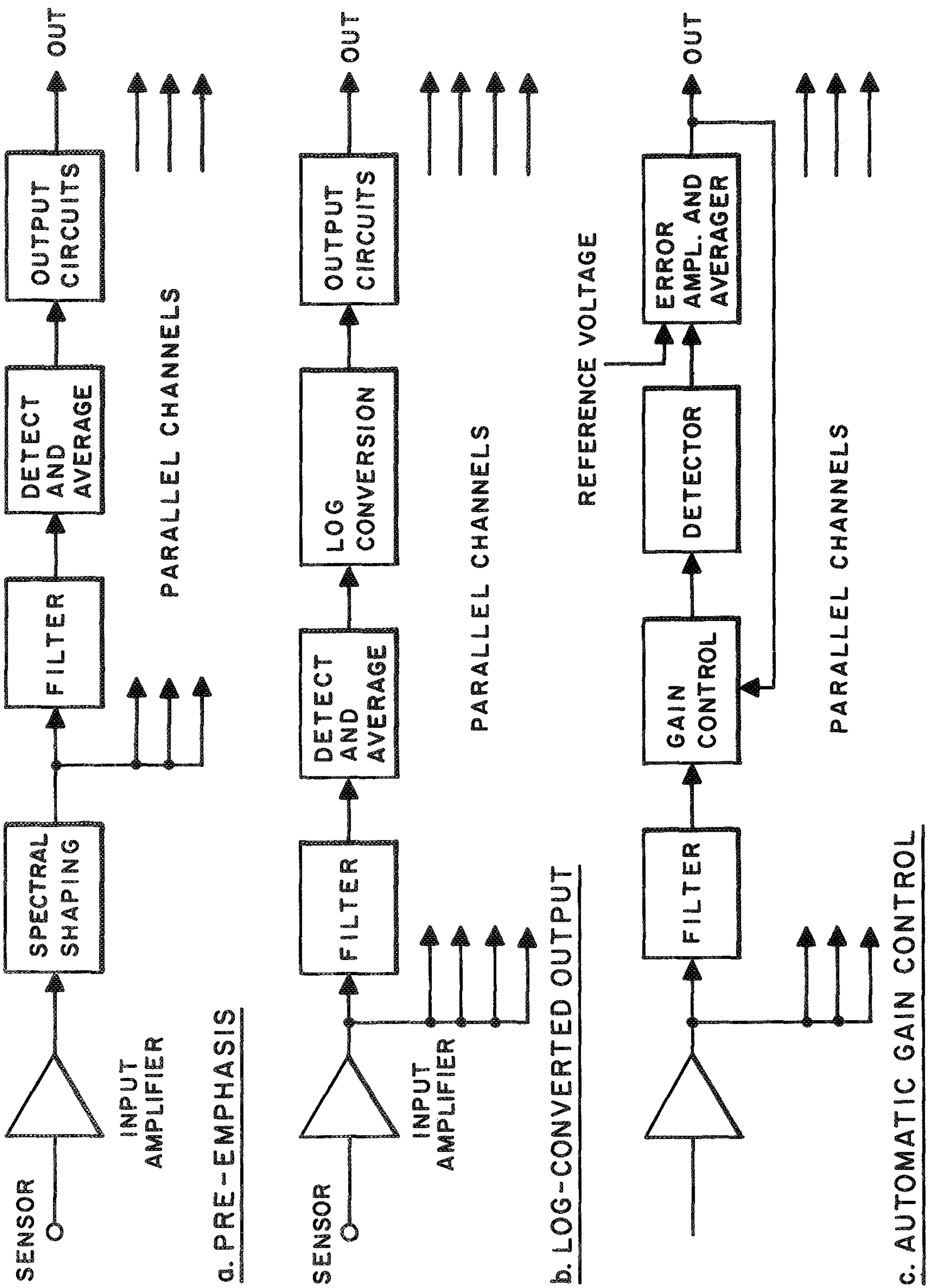


FIG.1 POTENTIAL ANALYZER CONFIGURATIONS

output and since the relationship between the system gain and the control voltage can be made almost exactly logarithmic, output can be given directly in dB.

After careful study, the automatic gain control (AGC) configuration was selected as the most promising technique for data compression. The advantages and disadvantages of each technique are summarized in Table I.

Following this selection, a breadboard design of a set of one-third octave band active filters was undertaken. A partial set of eight, functionally operational filters with nominal center frequencies of 100 Hz, 316 Hz, 1000 Hz, 3160 Hz, 10,000 Hz, 31,600 Hz, 100,000 Hz, and 200,000 Hz was constructed. Design considerations included selection of components so that a package design of minimum volume, suitable for flight environmental qualification testing, could be executed later with a minimum of functional redesign.

A block diagram of the breadboard analyzer design is shown in Fig. 2 and each of the blocks is described below.

Buffer Amplifier

A unity-gain buffer amplifier provides an impedance matching function from the high output impedance of the transducers to the relatively low impedance levels required by the filters. The buffer amplifier consists of a differential field effect transistor input amplifier and a PNP output transistor.

Active Filters

All of the active filters are designed to meet or exceed the American Standards Association Specification S1. 11-1966 Third-Octave Band Filter, Class II. A copy of this specification is appended to the report.

TABLE I

SYSTEM CONFIGURATION	ADVANTAGES	DISADVANTAGES
1. Pre-emphasis	Simplicity	Requires prior estimation of data.
2. Logarithmic Converted Output	Wider dynamic range than above. Logarithmic output (in dB).	Complex compared to above. Requires amplifier offset bias trim. Frequency response dependent on signal level. Dynamic range limited by detector capabilities.
3. Automatic Gain Control	Widest dynamic range. Logarithmic output (in dB). Frequency response independent of signal level. Good design flexibility.	Complexity

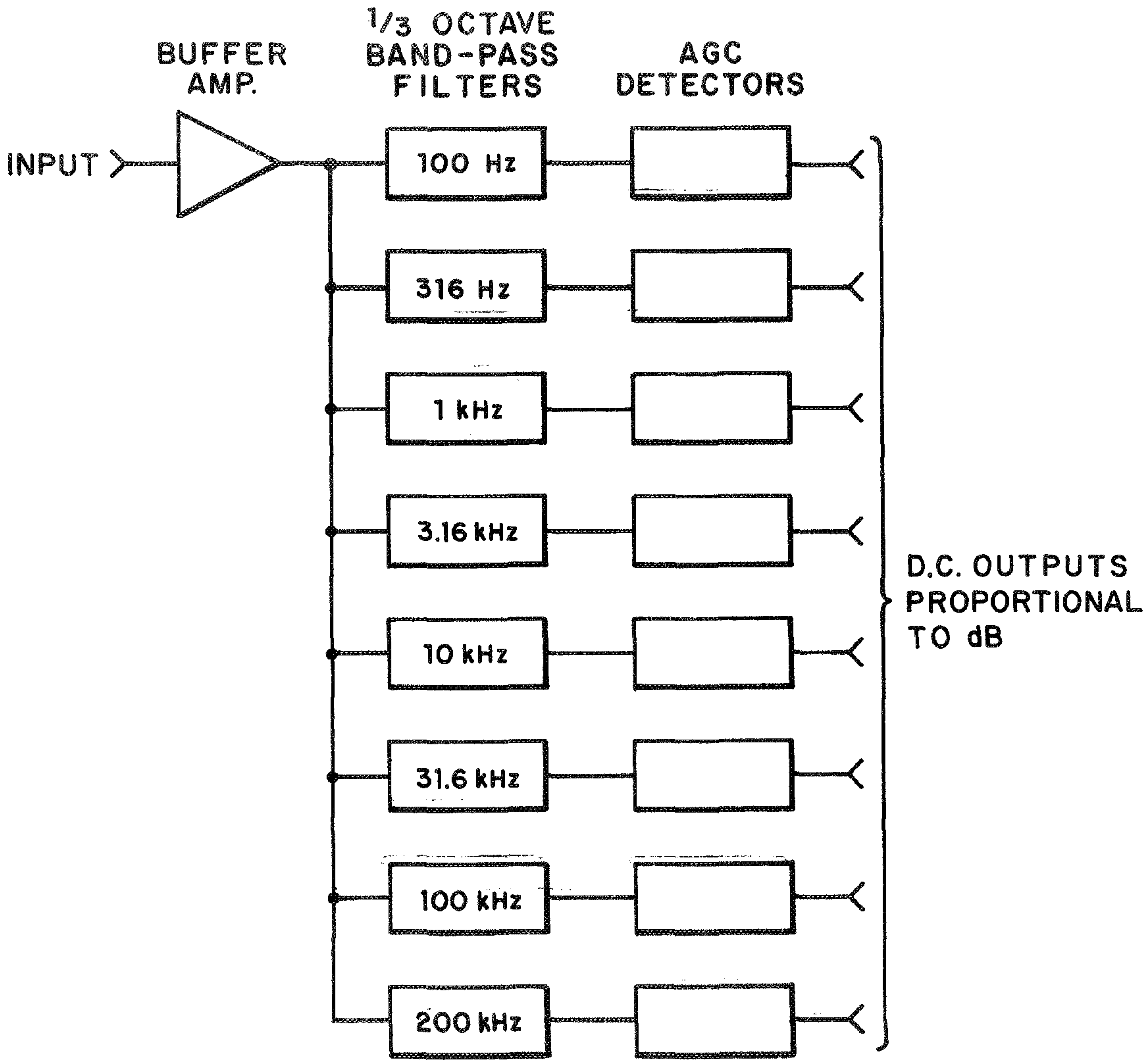


FIG.2 BLOCK DIAGRAM OF BREADBOARD ANALYZER

Low-Frequency Active Filters

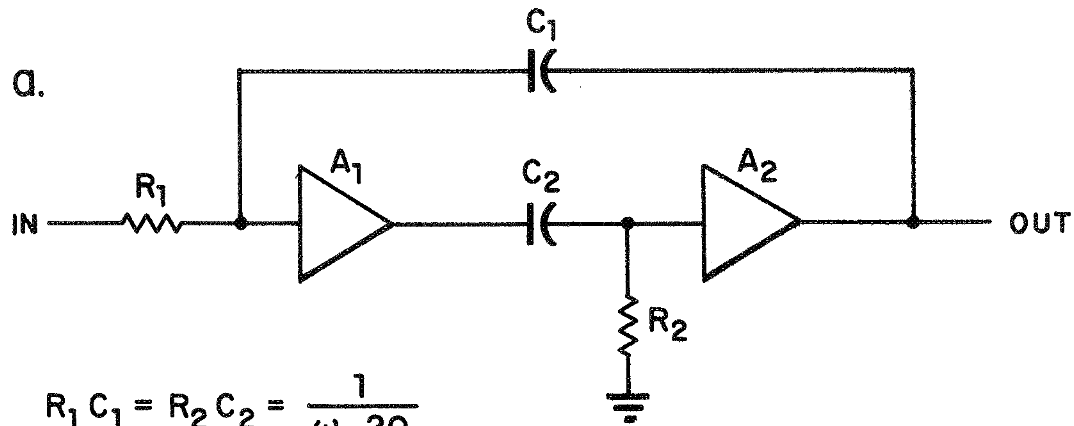
A negative feedback resonator circuit with low "Q" sensitivity is used for the filters with nominal center frequencies of 100 Hz, 316 Hz, 1000 Hz and 3160 Hz. The general form of the circuit and its basic design equations are shown in Fig. 3. The R.C. time constant products are inverse functions of the circuit's operating frequency, ω_o, and its "Q" factor, which allows a smaller capacitor size than could be used in low-frequency passive filters. The amplifier gain required is proportional to the square of Q, so the maximum Q available is severely limited by the gain. The amplifier feedback circuit is of high-pass form so compensation is required for 100% feedback at low frequencies.

The combination of high gain and drastic compensation limits the usefulness of this configuration to low frequencies. However, within its range (up to 5 or 10 kHz) the circuit has several advantages: total insensitivity of Q to component value changes, low sensitivity of Q to amplifier gain, and small R.C. time constant products as compared to the operating frequency. The breadboard circuit uses an emitter follower configuration with unity gain for the first amplifier and one half of a dual operational amplifier for the second amplifier. Each complete filter consists of two sections, tuned to 0.92 and 1.08 times the nominal center frequency, with Q of 6.1; these values provide a maximally-flat one-third octave band filter, i.e., (26% bandwidth).

High-Frequency Active Filters

The filters with nominal center frequencies of 10 kHz, 31.6 kHz, 100 kHz, and 200 kHz were built using the positive feedback form of resonator shown in Fig. 4. In this configuration the Q stability of the filter depends on the stability both of the component values and of the amplifier gain. The sensitivity of Q to capacitor values fortunately has opposite signs for capacitors C_1 and C_2; hence the net effect on Q will cancel if the capacitors change equally. The capacitor values are chosen to be equal so that identical components with approximately equal stability can be used. The metal film resistors used are very stable and have a minimal effect on Q stability. The effect of the amplifier gain is most important.

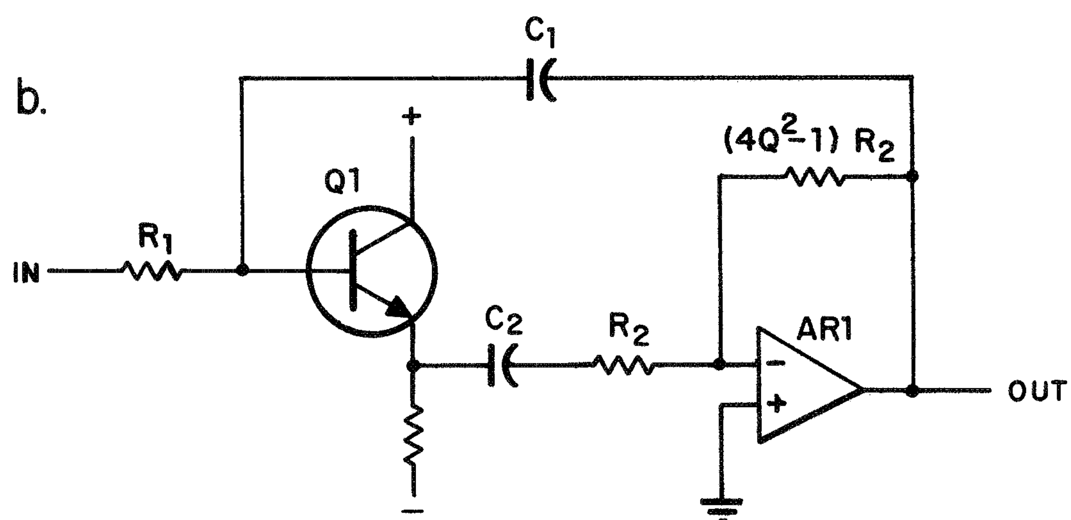
a.



$$R_1 C_1 = R_2 C_2 = \frac{1}{\omega_0 2Q}$$

$$-A_1 A_2 = 4Q^2 - 1$$

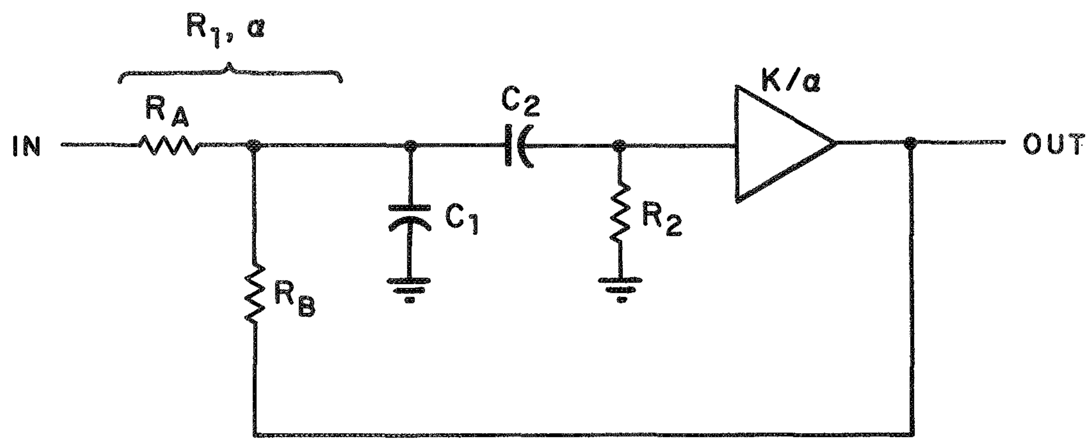
b.



$$A_1 = 1$$

$$A_2 = -(4Q^2 - 1)$$

FIG.3 FORM AND DESIGN EQUATIONS FOR NEGATIVE FEEDBACK Q INSENSITIVE RESONATOR



$$R_1 C_1 = \frac{0.5}{\omega_0} \qquad R_2 C_2 = \frac{2}{\omega_0}$$

$$R_1 = R_A \parallel R_B \qquad \alpha = \frac{R_A}{R_A + R_B}$$

$$K = 1.5 - \frac{1}{2Q} \quad \text{for} \quad C_1 = C_2$$

$$\text{for } \alpha = \frac{1}{2} \qquad K/\alpha = 3.0 - \frac{1}{Q}$$

FIG.4 FORM AND DESIGN EQUATION FOR POSITIVE FEEDBACK RESONATOR

Much experimentation was done with commercially available, integrated circuit amplifiers but none could achieve a simultaneously high input impedance, adequate slewing rate, and adequate bandwidth at a closed-loop gain of 3. Therefore, a discrete component, Field Effect Transistor (FET) input amplifier was designed. Its circuit consists of a differential input amplifier followed by a common emitter output stage, as shown in Fig. 5.

The positive feedback active resonator using the FET-input amplifier exhibited excellent Q stability for varying temperature. However, its output impedance was high enough to cause objectionable interaction when a second resonator section was cascaded with it to obtain the one-third octave bandwidth. This was remedied by placing an emitter follower between the filter sections which allowed the Q of each filter section to be independently adjusted by the amplifier gain, thus compensating for the cumulative effect of individual component variations. After these design modifications, the performance of the high-frequency active filters was excellent, as shown in the test results in Section III.

Detectors

The basic detector which in simplest form is just a diode rectifier, is crucial to the performance of any analyzer configuration. To reduce the errors due to the offset biasing voltage required by the diode, an operational amplifier is commonly used. In this circuit the diode is connected inside the feedback loop of the operational amplifier as shown in Fig. 6. The open loop gain of the amplifier reduces the diode voltage drop.

However, as frequency increases, the finite slewing rate of the amplifier output and the necessity for the amplifier output voltage to traverse two diode drops for each polarity reversal of the signal cause increasingly larger errors in the circut of Fig. 6. The frequency response performance of this circuit is illustrated by the 'A' family of curves in Fig. 7 which show that the frequency response is strongly dependent on signal amplitude level, that it begins to deteriorate at about 30 kHz, and that it is not adequate at any signal level above about 80 kHz. Increasing the amplifier compensation

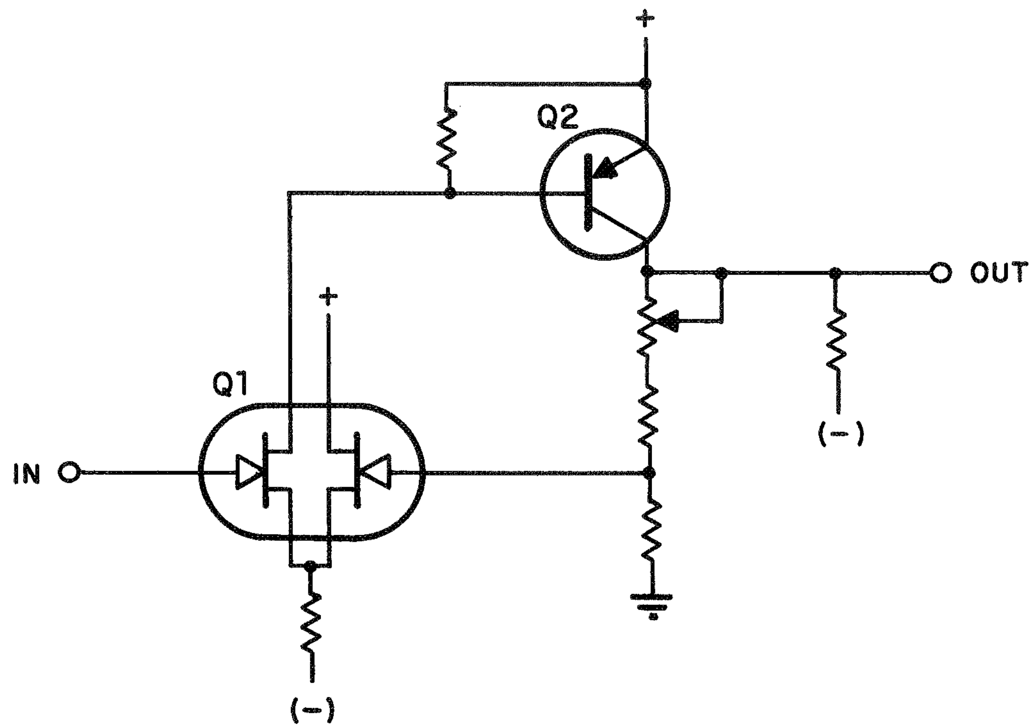


FIG.5 FET INPUT AMPLIFIER FOR HIGH FREQUENCY RESONATOR

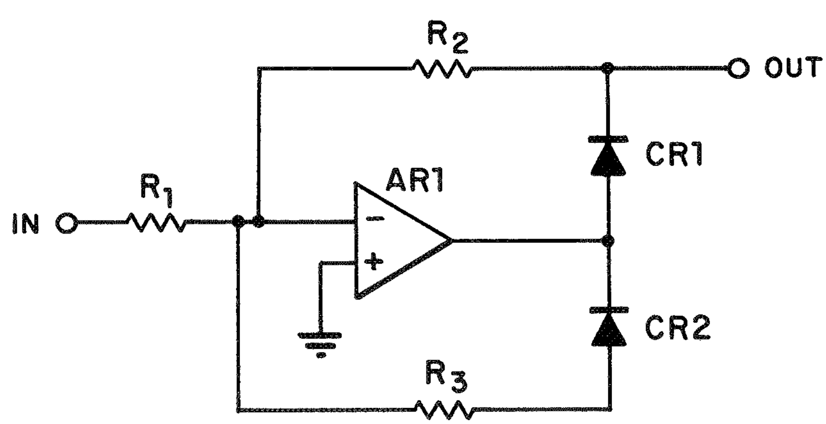
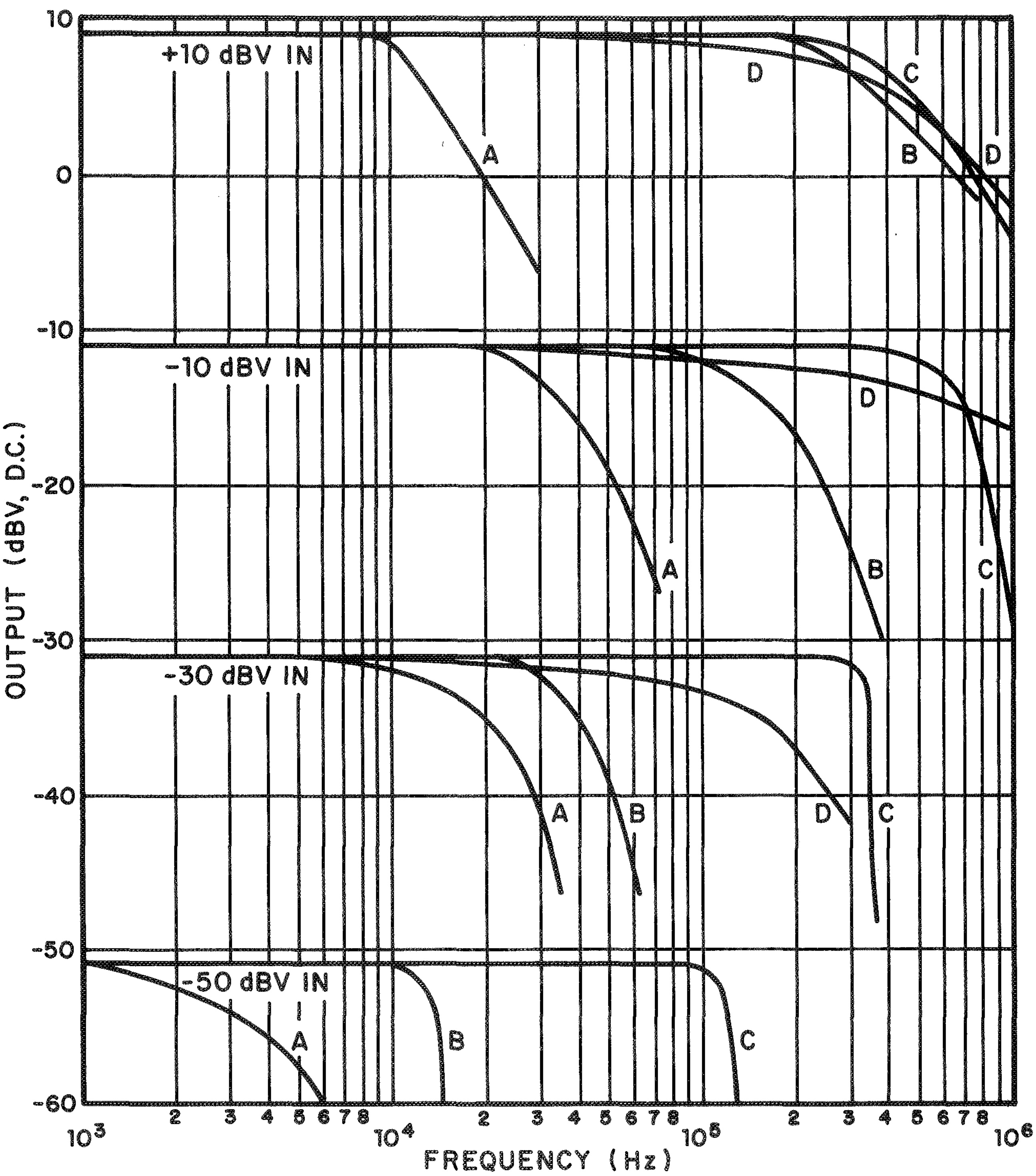


