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INSTRUMENTATION FOR ACOUSTICAL EVALUATION OF JET ENGINE TEST CELLS

SAMUEL LABATE

AND

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FOREWORD

This report was prepared by the firm of Bolt, Beranek and Newman, Inc., under Contract No. AF 33(616)-2151, Project No. 7211, 71707, entitled "Development of Special Research Methods and Equipment," for the Wright Air Development Center. Technical supervision was the responsibility of Dr. Henning von Gierke and Lt. Lother O. Hoeft of the Aero Medical Laboratory, Wright Air Development Center, Directorate of Research, Wright-Patterson Air Force Base, Ohio.

ABSTRACT

New instrumentation and techniques have been developed for use in conducting complex acoustical studies of the performance of aircraft engine test cells. The equipment and techniques have been designed expressly to utilize either the turbojet engine as a noise source or a supplementary noise source involving a small cannon firing 10 gauge blank shells.

In addition to portable instruments for on-the-spot analysis of sound pressure and vibration amplitude, twin-channel magnetic tape recorders are employed. Remote switching mechanisms used with this recording system allow noise samples from as many as 50 microphones to be obtained in as little as two minutes of engine running time. These recording techniques also make possible the use of an impulsive noise source, such as the cannon, in the evaluation of the acoustical properties of various components of an engine test facility.

Noise signals, recorded on one channel and annotated on the second channel of the tape recorders, are analyzed in one-third octave bands (or other suitable form) in the laboratory by an automatic data reduction system. This system re-records the original data onto a continuous tape loop, filters the signal from the tape loop into one-third octave bands, integrates the signal, corrects for system response, and plots the absolute sound pressure levels as a function of frequency on graph paper.

Many commercial components of the data-taking and reduction systems, from field microphones to the graphic level recorder, have been modified and new equipment has been designed and constructed where necessary in order to reduce temperature dependence, harmonic distortion and microphonics, improve frequency response and stability, and increase signal-to-noise ratio.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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SECTION I

PURPOSES OF THE TOTAL PROGRAM

The Air Force is currently sponsoring a comprehensive program of investigation involving an evaluation of the noise problems associated with Air Force bases. The overall aims of the entire program are twofold:

1. To determine the overall usefulness of several different types of aircraft engine test facilities from a combined economic, operational and acoustical standpoint; this information is to be used by the Air Force as a basis for planning future aircraft engine test facilities.

2. To accumulate the necessary technical information that will allow the Air Force to plan future air bases with an integrated approach to the overall noise problem on a particular base.

In order to carry out the aims of this program, it was proposed to perform a series of comprehensive acoustical surveys on a number of different types of aircraft engine test facilities and Air Force bases. From time to time it is also planned to undertake field measurements on various components of an aircraft engine test cell in order to accumulate information on the acoustical performance of specific treatments or noise control measures.

The anticipated field measurement program is designed to collect an extensive amount of technical information. Specific information is desired on such items as the following:

1. The noise source characteristics of various types of turbojet engines operating both inside test cells and in free field

2. The characteristics of the sound field inside and outside an aircraft engine test facility.

3. The acoustical effectiveness of particular noise control measures employed in various types of engine test facilities.

4. The acoustical properties of aircraft engine test cell structures such as stack directivity, effects of bends, cell radiation patterns, etc,.

5. The noise source characteristics of aircraft in flight and on the ground.

6. The effect of atmospheric conditions on the propagation of sound over large distances.

7. The sound field on an Air Force base and its environs owing to ground and flight operations.

8. The relation between air-base-generated noise and community reaction to this noise.

The accumulation of data required to achieve the specific aims of the program demanded a thorough review of conventional measuring techniques and measuring equipment. In view of the broad scope of the entire program it became evident that new techniques and equipment would be required in order to fulfill adequately the aims of the program. Many factors entered into the choice of instrumentation to carry out the vast number of anticipated field measurements. Some of the more important factors are listed below:

1. Initially at least nine different groups of aircraft engine test facilities scattered throughout the entire country were planned and surveys of several different types of Air Force bases were contemplated.

2. Engine and aircraft operating time for the purpose of obtaining acoustical data was to be kept to a minimum in order to reduce operating costs.

3. A high degree of accuracy for all field data was required.

4. The overall costs of field surveys and data reduction were to be kept at a minimum.

This report is limited to a detailed discussion of the instrumentation developed by Bolt Beranek and Newman Inc. prior to 1 January 1955 in the performance of the acoustical measurements associated with the test cell survey program under USAF Contract AF 33(616)-2151. Supplementary reports will be issued as additional instrumentation is developed.

SECTION II

SUMMARY OF TYPES OF INSTRUMENTATION SELECTED

From our studies made at the beginning of this program it was concluded that, in general, the most common methods for obtaining acoustical data in the field would be too time consuming and costly. Such methods generally involve a microphone, a sound level meter and an octave band analyzer for obtaining sound pressure level data as a function of frequency. Usually the analyzing equipment is taken into the field and the analysis of the sound is made and logged on data sheets at the time of measurement. These data must subsequently be corrected for system response and must be plotted on graphs for intercomparison.

In order to reduce the engine operating time to a minimum and still obtain large quantities of data, it was decided to gather samples of the noise in and around the test cells, to store them, and to analyze them at some later time. This technique has been used throughout the work on the first phase of this contract. It is made possible because of the availability of precision portable magnetic tape recorders. The principal components of the system are laid out in block diagram form in Fig. 1. The major components taken into the field are calibrated microphones and precision magnetic tape recorders. The desired samples of sound are recorded and stored on the magnetic tape recorder for analysis at a later date. In the laboratory the tape recorders are used to reproduce a signal identical to the signal that was experienced by the microphone at the time the field measurements were made.

To evaluate the acoustical effectiveness of any structure it is necessary to know its acoustical behavior as a function of frequency. In dealing with noise sources it is not only desirable to know the total noise power output but also to know how this energy is distributed in frequency. Therefore, from the beginning, we assumed that the recorded noise taken in the field would need to be analyzed in bands of suitable width.

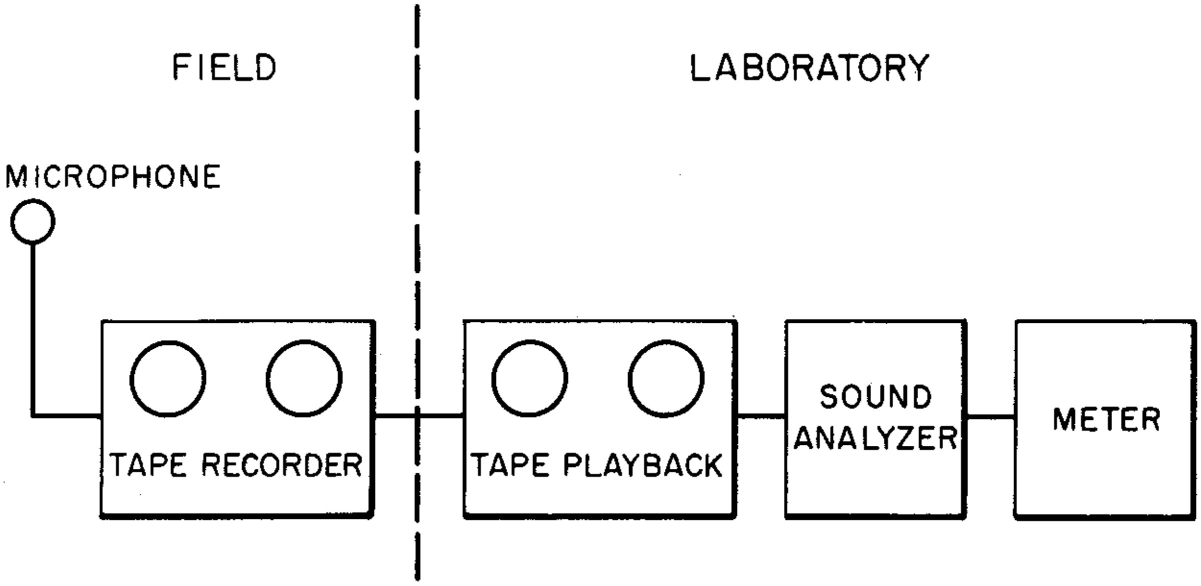


FIG. I SIMPLIFIED BLOCK DIAGRAM OF FIELD RECORDING AND LABORATORY ANALYSIS SYSTEM

To obtain a detailed frequency and amplitude analysis of all measured noise data taken in the field, an automatic data reduction system was developed. The data reduction is automatic in the sense that the results are plotted automatically and the plotted data contain the various corrections for the system response. These corrections include the frequency-calibration of the microphone, the frequency-response of the tape recorder, the frequency-response of the noise analyzer, and so on. A detailed description of this equipment is given in Sec. V.

Some of the primary advantages of using an automatic data reduction system for this program are as follows:

1. Field Survey Time is Reduced: When field data are recorded on magnetic tape for analysis at a later time, only very short samples of the signal are necessary from any given measurement position. In this way a tremendous saving in time can be achieved during field trips. With this equipment available, it is seldom necessary that a recorded sample need be more than ten seconds long. This short sample is played over and over to permit frequency analysis in any desired detail back in the laboratory. With this technique it is not uncommon to take several hundred to a thousand samples of the noise during the day.

2. A Higher Accuracy of Field Data is Obtained: Our experience indicates that higher precision measurements are possible with the use of tape recording techniques in the field and an automatic data reduction system in the laboratory than with conventional field equipment and manual data reduction techniques. The greater precision is in part attributable to improved methods for calibrating the instrumentation and in part because better techniques are incorporated for performing time and space averaging of the measured noise data. A very important advantage is that errors in direct reading of data in the field under stress of excitement are eliminated. Errors made in the laboratory, on the other hand, can be resolved by simply replaying the tape.

3. Use of an Explosive Noise Source is Made Feasible:

   An explosive noise source (a small cannon) was used extensively throughout this program as a means for evaluating the noise reduction through various types of acoustical treatments installed in aircraft engine test facilities. Special techniques are required in the analysis of impulse-types of noises. Here again, it is more expedient to handle these data in the laboratory from magnetic tape recordings made in the field.

4. Field Equipment is Adequately Portable: The field data measuring systems could be designed for reasonable portability.

5. <u>More Detailed Analyses are Possible</u>: In evaluating the acoustical behavior of sound attenuating structures, analysis into octave bands of frequency of the noise transmitted through them does not always give sufficient detail. A more useful analysis is one using one-third octave bands of frequency. However, if analysis into so many bands were to be undertaken directly in the field, the operating time requirements for the engines would be tripled over that required for octave-band analyses. With the automatic data reduction system, analysis into one-third octave bands is feasible since it increases the time in the laboratory only by a minute or so for each measurement position.

SECTION III

SUMMARY OF DATA TAKING PROCEDURES

In Fig. 2 are shown the locations of the microphone measuring positions used in the evaluation of a typical jet-engine test cell. As shown, these microphones are positioned to evaluate the attenuation of the intake stack acoustical structures and to measure the sound pressure distribution in the engine test area of the cell. During normal operation of the jet engine it is not practical to have either personnel or electronic equipment located inside the test cell. With the arrangement shown only microphones and specially built cathode-follower microphone preamplifiers and microphone selector switchboxes are in the cell proper.

The electrical signal from a microphone goes to a magnetic tape recorder which is usually positioned in the test cell control room. The "grids" of microphones indicated by the letters A, B, C, D and E, are often positioned as indicated in Fig. 2. The microphones in each grid are usually connected, through short cables 10 to 25 feet in length, to microphone switchboxes positioned nearby. The output of a microphone switchbox is connected to one channel (channel 1) of the twin-channel magnetic tape recorder located in the control room. The operator of the tape recorder can arbitrarily select the signal from any one of the microphones by remote control. A photograph of a typical control room set-up is shown in Fig. 3. In this figure, the three microphone switchboxes, which are normally located in the test cell, have been set on top of the tape recorders. The switching controls are in their normal position in front of the center tape recorder.

Assume, in this example of a typical test cell, that the intake acoustic treatment consists of parallel baffles located between planes A and B, a tuned duct between planes B and C, and a bend with acoustical treatment covering the end wall of the test cell at the bottom of the intake stack. There is no other acoustical treatment between grids C and E. The five microphones of grid E and the six microphones positioned around the engine are fed through a common control box to channel 1 of recorder X; the microphones on grids A and C are connected to channel 1 on tape