FIG.6 OPERATIONAL RECTIFIER



A µA709 WITH 0 dB COMPENSATION
B µA709 WITH 40 dB COMPENSATION AND INPUT COMPENSATION
C µA709 AS IN B PLUS CURRENT BUFFER AMP
D µA749 WITH 20 dB COMPENSATION PLUS INPUT COMPENSATION

NOTE: DATA FOR D AT -50 dB NOT TAKEN IN THIS FORM. SEE FIG. 25 FOR FINAL SYSTEM RESPONSE AT 200 kHz

FIG. 7 RESPONSE OF VARIOUS DETECTORS

to achieve a faster slewing rate improves the frequency response performance as shown by the 'B' family of curves in Fig. 7. However, it is still strongly dependent on signal amplitude level.

The frequency response performance was greatly improved by adding a separate grounded-base voltage-to-current amplifier after the operational amplifier. This extends the response, as shown by the 'C' family of curves in Fig. 7, so that it meets or exceeds the required specifications at all signal levels except the lowest 5dB or so. The circuit is quite complex, however; especially in view of the desired objectives of small size, low weight, low power consumption, etc. Therefore, a simpler circuit which uses an amplifier that incorporates a current rather than voltage output stage was chosen for the breadboard. The dual operational amplifier chosen has an open collector output used with an external current source (field-effect current diode). Its frequency response performance is shown by the 'D' family of curves in Fig. 7.

Gain Control Block

The gain control is used in the AGC circuit configuration to keep the detector signal level constant and to provide the logarithmic function for the system. A schematic of the gain control is shown in Fig. 8. Basically, the AGC circuitry derives a control voltage related to the overall amplitude of the input signal and uses it to vary the gain of an amplifier so that the signal level applied to the detector circuit remains essentially constant in amplitude. The derived voltage is also the output information of an analyzer channel.

The operation of the circuit can be explained as follows. The input signal is fed through input capacitor C_1 and resistor R_1 to the base of transistor Q_3. Feedback current from the collector of Q_3 through transistor Q_{1A} keeps the AC voltage at the base of Q_3 small and the AC current in Q_{1A} nearly equal to the AC current in R_1. Thus the AC collector current of Q_{1A} is established and controlled by the input voltage level. Q_{1A} and Q_{1B} are a matched pair of transistors connected as a current splitter. When the base voltage gain of the circuit is R2/R1.

When the base voltages of Q_{1A} and Q_{1B} are unequal, the ratio of their collector currents is exponentially related to the interbase voltage

$$\frac{I_2}{I_1} = \exp\left(\frac{qV}{kT}\right) . \qquad (1)$$

where I_2 and I_1 are the respective collector currents, q is the charge of an electron, V is the interbase voltage, k is Boltzmann's constant, and T is the absolute temperature. The temperature dependence is compensated for by a temperature-dependent voltage divider consisting of resistors R7 and R8; R8 has a positive temperature coefficient whose value is proportional to the absolute temperature. Thus we have shown that transistors Q_{1A} and Q_{1B} of the circuit of Fig. 8 form a precise AC gain control with an exponential, or logarithmic, operating characteristic. Transistors Q_{2A} and Q_{2B} keep the DC operating point of the gain control from shifting as the signal amplitude level and the circuit gain change, i.e., they keep the circuit symmetrical under all operating conditions.

In the complete AGC Detector the gain control is followed by an AC amplifier, an operational amplifier-rectifier and an integrator that compares the rectified output with a reference voltage. Figure 9 shows the AGC Detector circuit configuration schematically and also shows the differential equation of its response.

Summary

An analyzer design was completed which met the specified performance requirements of one-third octave band frequency-amplitude analysis from 100 Hz to 200 kHz over a 60 dB dynamic range. Test results which demonstrate these design goals are presented in the next section. The design required two different active filter circuit configurations to cover the frequency range. An automatic gain control circuit was used to convert the input signal logarithmically and reduce the range requirements on the detectors.

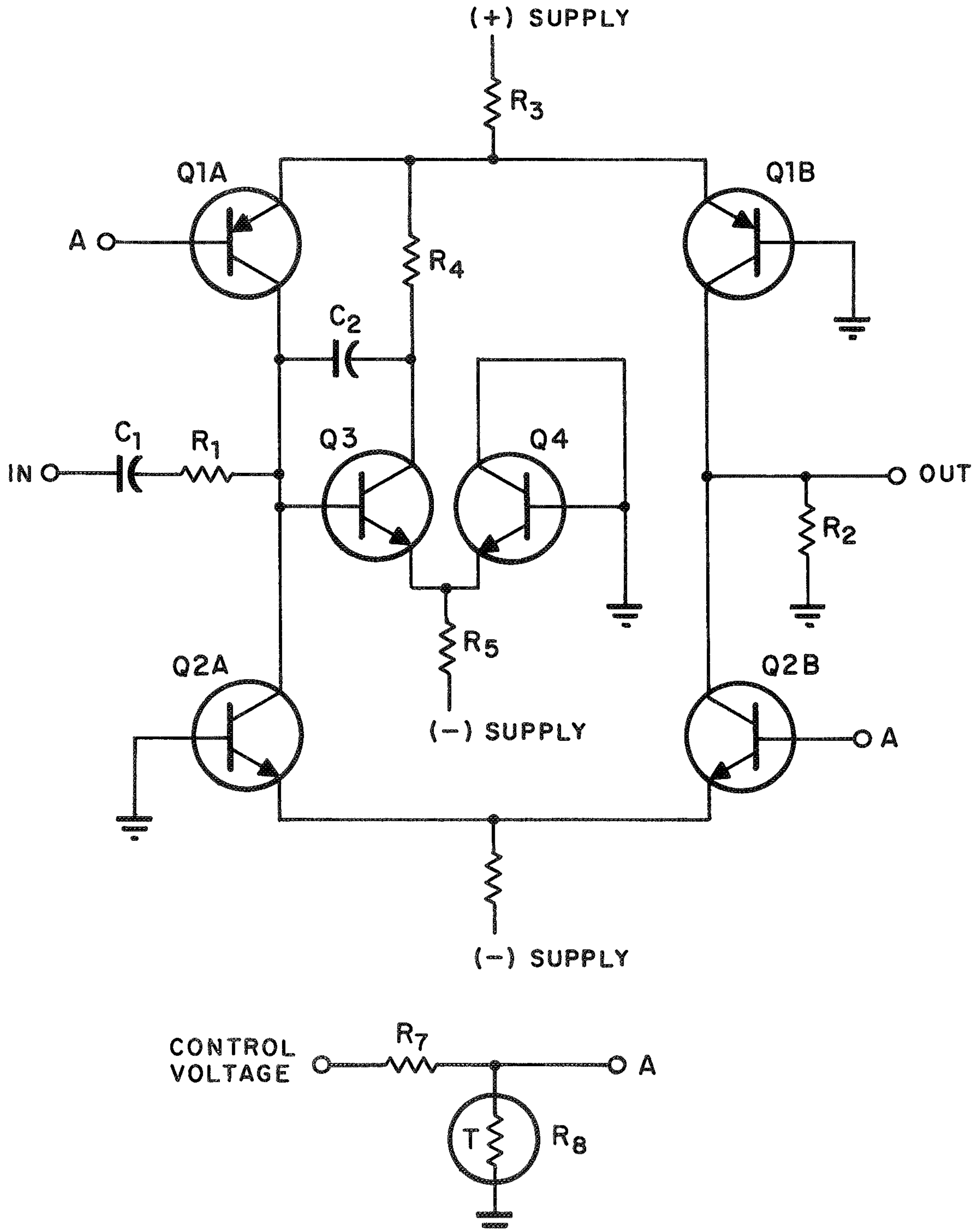
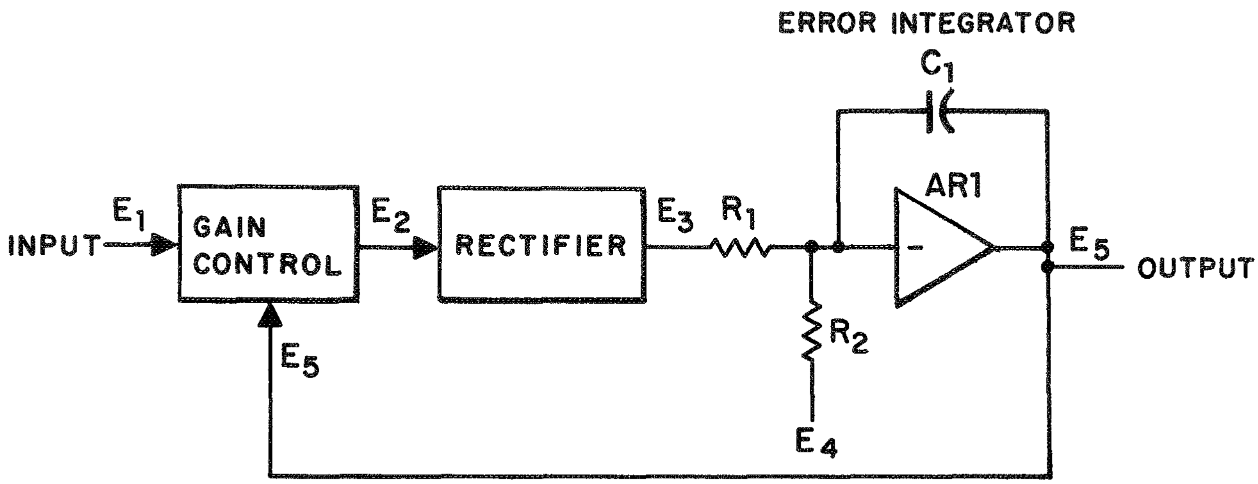


FIG.8 GAIN CONTROL BLOCK



$$E_2 = E_1 \epsilon^{KE_5}$$

$$E_3 = +|E_2|, \quad \text{at AR1 INPUT } \sum I = 0$$

$$\frac{E_3}{R_1} + \frac{E_4}{R_2} + C \frac{d}{dt} E_5 = 0$$

assume $E_1 > 0$

$$\frac{E_1}{R_1} \epsilon^{KE_5} + \frac{E_4}{R_2} + C_1 \frac{d}{dt} E_5 = 0$$

$$\epsilon^{KE_5} = \frac{R_1}{E_1} \left(-\frac{E_4}{R_2} - C_1 \frac{d}{dt} E_5 \right)$$

$$E_5 = \frac{1}{K} \log_\epsilon \left(-\frac{E_4 R_1}{E_1 R_2} - C_1 \frac{d}{dt} E_5 \right)$$

$$t \gg 0, \quad E_5 \cong \frac{1}{K} \log_\epsilon \left(\frac{-E_4 R_1}{E_1 R_2} \right) = \frac{1}{K} \left(-\log_\epsilon E_1 + \log_\epsilon \frac{-E_4 R_1}{R_2} \right)$$

FIG. 9 AGC DETECTOR ANALYSIS

The low-frequency active filter circuits have 21 discrete components, the high-frequency active filter circuits have 37 discrete components, and the AGC detector circuits have 42 discrete components. It is estimated that these circuits could be packaged in less than 2.5 cubic inches using conventional cordwood techniques. Very possibly, hybrid micro-electronic or integrated circuit packaging techniques could achieve a volume of less than 1 cubic inch.

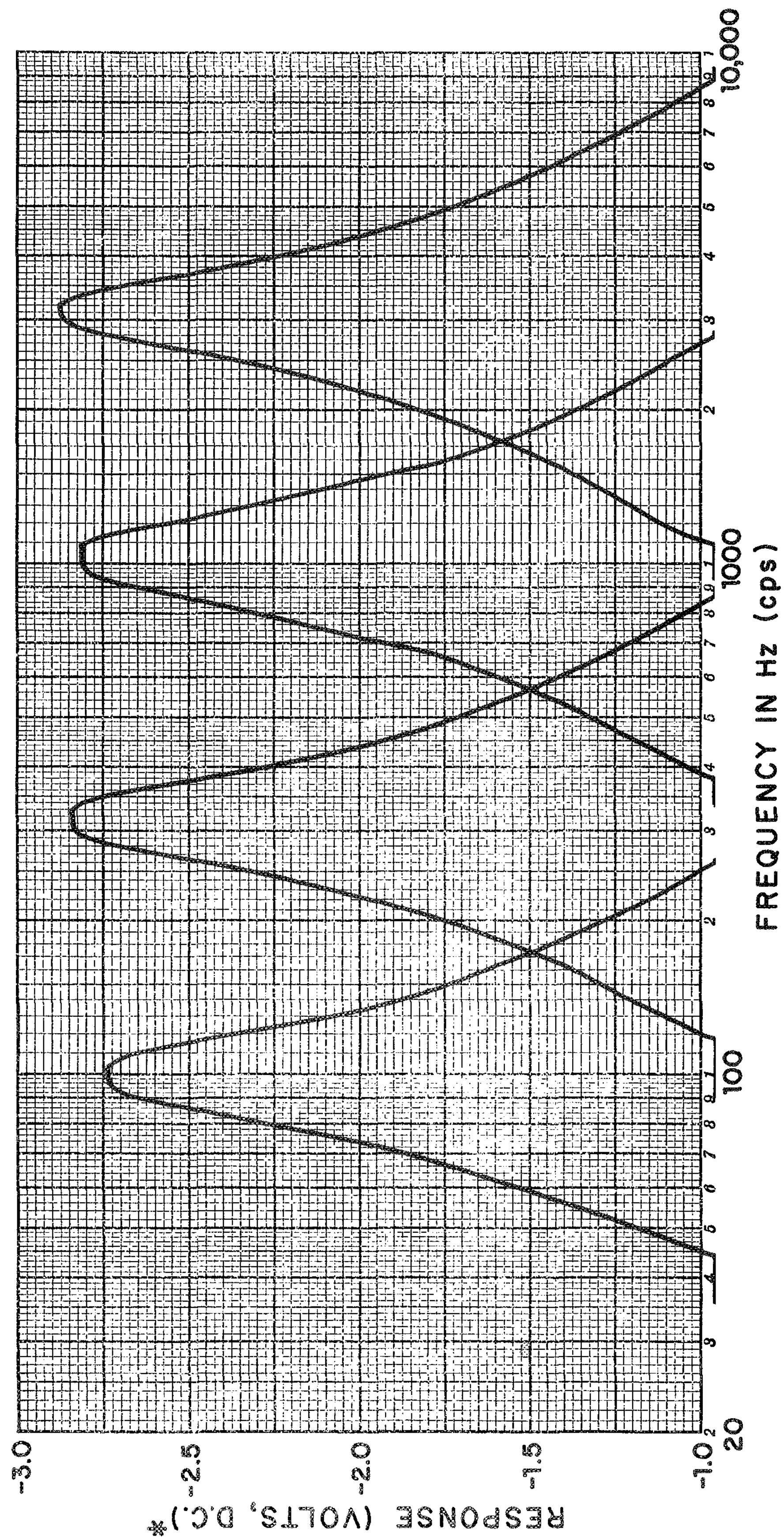
SECTION III
TEST RESULTS

A breadboard of eight channels of the proposed analyzer system consisting of seventeen printed-circuit cards interconnected in a chassis, was fabricated and tested according to program specifications. A block diagram of the prototype is shown in Fig. 2. The set of eight one-third octave band filters was selected to cover the frequency range of interest.

Transfer characteristics of the frequency amplitude response of the system at room temperature are shown in Figs. 10 and 11. The ordinate scale is the DC output voltage of each one-third octave band channel of the analyzer at the compression factor of 20 dB/volt (i.e., 1 dB becomes 0.05 volts at the output). The data were taken by applying a -30 dBv sine wave signal to the buffer amplifier input and recording the output of each channel without adjustment. The shape of the output of each of the filters is within the ASA S1.11-1966 Third-Octave Band Filter, Class II Specification. (See Appendix)

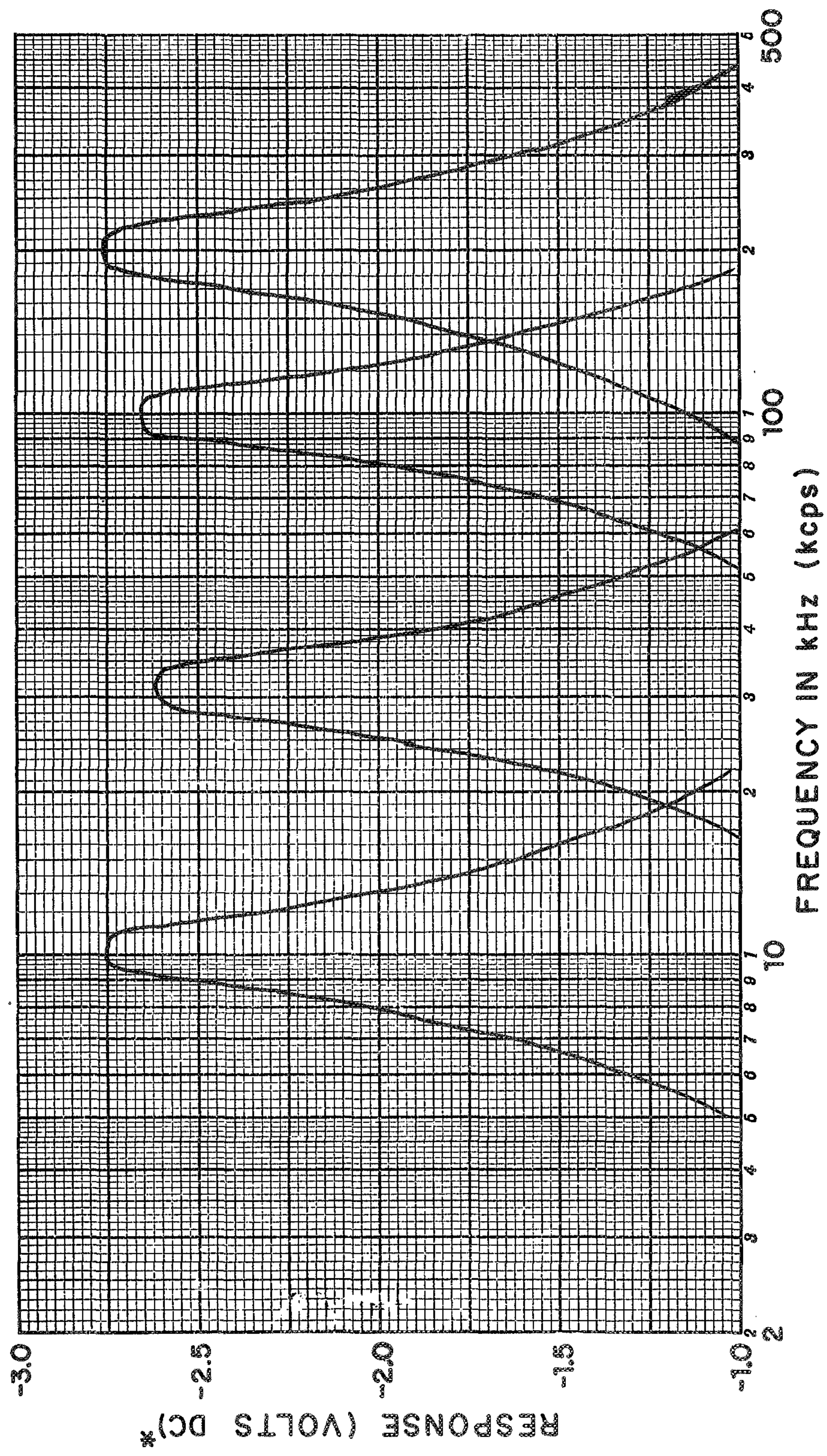
Similar data taken at 40°F are shown in Figs. 12 and 13; data taken at 120°F are shown in Figs. 14 and 15. The data are summarized in Figs. 16 and 17 in which minor gain changes of each channel have been normalized to allow better comparison of each channel's characteristics. In Fig. 16 the lower band skirt of the transfer characteristic spreads slightly for the 100 and 316 Hz channels at 40°F and in Fig. 17 here is a small spreading effect on the higher band skirt of the 200 kHz channel at 120°F. However, in general the channel characteristics are very stable for temperature.