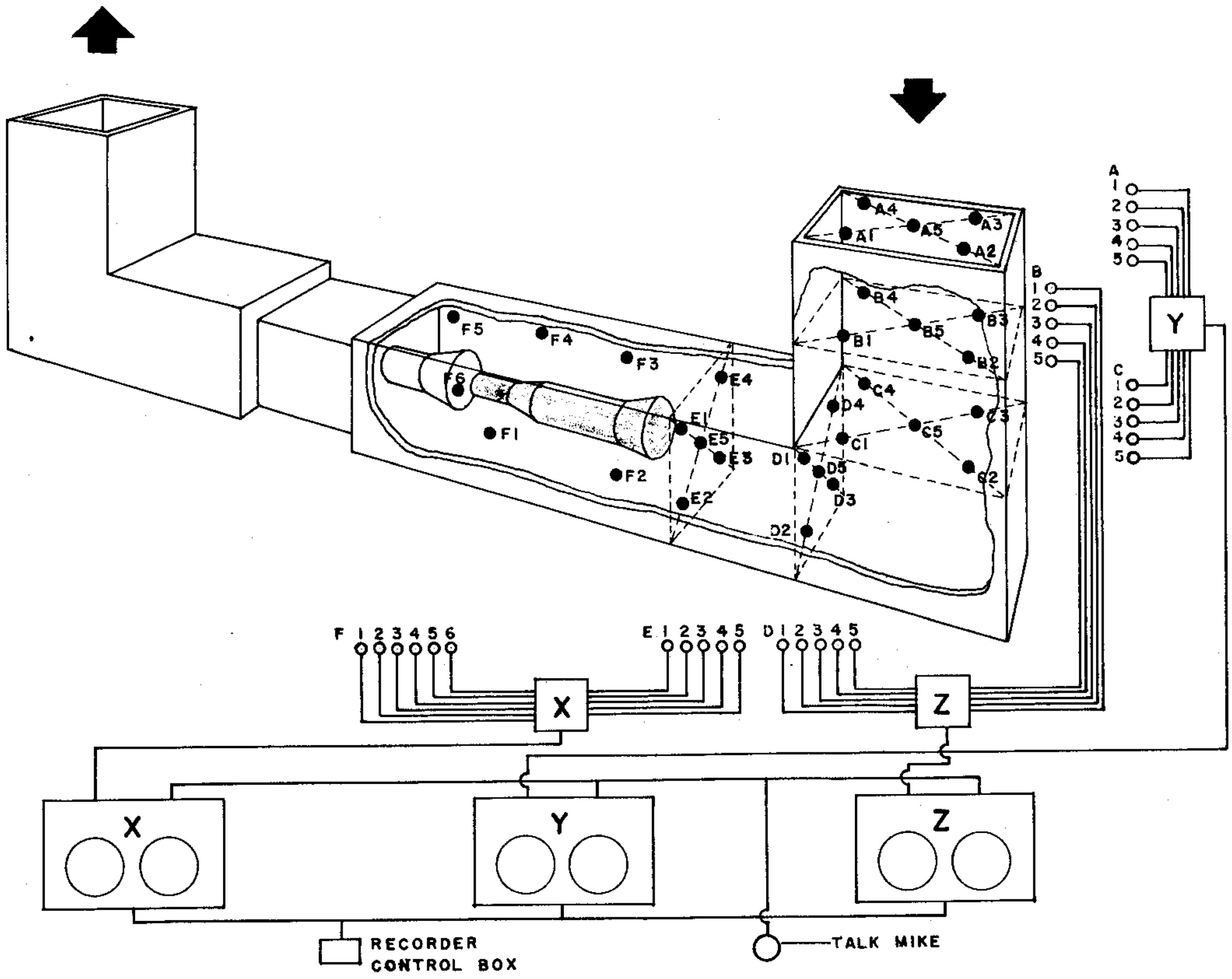


FIG. 2 TYPICAL TURBOJET ENGINE TEST CELL WITH SOME INTERNAL MICROPHONE POSITIONS AND TAPE RECORDER SET-UP

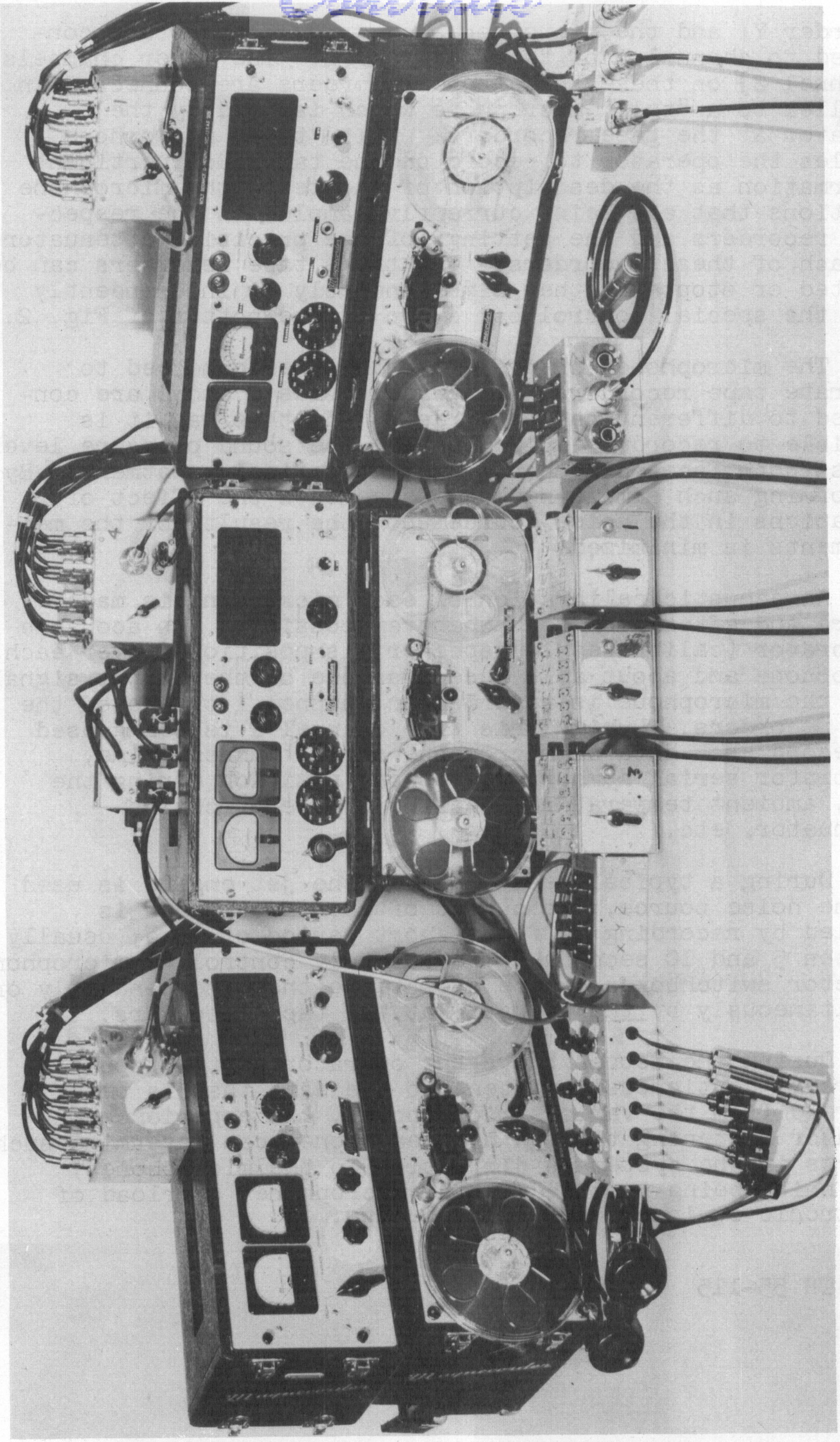


FIG. 3 PHOTOGRAPH OF CONTROL ROOM SET-UP FOR FIELD DATA-TAKING

recorder Y; and the microphones on grids B and D are connected to channel 1 of tape recorder Z. The other channels (channel Z) on these three tape recorders are connected in parallel to a "talk" microphone which is used by the operator at the tape recorders. This "talk" microphone enables the operator to record on the tape such pertinent information as the description of the test, the microphone positions that are being currently sampled on the respective recorders and the settings of the precision attenuators on each of these recorders. The three tape recorders can be started or stopped either simultaneously or independently with the special control box shown at the bottom of Fig. 2.

The microphones on grids A and B are connected to separate tape recorders. Likewise, grids C and D are connected to different tape recorders. In this way it is possible to record, simultaneously, the sound pressure levels across both faces of a particular acoustical treatment. By performing such simultaneous measurements the effect of variations in the noise source upon the results of the measurements is minimized.

An acoustic calibration of each microphone is made before and after each test whenever possible. An acoustic calibrator (calibrated loudspeaker) is positioned over each microphone and about a 10 second sample of the output signal from the microphone is recorded on channel 1 of one of the tape recorders. During this time, channel 2 is being used to record such data as microphone serial number, time, calibrator serial number, microphone position during the test, ambient temperature, setting of the precision attenuator, etc.

During a typical test in which the jet engine is used as the noise source, the output of each microphone is sampled by recording it for a short period of time, usually between 5 and 10 seconds. The remotely controlled microphone selector switchboxes can be operated either independently or simultaneously by the operator at the tape recorders.

During the actual tests the operator at the tape recorders continuously listens to the data that is being recorded from the various microphones. An experienced operator listening through his headphones can determine such defects in the system as distortion in the microphones, wind noise being produced at the microphone, overload of electronic equipment and 60-cycle hum.

Up until this point the discussion has been solely concerned with the study of the intake stack of the test cell. Evaluation of the acoustical treatment in the exhaust of a jet engine test cell under normal engine operating conditions is very difficult. The temperatures and wind velocities in exhaust systems are so high as to make standard measuring techniques impractical. Special high-temperature microphones with wind screens can be used under certain conditions.

In lieu of a better means for evaluating the acoustical treatment in the exhaust section of a jet engine test cell, a technique using an explosive noise source has been developed. This noise source is a very small cannon manufactured by the Winchester Arms Corporation that fires a 10 gauge blank shotgun shell. This explosive noise source produces a pulse similar in acoustic power level and spectral distribution to that of a jet engine operating at military power.

In a typical set-up, the cannon is positioned next to the jet engine inside the test cell. Data recording microphones are then hand-held in various grid positions over the entrance and exits of acoustical treatments in the exhaust. Generally one microphone is positioned in each of three different planes, and the three microphones feed channels 1 of the three separate tape recorders, respectively, during the time of each cannon shot. After each cannon shot the personnel holding the microphones simply move to the next position on their grid to prepare for the next shot. Taking data with the cannon goes exceedingly fast because the three hand-held microphones can be moved rapidly. By contrast, when the jet engine is used, all microphones, cables and switchboxes must be well secured and special precautions must be taken in the intake section of the cell so that small parts are not sucked into the intake of the jet engine.

In all of the measurements made outside the test cell the data recording microphones were held by hand. Not infrequently, the field microphone is several hundred to a thousand feet removed from the tape recorder. Usually the tape recorders remain stationary throughout the entire evaluation of any particular aircraft engine test facility. Two-way communication between the individuals holding microphones and the operator at the tape recorders is essential. The men holding the data recording field microphones wear head phones which are connected to the microphone that is held by the tape recorder operator. This microphone is the same one used to record the comments on channels 2 of the tape recorders. The man in the field speaks to the operator at the tape recorders over his data recording microphone. Head phones are also worn by men holding vibration pick-ups. Two-way communication between the operator at the tape recorders and the individuals holding microphones or vibration pick-ups is necessary so that the latter might be informed of change in engine operating conditions, necessity for repeating a particular measurement, faults in the measuring system, etc.

This completes the summary of the purposes of the total program, the types of instrumentation selected and the data-taking procedures. In the next two sections of this report, the field data-taking systems and the automatic data reduction system will be described in detail. Later sections deal with the calibrations, accuracies, modifications to and limitations of the components of the equipment used in the field and in the laboratory.

SECTION IV

FIELD DATA-TAKING SYSTEMS

This section presents a general discussion on the types of instruments and their accessories used to obtain field data for the work under this contract. More specific information on the behavior of each of these devices is covered in Sec. VII of this report entitled, "Modifications and Limitations of Equipment".

A. Microphones

Three types of general purpose microphones have been used for acoustic measurements in the field. These are:

1. Shure Brothers diaphragm Rochelle salt crystal microphone, Type 9898
2. Shure Brothers diaphragm barium titanate ceramic microphone, Type 98100
3. Altec condenser microphone, type 21BR150.

These microphones are connected to microphone preamplifiers and then to magnetic tape recorders through various lengths of cable. The Shure Brothers 9898 crystal microphone has been the most used microphone. It has satisfactory frequency response through most of the audio spectrum and it is rugged, dependable and inexpensive. It was not uncommon to have twenty to forty of these microphones positioned at various locations throughout an aircraft engine test cell. The barium titanate microphone is used where operating temperatures are likely to exceed 100°F but are below 200°F. The Altec condenser microphone assembly is used under certain circumstances to temperatures as high as 500°F. Photographs of the three types of microphones are shown in Fig. 4. The Altec 21BR150 is fitted into an Altec 150A preamplifier.

Acoustic Calibrator. The type of acoustic calibrator used is a modification of the General Radio Company Type 1552A, 400 cycles per second acoustic calibrator. Accompanying the calibrator is a 400 cps transistor oscillator, General Radio Company Type 1307-A. The calibrator is adjusted to produce a 100 db sound pressure level (re 0.0002 microbars) at 400 cps when it is positioned over one of the three microphones mentioned above. In this way a reference tone of known frequency and sound pressure level is recorded on the magnetic tape in the field. Back in the laboratory, this recorded tone is played back into the automatic data reduction system to establish the sound pressure levels for each graph. Whenever it is practicable, the acoustic calibrator is used before and after each test. A short sample of the 400 cps calibration tone is recorded from each microphone onto the magnetic tape. In this way the gain and stability of all of the components are checked frequently during the field trip. A photograph of the revised calibrator mounted on a transistor oscillator is shown in Fig. 5.

Microphone Preamplifiers. Preamplifiers of the simple cathode-follower type are used with all of the three types of microphones listed above. There are two types required. With the Altec condenser microphone the General Radio Company Type 1551-P1 or the Altec 150A condenser microphone preamplifier is used. The preamplifiers used for the Rochelle salt and ceramic microphones are of our own design. These preamplifiers are small and have self-contained battery power supplies. They are intended for use at the microphones and are required in order to permit the use of long lengths of cable between the microphones and the magnetic tape recorders. Microphone cable lengths of several hundred feet to several thousand feet are not uncommon between the noise measuring microphone and the magnetic tape recorder. See Fig. 6 for a photograph of one of the preamplifiers.

Microphone Switchboxes. Several remotely controlled microphone switchboxes have been constructed for use in aircraft engine test cells during normal engine operation. The switchboxes consist simply of an electrically operated selector switch which can select one of twelve microphone positions. The purpose of the switchboxes is to permit ease in sampling the signal from different microphones and to reduce the number of long microphone cables which need to be run between microphones and the magnetic tape recorders. See Fig. 7 for a photograph of a remotely controlled microphone switch.

FIG. 4 PHOTOGRAPH OF SHURE TYPE 9898, SHURE TYPE 98100 AND ALTEC TYPE 21BR150 MICROPHONES

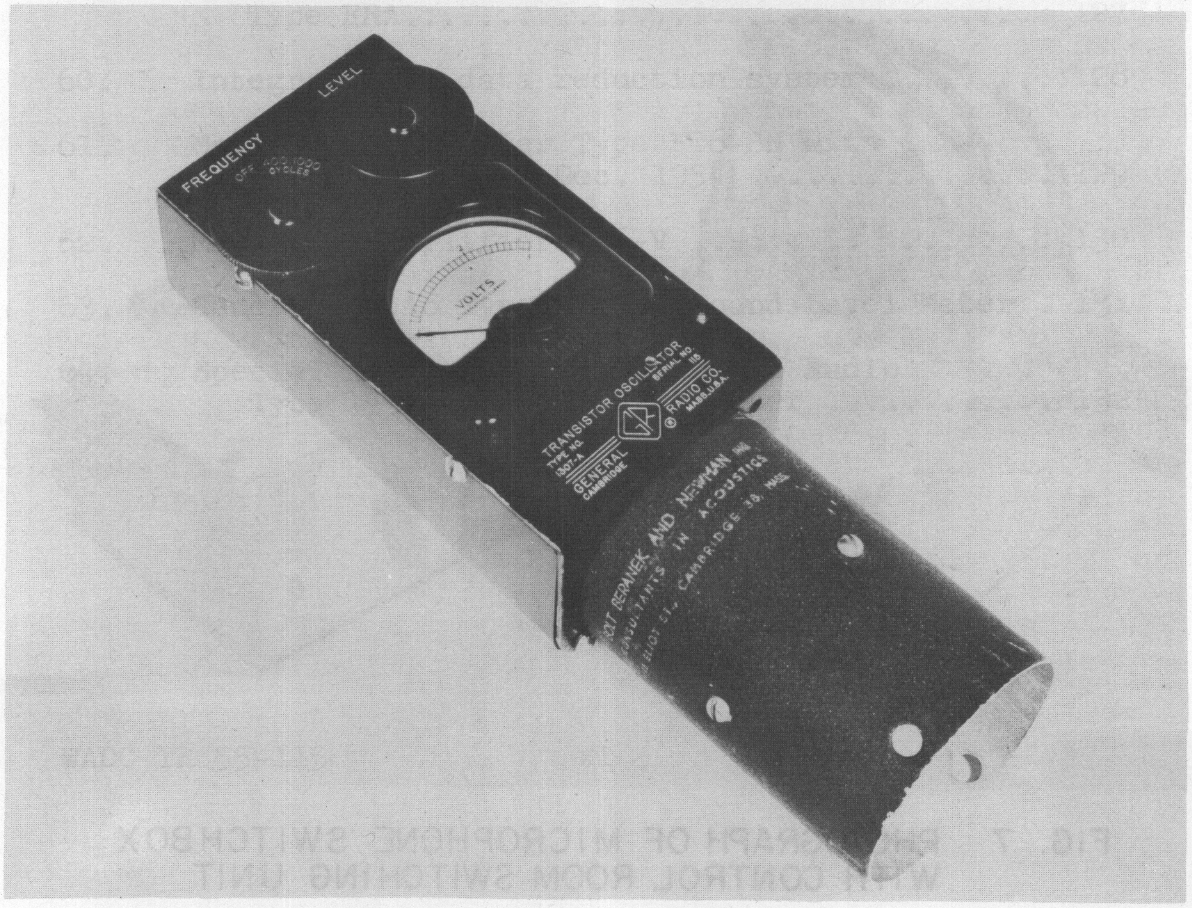


FIG. 5 PHOTOGRAPH OF MICROPHONE CALIBRATOR

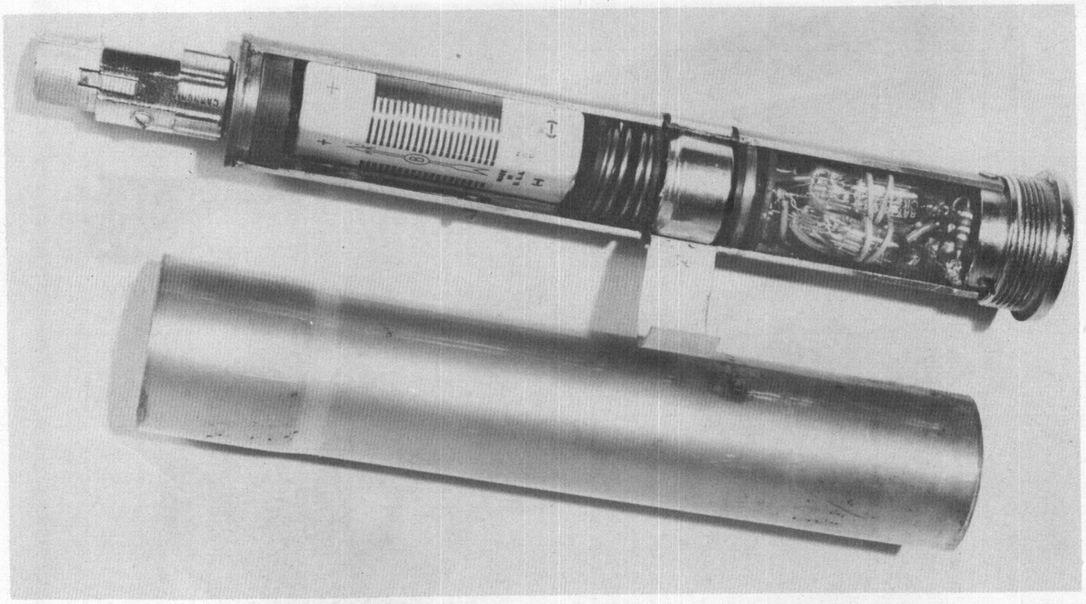


FIG. 6 PHOTOGRAPH OF BBN DRY-CELL OPERATED PREAMPLIFIER

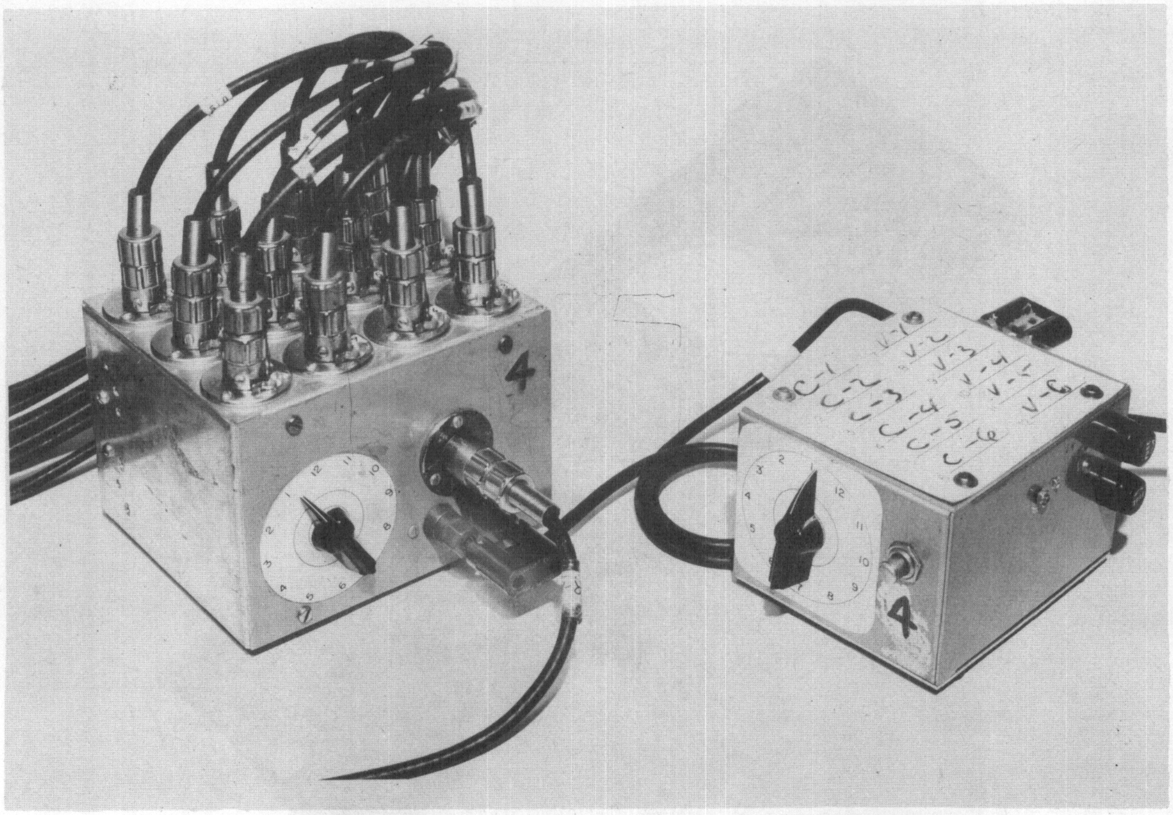


FIG. 7 PHOTOGRAPH OF MICROPHONE SWITCHBOX WITH CONTROL ROOM SWITCHING UNIT

B. Vibration Measuring Devices

In the acoustical evaluation of aircraft engine test cells it is often desirable to correlate the sound level measurements made in the air directly outside of the test cell with a particular radiating surface such as walls of the test cell. By making vibration measurements at various locations on the wall it is sometimes possible to determine what areas or surfaces are the principal contributors to the noise as measured at a distance from the test cell.

Vibration Pick-Ups. The MB Manufacturing Company Type 126 pick-up and the General Radio Company Type 759-P35 pick-up are used for vibration measurements. The General Radio pick-up yields an electrical voltage which is proportional to acceleration while the MB pick-up yields a voltage proportional to velocity. See Fig. 8 for photograph of vibration pick-ups. The electrical output signal of these pick-ups is handled in the same fashion as the microphone signals. Because of the low frequency limitation of the magnetic tape recorders it is not practical to record vibration signals on tape when an analysis is desired for frequencies below 20 cps.

Vibration Meter and Analyzer. Occasionally it is desirable to make vibration and sound pressure measurements in the sub-audible region of the frequency spectrum. To handle such infrequent measurements it is sufficient to use a General Radio vibration analyzer Type 762B. Another useful configuration is to feed the output of the vibration pick-up or microphone directly into (through a proper impedance matching device) a Krohn-Hite low frequency band pass filter Type 330A and use a General Radio vibration meter Type 761A as the indicating instrument. The use of a Krohn-Hite filter gives a much improved signal-to-noise ratio and a wider pass band than does the General Radio vibration meter and filter. The bandwidth of the Krohn-Hite filter is continuously adjustable while the bandwidth of the General Radio vibration analyzer is 2% of the mean frequency. See Fig. 8 for photograph of Krohn-Hite filter. The narrow bandwidth of the General Radio filter makes it tedious to use at low frequencies.

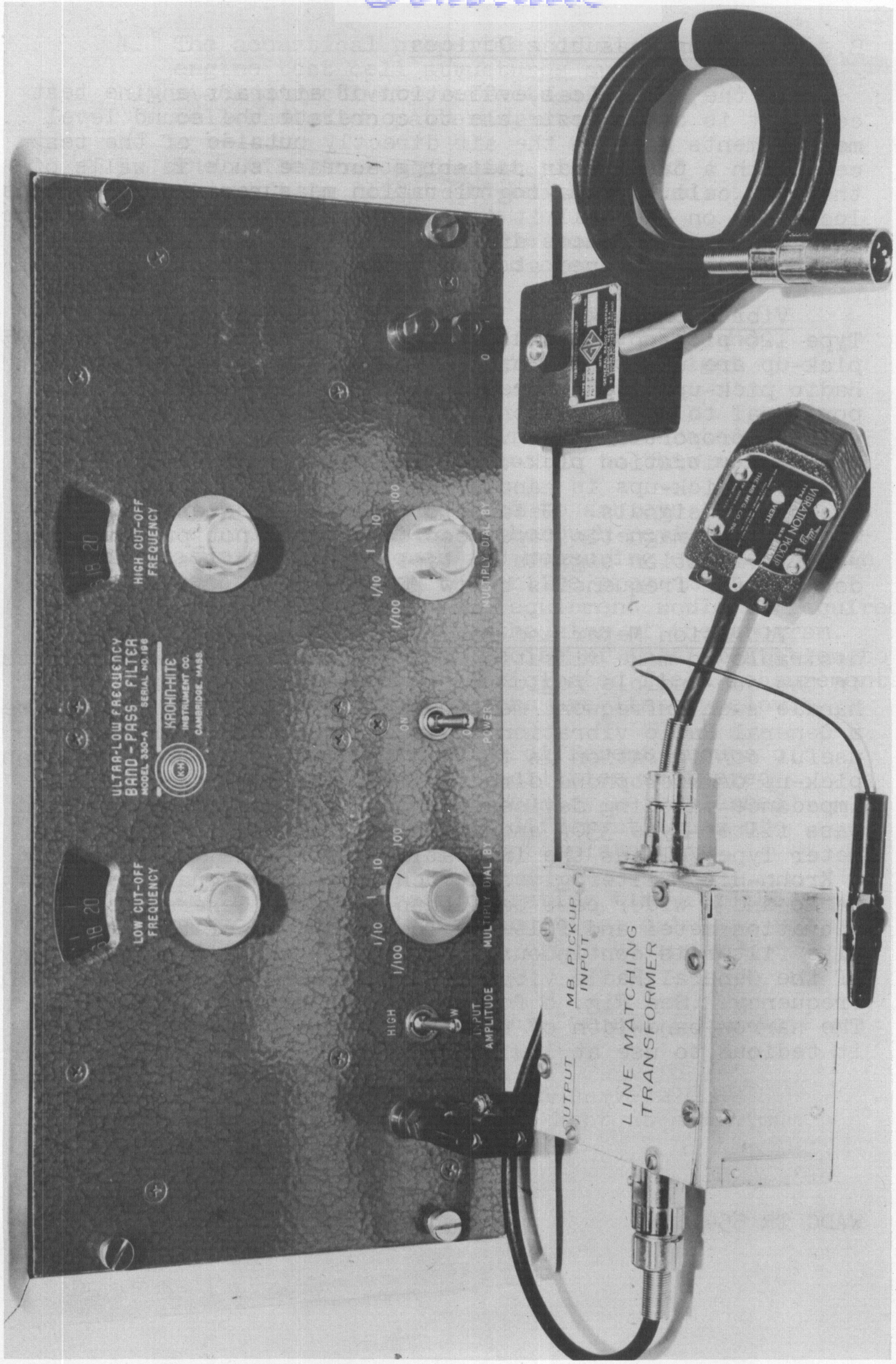


FIG. 8 PHOTOGRAPH OF VIBRATION PICK-UPS AND KROHN-HITE LOW FREQUENCY BAND PASS FILTER

C. Magnetic Tape Recorders.

From the discussions up to this point it is evident that the magnetic tape recorder is the heart of the field data equipment. This makes the accuracy, the dependability, and the flexibility of the magnetic tape recorder of foremost importance. It is necessary that the recorder should meet two additional requirements. First, it must be possible to record more than one channel of data similtaneously and secondly, the instruments must be portable. Of the commercially available tape recorders the type that at this writing seems most nearly to meet the needs of this program is the binaural tape recorder made by the Magnecord Corporation. Even so, extensive modifications have had to be made on these machines. These modifications are discussed in Section VII-J.

D. Sound Level Meter and Octave Band Analyzer

There is one disadvantage in the technique of recording the noise on magnetic tape and making the analyses at a later time. Unless each field trip is carefully planned in advance, and unless each microphone measuring location and all the various test conditions are carefully detailed in advance, there is some danger that the field trip might be completed lacking some specific data required to solve the problem. When one analyzes the data immediately as it is taken, it is possible to plan the next measurement based upon the results of the previous measurement and analysis. Such a procedure is necessary when there has not been an opportunity for the observer to familiarize himself with the problem beforehand.

Because of the complexity of the sound fields associated with aircraft engine test facilities and to overcome the disadvantage just discussed, the use of a sound level meter and octave band analyzer is used as an on-the-spot supplement to the tape recording technique. Octave band analyses taken directly in the field under various conditions assist in obtaining an understanding of the problem.

The sound-level meters and octave-band analyzers used in this program are manufactured by the General Radio Company and are Types 1551-A and 1550-A respectively. See photograph of these instruments in Fig. 9.

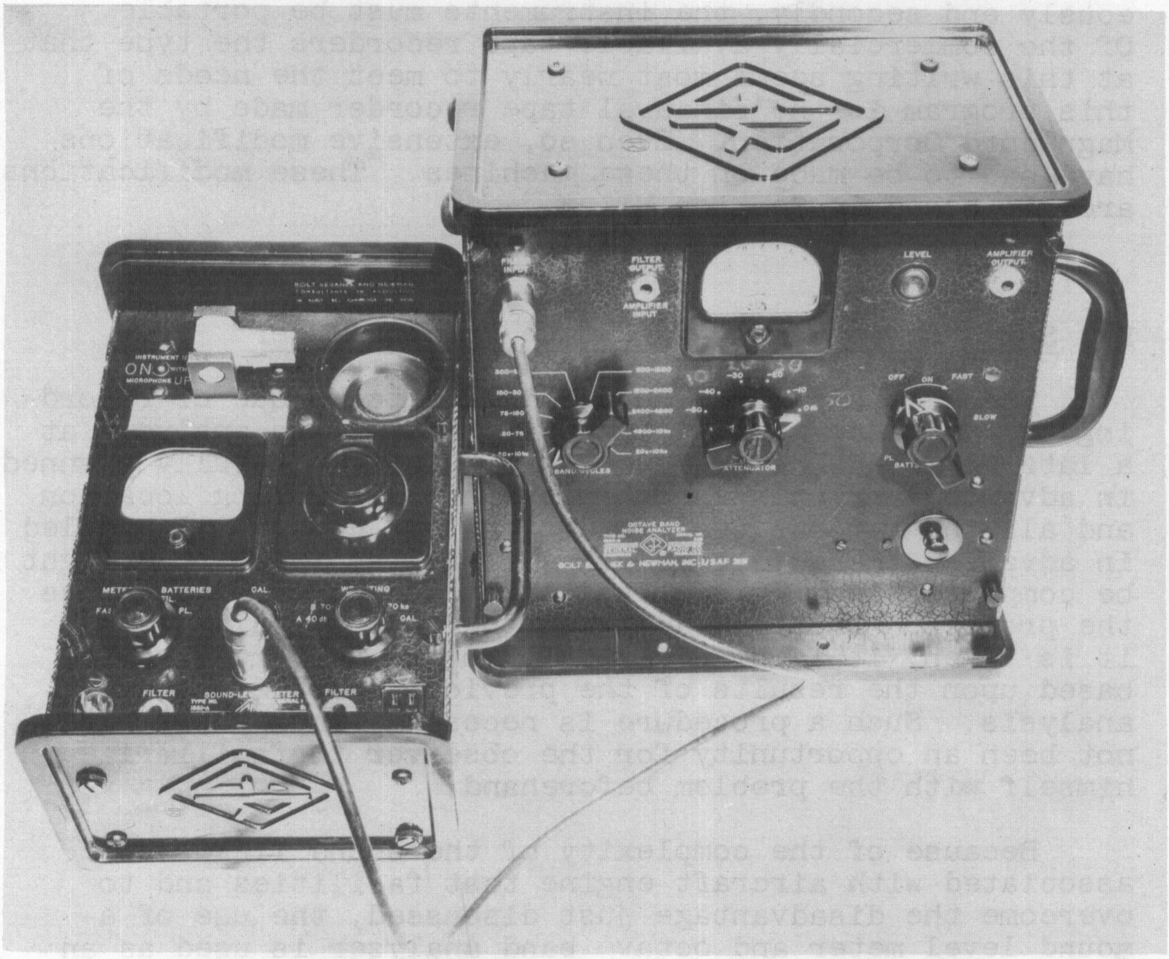


FIGURE 9

Photograph of General Radio Company Sound Level Meter Type 1551A and General Radio Company Octave Band Analyzer Type 1550A.

SECTION V

AUTOMATIC DATA REDUCTION SYSTEM

During a field trip it is essential to have in mind continuously the methods which are to be used for reducing and analyzing the data that is being tape recorded. To lose sight of this objective can prove awkward when one attempts to analyze the magnetic tape in the laboratory. Experience has shown that it requires between two and ten times longer to reduce the data than it does originally to record the data on magnetic tape. The time required is dictated by how detailed and accurate a frequency analysis is desired. Realizing that reducing and presenting the field data for interpretation is often the most costly link between the problem and its solution, a semi-automatic data reduction system has been designed and constructed to reduce the amount of time required to process field data.

A. Components

The noise that was tape recorded in the field is played back in the laboratory into the system outlined schematically in Fig. 10 and shown by the photograph of Fig. 11. The recording from the field is re-recorded onto the loop-storage recorder. This loop-storage recorder contains a continuous magnetic tape loop which is just long enough to accommodate the sample of data to be reduced. After the specimen is on the loop storage recorder, it can be played over and over again continuously for an indefinite time. The advantages of such a loop recorder are apparent. With this device it is possible to analyze conveniently bits of data that are only a few seconds in duration.

The information from the loop recorder is fed through one of three types of frequency analyzers: an octave band filter, a one-third octave band filter, or a very narrow band filter. The work on this contract is concerned primarily with noise from jet engines. Jet-engine noise has a broad band frequency distribution which is suitable for octave band and one-third octave band analysis. Frequently, however, it is desirable to hunt out pure-tone components with the narrow band analyzer.