Figures 18 through 25 present data from a series of tests performed to establish the dynamic range of each channel and the effect of temperature on this dynamic range. The data were obtained by applying a sine wave signal of -30 dBv at the nominal center frequency of each one-third octave band channel to the input buffer



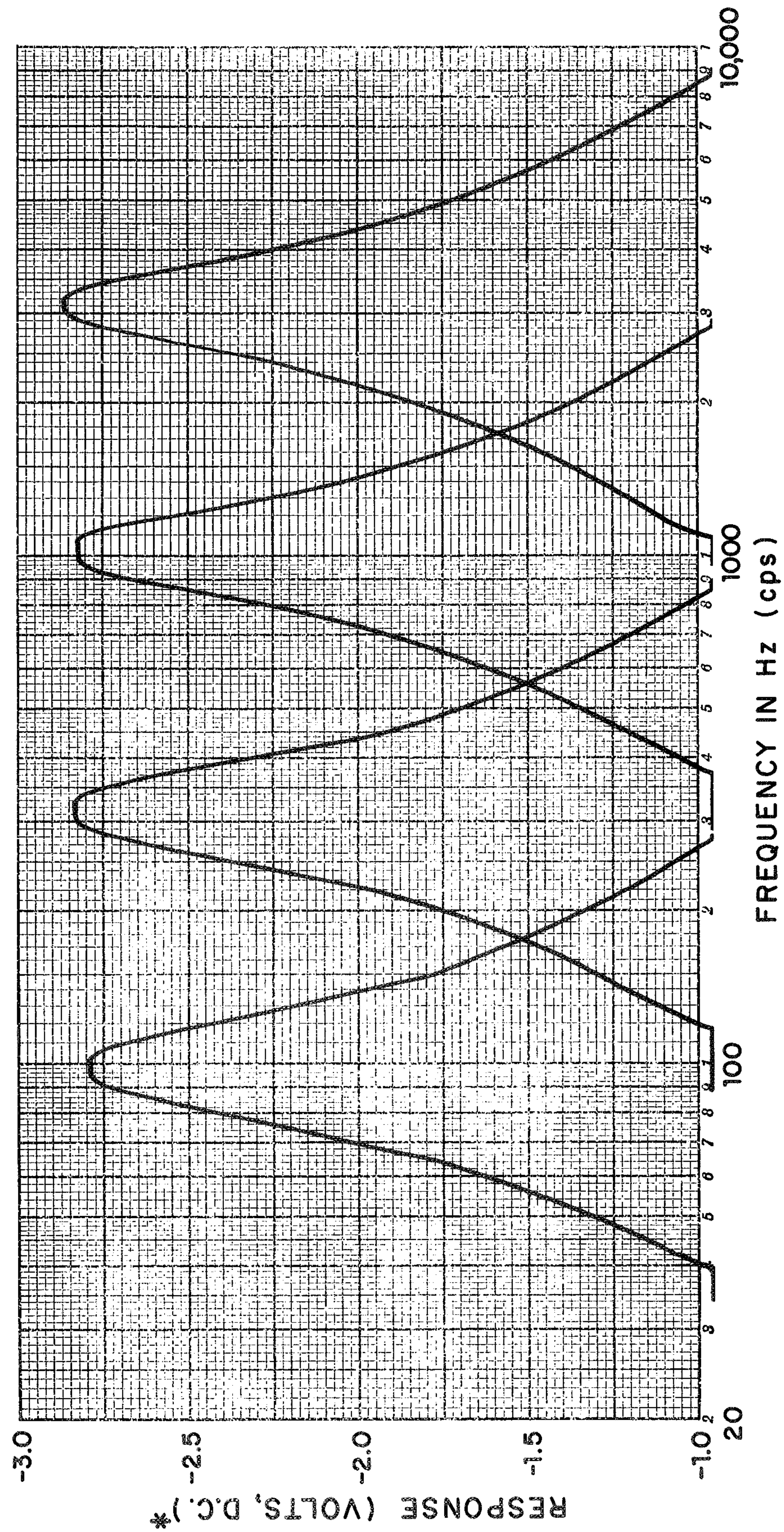
*TRANSFER CHARACTERISTIC -20 dB/VOLT

FIG.10 FREQUENCY RESPONSE AT 70°F FOR 100, 316, 1000 AND 3160 Hz CHANNELS



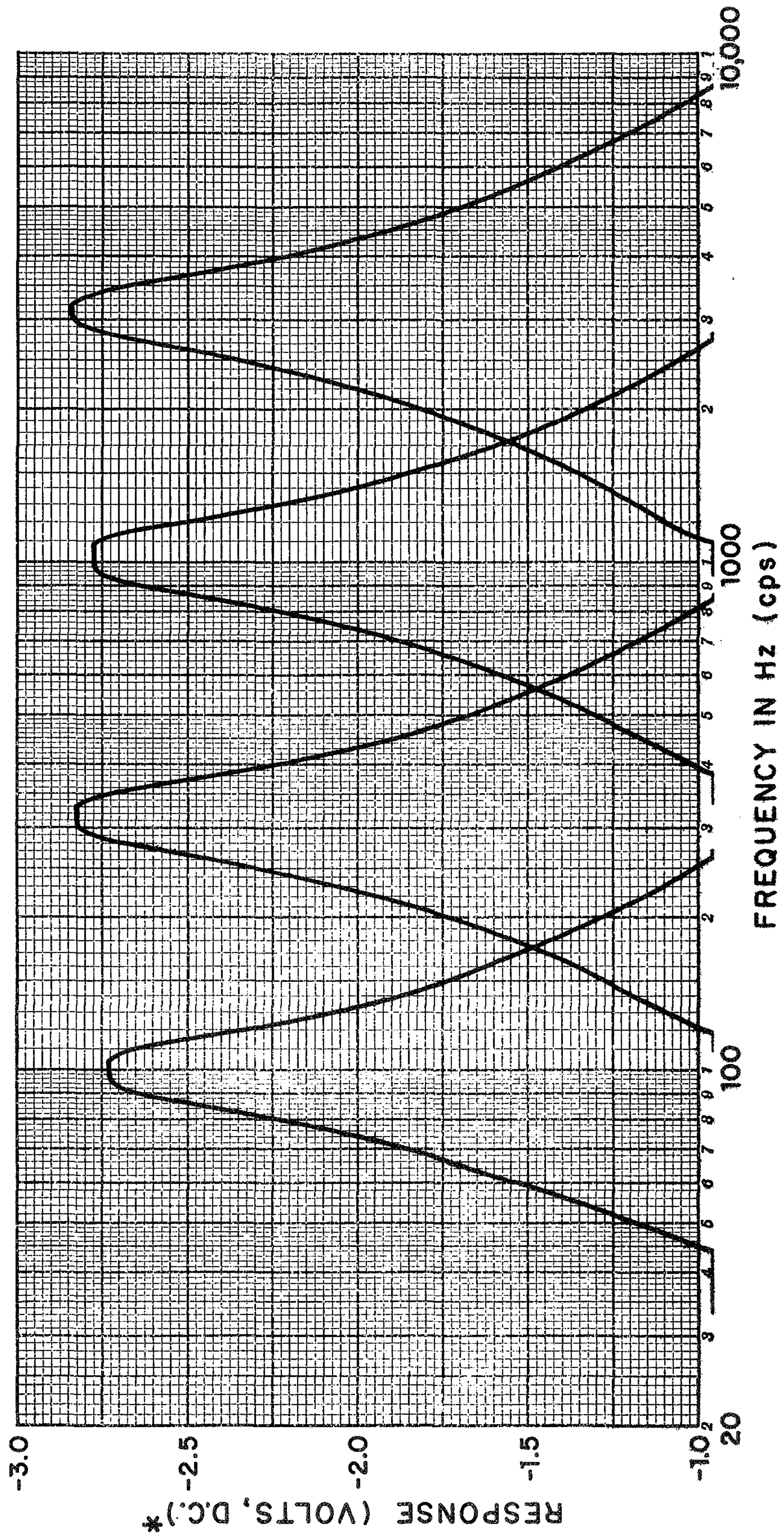
*TRANSFER CHARACTERISTIC -20 dB/VOLT

FIG.11 FREQUENCY RESPONSE AT 70°F FOR 10.0, 31.6, 100 AND 200 kHz CHANNELS



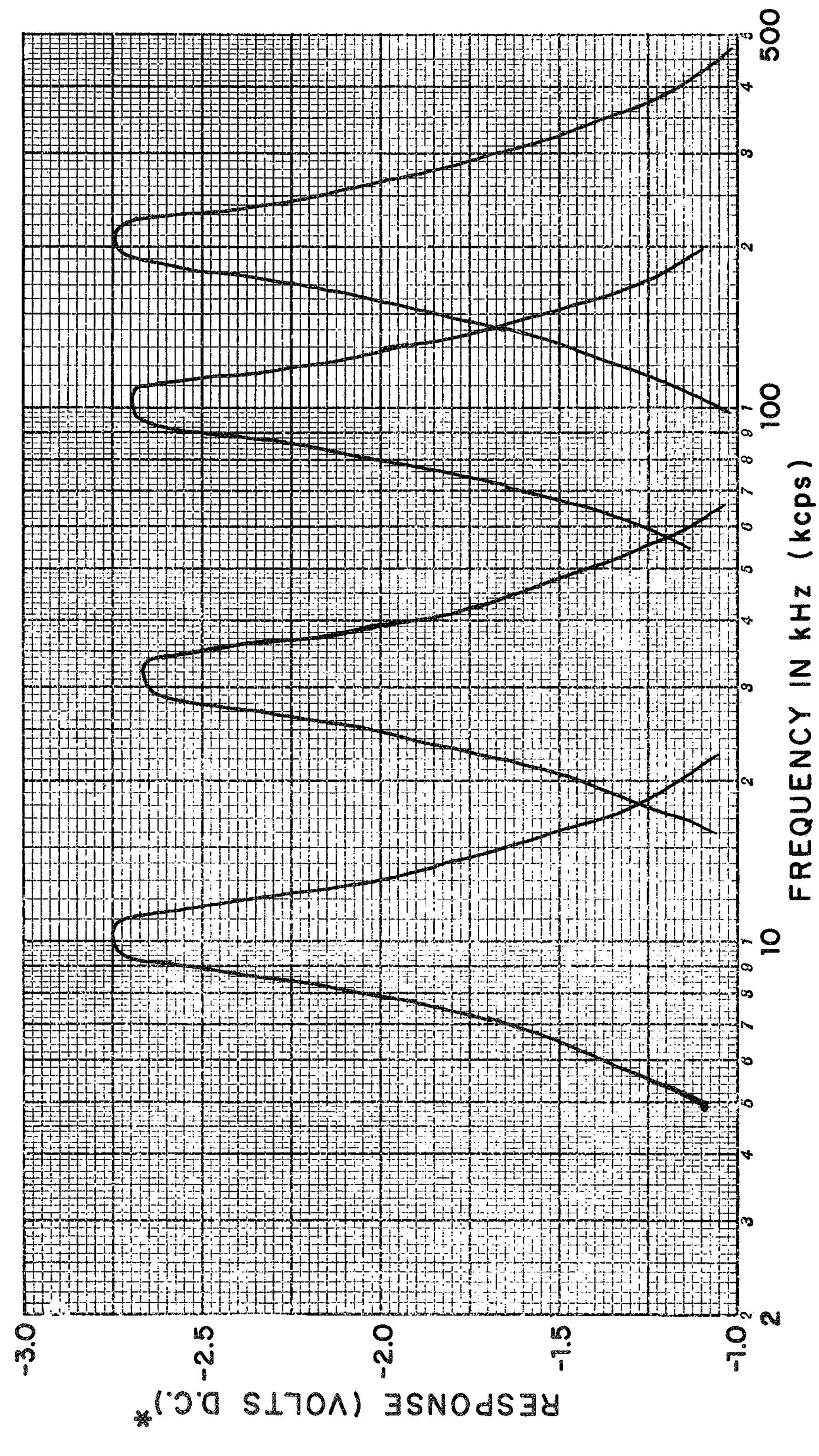
*TRANSFER CHARACTERISTIC-20 dB/VOLT

FIG.12 FREQUENCY RESPONSE AT 40°F FOR 100, 316, 1000 AND 3160 Hz CHANNELS



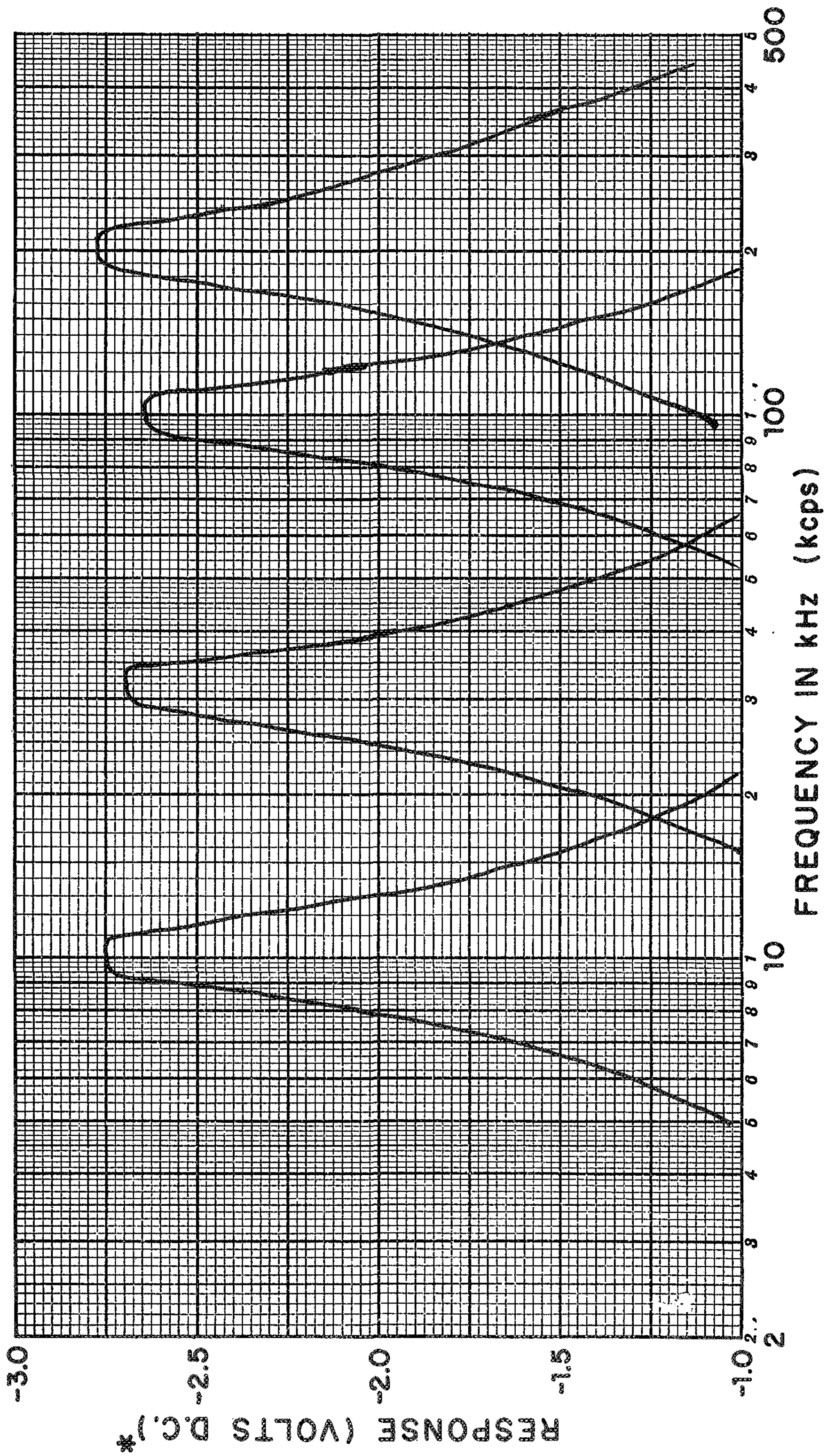
*TRANSFER CHARACTERISTIC -20 dB/VOLT

FIG.13 FREQUENCY RESPONSE AT 120°F FOR 100, 316, 1000 AND 3160 Hz CHANNELS



*TRANSFER CHARACTERISTIC-20 dB/VOLT

FIG. 14 FREQUENCY RESPONSE AT 40°F FOR 10.0, 31.6, 100 AND 200 kHz CHANNELS



*TRANSFER CHARACTERISTIC-20 dB/VOLT

FIG.15 FREQUENCY RESPONSE AT 120°F FOR 10.0, 31.6, 100 AND 200 kHz CHANNELS

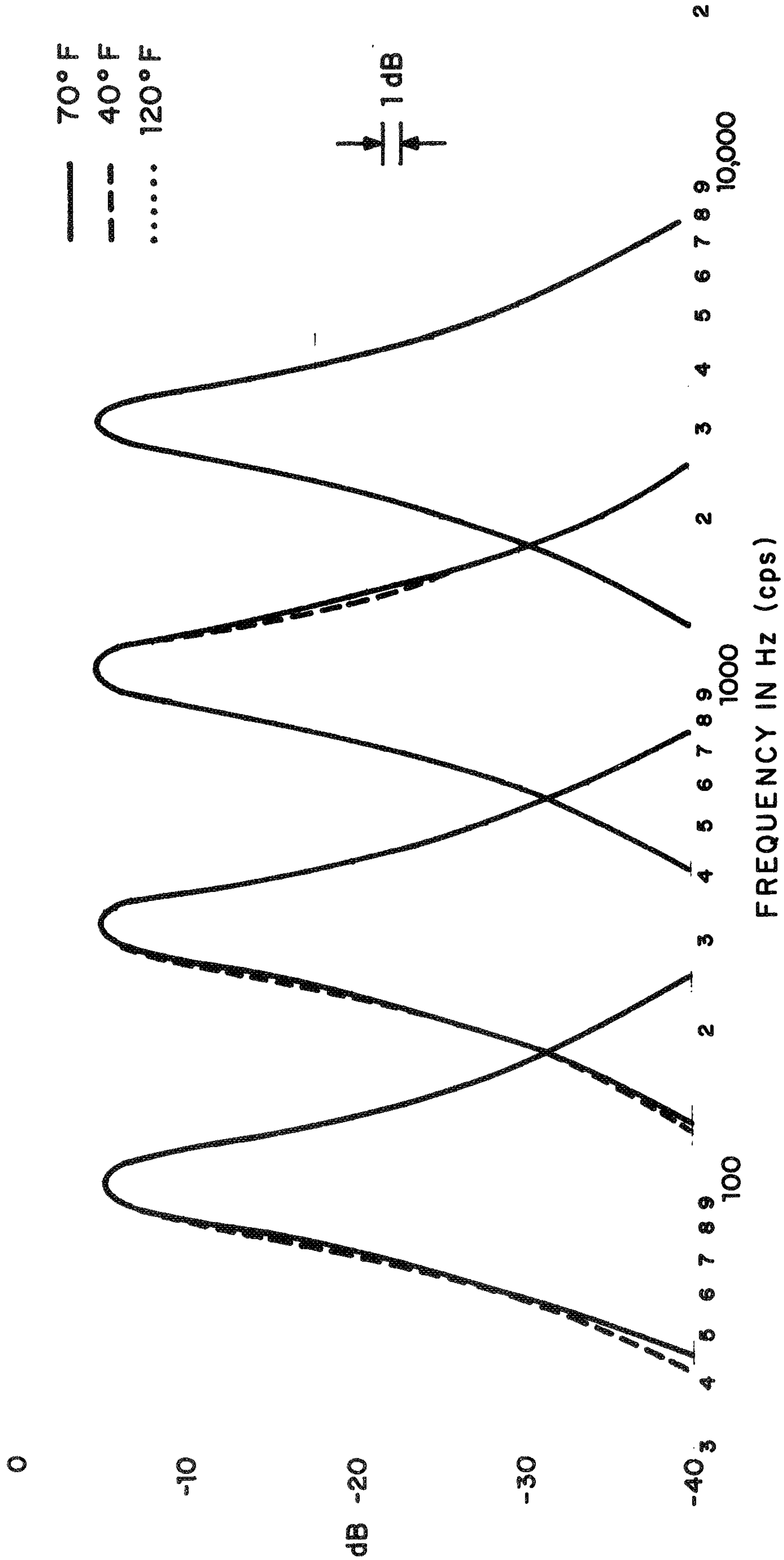


FIG. 16 CHANNEL CHARACTERISTICS WITH NORMALIZED GAIN AT THREE TEMPERATURES (LOW FREQUENCY)

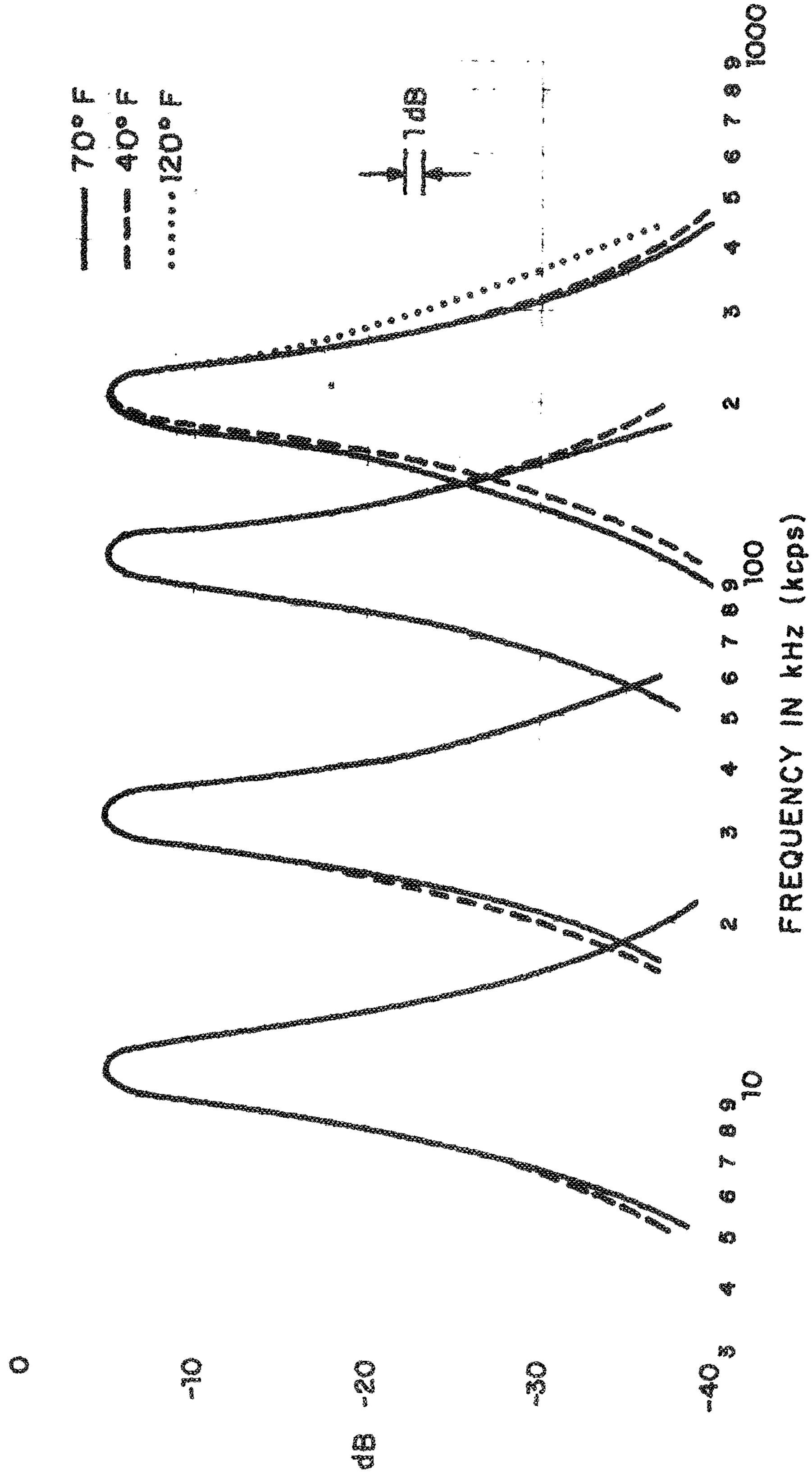


FIG.17 CHANNEL CHARACTERISTICS WITH NORMALIZED GAIN AT THREE TEMPERATURES (HIGH FREQUENCY)

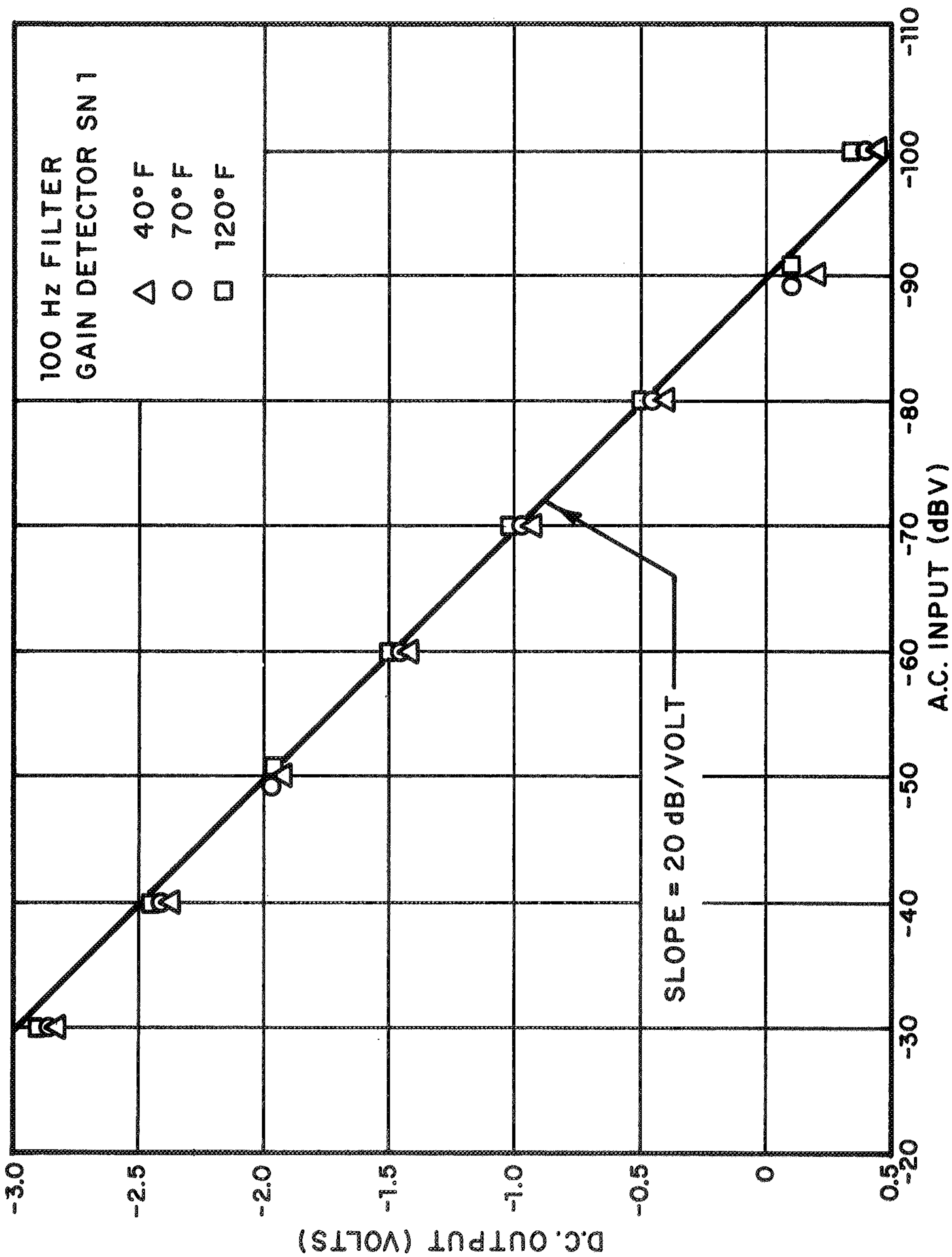


FIG.18 TRANSFER CHARACTERISTIC VS. TEMPERATURE

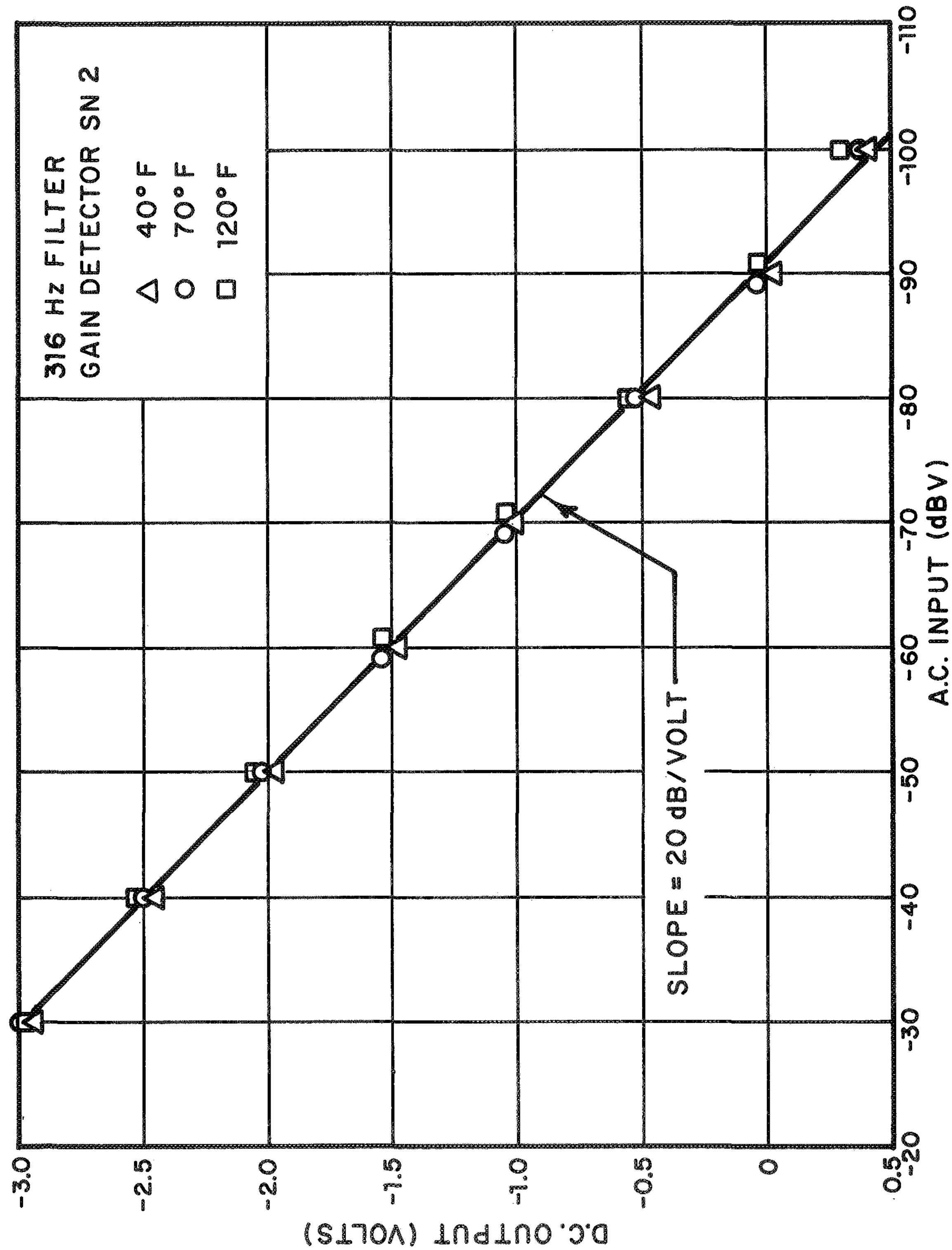


FIG. 19 TRANSFER CHARACTERISTIC VS. TEMPERATURE

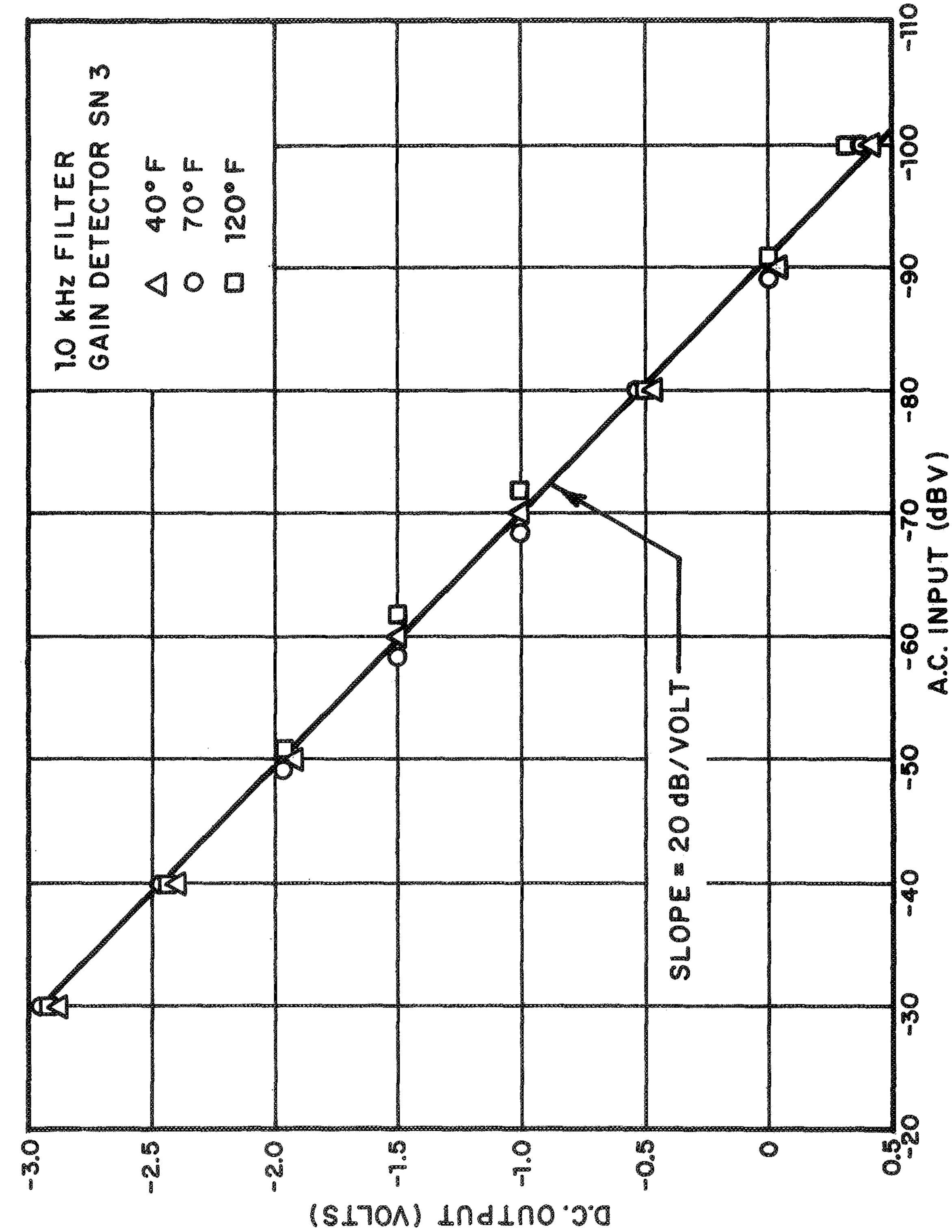


FIG.20 TRANSFER CHARACTERISTIC VS. TEMPERATURE

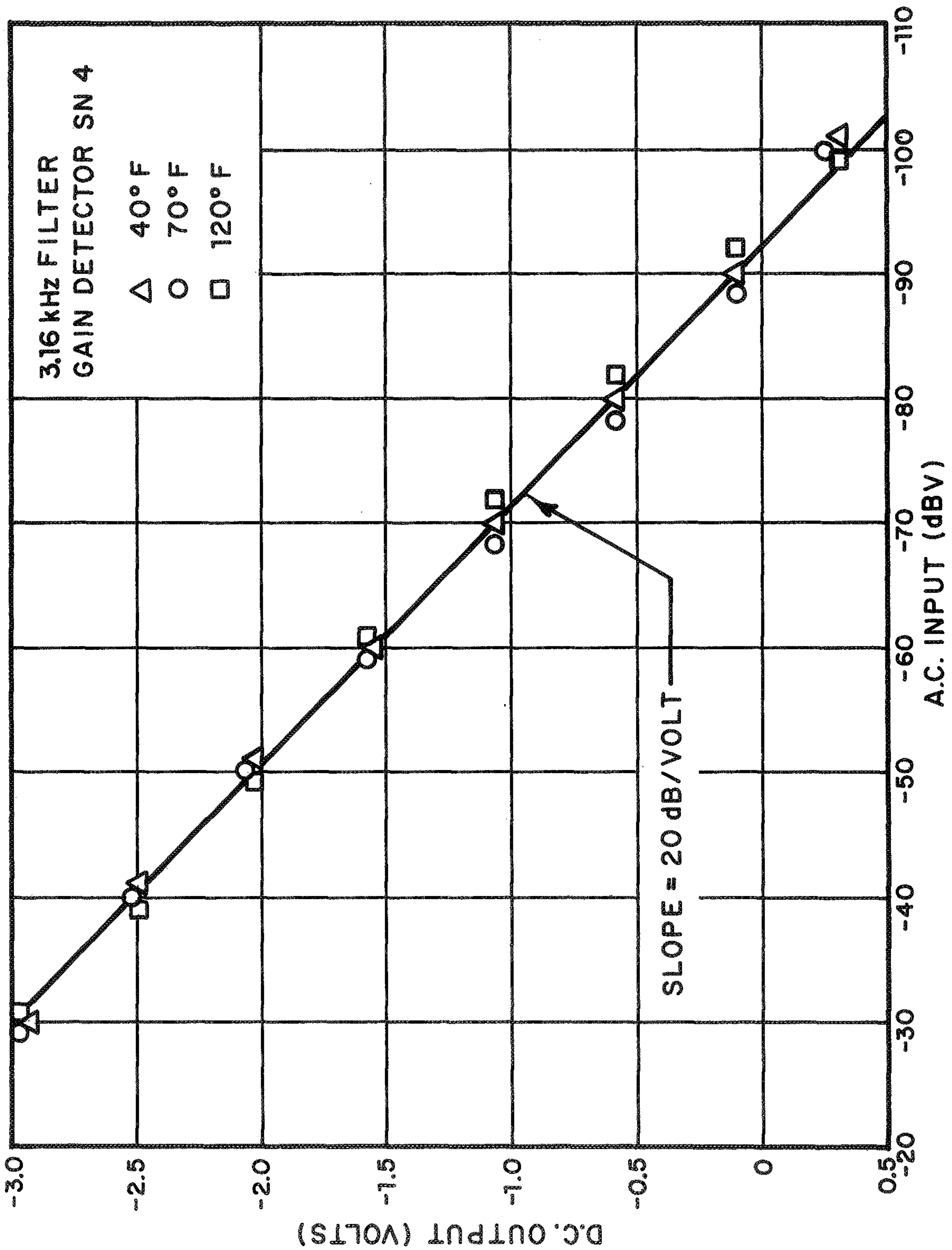


FIG. 21 TRANSFER CHARACTERISTIC VS. TEMPERATURE

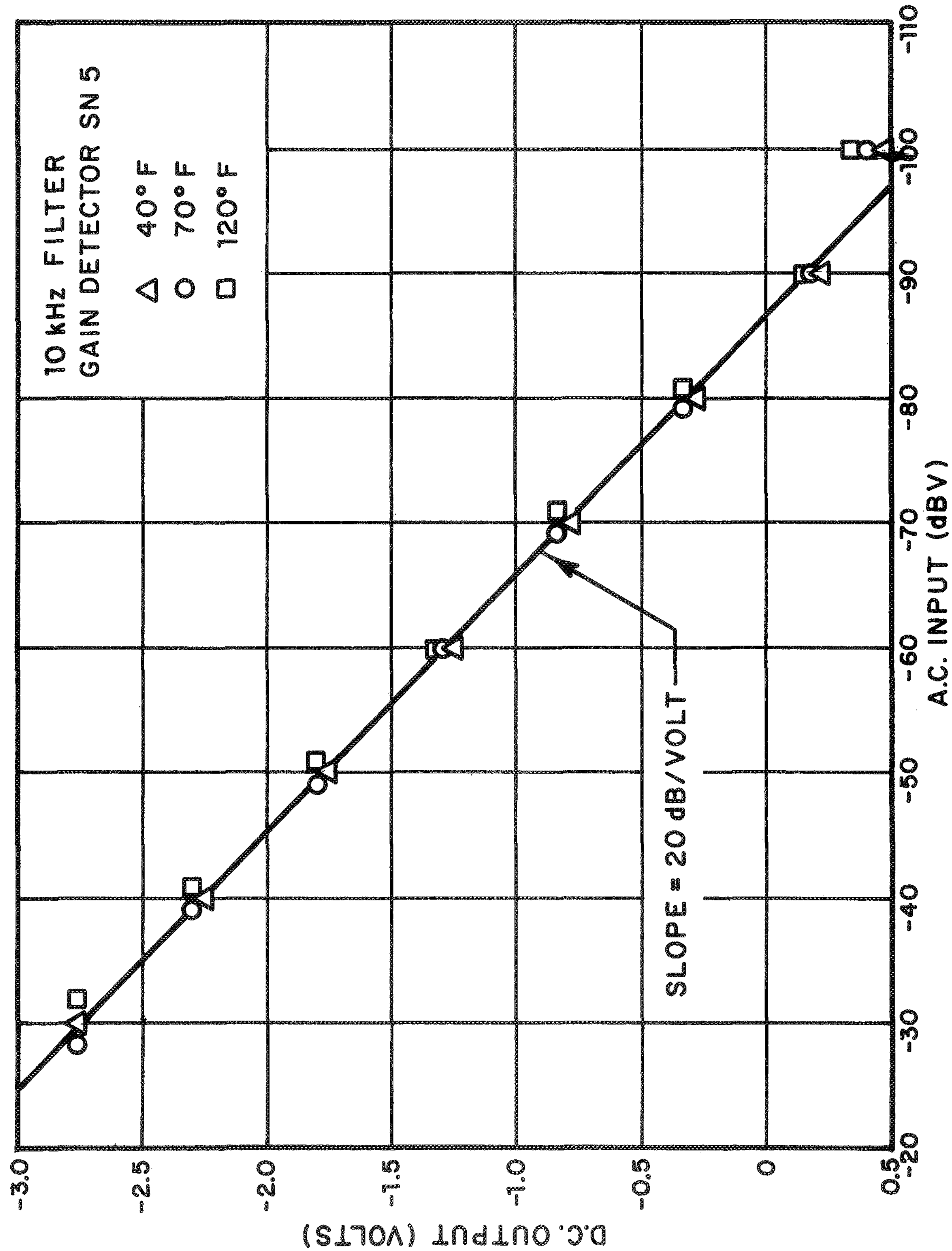


FIG.22 TRANSFER CHARACTERISTC VS. TEMPERATURE

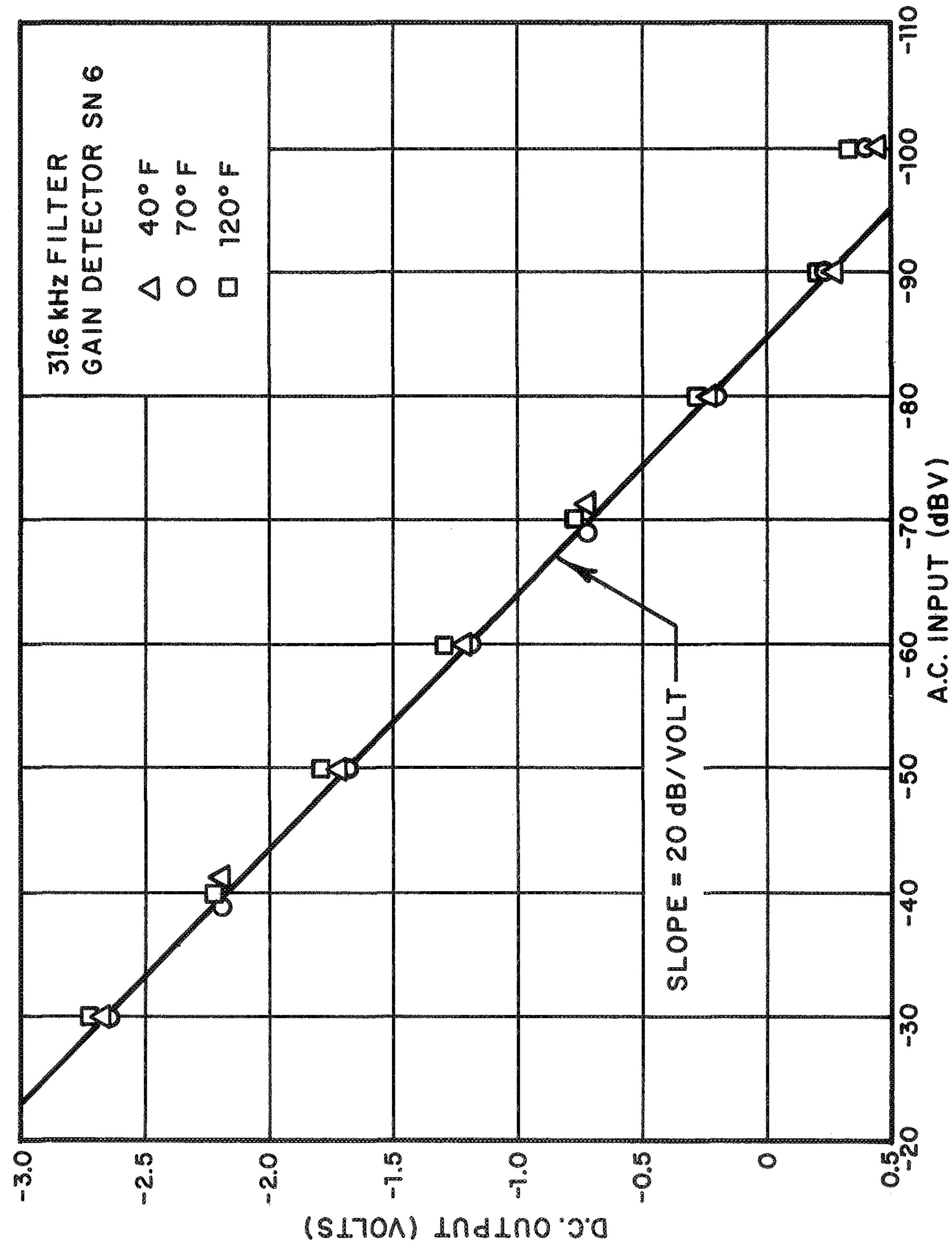


FIG. 23 TRANSFER CHARACTERISTIC VS. TEMPERATURE

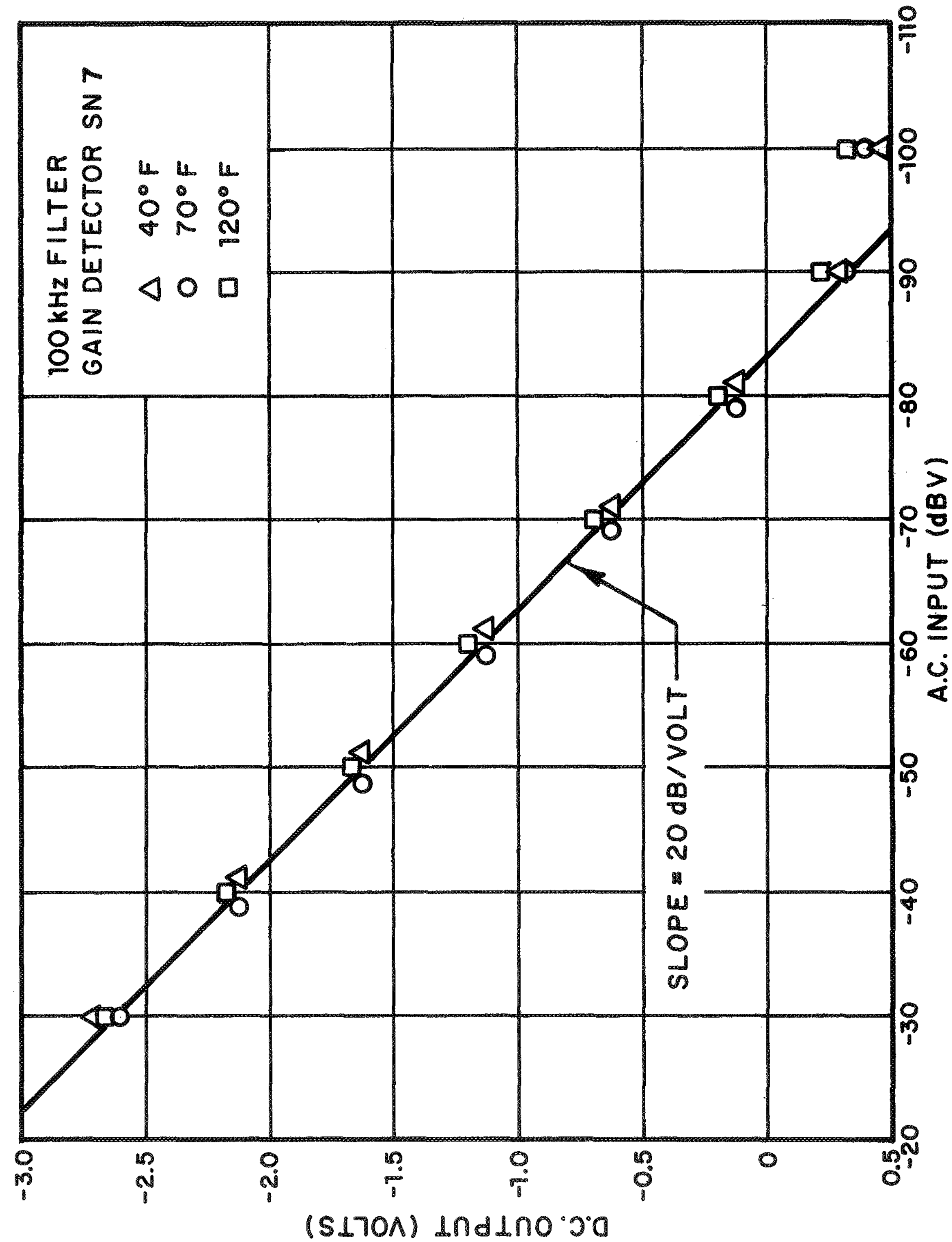


FIG. 24 TRANSFER CHARACTERISTIC VS. TEMPERATURE

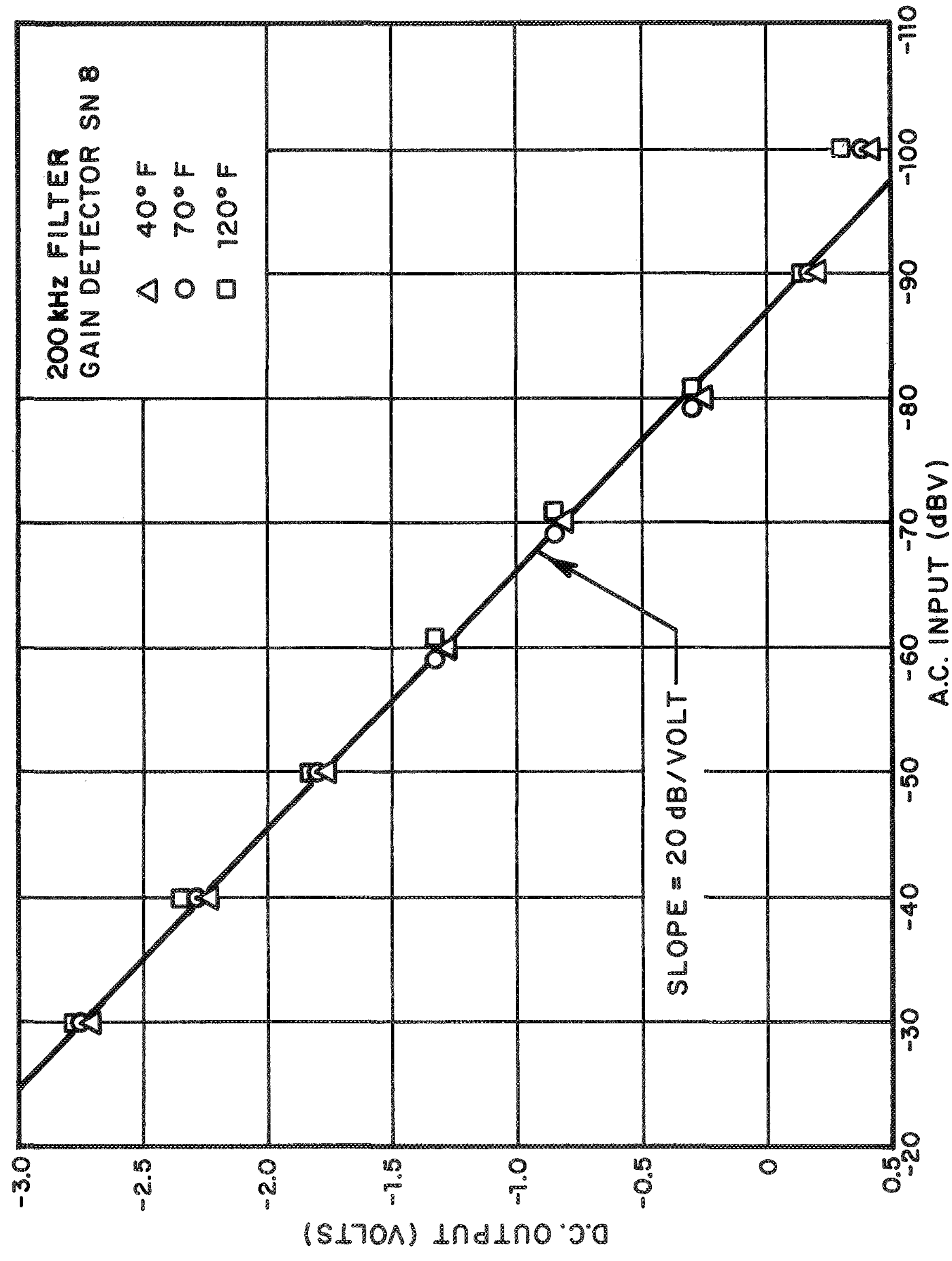


FIG. 25 TRANSFER CHARACTERISTIC VS. TEMPERATURE

amplifier and recording the output; the input level was reduced 60 dB in 10 dB steps at each of the three temperatures. Figures 18 through 25 indicate that the analyzer has a full 60 dB dynamic signal amplitude range. Table II summarizes the maximum deviations of each channel during these tests. We see that the channels are logarithmic within these tolerances over a dynamic range of 60 dB and a temperature range of 40 to 120°F.

TABLE II

Maximum Output Deviation Over a Range of 60 dB and Temperatures of 40 to 120° F

Filter (kHz)	Low Deviation	High Deviation
0.1	-3 dB	+1 dB
0.316	-1.5 dB	+1 dB
1.0	-1.5	+0
3.16	-1.0	+0
10.0	-1.5	+0
31.6	0	+1.5
100.0	0	+2
200.0	-1	+1.5

Since the data reported in this section have been for the complete breadboard analyzer they are representative of that which could be achieved for a full system.

SECTION IV
CONCLUSIONS