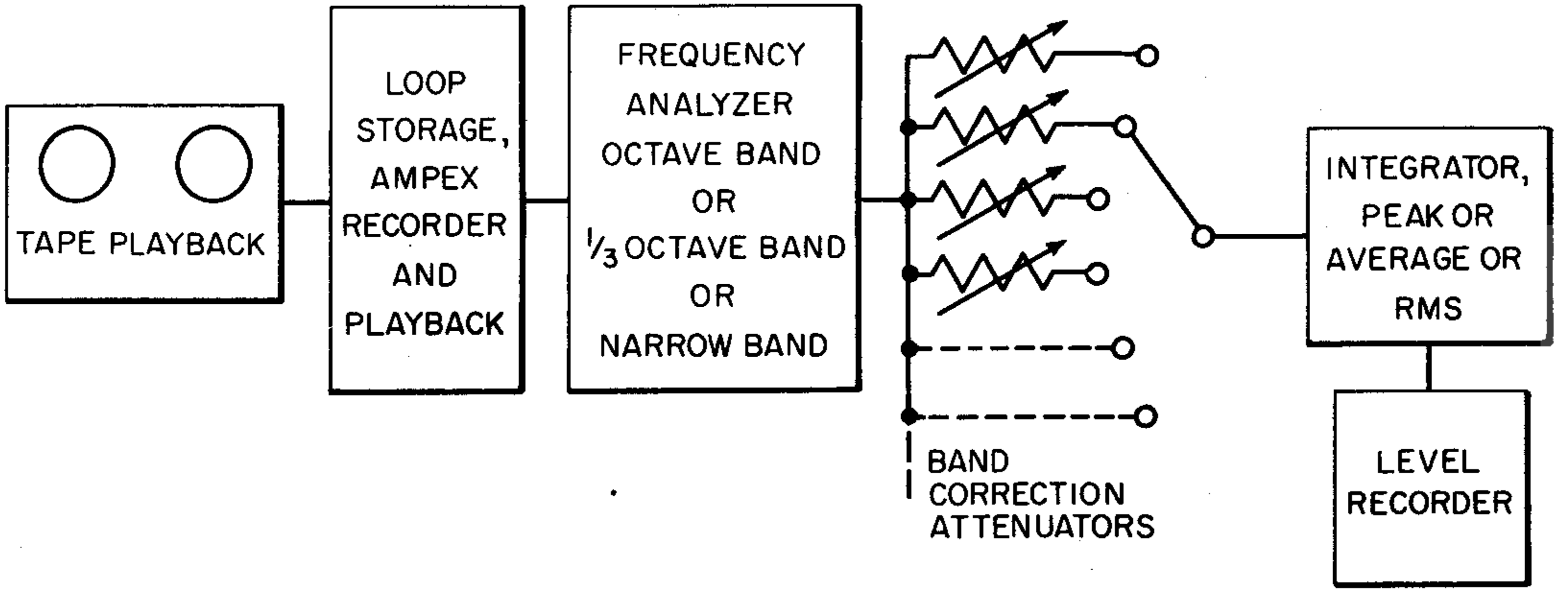


FIG. 10 SCHEMATIC DIAGRAM OF LABORATORY DATA REDUCTION SYSTEM

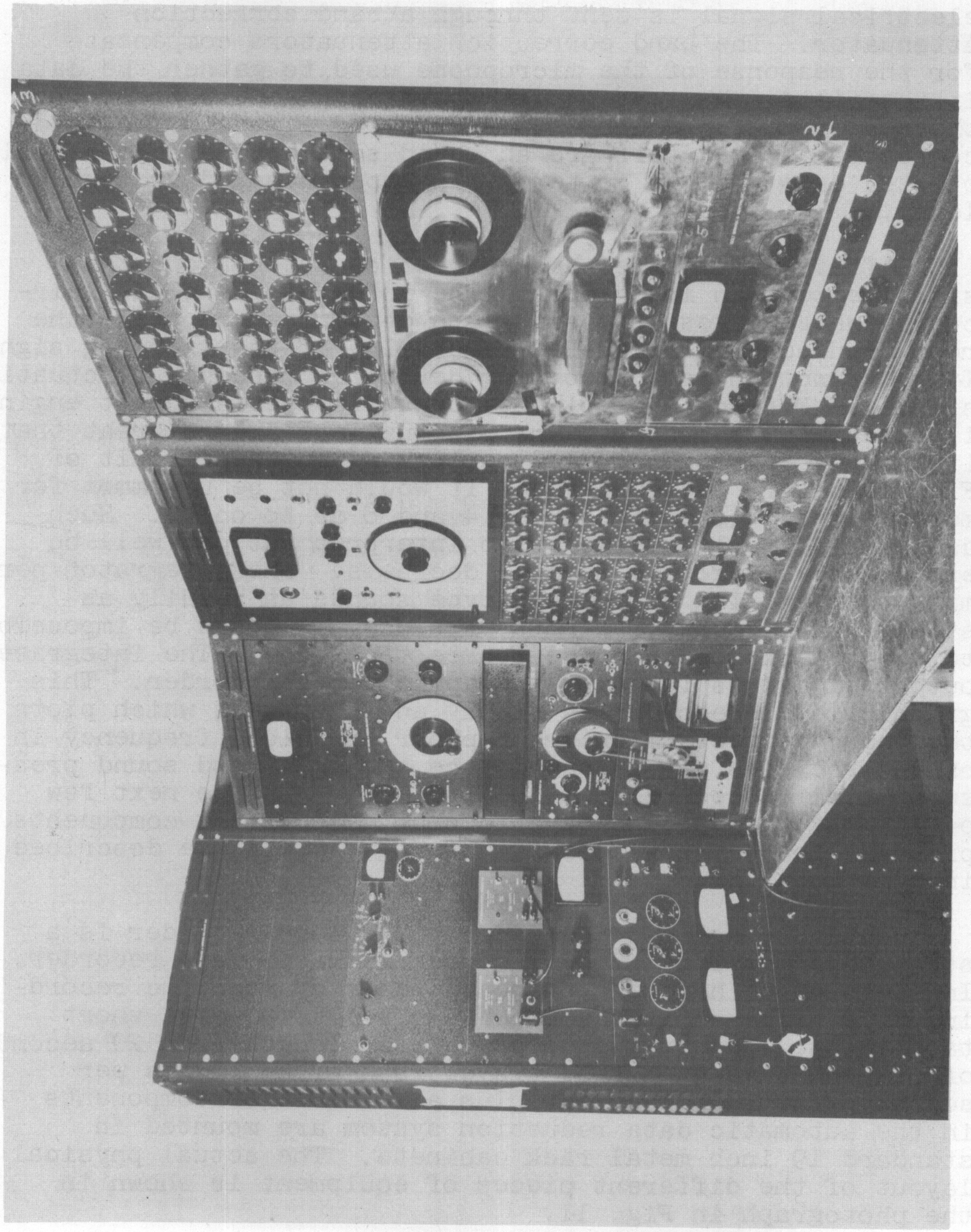


FIG. 11 PHOTOGRAPH OF AUTOMATIC DATA REDUCTION SYSTEM

After leaving each band filter, the reproduced electrical signal is sent through a band correction attenuator. The band correction attenuators compensate for the response of the microphone used to gather the data in the field, the response of the field tape recorders, the response of the loop storage recorder, etc. The band correction attenuators are adjusted so that the automatically-plotted data will be in terms of absolute sound pressure level.

After leaving the band correction attenuators the signal enters an integrator. The integrator includes circuitry which makes it possible to determine the peak, the root-mean-square, or the average value of the incoming signal. It can function as a smoothing device on randomly fluctuating signals. Most of the noise generated by jet aircraft engines is random in character. The fluctuations are so great that if a sound level meter were positioned in the circuit of Fig. 10 before the integrator it would not be uncommon for meter fluctuations of between 4 and 8 db to occur. Such data are not only difficult to interpret but can well be erroneously judged by several decibels. The integrator permits the handling of impulse type sounds as readily as steady state sounds. Without its use, it would be impossible to use the explosive noise source technique. The integrated output signal is fed into a graphic level recorder. This graphic level recorder is simply an instrument which plots the reduced spectrum on graph paper on which frequency in bands or cycles per second is the abscissa, and sound pressure level in decibels is the ordinate. In the next few paragraphs the various functions of each of the components pictured in the block diagram of Fig. 10 will be described in more detail.

Data-Storage Loop Recorder. The loop recorder is a standard Ampex Type 350 full-track magnetic tape recorder. In addition to handling standard reels of magnetic recording tape, the machine has been adapted to receive short tape loops. These tape loops vary in length from 20 seconds of playing time at a tape travel rate of 15 inches per second. The loop recorder plus all the other components in the automatic data reduction system are mounted in standard 19 inch metal rack cabinets. The actual physical layout of the different pieces of equipment is shown in the photograph in Fig. 11.

Band Pass Filters. All of the data recorded in the field on magnetic tape is played back through one or more of three frequency analyzers. The analyzer with the broadest band width is the General Radio octave band analyzer Type 1550-A. The particular octave band analyzer used with the data reduction system has been modified to permit automatic switching. It is not rack mounted and does not appear in Fig. 11. This analyzer divides the audio-spectrum between 20 and 10,000 cps into 8 bands of frequency. The one-third octave band analyzer is used for analyses where greater detail of the frequency spectrum is desired. The basic operation of the one-third octave band analyzer is identical with the octave band analyzer except that there are approximately 24 frequency bands in the audio-spectrum instead of eight. The one-third octave analyzer used in this system is a Bruel and Kjaer Spectrometer Type 2109, sold by the Brush Electronics Company. This compromise between extremely narrow band and broad octave band analyzers has been found very satisfactory and is being used more than either of the other two analyzers.

For special work that requires even greater detail in analysis, a very narrow bandwidth analyzer is used. This analyzer is a General Radio Company Type 736-A. It has a constant frequency bandwidth of 4 cps. Besides the bandwidth, there is one other significant difference among these analyzers. The octave and one-third octave filters have discrete fixed frequency bands whose outputs are sampled individually. On the other hand, the narrow band analyzer has only one filter which is tuned continuously through the audio-spectrum.

Response Correction Attenuators. Each octave and one-third octave filter band has a precision attenuator at its output. These attenuators are each one db per step and by their use it is possible to correct the system response to the nearest 0.5 db. The attenuators are used to compensate for any deviation in the system from a flat frequency response. The band correction attenuators can be seen in the lower center of the photograph of Fig. 11. There are 30 attenuators and each has a maximum range of 18 db.

Noise Integrator. The analyzed signal entering the noise integrator is first amplified then rectified. From this can be selected either (a) the peak value of the rectified signal, (b) the average value of the rectified signal or (c) the average value of the rectified signal squared. One of these three signals is then applied to a conventional Miller integrator having a very long time constant. The signal output of the integrator is fed through an AC chopper to produce an AC output signal equal to the voltage on the charging condenser in the integrator. Three operations take place on the charging condenser in the integrator. In the first phase of the cycle the condenser is charged proportional to the amount of signal which is being fed from the frequency analyzer. At the end of a given time the charged condenser is removed from the integrator circuit and applied to an output circuit. While this previously charged condenser is being "looked at", another condenser is being charged by the integrator from the signal of the next progressively higher frequency band being analyzed. At the conclusion of this time period, the condenser that has been "looked at" is short-circuited and the second condenser is connected to the output circuit. The third condenser moves from the short-circuited position to the integrator to be charged. The positions of these three condensers are continuously advanced one step for each integration time. In this way no time is lost in observing the integrated signal of one frequency band while another frequency band is being integrated. The noise integrator was constructed in our own laboratory.

Graphic Level Presentation of Data. The integrated noise signal is presented on a Sound Apparatus Type FRA Graphic Level Recorder. This level recorder writes with an ink pen on a roll chart having a four-inch wide graph. The ordinate of this graph is perpendicular to the long axis of the chart. The ordinate of this particular equipment is calibrated in decibels and has a range of 5 db, 10 db, or 20 db per inch. The audio frequency is generally plotted along the abscissa. A typical one-third octave band recording is shown in Fig. 12, along with the one-third octave band graph paper specifically designed for use with the record. The ordinate and abscissa have been planned so that the two sheets may be overlayed. By this means data can be rapidly transferred to the final graph.

B. Special Operational Features

A brief discussion of the means for inter-connecting and controlling equipment in the automatic data reduction system can now be presented.

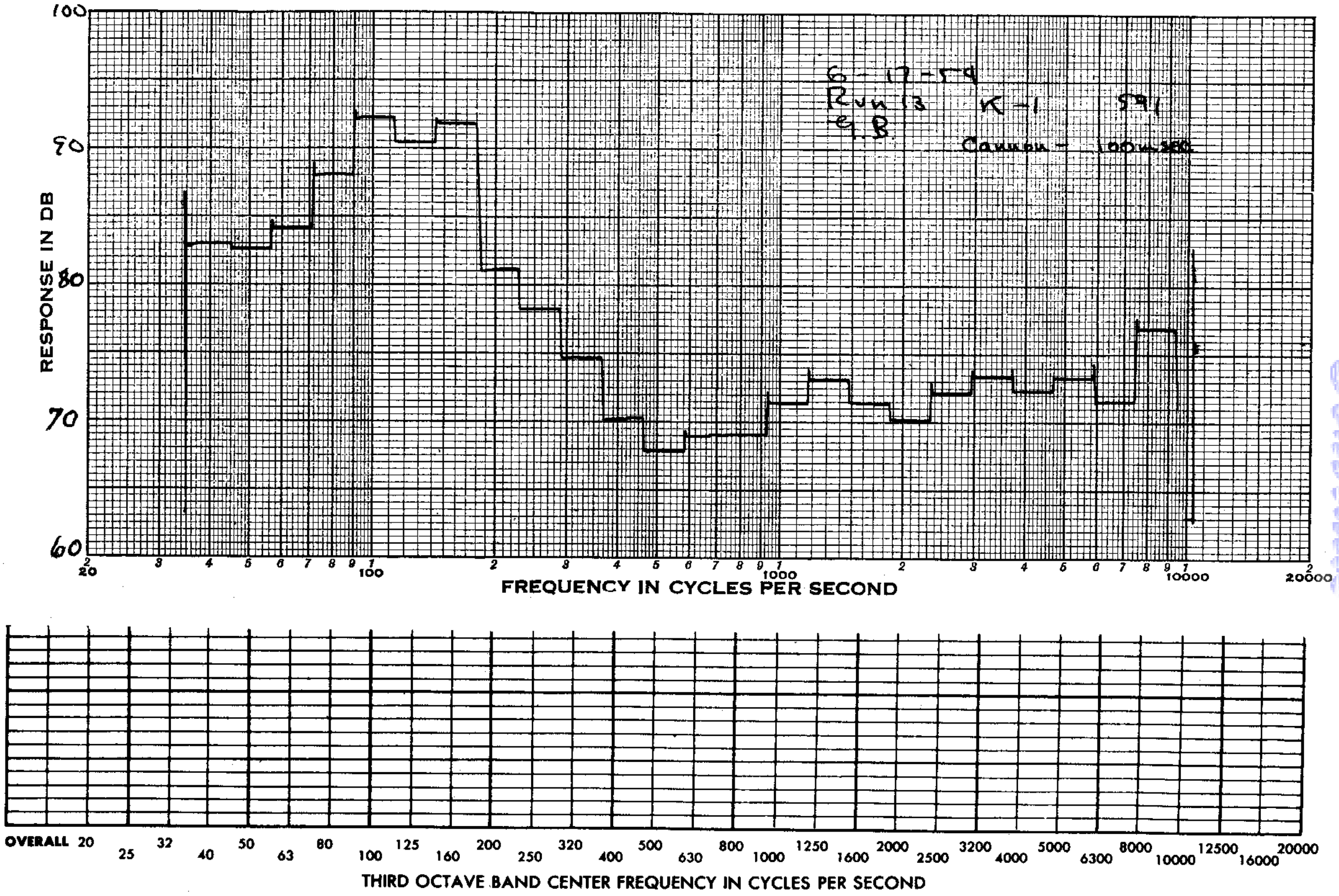


FIG. 12 SAMPLE OF LEVEL RECORDER GRAPH OF SOUND PRESSURE LEVELS IN ONE THIRD OCTAVE BANDS AND SPECIAL ONE THIRD OCTAVE BAND GRAPH PAPER USED IN REPLOTTING DATA

Switch Panel. The switch panel takes the place of the conventional patch panel for the purpose of interconnecting the equipment associated with the automatic data reduction system and the calibration systems. There is an individual switch for the input and one for the output of each piece of equipment. There are 35 of these switches all located together on a front panel. All are identical and are conventional 14-position, single-section switches. All number one positions on the switches are tied in parallel, all number two positions are tied in parallel, all number three positions are in parallel, etc. The wiper arm on each switch is connected to its respective piece of equipment. In this manner the switches may be used as paralleling devices to connect the output of one piece of equipment to the input of another. Of the 14 positions on each switch only 12 of the positions are paralleled with the respective 12 positions on all other switches. One of the two remaining positions is used as a ground and the other as an open circuit. With this paralleling switch panel it is usually unnecessary to use any patch cords between the various pieces of equipment although that possibility is provided for also. The switch panel may be seen at the upper right hand section of Fig. 11.

Automatic Features. The paralleling switch panel just discussed provides flexibility to the hook up of different equipment such as for the acoustic calibration of microphones, the electrical calibration of apparatus, and the reduction of field data. It serves the important function of saving time in changing from one type of set-up to another.

Great savings of time in the reduction of field data are accomplished also through the use of several automatic operating features. Assume that the equipment in the data reduction system is connected as shown earlier in Fig. 10, using the one-third octave band frequency analyzer. The time that is required to reduce a specific sample of data is determined by the length of the magnetic tape on the loop recorder. In general, loop lengths of from 2 to 20 seconds are used. The character of the recorded noise determines the choice of loop length. This tape loop is made by splicing together the two ends of a short piece of standard magnetic recording tape. At the time the splice is made, a small bit of silver paint is applied to the back side of the splice. After being threaded into the recorder the loop is ready for use. With each complete round-trip of the tape loop the silver paint on the back of the tape splice closes an electrical contact. The closing of this contact performs the following functions simultaneously. The one-third octave filter steps ahead to the next filter band, the band correction attenuator switches to the next filter band, a capacitor in the integrator is switched from the charge circuit to the sensing circuit, the chart of the graphic level recorder is pulled through a distance of one-third octave frequency while the pen writes the output voltage received from the integrator sensing circuit. Each time the loop on the storage recorder makes one complete revolution the analysis of a different frequency band is performed and presented graphically. After the loop has gone around a sufficient number of times to complete the analysis in all the frequency bands the information on the loop is erased and a new sample is re-recorded onto the loop from the field-data tape recorder. A caution that must be exercised is to make certain that each piece of electronic equipment is operating in its optimum dynamic range so that the data presented are not in error due to equipment overload. The same automatic band stepping procedure may be used when making an octave band analysis as in making a one-third octave band analysis.

A different approach is required for making a narrow band analysis using a General Radio Type 736A narrow band analyzer. For this operation the loop-recorder is run continuously without any switching activities while the narrow band analyzer sweeps very slowly through the audio spectrum. The frequency dial of the narrow band analyzer is chain driven by the graphic level recorder. The gearing is designed to keep the frequency in the band pass of the narrow band analyzer in step with the printed frequency chart coming from the graphic level recorder. The band correction attenuators, of course, cannot be used in connection with the narrow band analyzer. The integrator, if it is used at all, serves a different purpose; namely, by monitoring the voltage fluctuations in the integrating condenser it acts as a smoothing or damping device.

Photoelectric-Cell Trip Circuit on Loop Recorder. A photo-cell trip circuit was built to aid in transferring short specimens of data from the field-data tape recorder to the loop-storage recorder. A miniature photoelectric cell is positioned on the field-data tape recorder to "look" at the back of the recorded tape. By applying wax crayon or other marker on the back of the magnetic tape on the field-data tape recorder at the beginning and end of the specific short sample the photoelectric cell can be used to start and stop the loop storage recorder and re-record only the information that lies between the two crayon marks. This feature was designed specifically for "picking" off cannon shots and re-recording them onto the loop storage recorder.