The design, fabrication and test evaluation work that has been performed provides the technology for a compact spectrum analyzer of extended signal amplitude and frequency range for use onboard space vehicles. The technology developed, significantly reduces the requirement for wide dynamic range and wide bandwidth on telemetry links or on-board data storage equipment when dynamic pressure or vibration measurements are made. Testing of prototype hardware demonstrates that the analyzer is practical and that the design could be easily adapted to octave band or half-octave band analysis.

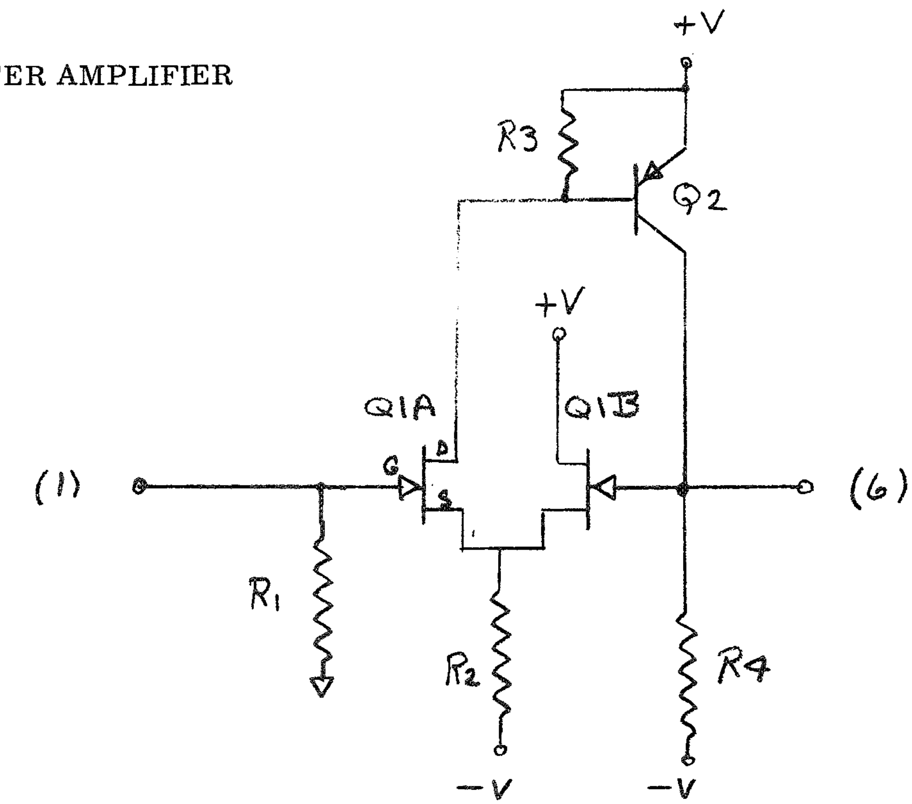
In designing the analyzer, circuit techniques were devised to extend the bandwidth of commercially available operational amplifiers. Also, a solid state automatic gain control circuit with logarithmic relationship between control voltage and gain was devised, built and tested. Both of these circuits could be useful in other applications.

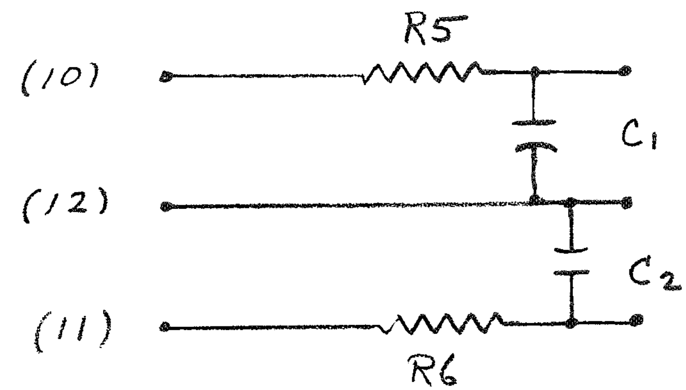
Some follow-up tasks would be to engineer the compact and rugged packaging necessary for flight use, to minimize power consumption, to construct and test the one-third octave band filters which were omitted in this work in order to achieve a full complement spectrum analyzer, and to perform environmental qualification and acceptance testing for a flight program.

APPENDIX A

SCHEMATICS

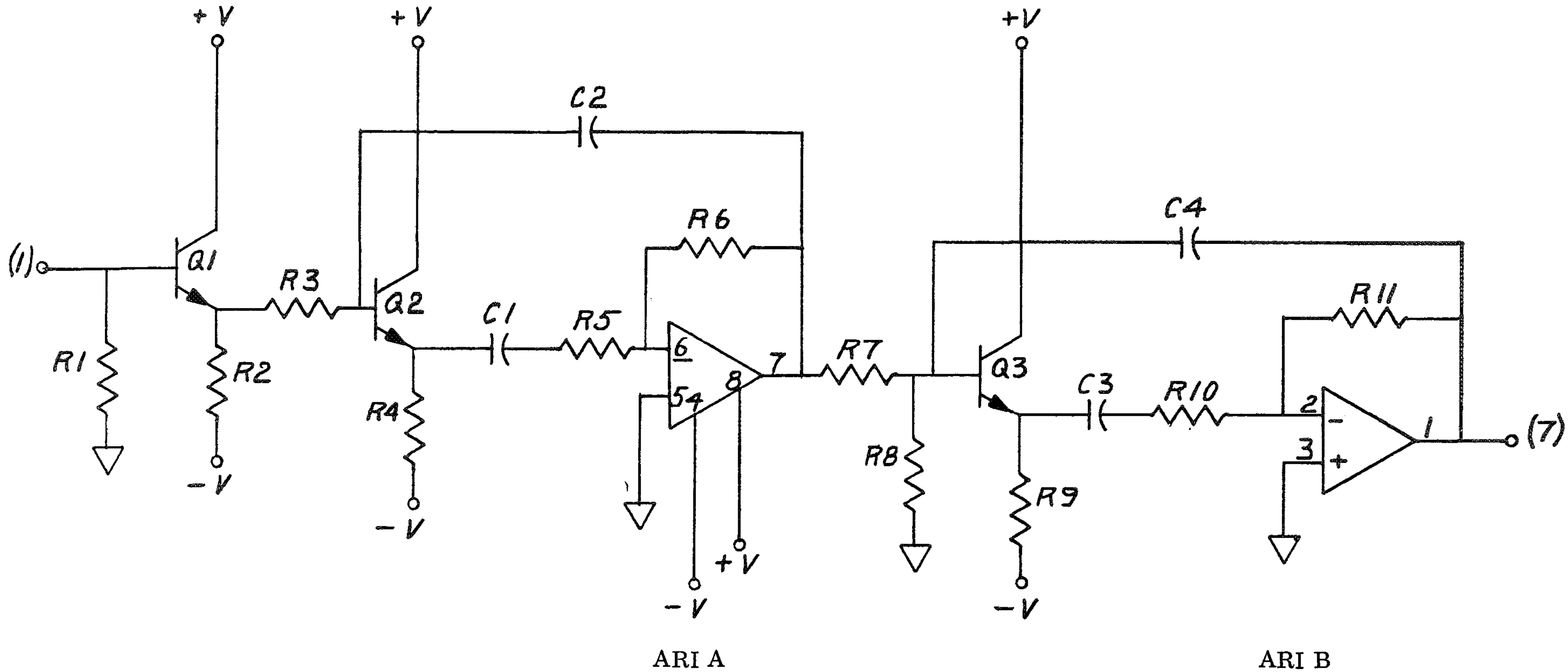
BUFFER AMPLIFIER





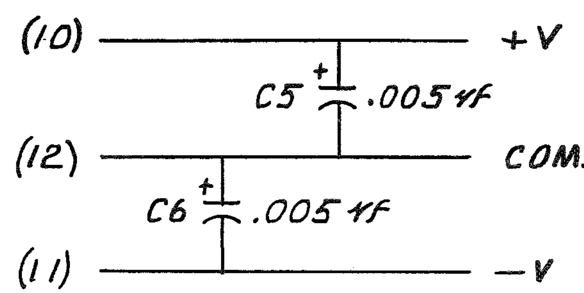
R1	100K	5%
R2	39K	5%
R3	2.7K	5%
R4	4.7K	5%
R5	47	5%
R6	47	5%
C1	10MF/ 20V	
C2	10MF/ 20V	
Q1	LS3954	
Q2	2N3906	

100 HZ FILTER

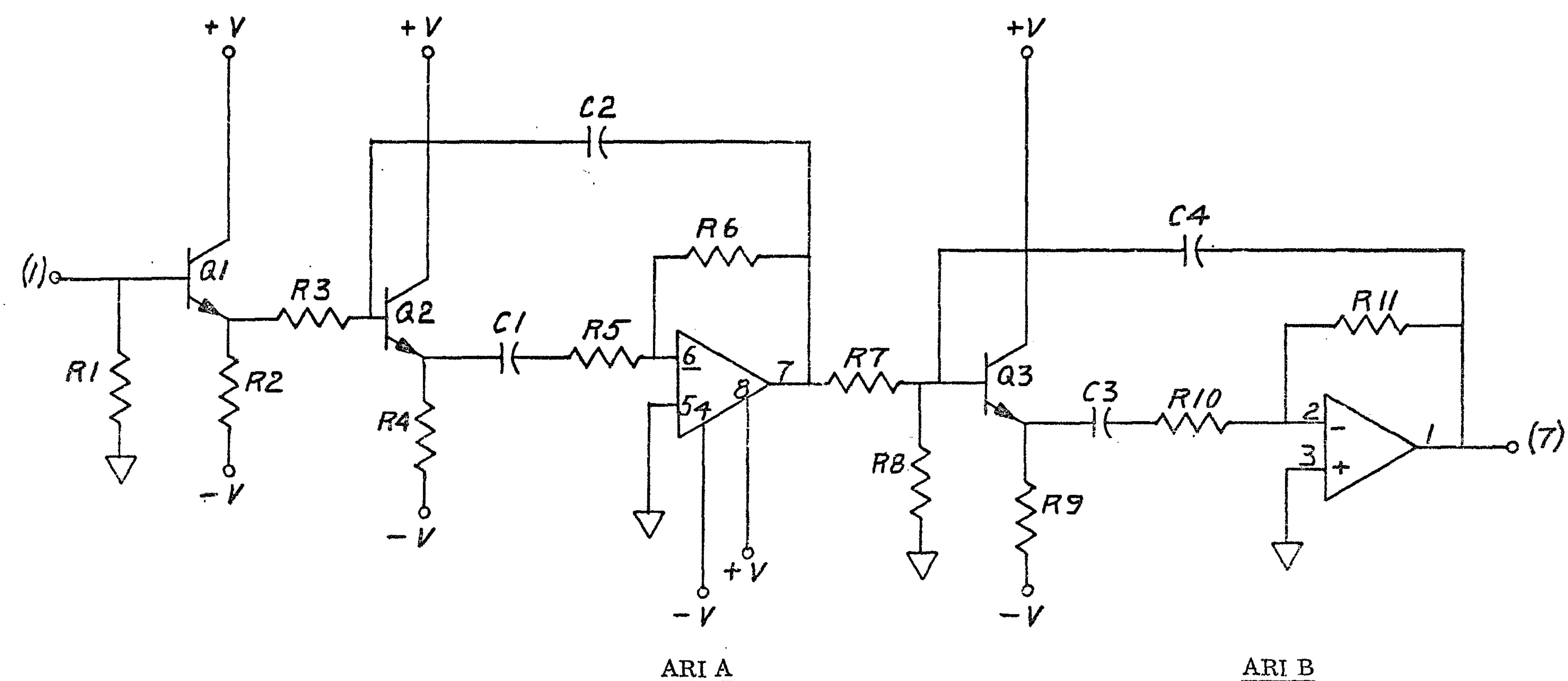


R1	10K	5%
R2	15K	5%
R3	14.3K	1%
R4	15K	5%
R5	1.43K	1%
R6	215K	1%
R7	105K	1%
R8	13.7K	1%
R9	15K	5%
R10	1.21K	1%
R11	178K	1%

C1	0.1	MFD	5%
C2	0.01	MFD	1%
C3	0.1	MFD	5%
C4	0.01	MFD	2%
C5	.005	MFD	CERAMIC
C6	.005	MFD	CERAMIC
ARI	MC1458G		(MOTOROLA)
Q1	2N2222		(MOTOROLA)
Q2	2N2222		(MOTOROLA)
Q3	2N2222		(MOTOROLA)

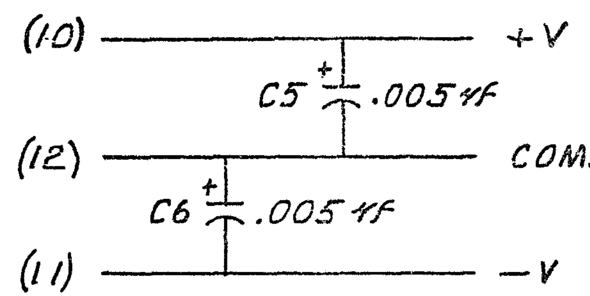


316 HZ FILTER

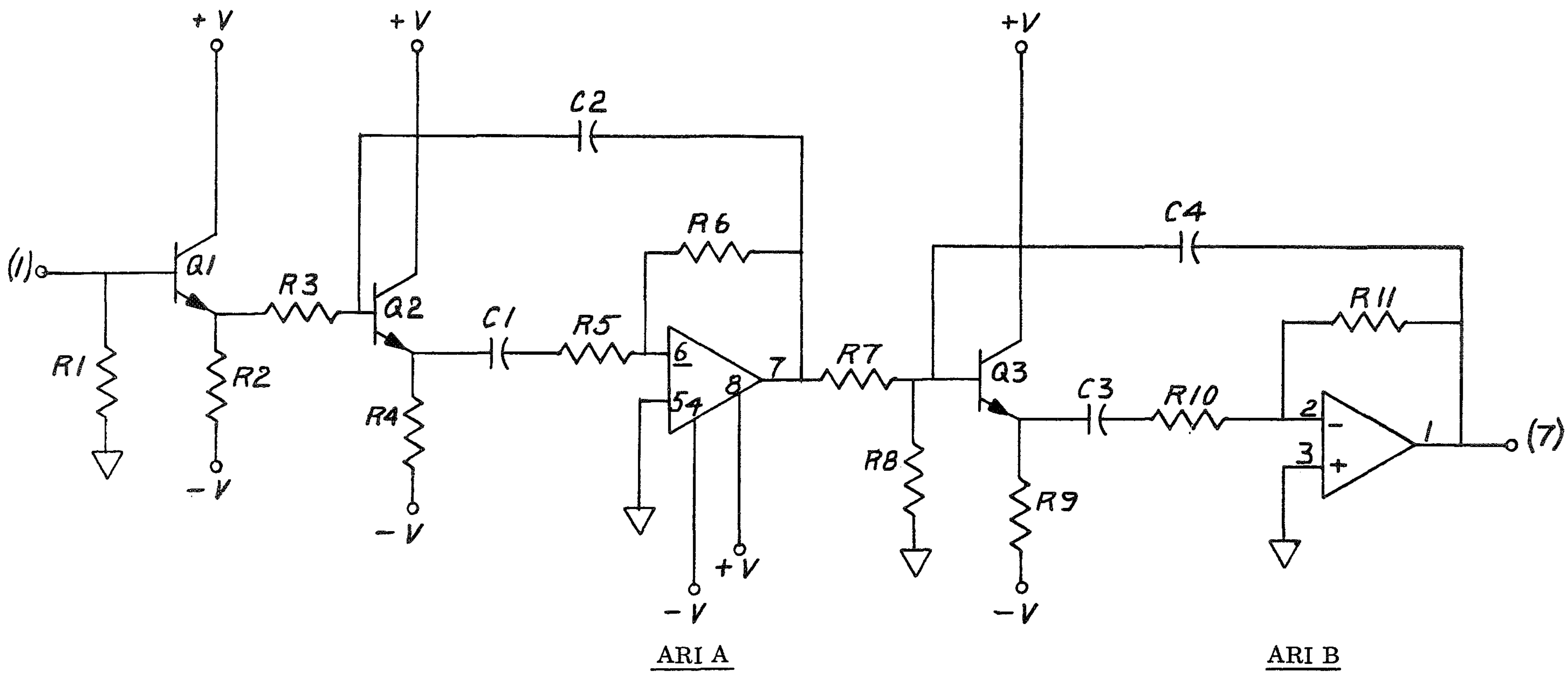


R1	10K	5%
R2	15K	5%
R3	38.3K	1%
R4	15K	5%
R5	3.83K	1%
R6	562K	1%
R7	274K	1%
R8	35.7K	1%
R9	15K	5%
R10	3.16K	1%
R11	464K	1%

C1	.012	MFD	5%
C2	.0012	MFD	5%
C3	.012	MFD	5%
C4	.0012	MFD	5%
ARI	MC1458G		(MOTOROLA)
Q1	2N2222		(MOTOROLA)
Q2	2N2222		(MOTOROLA)
Q3	2N2222		(MOTOROLA)

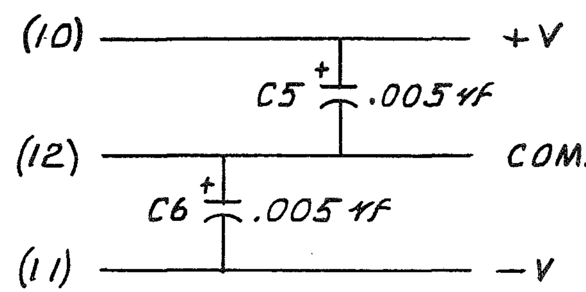


1.0 KHZ FILTER

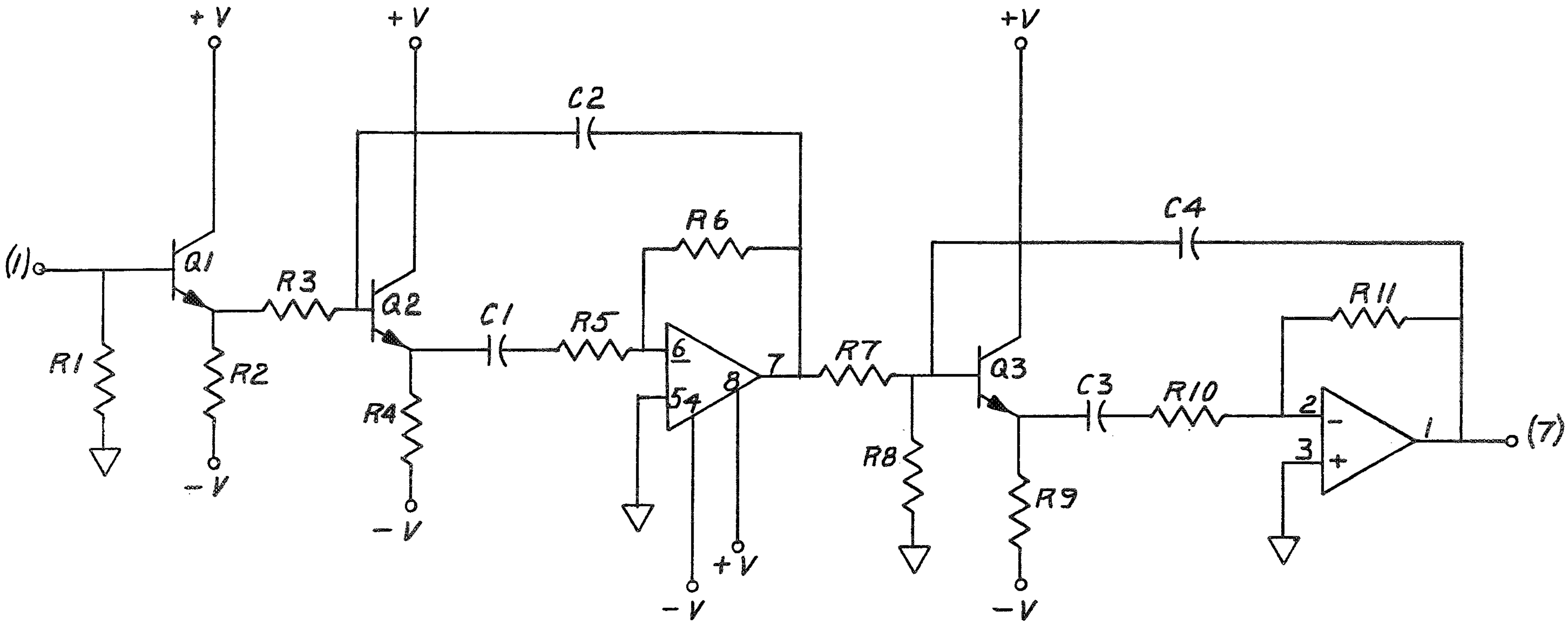


R1	10K	5%
R2	15K	5%
R3	11.8K	1%
R4	15K	5%
R5	1.18K	1%
R6	174K	1%
R7	86.6K	1%
R8	11.3K	1%
R9	15K	5%
R10	1.0K	1%
R11	147K	1%

C1	.012	MFD	5%
C2	.0012	MFD	5%
C3	.012	MFD	5%
C4	.0012	MFD	5%
ARI	MC1458G		(MOTOROLA)
Q1	2N2222		(MOTOROLA)
Q2	2N2222		(MOTOROLA)
Q3	2N2222		(MOTOROLA)



3.16 KHZ FILTER

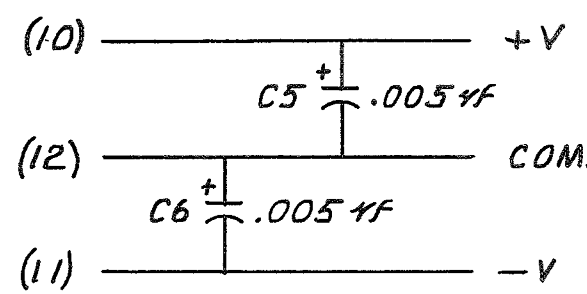


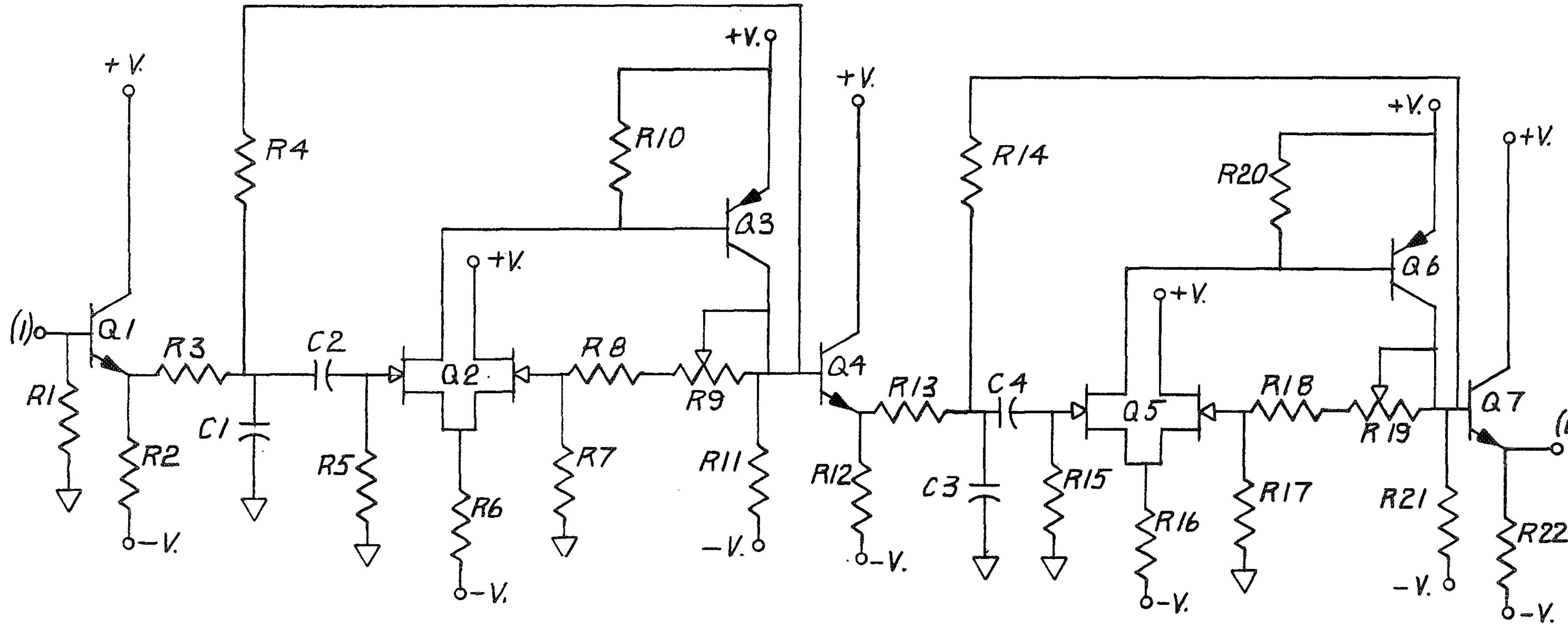
ARI A

ARI B

R1	10K	5%
R2	15K	5%
R3	38.3K	1%
R4	15K	5%
R5	3.83K	1%
R6	562K	1%
R7	274K	1%
R8	35.3K	1%
R9	15K	5%
R10	3.16K	1%
R11	464K	1%

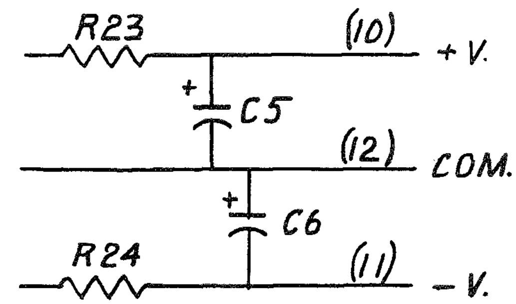
C1	.0012 MFD	5%
C2	.00012 MFD	5%
C3	.0012 MFD	5%
C4	.00012 MFD	5%
A1	MC1458G	(MOTOROLA)
Q1	2N2222	(MOTOROLA)
Q2	2N2222	(MOTOROLA)
Q3	2N2222	(MOTOROLA)



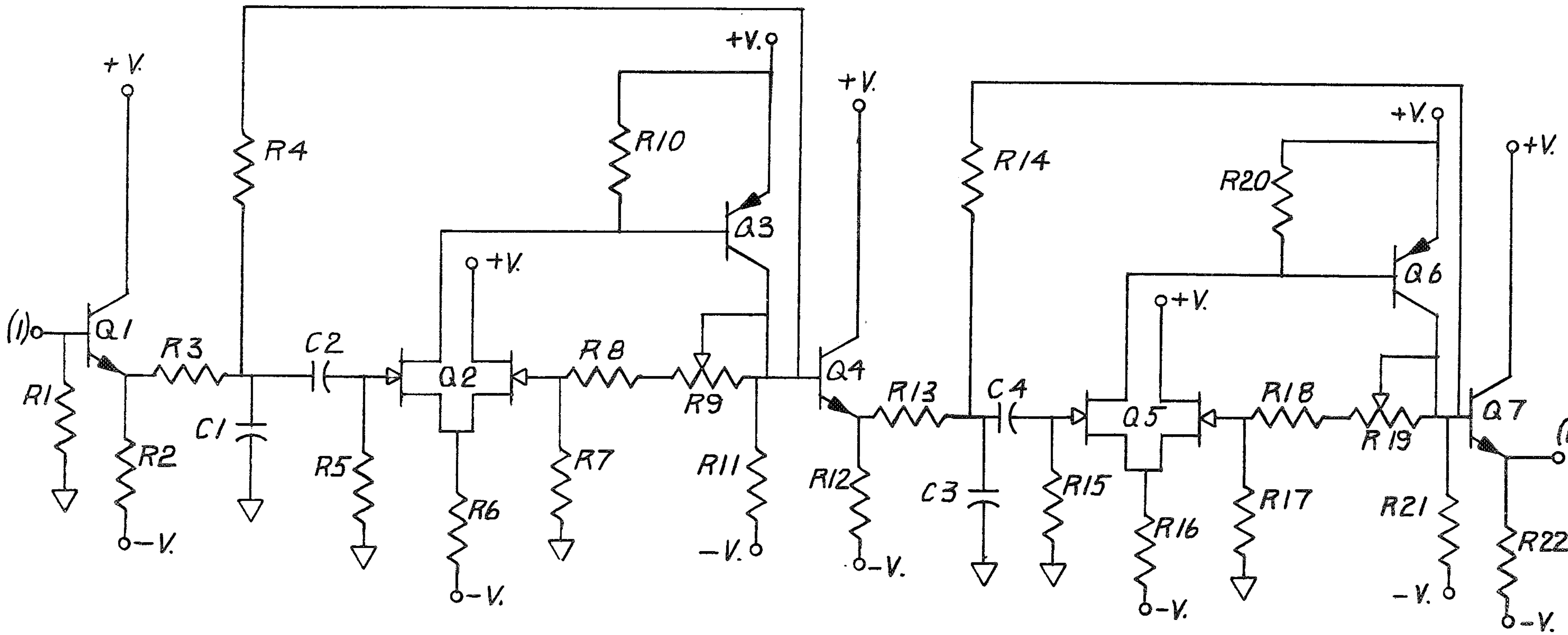


10.0 KHZ FILTER

R1	10K	5%	R19	1K	POT
R2	10K	5%	R20	2.7K	5%
R3	38.2K	1%	R21	4.7K	5%
R4	38.2K	1%	R22	10K	5%
R5	64.4K	1%	C1	470	PF
R6	39K	5%	C2	470	PF
R7	4.64K	1%	C3	470	PF
R8	9.31K	1%	C4	470	PF
R9	1K	POT	Q1	2N2222	
R10	2.7K	5%	Q2	LS3954	
R11	4.7K	5%	Q3	2N3906	
R12	4.7K		Q4	2N2222	
R13	32.5K	1%	Q5	LS3954	
R14	32.5K	1%	Q6	2N3906	
R15	56.2K	1%	Q7	2N2222	
R16	39K	5%			
R17	4.64K	1%			
R18	9.31K	1%			



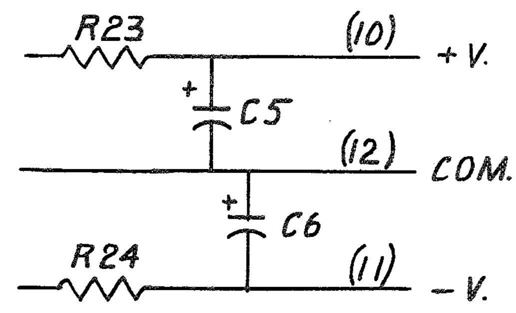
R23	47	5%
R24	47	5%
C5	10µf/20V	
C6	10µf/20V	



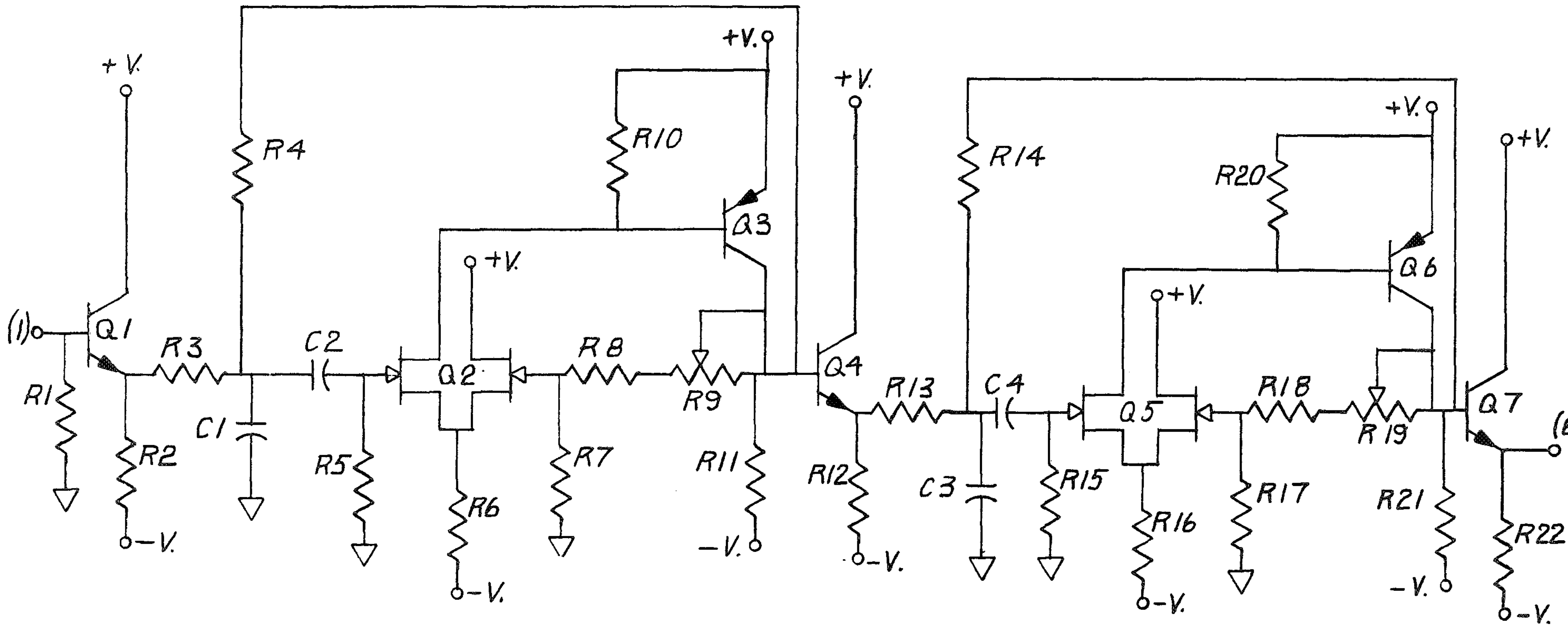
31.6 KHZ FILTER

R1	10K	5%
R2	10K	5%
R3	11.7K	1%
R4	11.7K	1%
R5	21.5K	1%
R6	39K	5%
R7	4.64K	1%
R8	9.31K	1%
R9	1K	POT
R10	2.7K	5%
R11	4.7K	5%
R12	4.7K	5%
R13	9.9K	1%
R14	9.9K	1%
R15	19.6K	1%
R16	39K	5%
R17	4.64K	1%
R18	9.31K	1%

R19	1K	POT
R20	2.7K	5%
R21	4.7K	5%
R22	10K	5%
C1	470 PF	5%
C2	470 PF	5%
C3	470 PF	5%
C4	470 PF	5%
Q1	2N2222	
Q2	LS3954	
Q3	2N3906	
Q4	2N2222	
Q5	LS3954	
Q6	2N3906	
Q7	2N2222	



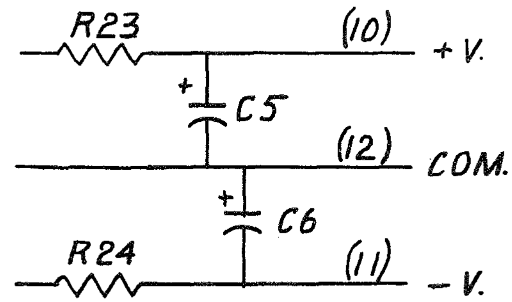
R23	47	5%
R24	47	5%
C5	10μf/20V	
C6	10μf/20V	



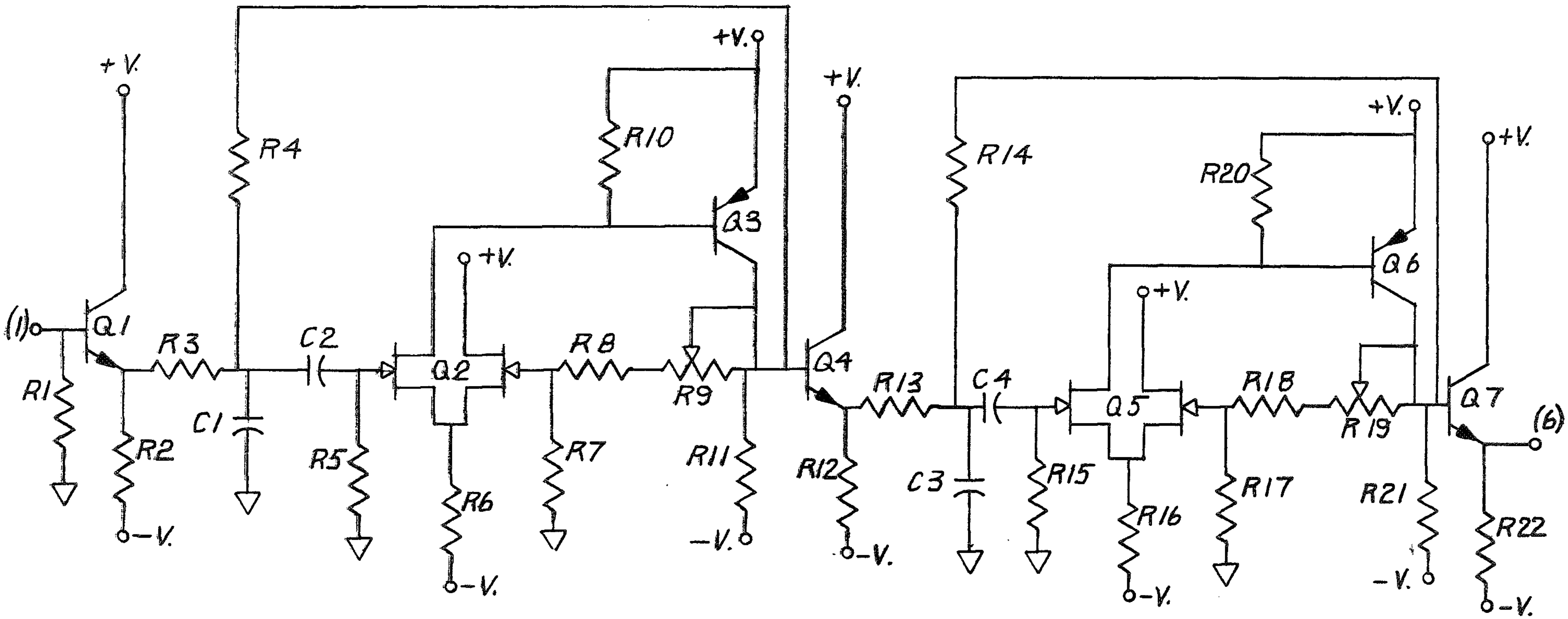
100 KHZ FILTER

R1	10K	5%
R2	10K	5%
R3	38.2K	1%
R4	38.2K	1%
R5	58.8K	1%
R6	39K	5%
R7	4.64K	1%
R8	9.31K	1%
R9	1K	POT
R10	2.7K	5%
R11	4.7K	5%
R12	4.7K	5%
R13	32.5K	1%
R14	48.3K	1%
R15	73 K	1%
R16	39K	5%
R17	4.64K	1%
R18	9.31K	1%
R19	1K	POT