The particular field data that is to be re-recorded is first selected by listening to the play-back of the magnetic tape recorded in the field and then edited by making crayon marks on the back of the field data tape. Although the photo-cell trip circuit is used primarily with cannon shots, it is also useful when several samples of engine data are required on one tape loop. Space averaging of the electrical signals from the different microphones positioned in a grid over the face of an acoustical treatment in a test cell (like that shown in Fig. 2) is a good example. The microphones in Fig. 2 were positioned so that each microphone covered approximately the same cross-sectional area. Space averaging over the grid requires averaging the electrical signals from each microphone in proportion to the area that it represents. Equal recorded samples (from two to four seconds) are selected from each microphone and are re-recorded onto the loop storage recorder. This data is then reduced automatically in the regular fashion with the electrical averaging of the five microphone positions being done in the integrator.

Integrator Blanking Circuit. Oftentimes it is difficult to reduce recorded cannon shots because of high background noise present at the time the recordings were made. This is particularly true when the cannon is fired inside of an aircraft engine test cell and magnetic tape recordings of this shot are being made outside the test cell with other noise sources operating in the vicinity. It is essential that the cannon shot sound level be substantially above the background noise level. It is possible to maintain a good signal-to-noise ratio by analyzing the first 150 milliseconds of the cannon noise. The background noise can be eliminated by a blanking circuit. The blanking, or gating circuit actually operates by shorting out the signal input to the integrator. In this way the integrating circuit can be closed to all extraneous noises until such time as the wanted signal comes through. The gating-circuit is triggered by the cannon shot signal on the loop. In addition to this gating-circuit there is another blanking circuit on the charging condenser in the integrator. This circuit keeps the integrator shorted during the period when the three capacitors in the integrator are shifting position, the frequency bands are being switched and until the splice on the loop has passed by the record and reproduce heads. This eliminates all extraneous switch and splice pops from entering the integrator.

C. Procedure for Obtaining Complete System Calibration

The system-response correction attenuators were described earlier in this report. The reduced field data presented by the graphic level recorder will be in terms of absolute sound pressure level in all frequency bands if these attenuators have been properly set. It requires between ten and fifteen minutes to obtain the complete frequency response of the electrical system including all links that make up the system from the field-data microphone through to the graphic level recorder which presents the reduced data. The system calibration is the first step taken before reducing any recorded field data.

The field-data tape recorder is set up on the bench next to the automatic data reduction system and is hooked up as shown by the block diagram in Fig. 10. A sweep frequency tone is recorded onto a blank section of magnetic tape on the field data tape recorder. This sweep tone comes from a General Radio Type 1304A beat frequency oscillator which generates a pure tone of constant amplitude between 20 and 20,000 cps and has a log-frequency tuning dial. The oscillator tuning dial is motor-driven to sweep between 20 cps to 20,000 cps in approximately 10 seconds. This constant amplitude sweep signal is recorded on the field-data tape recorder at a nominal level. If any spectrum shaping networks or other special networks were used on the field trip in the microphone line between the microphone and the tape recorder these units are again inserted between the sweep oscillator and the tape recorder. After this short sweep tone has been recorded on the field data tape recorder it is "analyzed" in the same fashion that the microphone data is handled.

The loop on the loop storage recorder must be long enough to accommodate the entire sweep. The band correction attenuators are all set at zero. Each time the loop goes around once the tone sweeps through a different filter band. The integrator output of each filter band is plotted by the graphic level recorder. The sweep tone has a logarithmic frequency response (i.e., the rate of sweep in cps per second is increased with increasing frequency) and the octave and one-third octave band filters are of constant-percentage bandwidth. Therefore, the sweep tone is present in the frequency pass band of each filter for the same length of time.

The frequency band spectrum that comes from the graphic level recorder is the relative frequency response of the entire system excluding the acoustic response of the microphone. To add this correction, it is necessary to know the exact position of the field-data microphone at the time the magnetic recording was made. Knowing the position it is possible to say whether the sound impinged on the diaphragm at random, grazing, or normal incidence. The response for the correct angle of incidence of the microphone is then added to the electrical system response that has just been measured. These combined correction numbers are then set up on the band correction attenuators for the respective frequency bands. After this has been done the automatic data reduction system yields graphs as though the entire system had a flat frequency response.

D. Procedure for Establishing Absolute Sound Pressure Level

Now that the entire system has been compensated to a flat frequency response it is only necessary to establish the absolute sound pressure level at a reference frequency. The acoustic calibrators described earlier in Sec. IV-A are used for this purpose. These small 400 cps pure tone sound sources produce an absolute sound pressure level at the microphone of 100 db when they are properly positioned over the microphone. Samples of this 400 cps calibration are frequently recorded for each microphone on the field data tape recorder. These calibration tones are then sent through the data reduction system as any other sample of data. The frequency analyzer is set to the 400 cycle band and the position of the ink line drawn on the graphic level recorder represents a sound pressure level of 100 db re 0.0002 microbars.

It is important to remember that the sample of the calibration tone transferred to the tape loop and integrated must be exactly the same length in time as the sample of data that is analyzed through the integrator. If the two are not exactly the same length in time their relationship must be known so that a correction factor can be applied to the decibel scale on the data coming from the graphic level recorder. If a sample of recorded field data is integrated for a period twice as long as the calibration tone associated with this recording system the reduced data will come out 6 db too high.

For the work performed under this contract, it is not necessary that the absolute level of the data from the automatic data reduction system be known when the cannon is used. We could, if we wished, determine the absolute peak, the root-mean-square, or the average of the impulse. Usually it is important only that the cannon-shot data be relative to a common base. The calibration tone is recorded for a time equal to the duration of the cannon shot, i.e., 150 milliseconds. When space averaging is desired for a plane containing, say, five microphones in an engine test cell, five cannon shot records are dubbed onto one tape loop and reduced. For this case a 750 millisecond sample of the 100 db calibration tone from the data recording microphone is used for calibrating the system.

With the use of the acoustic calibrator it is not necessary to know the absolute sensitivity of the microphones or the voltage gains of any of the amplifiers associated with the data taking system or the automatic data reduction system. A very distinct advantage of the calibration-tone method is that one can detect changes in microphone sensitivity. Another advantage is that the entire system is calibrated at one time so that the frequency response is known within a narrow tolerance. Suppose that the system has ten different individual components such as tape recorders, amplifiers, analyzers, etc. If the frequency response of each of these ten components is measured individually the response of each component would be obtained to a tolerance of, say ± 0.5 db. Knowing the response of each instrument it is now necessary to add all ten or these responses together to get the response of the entire system. The maximum error could be ten units times 0.5 db per unit or a total of 5 db. However, with the one calibration technique the error can be made the same as for a single component, i.e., say 0.5 db.

In the establishment of the absolute sound pressure level of the data reduction system, there are many attenuators for balancing gain levels in various portions of the system whose settings must be observed. Every major component in the data reduction system has one or two precision attenuators connected with it. All of these are step attenuators having various values of attenuation per step (0.5, 1, 5, 10, and 20 db per step). Usually it is not necessary to change more than one attenuator after the analysis of a given set of data is under way. To reduce recorded field data from several different microphones such as those positioned in a grid across the face of the test cell, it is necessary to vary the amplitude of the signal coming out of the field data recorder with an attenuator that can increase or decrease the signal in 0.5 db steps.

As previously mentioned, microphone calibration in the field is obtained only for the frequency of 400 cps. The Rochelle-salt crystal microphones used in this work have a relatively flat response between 20 and 1,000 cps. At frequencies above 1,000 cps these microphones no longer have a flat response. It is therefore necessary to provide special equipment for determining the exact acoustical response at these higher frequencies. Such calibration facilities are described in the next section.

SECTION VI

CALIBRATION FACILITIES

A major portion of the facilities for both the acoustical and electrical calibration of various apparatus is an integral part of the automatic data reduction system. Methods for obtaining calibration of different apparatus is not unlike some of the techniques used for the automatic reduction of field data.

A. Acoustical Calibration of Microphones

The techniques for measuring the frequency response of electronic equipment by electrical methods in the audio range are straightforward and well known. However, there are generally many subtle difficulties encountered in the calibration of microphones. In this work the "free-field" method of microphone calibration has been used. Two other common techniques may be used for the calibration of microphones, the "random-field" and the closed-coupler techniques. "Random-field" calibrations are performed in diffused reverberant sound fields. The frequency spectrum of the reverberant sound in the room is measured at a particular position with a standard microphone whose frequency characteristics are known. The standard microphone is then removed and the microphone whose response is desired is positioned at the same place. By comparing the frequency spectrum measured by the standard microphone with that measured by the uncalibrated microphone it is possible to arrive at a calibration for the latter. In the closed-coupler method of calibration the measurements are carried out in a small airtight cavity. This method of calibration is capable of producing results of highest accuracy for the calibration of pressure sensitive devices.

The high frequency response of a microphone calibrated in a closed coupler will not be the same as when it is calibrated in open space, because of diffraction effects. Furthermore, the closed-coupler technique does not lend itself well to the calibration of microphones having diaphragms with low mechanical impedance. The calibration of microphones in a diffuse sound field is the easiest technique and is used where diffuse sound fields are to be measured and where high accuracy is not of primary importance. However, in many instances, knowing only the random-incidence response of a microphone is not sufficient.

Most of the shortcomings encountered in the two methods discussed above are of less importance in the free-field method of microphone calibration. In practice, free-field calibrations are usually carried out in anechoic chambers. Ideally, a microphone is positioned in front of a sound source which emits only plane or spherical waves. Ideally, the waves that strike the walls of the room are completely absorbed thus permitting no echoes or reflections in the room. However, an anechoic chamber that meets this requirement over the entire audio spectrum between 20 and 20,000 cps is exceedingly large and costly. To combat these two factors, two test chambers have been constructed, one for low frequency measurements and the other for high frequency measurements, thereby greatly reducing the requirements to be set by a single chamber.

Calibration at Low Frequencies. The calibration of microphones at low frequencies is carried out in the duct shown in Fig. 13. This duct is approximately 28 ft long and has a square cross-section measuring 12 in. on a side. A 12 in. loud speaker is mounted at one end of the duct with the anechoic chamber as its backing. An 8 ft long acoustical terminating wedge is positioned at the opposite end of the duct. The sides of the duct are of rigid double-wall construction consisting of 3/4 in. plywood with the entire space between the two walls filled with sand. The heavy construction and sand filled walls are used to prevent unwanted resonances in the side walls of the duct. Even with such precautions resonance problems are encountered.

The test duct has access hatches located every 4 ft along its length. Each of these hatches has been carefully detailed with double hollow rubber gasketing and is hinged and locked securely in place.

The low frequency duct is used for the comparison calibration of microphones for frequencies below 550 cps. The microphone under test is normally located in the duct 10 ft from the loudspeaker. Because the duct is 1 ft sq on the inside, the first transverse resonance in the duct appears at approximately 550 cps at room temperature.

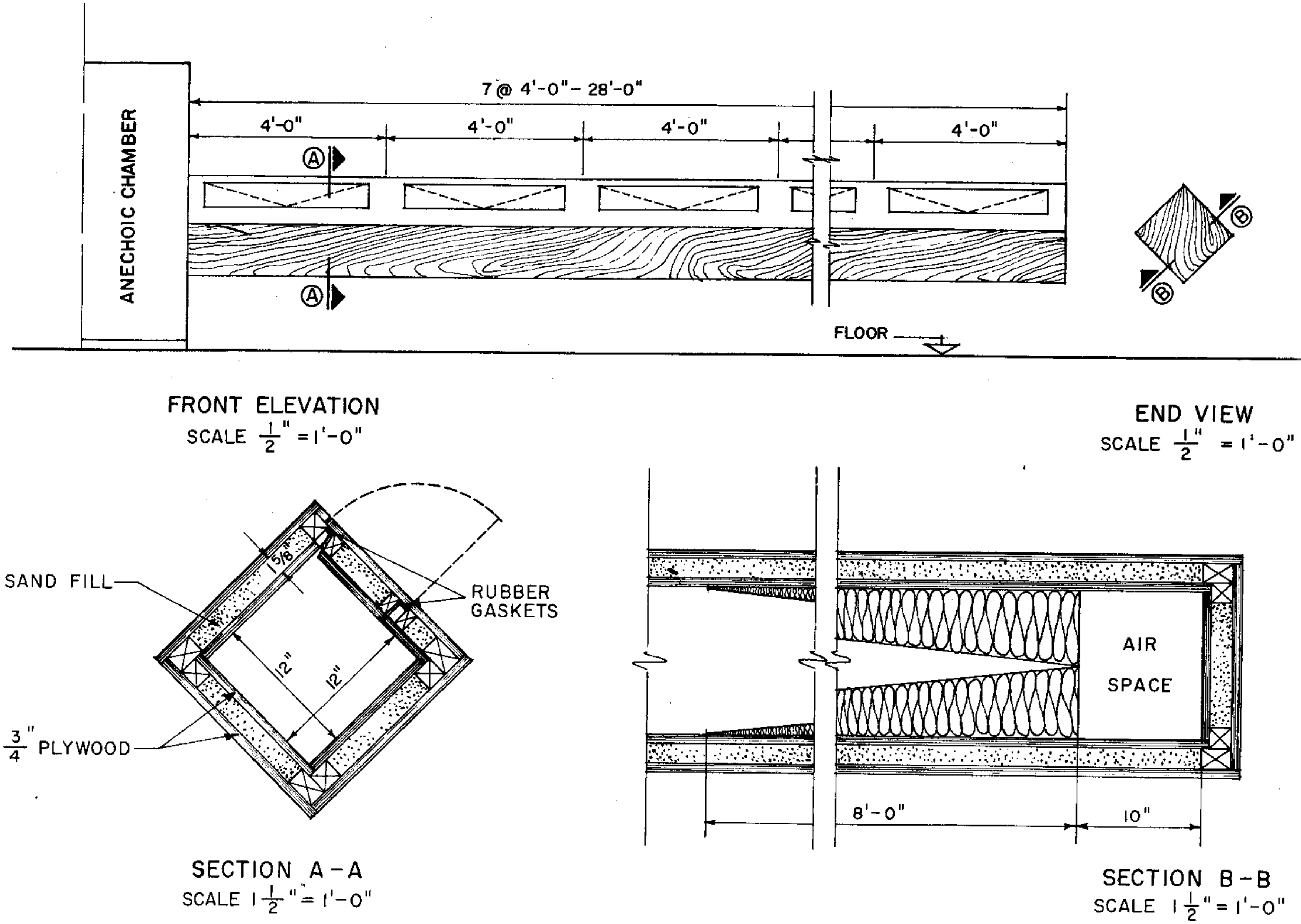


FIG. 13 LOW FREQUENCY DUCT DETAILS

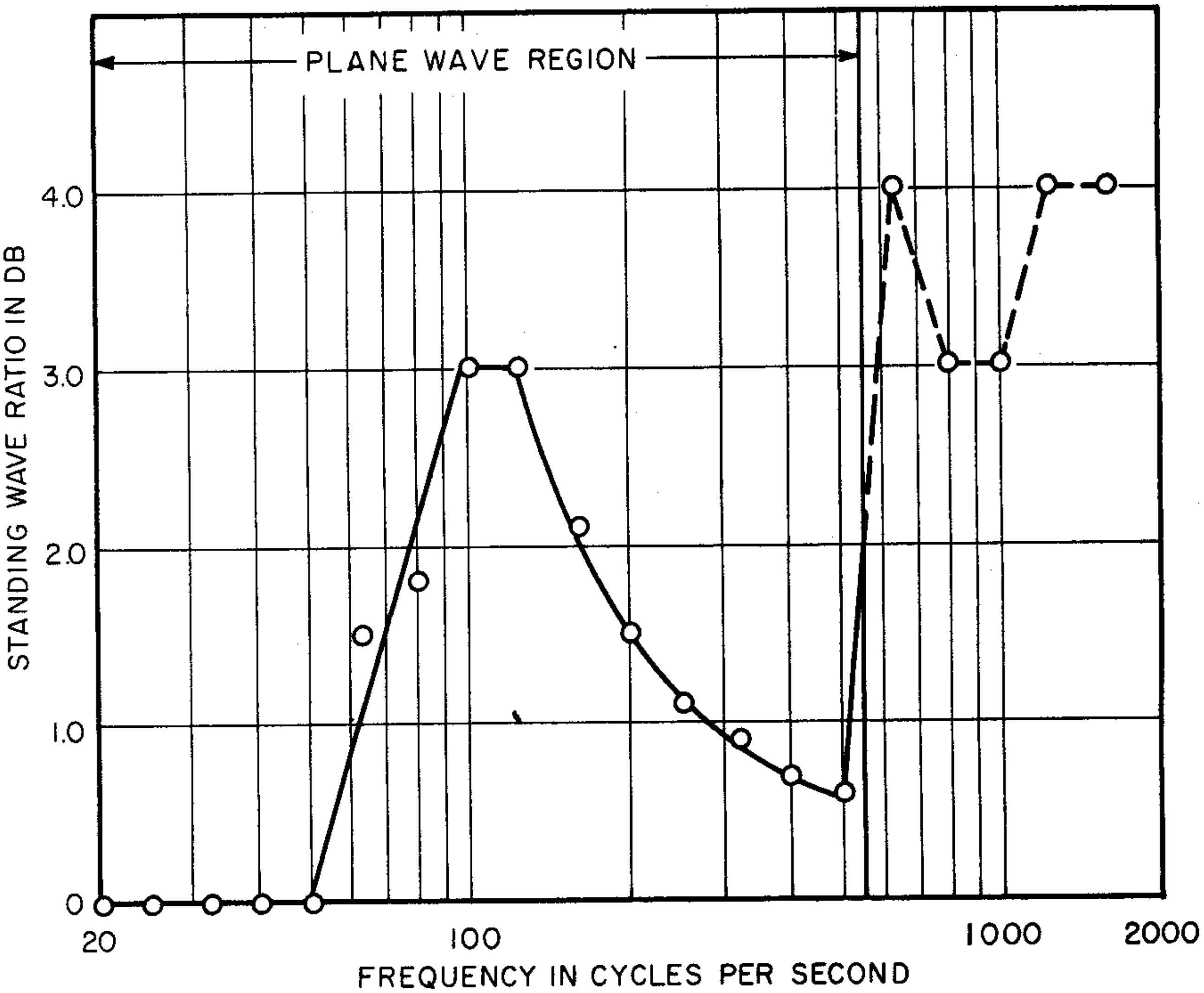
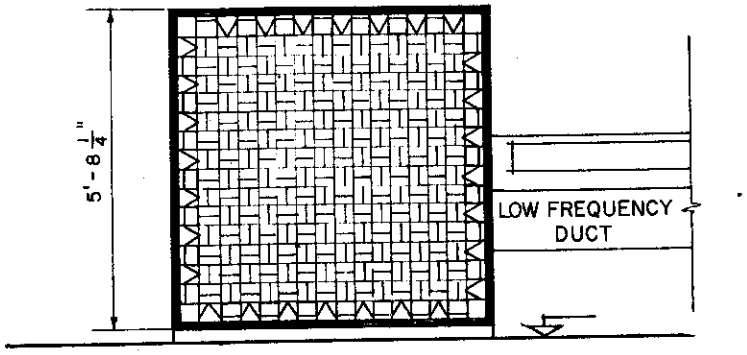