R20	2.7K	5%
R21	4.7K	5%
R22	10K	5%
C1	47 PF	5%
C2	47 PF	5%
C3	47 PF	5%
C4	47 PF	5%
Q1	2N2222	
Q2	LS3954	
Q3	2N3906	
Q4	2N2222	
Q5	LS3954	
Q6	2N3906	
Q7	2N2222	



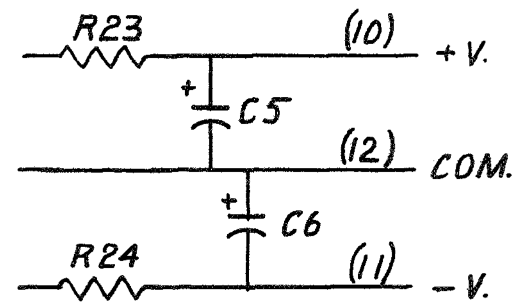
R23	47	5%
R24	47	5%
C5	10µf/20V	
C6	10µf/20V	



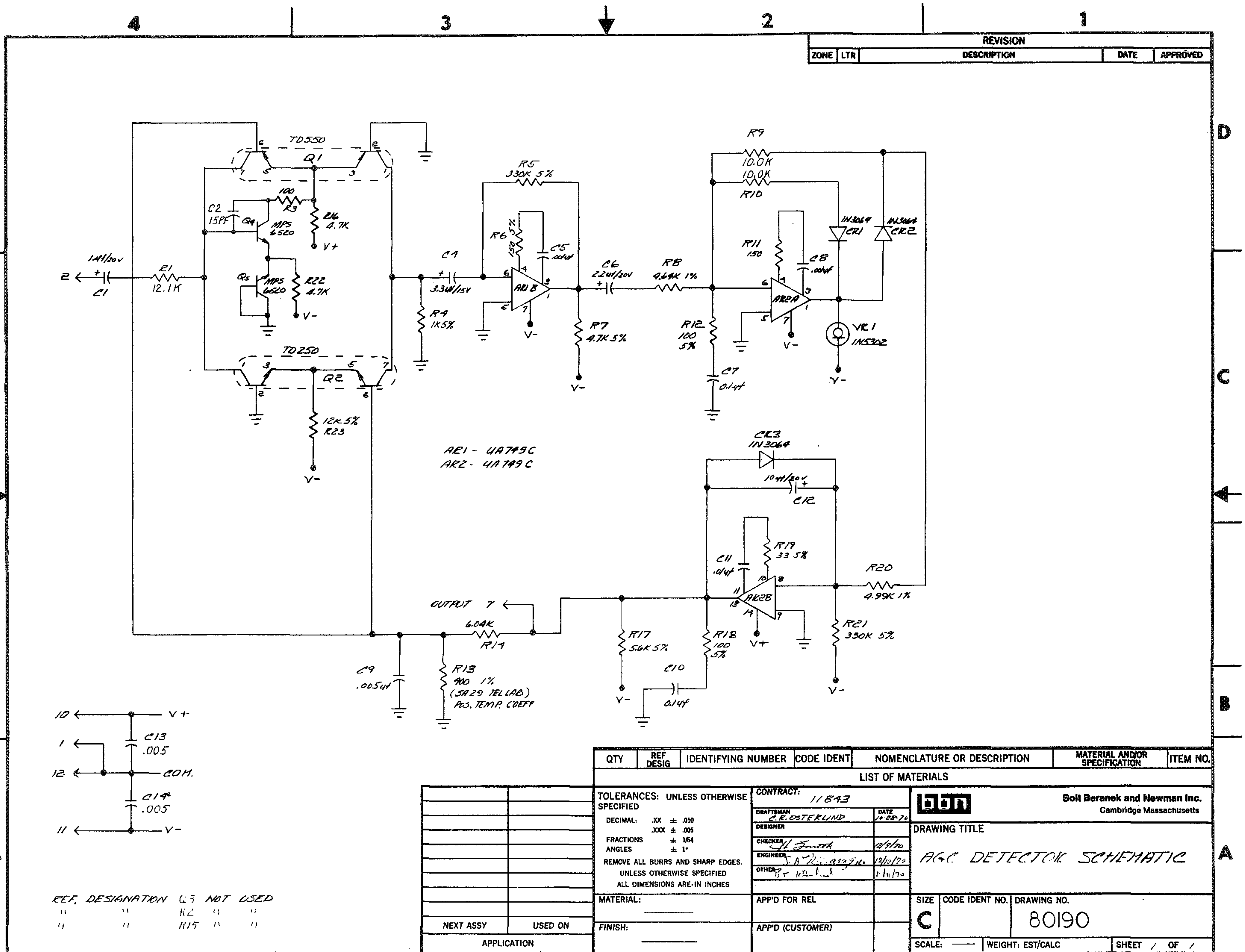
200 KHZ FILTER

R1	10K	5%
R2	10K	5%
R3	14.7K	1%
R4	14.7K	1%
R5	25.0K	1%
R6	39K	5%
R7	4.64K	1%
R8	9.31K	1%
R9	1K	POT
R10	2.7K	5%
R11	4.7K	5%
R12	4.7K	5%
R13	12.1K	1%
R14	12.1K	1%
R15	22.3K	1%
R16	39K	5%
R17	4.64K	1%
R18	9.31K	1%

R19	1K	POT
R20	2.7K	5%
R21	4.7K	5%
R22	10K	5%
C1	56 PF	5%
C2	56 PF	5%
C3	56 PF	5%
C4	56 PF	5%
Q1	2N2222	
Q2	LS3954	
Q3	2N3906	
Q4	2N2222	
Q5	LS3954	
Q6	2N3906	
Q7	2N2222	



R23	47	5%
R24	47	5%
C5	10µf/20V	
C6	10µf/20V	


REVISION
ZONE LTR DESCRIPTION DATE APPROVED
TD550
Q1
TD250
Q2
C2 15PF
Q4 MPS 6520
Q5 MPS 6520
100 R3
R16 4.7K V+
R22 4.7K V-
12K 5% R23
1Mf/20V C1
R1 12.1K
C4 3.3Mf/15V
R4 1K5%
R5 330K 5%
R6 150 5%
C5 .001uf
AR1 B
R7 4.7K 5%
C6 2.2uf/20V
R8 4.64K 1%
R9 10.0K
R10 10.0K
R11 150
C8 .001uf
AR2A
1N3064 CR1
1N3064 CR2
VR1 1N5302
R12 100 5%
C7 0.1uf
AR1 - UA749C
AR2 - UA749C
CR3 1N3064
10uf/20V C12
R19 33 5%
C11 .01uf
AR2B
R20 4.99K 1%
R21 330K 5%
OUTPUT 7
6.04K R14
R17 5.6K 5%
R18 100 5%
C10 0.1uf
C9 .005uf
R13 900 1% (5A29 TEL LAB) POS. TEMP. COEFF
10 V+
C13 .005
1
12 COM.
C14 .005
11 V-
REF. DESIGNATION Q3 NOT USED
" " R2 " "
" " R15 " "
QTY | REF DESIG | IDENTIFYING NUMBER | CODE IDENT | NOMENCLATURE OR DESCRIPTION | MATERIAL AND/OR SPECIFICATION | ITEM NO.
LIST OF MATERIALS
NEXT ASSY USED ON
APPLICATION
TOLERANCES: UNLESS OTHERWISE SPECIFIED
DECIMAL: .XX ± .010 .XXX ± .005
FRACTIONS ± 1/64
ANGLES ± 1°
REMOVE ALL BURRS AND SHARP EDGES.
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS ARE IN INCHES
MATERIAL:
FINISH:
CONTRACT: 11843
DRAFTSMAN C.R. OSTERLUND DATE 10-28-70
DESIGNER
CHECKER 12/9/70
ENGINEER 12/10/70
OTHER 1/11/71
APP'D FOR REL
APP'D (CUSTOMER)
bbn
Bolt Beranek and Newman Inc.
Cambridge Massachusetts
DRAWING TITLE
AGC DETECTOR SCHEMATIC
SIZE C
CODE IDENT NO.
DRAWING NO. 80190
SCALE: —
WEIGHT: EST/CALC
SHEET 1 OF 1

APPENDIX B

Pertinent data from the American Standard Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets.

S1.11-1966

Sponsored by the Acoustical Society of America

Approved May 4, 1966
American Standards Association Incorporated

1. Purpose and Scope

1.1 Purpose. The purpose of this standard for filter sets is to specify particular bandwidths and characteristics which may be used to ensure that all analyses of noise will be consistent within known tolerances when made with similar filter sets meeting these specifications.

1.2 Scope. The standard for filter sets is suited to the requirements for analyzing, as a function of frequency, a broadband electrical signal. For acoustical measurements an electro-acoustic-transducer and amplifier are employed to convert the acoustic signal to be analyzed into the required electrical signal.

2. Definitions

These definitions are based upon those given in American Standard Acoustical Terminology (Including Mechanical Shock and Vibration), S1.1-1960.

2.1 Wave Filter (Filter). A wave filter is a transducer for separating waves on the basis of their frequency. It introduces relatively small insertion loss to waves in one or more frequency bands, and relatively large insertion loss to waves of other frequencies. (See 6.12 of American Standard S1.1-1960.)

2.2 Band-Pass Filter. A band-pass filter is a wave filter that has a single transmission band extending from a lower band-edge frequency greater than zero to a finite upper band-edge frequency.

NOTE: This definition is identical to the definition in 6.15 of American Standard S1.1-1960 except that the words "band-edge frequency" are substituted for "cutoff frequency." Cutoff frequency in 6.16 of American Standard S1.1-1960 is restricted to a frequency at which the response is 3 dB below the maximum response. In this standard the restriction does not apply to the frequencies limiting the passband. Therefore, the term "band-edge frequency" is used to avoid confusion. See 3.3 and Appendix B.

2.3 Filter Bandwidth. The bandwidth of a filter is the difference between the upper and lower band-edge frequencies, and defines the transmission band or pass band. In this specification the bandwidth is described by the interval in octaves between the upper and lower band-edge frequencies.

2.4 Spectrum. The spectrum of a function of time is a description of its resolution into components, each of a different frequency and (usually) different in amplitude and phase. [See 1.34 (1) of American Standard S1.1-1960.] A *Continuous Spectrum* is the spectrum of a wave the components of which are continuously distributed over a frequency region. (See 1.37 of American Standard S1.1-1960.) A *White Noise Spectrum* is a continuous spectrum whose spectrum density (mean-square amplitude per unit frequency) is independent of frequency over a specified frequency range.

2.5 Transmission Loss. Transmission Loss is the reduction in the magnitude of some characteristic of a signal, between two stated points in a transmission system. (See 4.29 of American Standard S1.1-1960.)

NOTE 1: In this specification the *Transmission Loss* is the reduction in power level or voltage level between the input applied to the filter in series with its proper input terminating impedance, and the output delivered by the filter to its proper load impedance.

NOTE 2: In this specification the *Transmission Loss Characteristic* of a filter, representing the change of Transmission Loss with frequency, is specified with respect to the minimum Transmission Loss in the passband measured when the filter is inserted between the proper terminating impedances.

NOTE 3: *Attenuation* (not defined in American Standard S1.1-1960) is frequently used as synonymous with Transmission Loss as defined above, in connection with filter characteristics.

NOTE 4: *Insertion Loss* is a term also frequently used in connection with filters. The Insertion Loss resulting from insertion of a transducer in a transmission system is 10 times the logarithm to the base 10 of the power delivered to that part of the system that will follow the transducer, before insertion of the transducer, to the power delivered to that same part of the system after insertion of the transducer. (See 7.2 of American Standard S1.1-1960.) For passive filters operated between resistive terminating impedances, the *Insertion Loss Characteristic* employing the minimum value as referent is the same as the *Transmission Loss Characteristic.*

2.6 Terminating Impedances. The terminating impedances are the impedances of the external input and output circuits between which the filter is connected.

2.7 Peak-to-Valley Ripple. When the transmission loss characteristic in the transmission band contains a series of maxima and minima, or ripples, the peak-to-valley ripple is defined as the difference in decibels between the extremes of minimum and maximum transmission loss in the pass band region.

3. Requirements

3.1 Filter Sets. The filter set shall provide a number of filter bands according to the schedules listed in Table 1, and shall bear the corresponding Type symbol:

R for Restricted Range
E for Extended Range
O for Optional Range

The filter bands are identified by the designation mean frequency f_m of the band as defined in 3.2.

3.2 Nominal Mean Frequency, f_m

3.2.1 *Band Designation Frequencies.* The values of mean frequency, f_m, used for band designation in Table 1 are based upon the recommendations of 5.2, page 3, of American Standard S1.6-1960. Band designation frequencies shall be rounded according to American Standard S1.6-1960.

3.2.2 *Precise Values of f_m.* Precise values of nominal mean frequency f_m shall be calculated from the formulas given in Table 2.

3.3 Nominal Frequency Bandwidths. The nominal band-edge frequencies and bandwidths for the octave, half-octave, and third-octave band filters are defined by the relations given in Table 3. The frequency f_m in each band is the geometric mean of the upper and lower nominal band-edge frequencies, f_1 and f_2, which are defined by Table 3.

3.4 Transmission Loss vs Frequency Characteristics of Individual Filters. When tested as specified in Section 4, the separate filters of a set shall conform to the requirements in the paragraphs below. For each filter characteristic, transmission loss is specified with respect to the minimum transmission loss in the frequency range f_1 to f_2 delineated in Table 3. Transmission loss characteristics are grouped under three classes (I, II, or III) depending upon the steepness of the slope of the transmission loss vs frequency curve. Filter designations must bear the appropriate Class symbol.

NOTE: In the transmission loss characteristics specified below, the mathematical statement is the governing consideration. The graphical representation accompanying each characteristic requirement is added for convenience. The actual filter characteristic, in addition to falling within the transmission loss limits shown, must simultaneously meet the requirements on *Passband Uniformity* (see 3.6) and on *Effective Bandwidth* (see 3.7). On each plot a dotted curve is shown as an example of a characteristic meeting all requirements.

Table 1

Table of Filter Bands To Be Provided

Band Number	Mean Frequency f_m (c/s)	Octave Bands		Half-Octave Bands		Third-Octave Bands		Any Band
		Type R	Type E	Type R	Type E	Type R	Type E	Type O
14	25						x	Filter Bands as Specified by the Manufacturer
15	**31.5**		x		x		x	
16	40						x	
16.5	45				x			
17	50						x	
18	**63**		x		x		x	
19	80						x	
19.5	90				x			
20	100					x	x	
21	**125**	x	x	x	x	x	x	
22	160					x	x	
22.5	180			x	x			
23	200					x	x	
24	**250**	x	x	x	x	x	x	
25	315					x	x	
25.5	355			x	x			
26	400					x	x	
27	**500**	x	x	x	x	x	x	
28	630					x	x	
28.5	710			x	x			
29	800					x	x	
30	**1000**	x	x	x	x	x	x	
31	1250					x	x	
31.5	1400			x	x			
32	1600					x	x	
33	**2000**	x	x	x	x	x	x	
34	2500					x	x	
34.5	2800			x	x			
35	3150					x	x	
36	**4000**	x	x	x	x	x	x	
37	5000					x	x	
37.5	5600				x			
38	6300						x	
39	**8000**		x		x		x	
40	10000						x	
40.5	11200				x			
41	12500						x	
42	**16000**						x	
43	20000						x	

Table 2
Nominal Mean Frequencies, f_m

Octave Bands	$f_m = 10^{3n/10}$
Half-Octave Bands	$f_m = 10^{3n/20}$
Third-Octave Bands	$f_m = 10^{3n/30}$

NOTE: n is any integer, positive, negative, or zero.

Table 3
Nominal Band-Edge Frequencies and Frequency Bandwidths

	Octave Band	Half-Octave Band	Third-Octave Band
Formula	$f_1 = 2^{-1/2} f_m$	$f_1 = 2^{-1/4} f_m$	$f_1 = 2^{-1/6} f_m$
	$f_2 = 2^{1/2} f_m$	$f_2 = 2^{1/4} f_m$	$f_2 = 2^{1/6} f_m$
Numerical Value	$f_1 = 0.7071 f_m$	$f_1 = 0.8409 f_m$	$f_1 = 0.8909 f_m$
	$f_2 = 1.4142 f_m$	$f_2 = 1.1892 f_m$	$f_2 = 1.1225 f_m$
Bandwidth $f_2 - f_1$	$0.7071 f_m$	$0.3483 f_m$	$0.2316 f_m$

f_1 = nominal lower band-edge frequency
f_2 = nominal upper band-edge frequency
f_m = calculated from formulas of Table 2

3.4.1 *Octave Band Filters — Class I*

(1) At any frequency, f, in the range from $\frac{3f_m}{4}$ to $\frac{4f_m}{3}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{8}{5} \left[1 + 3\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^2\right] \text{ decibels.}$$

(2) At any frequency, f, in the range from $\frac{f_m}{5}$ to $\frac{f_m}{\sqrt{2}}$ the transmission loss shall be more than

$$10 \log_{10} \left[\frac{1}{8}\left(\frac{f_m}{f}\right)^6\right] \text{ decibels.}$$

(3) At any frequency, f, in the range from $\frac{f_m}{10}$ to $\frac{f_m}{5}$ the transmission loss shall be more than

$$10 \log_{10} \left[1 + \frac{25}{8}\left(\frac{f}{f_m}\right)^4\right] \text{ decibels.}$$

(4) At any frequency, f, in the range from $\sqrt{2} f_m$ to $5f_m$ the transmission loss shall be more than

$$10 \log_{10} \left[\frac{1}{8}\left(\frac{f}{f_m}\right)^6\right] \text{ decibels.}$$

(5) At any frequency, f, in the range from $5f_m$ to $10f_m$ the transmission loss shall be more than

$$10 \log_{10} \left[1 + \frac{25}{8}\left(\frac{f}{f_m}\right)^4\right] \text{ decibels.}$$

(6) At any frequency, f, below $\frac{f_m}{10}$ or above $10f_m$ the transmission loss shall be more than 45 decibels.

(7) A graphical representation of the allowable limits is given in Fig. 1.

3.4.2 *Octave Band Filters — Class II*

(1) At any frequency, f, in the range from $\frac{3f_m}{4}$ to $\frac{4f_m}{3}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{5}{4} \left[1 + 30\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^6\right] \text{ decibels.}$$

(2) At any frequency, f, in the range from $\frac{f_m}{8}$ to $\frac{f_m}{\sqrt{2}}$ and from $\sqrt{2} f_m$ to $8f_m$ the transmission loss shall be more than

$$10 \log_{10} \frac{2}{3} \left[1 + 4\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^6\right] \text{ decibels.}$$

(3) At any frequency, f, below $\frac{f_m}{8}$ or above $8f_m$ the transmission loss shall be more than 60 decibels.

(4) A graphical representation of the allowable limits is given in Fig. 2.

3.4.3 *Half-Octave Band Filters — Class II*

(1) At any frequency, f, in the range from $\frac{6f_m}{7}$ to $\frac{7f_m}{6}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{5}{4} \left[1 + 200\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

(2) At any frequency, f, in the range from $\frac{9f_m}{100}$ to $2^{-1/4} f_m$ and from $2^{1/4} f_m$ to $\frac{100 f_m}{9}$ the transmission loss shall be more than

$$10 \log_{10} \left[68\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

(3) At any frequency, f, below $\frac{9f_m}{100}$ or above $\frac{100 f_m}{9}$ the transmission loss shall be more than 60 decibels.

(4) A graphical representation of the allowable limits is given in Fig. 3.

3.4.4 *Half-Octave Band Filters — Class III*

(1) At any frequency, f, in the range from $\frac{6f_m}{7}$ to $\frac{7f_m}{6}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{5}{4} \left[1 + 200\left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

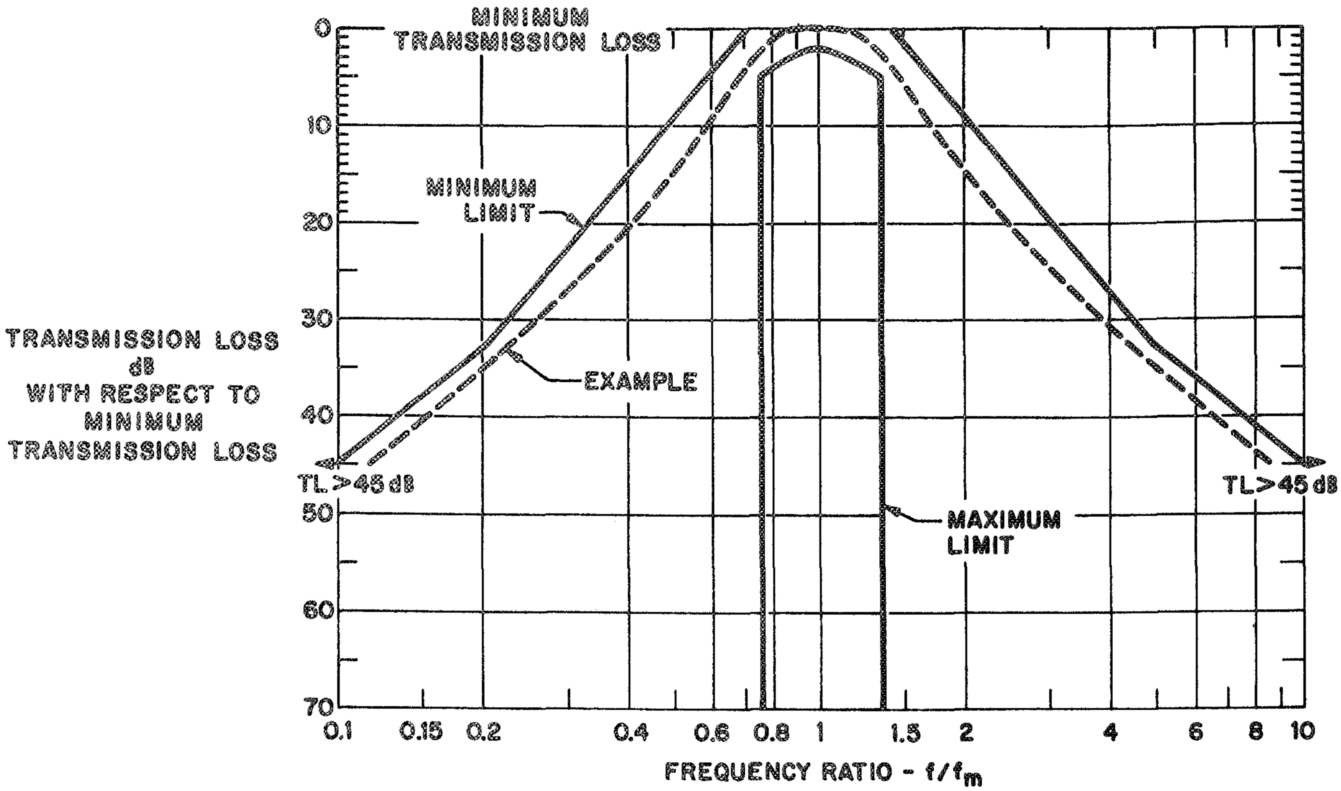


Fig. 1

Transmission Loss Limits — Octave Band Filter, Class I

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

(2) At any frequency, f, in the range from $\frac{f_m}{6}$ to $2^{-1/4}f_m$ and from $2^{1/4}f_m$ to $6f_m$ the transmission loss shall be more than

$$10 \log_{10} \left[\frac{5}{9} + 250 \left(\frac{f}{f_m} - \frac{f_m}{f}\right)^6\right] \text{ decibels.}$$

(3) At any frequency, f, below $\frac{f_m}{6}$ or above $6f_m$ the transmission loss shall be more than 70 decibels.

(4) A graphical representation of the allowable limits is given in Fig. 4.

3.4.5 *Third-Octave Band Filters — Class II*

(1) At any frequency, f, in the range from $\frac{9f_m}{10}$ to $\frac{10f_m}{9}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{5}{4} \left[1 + 1040 \left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

(2) At any frequency, f, in the range from $\frac{f_m}{8}$ to $2^{-1/6}f_m$ and from $2^{1/6}f_m$ to $8f_m$ the transmission loss shall be more than

$$10 \log_{10} \frac{1}{4} \left[1 + 1040 \left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

(3) At any frequency, f, below $\frac{f_m}{8}$ or above $8f_m$ the transmission loss shall be more than 60 decibels.

(4) A graphical representation of the allowable limits is given in Fig. 5.

3.4.6 *Third-Octave Band Filters — Class III*

(1) At any frequency, f, in the range from $\frac{9f_m}{10}$ to $\frac{10f_m}{9}$ the transmission loss shall not be more than

$$10 \log_{10} \frac{5}{4} \left[1 + 1040 \left(\frac{f}{f_m} - \frac{f_m}{f}\right)^4\right] \text{ decibels.}$$

(2) At any frequency, f, in the range from $\frac{f_m}{5}$ to $2^{-1/6}f_m$ and from $2^{1/6}f_m$ to $5f_m$ the transmission loss shall be more than

$$10 \log_{10} \left[\frac{8}{13} + 2500 \left(\frac{f}{f_m} - \frac{f_m}{f}\right)^6\right] \text{ decibels.}$$

(3) At any frequency, f, below $\frac{f_m}{5}$ or above $5f_m$ the transmission loss shall be more than 75 decibels.

(4) A graphical representation of the allowable limits is given in Fig. 6.

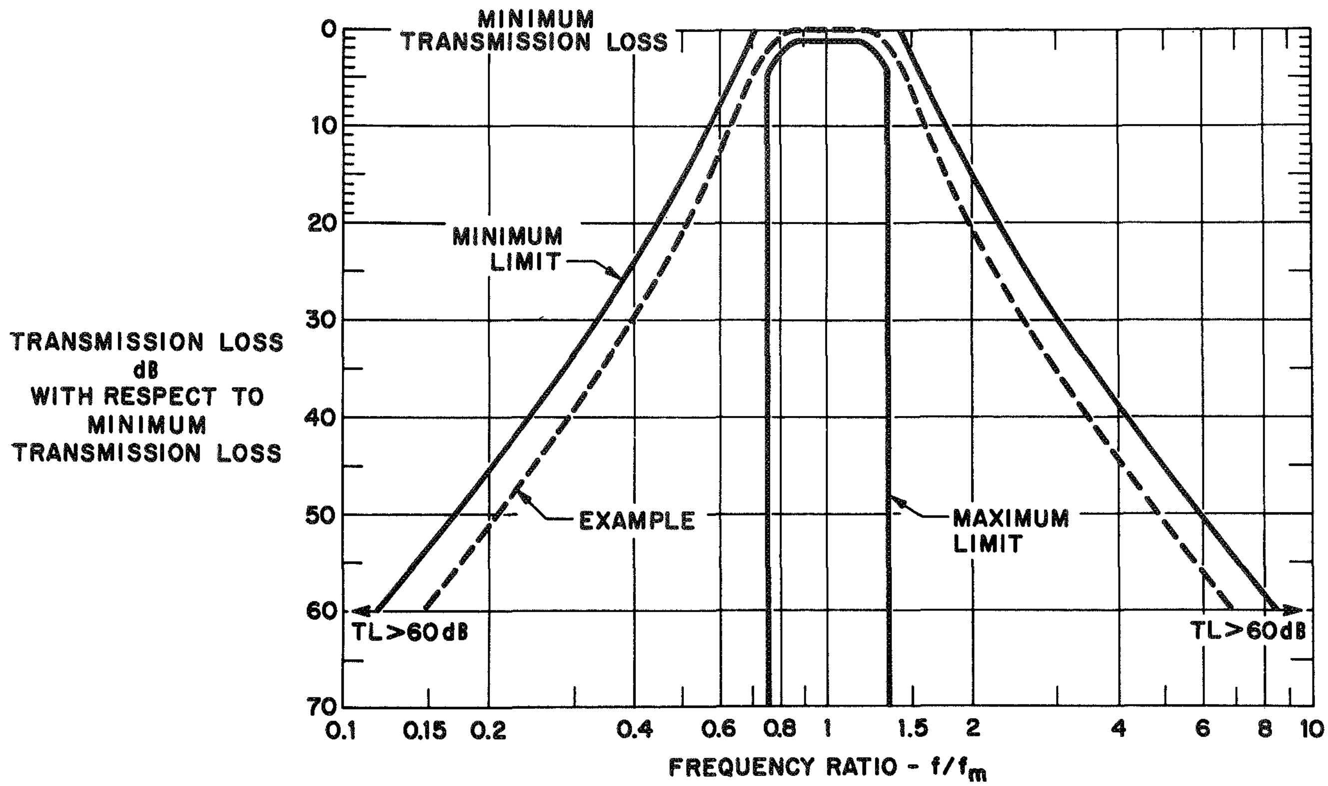


Fig. 2

Transmission Loss Limits — Octave Band Filter, Class II

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

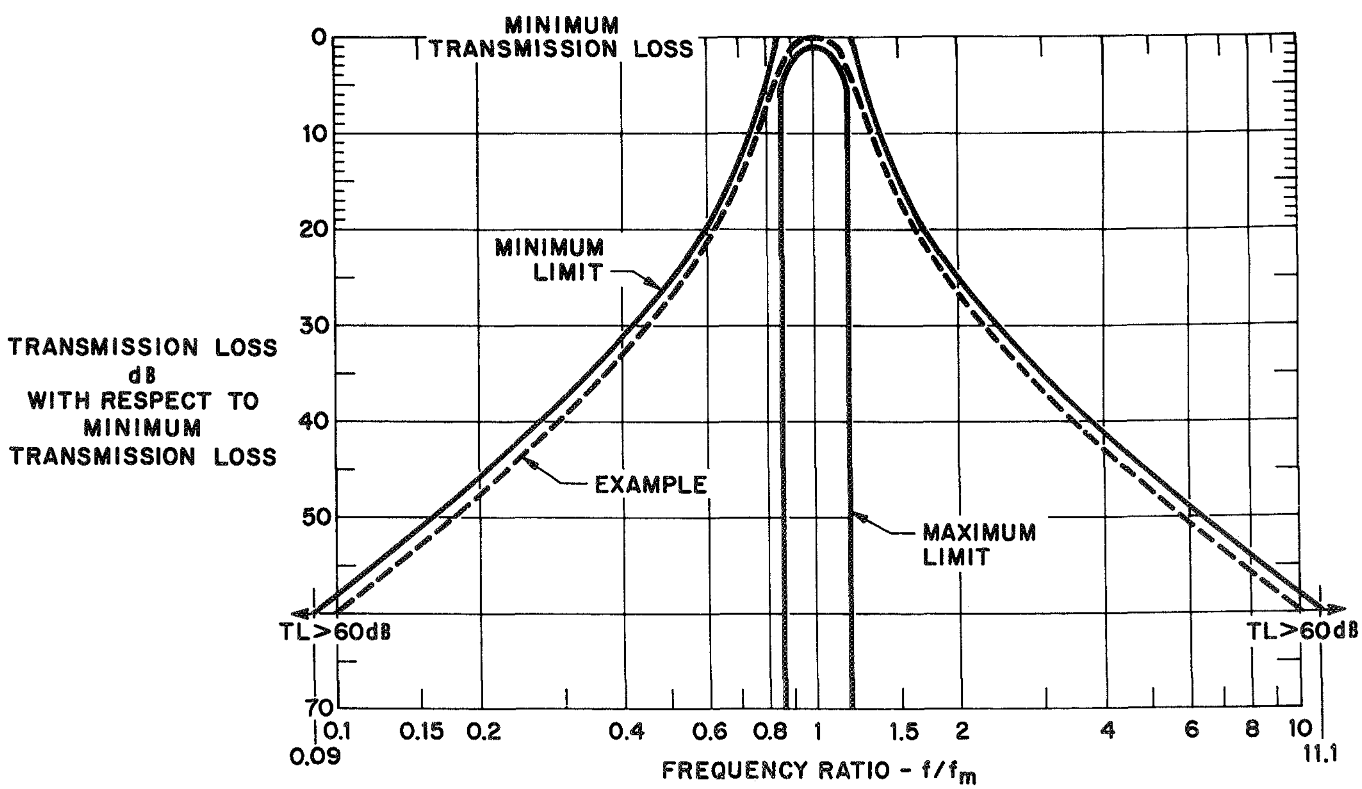


Fig. 3

Transmission Loss Limits — Half-Octave Band Filter, Class II

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

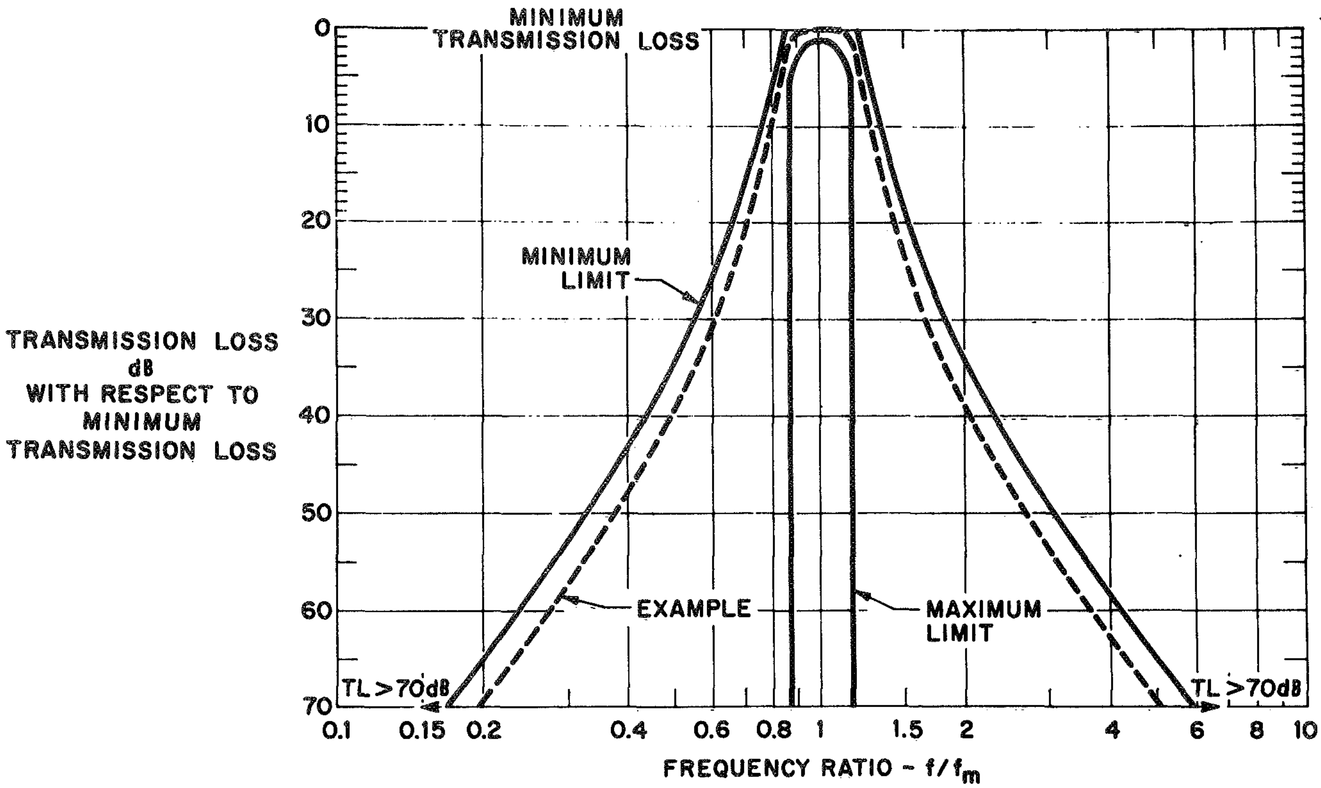


Fig. 4

Transmission Loss Limits — Half-Octave Band Filter, Class III

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

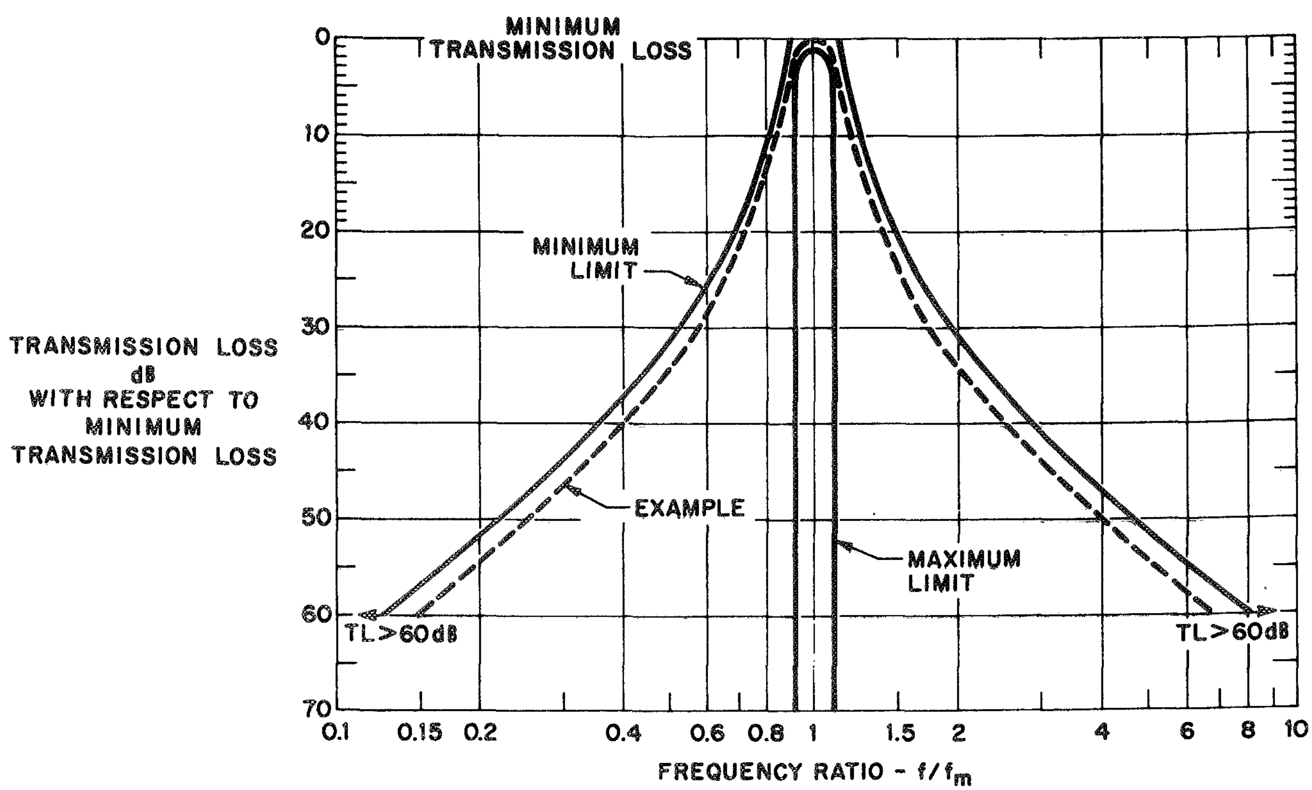


Fig. 5

Transmission Loss Limits — Third-Octave Band Filter, Class II

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

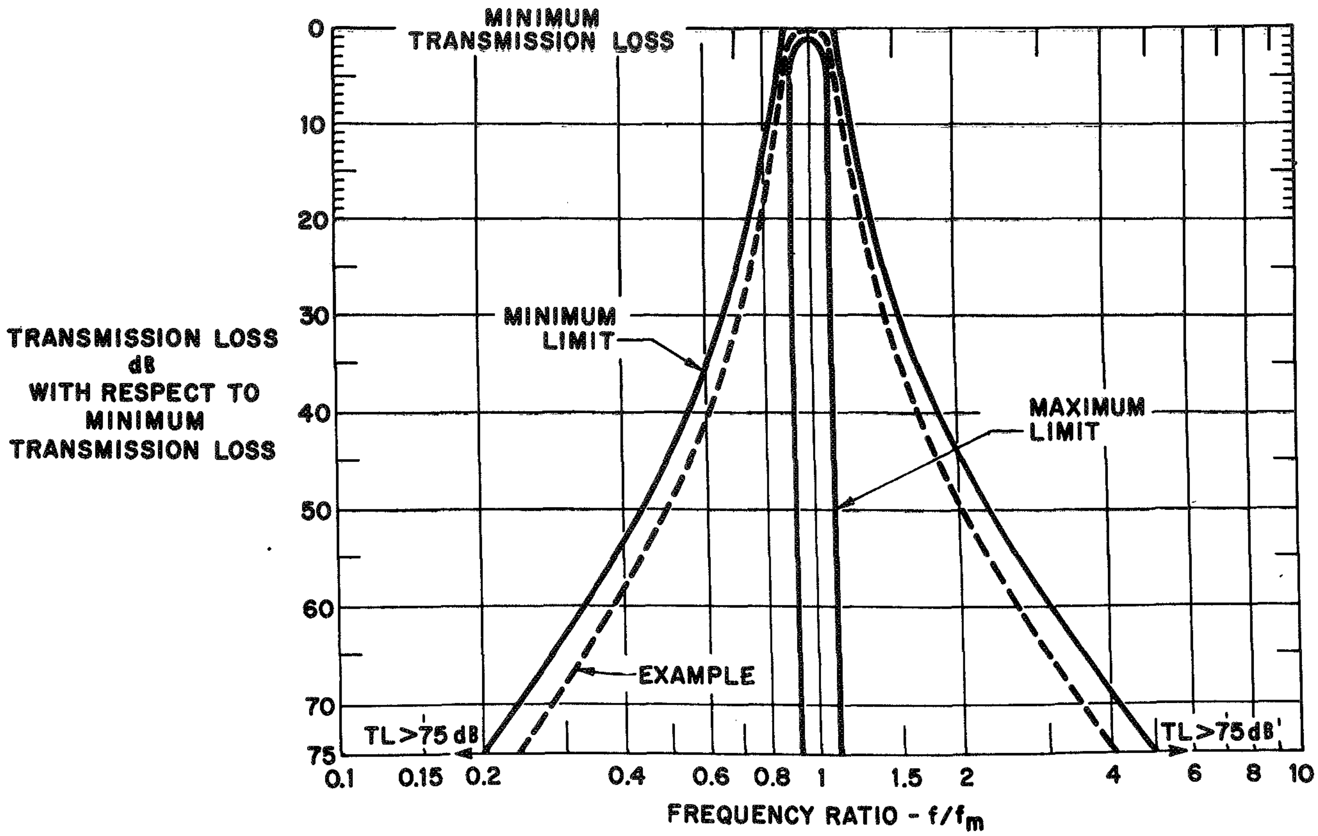


Fig. 6

Transmission Loss Limits — Third-Octave Band Filter, Class III

(Filter Characteristic Must Also Meet Requirements in 3.6 and 3.7)

3.5 Frequency Tolerance on Geometric Mean Frequency. For each band designated on the filter set in accordance with Table 1 of 3.1 or its extension, the geometric mean of the two frequencies where the transmission loss is 6 dB greater than the minimum transmission loss shall not depart by more than the tolerances shown in Table 4 from the designated preferred frequency nominal f_m calculated by the formulas of Table 2.

Table 4
Frequency Tolerances
on Geometric Mean Frequency, f_m

	Octave Bands	Half-Octave Bands	Third-Octave Bands
Tolerance	± 5%	± 3%	± 3%

3.6 Tolerance on Passband Uniformity. The peak-to-valley ripple in the transmission loss characteristic between the upper and lower nominal band-edge frequencies shall not exceed the values given in Table 5 for filters of the indicated bandwidths and classes.

3.7 Effective Bandwidth. For each filter band, the total integrated random white noise power (constant noise power per unit frequency) passed by the filter shall be within ±10 percent of that which would be passed by an ideal filter with flat passband between the nominal band-edge frequencies of 3.3 and infinite attenuation outside the passband. The white noise power passed by such an ideal filter is given by:

$$2^{-1/2} f_m P_m = 0.7071 f_m P_m \text{ for Octave bands}$$

$$(2^{1/4} - 2^{-1/4}) f_m P_m = 0.3483 f_m P_m \text{ for Half-Octave bands}$$

$$(2^{1/6} - 2^{-1/6}) f_m P_m = 0.2316 f_m P_m \text{ for Third-Octave bands}$$

where P_m is the noise power per unit frequency at the filter midband frequency f_m. The minimum transmission loss in the passband shall be used as the reference for calculating the effective bandwidth.

NOTE: See Appendix B for the nominal band-edge frequency transmission loss required to produce zero bandwidth error for Butterworth filters.

Table 5
Tolerance on Passband Uniformity

Filter Band	Filter Class	Maximum Allowable Peak-to-Valley Ripple dB
Octave	all	2
Half-Octave	II	1
	III	0.5
Third-Octave	II	1
	III	0.5