FIG. 14 STANDING WAVE RATIO IN LOW FREQUENCY CALIBRATION DUCT

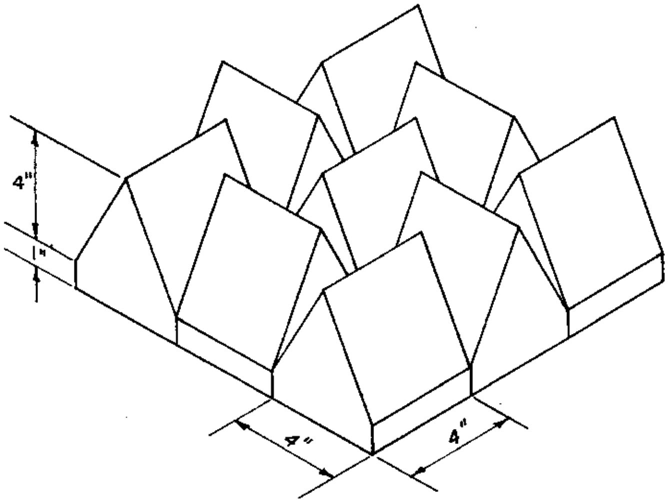
Figure 14 shows the standing wave ratio in the duct, i.e., twenty times the logarithm of the ratio of the maximum to the minimum sound pressure in the duct as measured with a traveling microphone. The sound pressure level in the duct is over 100 db with only 1/4 watt available electrical power applied to the loudspeaker. The duct was made long so that it would be possible to determine the standing wave ratio down to 20 cps. Actually, for frequencies under approximately 50 cps, the duct effectively "attenuates" the sound by transmission through the sidewalls so that no standing wave pattern is observed. Figure 14 shows that the low frequency duct has a standing wave ratio, expressed logarithmically, that is equal to or less than 3 db below 500 cps, except in a narrow region near 100 cps. Although the first cross-mode in the duct appears at 550 cps, it is possible to use the duct up to 1000 cps with pressure sensitive microphones if exact positioning of the two comparison microphones is maintained. As stated previously in this report, all microphones used on this contract are pressure sensitive devices.

Calibration at High Frequencies. A small anechoic chamber has been built to supplement the low frequency duct for the frequency range of 500 to 20,000 cps. The structural details of this chamber are shown in Fig. 15. The chamber is square and has an inside dimension of approximately 5 ft on a side. All six of the inside surfaces are covered with small acoustical terminating wedges which are 5 in. deep and backed by 1 in. deep compartmented air spaces. One side wall of the chamber is hinged so that it may be opened to permit easy accessibility to microphones and the sound source inside. The sound source is a modified Altec Type 633 microphone. The modified pressure unit has been removed from its conventional case and is now mounted in a small sphere approximately 2 in. in diameter as shown in Fig. 16. This source is suspended near the center of the chamber. The microphone under test is positioned in front of the source at a nominal distance of 1 ft. Such a small distance is used to increase the ratio of direct to reflected sound and the ratio of desired signal to unwanted noise. The free-field frequency response of this small source is shown in Fig. 17. Because of its small size the source is not capable of handling more than 1/25 watt of available electrical input power.

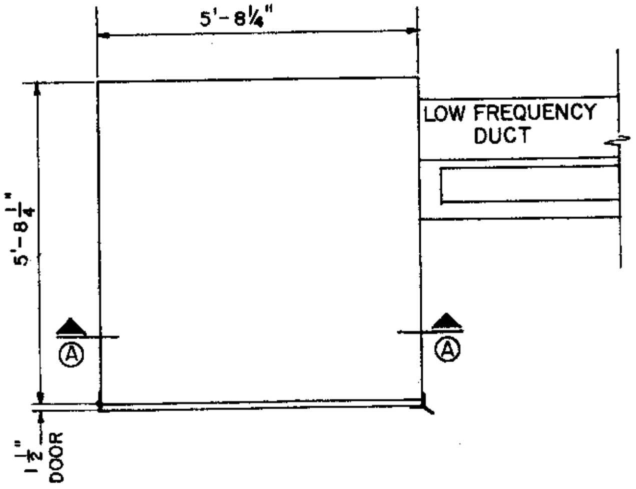
A simple method for evaluating the free field in the high frequency chamber is to verify that the sound pressure



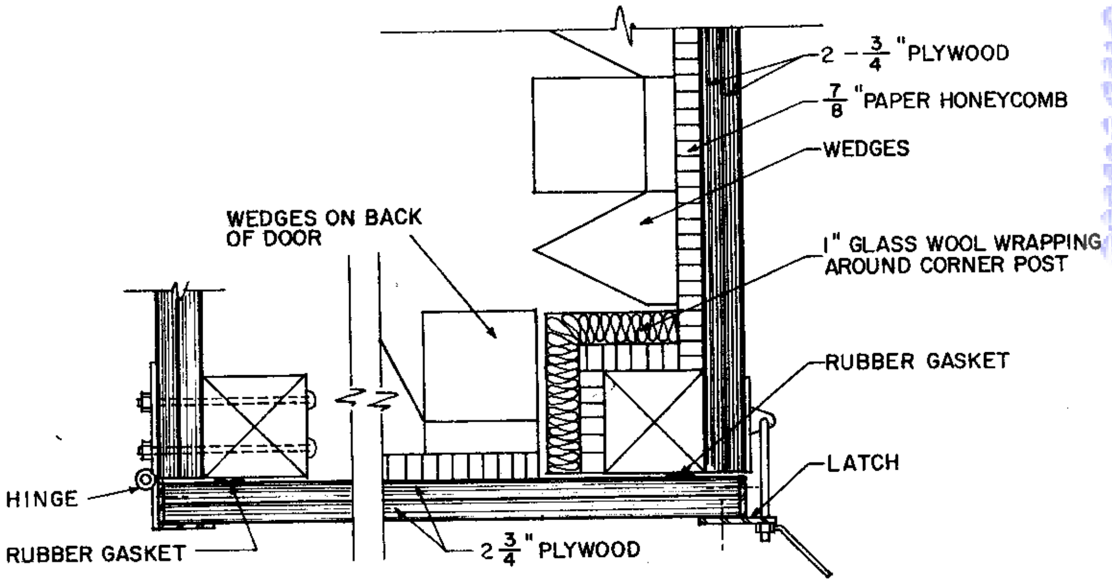
SECTION A–A
SCALE $\frac{1}{2}$" = 1'-0"



ISOMETRIC OF WEDGES



PLAN VIEW
SCALE $\frac{1}{2}$" = 1'-0"



DETAIL, SHOWING DOOR & WALL CONSTRUCTION
SCALE 3" = 1'-0"

FIG. 15 ANECHOIC CHAMBER DETAILS

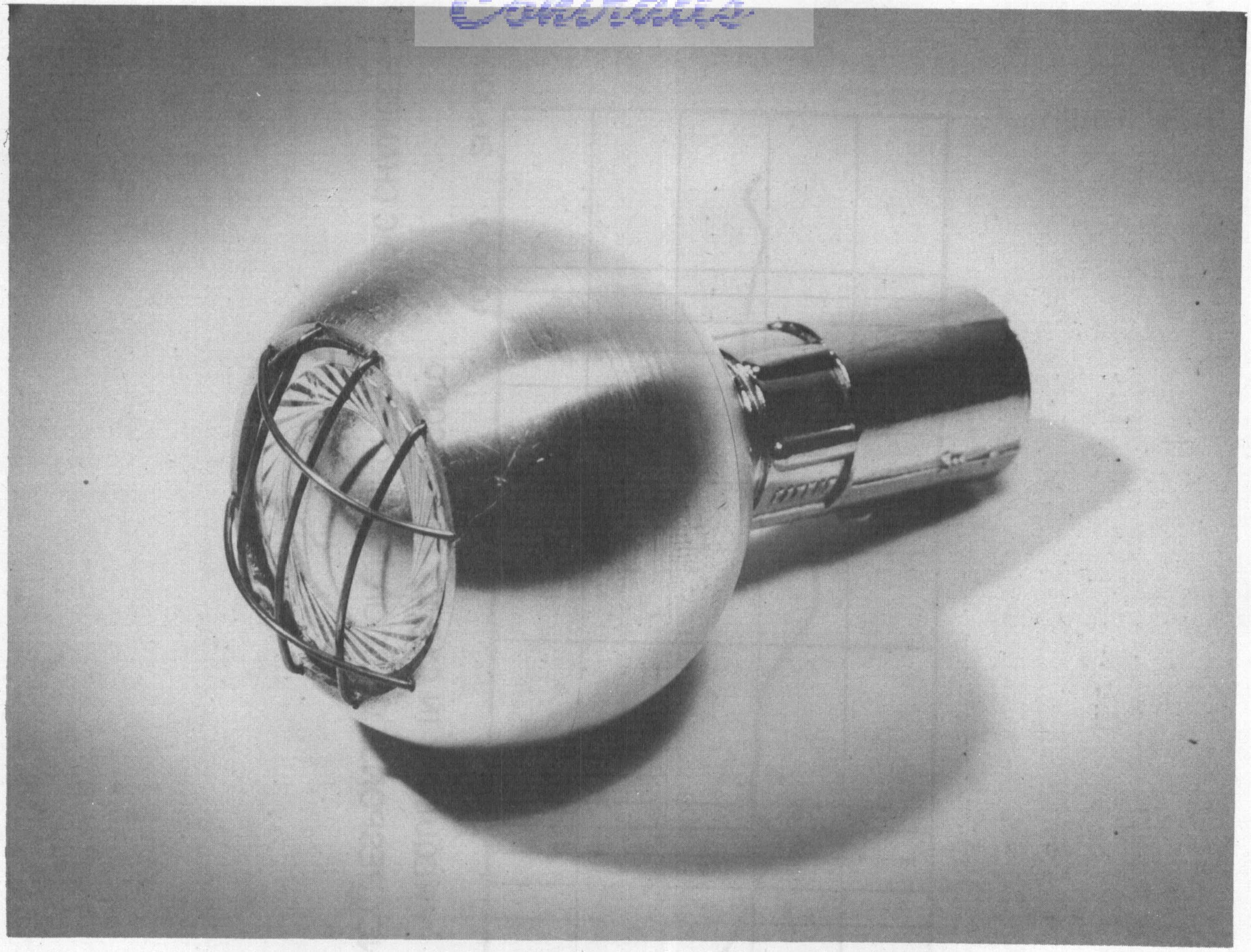


FIGURE 16

Photo of modified sound source used in Anechoic Chamber

decreases inversely with distance measured from the acoustic center of the source. A plot of how well the sound field in the chamber follows the inverse distance law for frequencies from 500 cps to 3000 cps and for various distances from the sound source is shown in Fig. 18. The straight lines drawn are best, 6 db/double distance variations. For frequencies above 1 kc the inverse square law expected for spherically-radiated power is closely followed for the range of distances studied. At lower frequencies, there appears to be a deviation from inverse square which may be explained by assuming the presence of a 1 db standing wave ratio due to reflections from the walls.

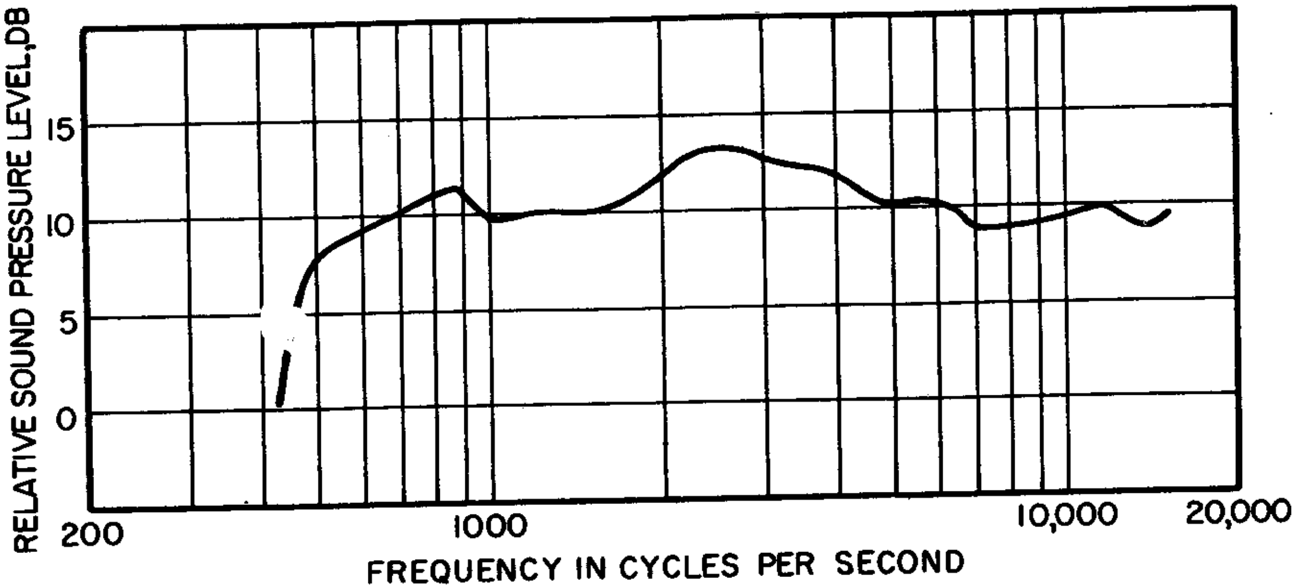


FIG. 17 FREQUENCY RESPONSE OF SOUND SOURCE IN ANECHOIC CHAMBER

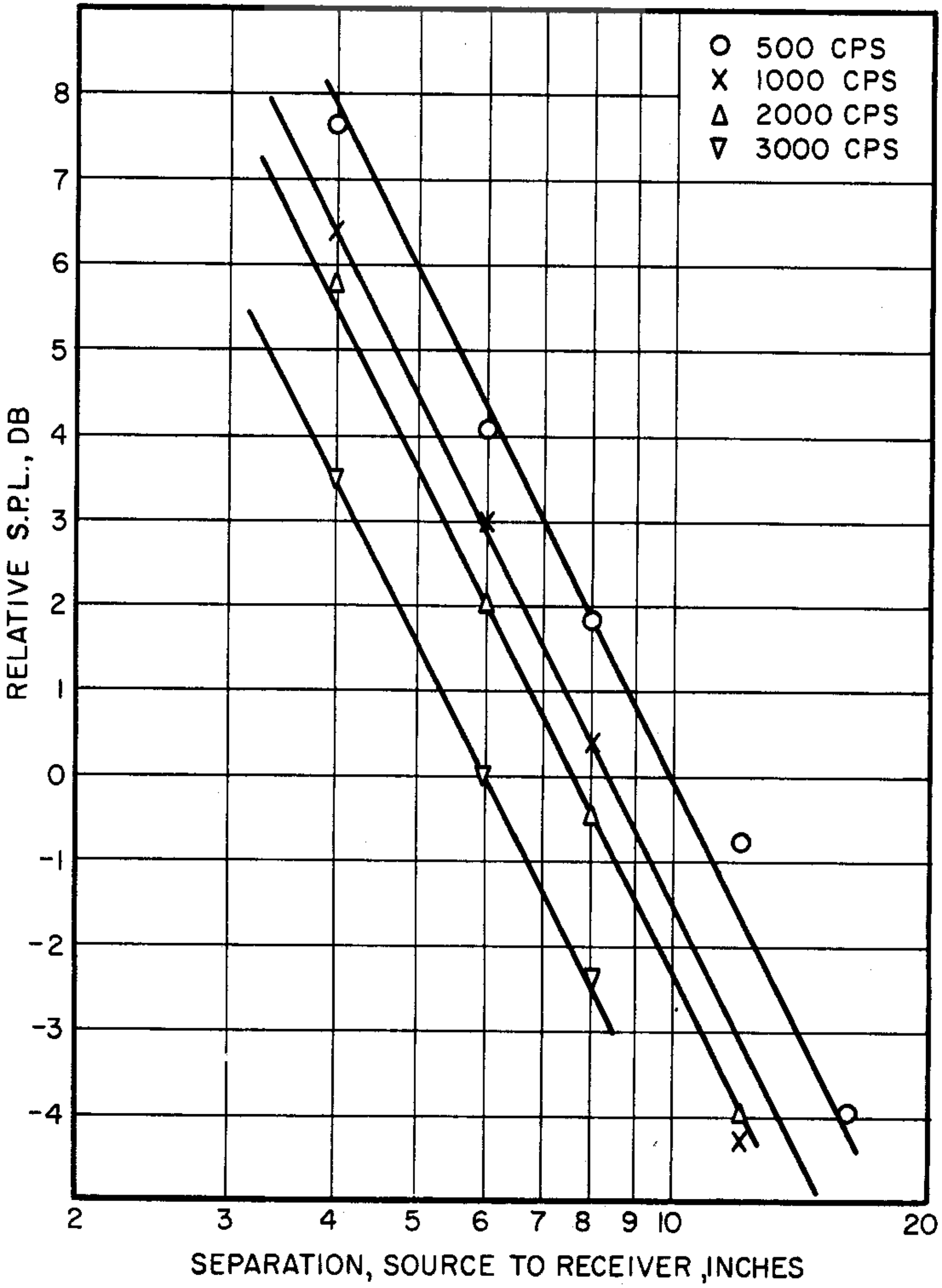


FIG. 18 FREE FIELD CHARACTER OF ANECHOIC CHAMBER

Methods of Calibration. There are different techniques at our disposal for calibrating microphones in the low frequency duct and the high frequency chamber, depending upon the accuracy of measurement desired. The absolute free-field pressure calibration could be obtained in the anechoic chamber by using the reciprocity technique. This method of calibration is tedious and difficult to perform and as yet has not been attempted in our test chamber. Instead, the comparison method is used. To calibrate a microphone having unknown characteristics, one microphone whose characteristics are known is required, in addition to the sound source. The techniques are similar whether the tests are performed in a reverberant or a "free" sound field.

To determine the open circuit voltage response of an uncalibrated microphone, an insert resistor technique is employed. Figure 19 shows a simple sketch of the basic measuring set-up. The signal generator shown at the left feeds either the sound source in the chamber or a precision attenuator. The indicating meter shown at the right receives its signal either from the uncalibrated microphone or from a voltage coming from the precision attenuator applied in series with the microphone. The attenuator is adjusted so that when the output from the signal generator is switched back and forth between the sound source and the attenuator the same reading on the indicating meter is obtained. If the signal generator is a pure tone oscillator the comparison is repeated at many different fixed frequencies. From one to ten different frequencies are observed in an octave, depending on the roughness of the response curve.

The same procedure is then repeated for the standard microphone as for the uncalibrated microphone. The setting of the precision attenuator is noted and recorded at each fixed frequency point. When the standard microphone is under test, the attenuator settings are recorded at exactly the same frequencies as were used in matching the output signal for the uncalibrated microphone. If the open-circuit voltage response of the standard microphone is known, the open-circuit voltage response of the uncalibrated microphone is found directly by comparing the differences in the precision attenuator settings at each frequency. With the observance of such precautions as elimination of ground loops, hum, etc., comparison calibrations can be made with high accuracy. The only fundamental limitation on the entire system is the accuracy of the precision attenuator.

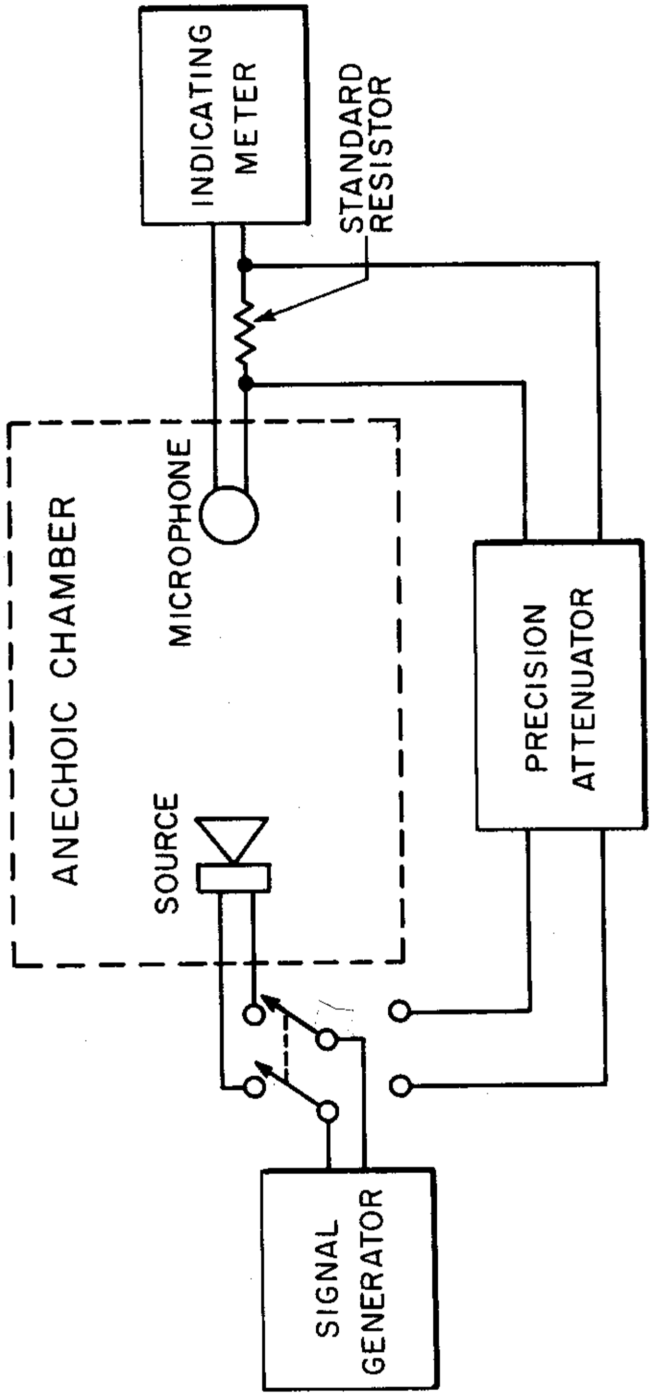


FIG. 19 INSERT VOLTAGE TECHNIQUE FOR MICROPHONE CALIBRATION BY COMPARISON WITH STANDARD

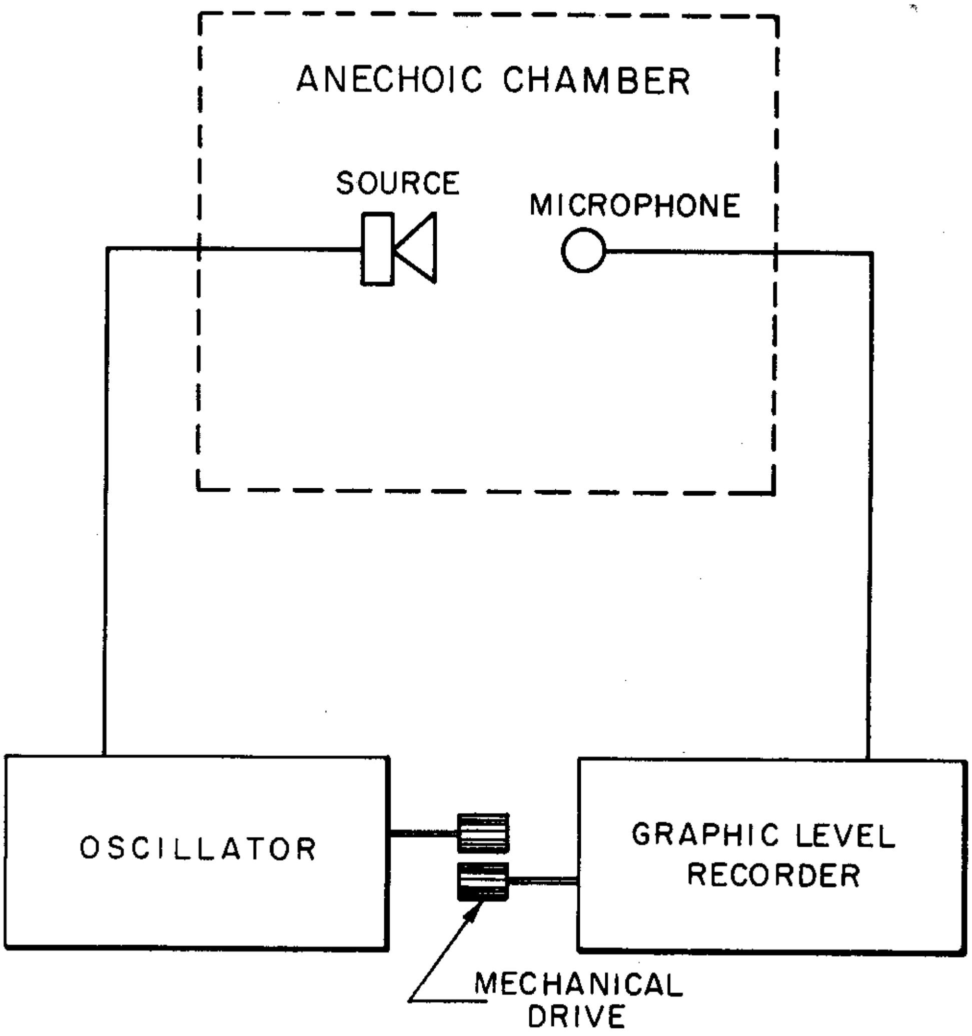


FIG. 20 GRAPHIC LEVEL RECORDER COMPARISON CALIBRATION OF MICROPHONES FOR PURE TONE RESPONSE

A much faster but less precise means for comparison calibration of microphones is illustrated in Fig. 20. Here, the differences between the frequency responses of the two microphones is determined by subtracting two curves obtained on a graphic level recorder -- one curve for the response of the standard and one curve for the uncalibrated microphone. The microphones must be located at the same position in the test chamber. The tuning dial of the audio-oscillator is mechanically driven to sweep through the desired frequency range once for the response of each microphone. The signal output of the oscillator is fed through an appropriate amplifier to the sound source in the test chamber. The sound is picked up by the microphone under test and amplified and sent to the graphic level recorder. The mechanical drive of the sweep oscillator and the graphic level recorder are linked together so that the frequency scale on the chart coming from the graphic level recorder can be synchronized with the signal from the oscillator. The frequency response curves plotted by the graphic level recorder for the standard microphone and for the uncalibrated microphone are superimposed to determine the relative frequency response of the uncalibrated microphone with reference to the standard microphone. This last step is necessary because the sound source in the test chamber does not have a flat frequency response.

When microphones are calibrated in a diffuse sound field the exact orientation of the microphone with respect to the sound source is unimportant. For the calibration of microphones in a free-field test chamber the exact orientation of the microphones with respect to the sound source is extremely important. If the sound strikes the microphone perpendicular to the face of the diaphragm there will be pressure doubling at higher frequencies. This phenomenon causes microphones to be more sensitive to sounds that are received at an angle perpendicular to the face of the diaphragm than at any other angle of incidence. In addition, diffraction effects cause the microphone sensitivity to be strongly dependent on angle of incidence and frequency of the sound when the diameter of the microphone is greater than approximately one quarter wavelength of the sound. The three types of pressure sensitive microphones used in this work have diaphragms and bodies of dimension approximately 1/2, 1 and 2 inches so that these effects become important for frequencies greater than approximately 6600 cps, 3300 cps, and 1600 cps respectively.

When the wavelength of the incident sound is comparable to the dimensions of the microphone the microphone sensitivity for normal sound incidence (with respect to the microphone diaphragm) is between 6 and 20 db greater than it is for grazing sound incidence. The larger the diameter of the microphone, the more pronounced is this effect. Microphones can be calibrated to greater accuracy at the higher frequencies if they are positioned at normal incidence with respect to the sound source in the anechoic test chamber. In this way the increased sensitivity at normal incidence helps to discriminate against reflections from the side walls of the chambers received at other angles of incidence at the diaphragm. However, at some time the microphone calibrations have to be performed at many angles of incidence to obtain the calibration for grazing incidence and random incidence. After this has been done for several microphones a generalized correction can be determined for obtaining the random and grazing incidence responses from the normal incidence response for microphones of the same physical configuration.

Up until this point, repeated mention has been made of the necessity of a reference microphone in all comparison measurements. Absolute calibrations of reference microphones can be obtained by well-known reciprocity measurements involving an acoustic source, a receiver and a reversible transducer used either in a pressure coupler or in a free sound field. The coupler technique uses an enclosure of dimensions which are small compared with the wavelengths of the sound, so that the acoustic pressure changes are uniform throughout the coupler. Compared with a reciprocity calibration in an anechoic chamber, a closed coupler calibration is relatively fast and inexpensive. But the response values obtained by a closed coupler technique must be adjusted by a diffraction correction to yield the free-field sensitivity of the microphone. In Column 2 of Table 1 are presented the most recent data on a pressure coupler calibration of Western Electric Type 640AA microphone, Serial No. 747, which is the laboratory standard used in this program. The calibration was performed by Shure Brothers, Inc. of Chicago, Illinois, on 30 November 1954. In Column 3 are the 0° incidence diffraction corrections given by the American Standards Association Z24.4-1949 for the WE 640AA. Column 4 presents the algebraic sum of Columns 2 and 3 which is therefore the normal incidence, grid-off, free-field sensitivity of WE 640AA, Serial No. 747, calibrated 30 November 1954. Although the WE640AA is generally accepted as the best standard microphone available today, its sensitivity is known to change slightly with time. For this reason this standard is being recalibrated by either pressure coupler or free-field reciprocity methods every six months.

TABLE I

FREQUENCY RESPONSE OF WE640AA MICROPHONE SERIAL NUMBER 747

30 NOVEMBER 1954

1.	2.	3.	4.
Frequency (cps)	Microphone sensitivity closed coupler grid off (db re 1 volt per microbar)	0° Incidence diffraction correction Z24.4-1949 (db)	Microphone sensitivity free field 0° incidence, grid off (db re 1 volt per microbar)
50	-52.1	0.0	-52.1
100	-52.1	0.0	-52.1
200	-52.1	0.0	-52.1
300	-52.1	0.0	-52.1
500	-52.1	0.1	-52.0
700	-52.0	0.2	-51.8
1000	-51.9	0.3	-51.6
1500	-51.9	0.5	-51.4
2000	-51.9	0.9	-51.0
3000	-51.9	2.2	-49.7
4000	-51.9	3.5	-48.4
5000	-51.9	4.9	-47.0
6000	-52.0	6.5	-45.5
7000	-52.1	7.9	-44.2
8000	-52.4	8.8	-43.6
9000	-53.2	9.2	-44.0
10000	-53.7	9.4	-44.3

For reasons discussed earlier, the greater portion of the field data for the work on this contract is analyzed and reduced into octave or one-third octave frequency bands. This type of analysis requires that the microphone response be in terms of one-third octave or octave bands of frequency. The response in bands is obtained by graphical integration of the pure tone frequency response assuming a certain noise spectrum or by actually measuring the frequency response of a microphone in the test chamber with frequency bands of noise of a certain spectrum applied to the sound source. One method for doing this would be to substitute for the oscillator of Fig. 20 a broad-band random-noise generator. The noise signal from the microphone would then be fed into an octave or one-third octave filter and the analysis would be plotted by the graphic level recorder. This technique is limited to an accuracy of not better than ± 2 db because of the output variations with time inherent with most random noise generators and because of the rapid variations of the graphic level recorder writing pen in its attempt to follow the character of the noise signal.

An improved scheme for obtaining the band response is shown in block diagram form in Fig. 21. With this system a sweep-frequency tone (from 20 to 20,000 cps) is recorded on the Ampex Recorder tape loop and then applied to the sound source in the test chamber. For each loop cycle the output of the measuring microphone is sent through a different band of the one-third octave band analyzer and integrated and presented on the graphic level recorder. This is similar to the system which is used for the automatic reduction of tape-recorded field data and which was described above in Sec. V-C.

The calibration procedure is started by first running a response using the standard microphone in the test chamber. The filter-band response that is produced from the graphic level recorder using the standard is compared with the known filter-band response of the standard or reference microphone. The band correction attenuators are then set to compensate for any deviation in these two responses. A repeat of the analysis should then produce from the graphic level recorder a frequency band spectrum that is equal to that known for the particular standard microphone within ± 0.5 db in all frequency bands. The system is now ready for the absolute frequency calibration of any pressure microphone.

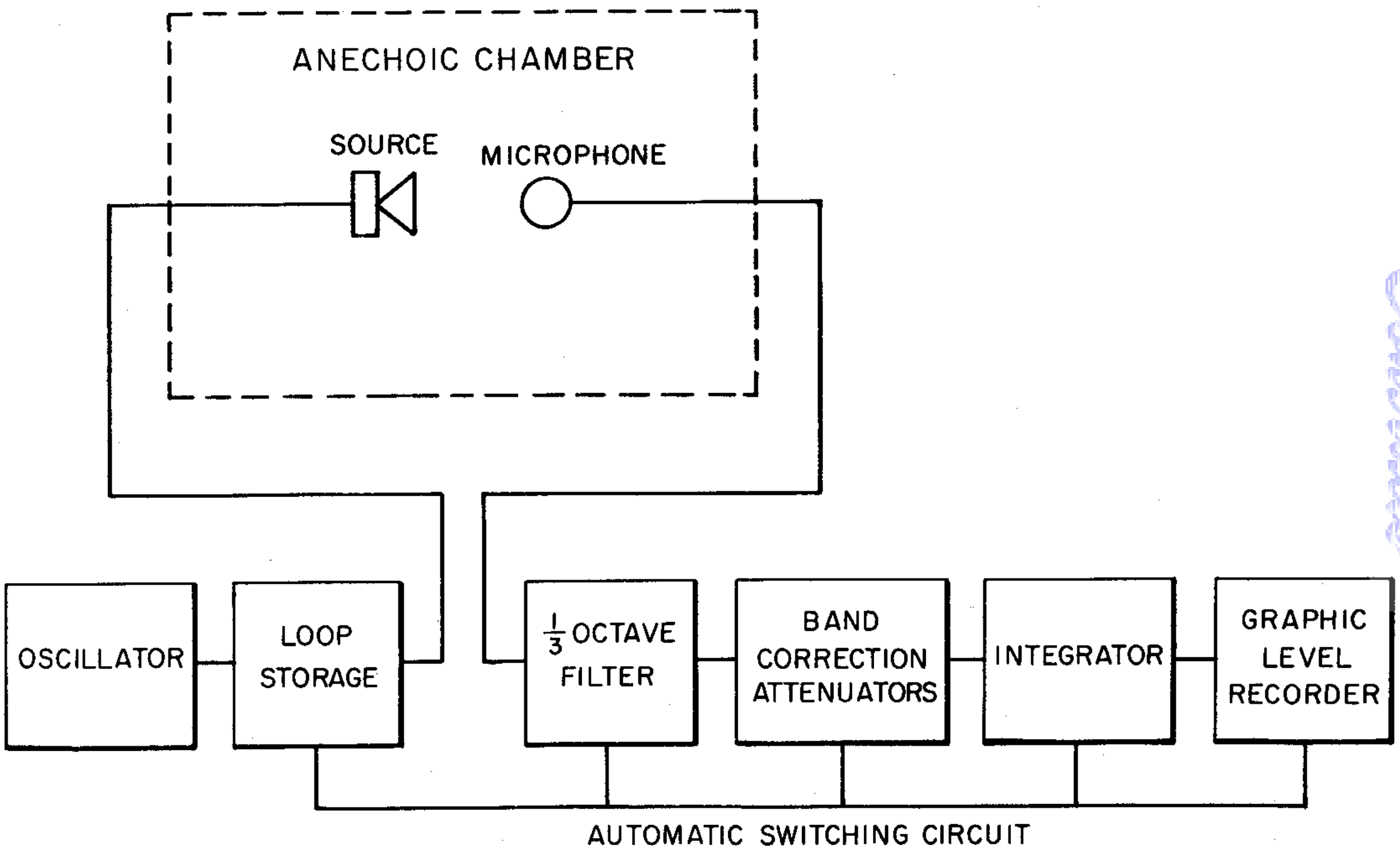


FIG. 21 GRAPHIC LEVEL RECORDER COMPARISON CALIBRATION OF MICROPHONES FOR 1/3 OCTAVE BAND RESPONSE

A realistic appraisal of the shortcomings in this calibration system shows that for a particular noise spectrum a microphone can be calibrated by this method to an accuracy of approximately ± 1 db and with a total deviation of occasionally as much as 1.5 db in a particular frequency band. Above 2000 cps, this method of calibration is particularly useful for calibrating microphones that do not have a smooth frequency response through any or all portions of the audio spectrum. Microphones, other than the condenser type, often have peaks and valleys in their response at high frequencies both of which might fall within a particular frequency band.

Not much is gained by using this calibration technique on microphones that have a very smooth frequency response even though the response is not flat with frequency. The one-third octave frequency band response for such microphones is readily derived graphically from a pure tone frequency response of the microphone. The calibrations for frequency bands and for pure tones take approximately the same amount of time to perform. Between 30 and 40 microphones can be compared with a standard microphone in the frequency range above 1000 cps by either method, within about one hour.

Calibration at High Sound Pressure Levels. It is becoming increasingly important to have a better understanding of the performance of microphones in high intensity sound fields. At high sound pressure levels microphones no longer operate as linear transducers. If microphones are operated in their non-linear range, it is impossible to obtain accurate acoustic measurements. Two methods have been developed for calibration at high sound pressure levels. The earlier method (since superseded) shall be described first.

A shock tube has been constructed in our laboratory for testing harmonic distortion of microphones during passage of a shock wave at sound pressures up to one atmosphere. The shock tube itself is a 30 ft long heavy-walled steel pipe with an inside diameter of 3 inches. One end of the shock tube is open, the other end is closed. A plastic diaphragm is inserted into the shock tube about 6 ft from the closed end in such a manner that it completely seals off that section. An air compressor is then used to pump air into the closed-end section to a predetermined pressure.

To produce a shock wave, an electrically operated solenoid punctures the diaphragm thereby causing a shock wave to travel toward the open end of the tube. The microphone is located in a small opening in the side of the shock tube and is used to measure the pressure of the passing shock wave. A specially built insensitive-diaphragm standard microphone is used that is capable of measuring the highest shock pressures accurately without distortion. This then provides a means for evaluating harmonic distortion by comparison with other types of microphones whose high-pressure responses are unknown. The output signals from either the reference microphone or the microphone being tested can be observed on an oscilloscope and photographed. Whenever a more detailed analysis is desired the microphone signals can be recorded upon the loop storage recorder of the automatic data reduction system and analyzed in the same manner as other impulse data. The difficulty in interpreting the results of the shock tube test has resulted in the development of an alternative, and superior technique.

In the present method for measuring distortion of microphones at high sound pressure levels, a resonance tube is used. A simple sketch of the apparatus is shown in Fig.22. The basic unit consists of an inexpensive 8" diameter loudspeaker mounted at the open end of a 9" long steel pipe. A microphone is positioned at the closed end of the pipe. A nominal pipe diameter of 2 1/2" or smaller is used, depending upon the size necessary to accommodate the microphone. When the microphone to be tested is sufficiently small, such as the Altec 21BR series, it is possible to have two microphones at the end of the pipe. In this way, one may monitor the pressure at the end of the pipe with an insensitive blast type microphone for which the distortion(for the same acoustic pressure)in orders of magnitude lower than that of the microphone being tested. The output signals of the microphones are connected to a frequency analyzer or distortion meter. The frequency of excitation to the loudspeaker is adjusted for resonance in the tube to give maximum pressure at the microphones. This point of resonance can either be observed as a maximum electrical impedance at the loudspeaker voice coil or as the maximum output at the microphone with a constant voltage and varying frequency applied to the loudspeaker. The length of the pipe has been selected so that, when it is tuned to a frequency near that of the fundamental frequency of the loudspeaker, maximum pressures can be obtained at the end of the pipe where the

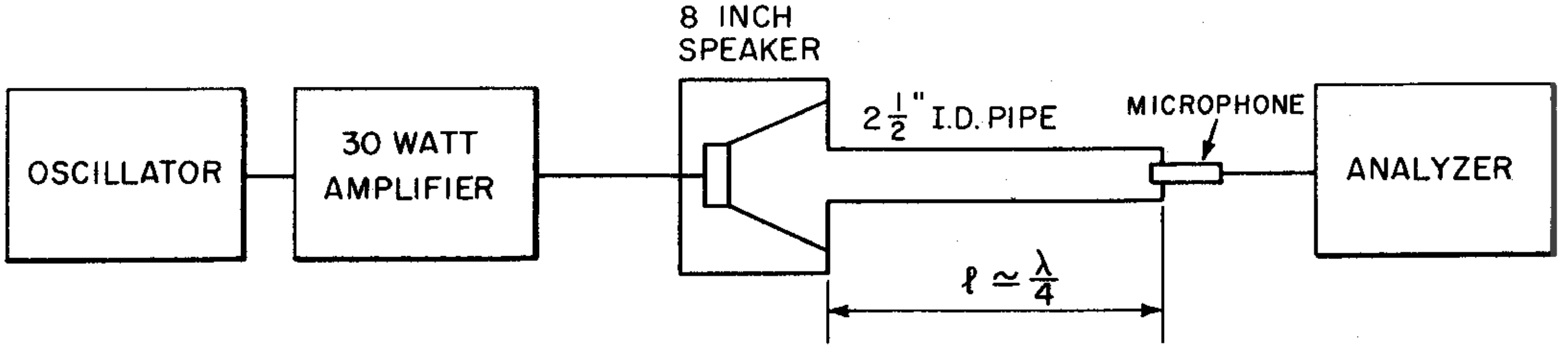


FIG. 22 RESONANCE TUBE FOR TESTING MICROPHONE DISTORTION AT HIGH SOUND PRESSURE LEVELS

microphones are being tested. The harmonic distortion generated by the loudspeaker and the harmonic distortion generated in the tube do not fall at precisely the same frequencies. In this way high sound pressure levels with relatively small distortion can be presented to the microphone even though there is some electrical distortion produced by the power amplifier driving the loudspeaker. The system will produce sound pressure levels of 170 db at 400 cps with 0.6% total harmonic distortion with a power input to the loudspeaker of 12 watts.

B. Electrical Calibration of Equipment

In order to obtain meaningful acoustic measurements, it is important to know, first, where to position the microphone and how to operate the measuring equipment. A thorough understanding of the shortcomings and limitations of the measuring equipment is equally important. Without this understanding it is often impossible to determine the validity and the accuracy of any acoustical measurement. Manufacturers of acoustic measuring apparatus tend to publish inadequate information on many of the important limitations in their products. As a result many people often, unknowingly, perform acoustical measurements that are invalid because of subtle limitations in their measuring equipment.

The procedures followed for evaluating the performances of electronic equipment used in the audio frequency range is in general more straightforward than the methods used for acoustic calibration of systems. Different tests are performed on apparatus to determine such things as the frequency response, distortion, dynamic range, temperature effect etc. These evaluations are carried out with the aid of several of the pieces of equipment in the automatic data reduction system.

Frequency Response. One of the quantities easily measured in amplifiers, magnetic tape recorders, band pass filters, etc. is the frequency response. The most common method utilizes an oscillator whose frequency is continuously adjustable. The output of this oscillator is applied to the input of the equipment under test and a voltmeter or graphic level recorder attached to the output of the same equipment. The technique is rapid and can yield the frequency response over the entire frequency range plotted out on the graphic level recorder in less than a minute's time. This method is the most practical when results are required not closer than 0.5 db. When greater accuracy is desired the insert calibration technique is employed.

There are several variations of this method of which one is sketched out in **Fig.** 23. In this set-up it is necessary that the instrument under test have a voltage gain determined between input and output of not less than unity. The indicating meter is switched alternately between the input of the instrument being tested and the output of the precision attenuator. It is important that the load impedance of the indicating meter be independent of frequency and, preferably, a hundred or more times higher than the output impedance of the signal generator. At each setting of the frequency of the oscillator, the precision attenuator is adjusted so that the signal at its output is precisely equal to the signal output of the oscillator. This balanced condition is observed on the indicating meter and the setting of the precision attenuator recorded. The accuracy of the measuring technique is fundamentally limited by the accuracy of the attenuator. It is not necessary that the oscillator and the indicating meter have a flat frequency response. In practice, frequency response measurements can be made to the nearest 0.1 db by using this technique.

A variation of the scheme just described is shown in Fig. 24. This set-up is used when testing an instrument that has a voltage gain of less than unity between the input and output. Passive networks and attenuators are readily measured with the system.

Acoustic measuring instruments often respond quite differently to pure tones and random noise. Indicating meters, graphic level recorders, and other devices containing non-linear circuit elements which are calibrated to read the true rms value of a pure sine wave signal can be in error as much as 1 to 10 db when reading a random noise signal. The indicating meters then read 0.7 db low on random noise because these indicating instruments have their dial readings calibrated for the rms value of pure tones. The electronic circuitry associated with the indicating meter is usually chosen to indicate something nearer to the peak or the average of the incoming signal rather than the true rms. The reason for this choice is that rms circuitry has been bulky and expensive. Most sound level meters respond to the

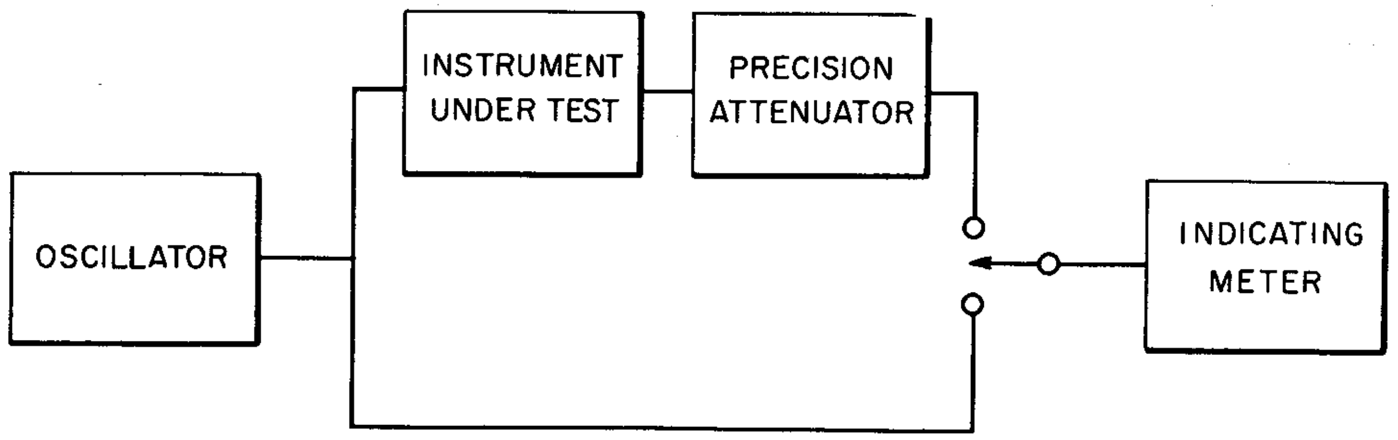


FIG. 23 INSERT CALIBRATION TECHNIQUE FOR DETERMINING FREQUENCY RESPONSE OF EQUIPMENT WITH VOLTAGE GAIN GREATER THAN UNITY

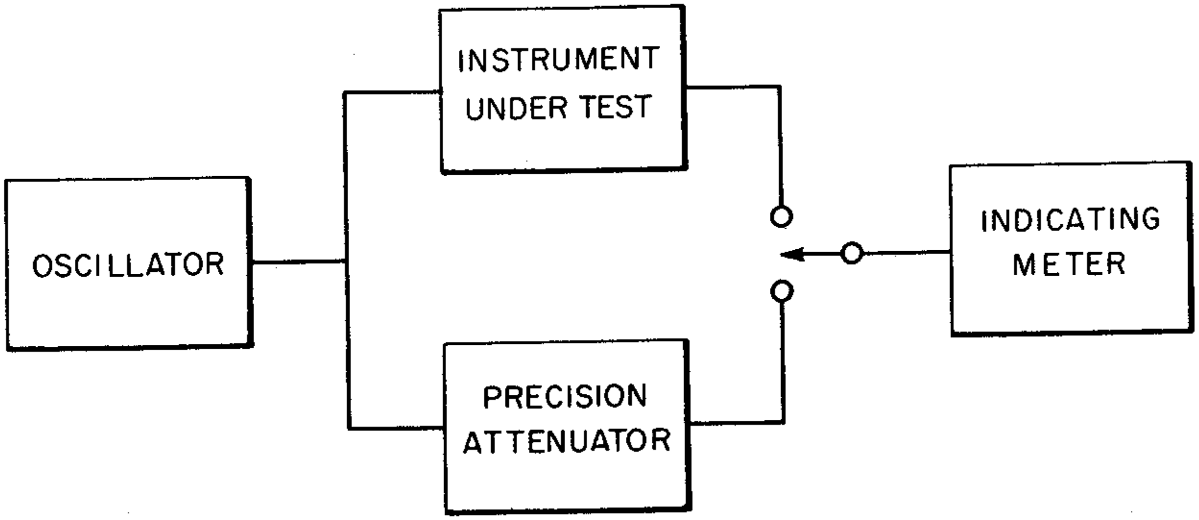


FIG. 24 INSERT CALIBRATION TECHNIQUE FOR DETERMINING FREQUENCY RESPONSE OF EQUIPMENT WITH VOLTAGE GAIN LESS THAN UNITY

average value of the rectified input signal. Graphic level recorders usually respond to a level nearer to the peak value of the input signal. Squaring circuits have recently been developed which should make it possible and practical to have true rms indicating circuits on portable equipment.

Because of the difficulty encountered with true rms circuits, the rectified average at the input of the integrator has been used for all noise analysis to this date. The error encountered by using the average value rather than the rms value is 0.7 db for strictly random noise.

Microphones, magnetic tape recorders, amplifiers, and filters for the most part perform linear operations on the signal and therefore their response to both pure tones and noise is identical.

Distortion. The amount of harmonic distortion present in acoustic measuring equipment becomes particularly important when one measures noise spectra which have most of their energy concentrated in pure tone components or in the lower end frequency region of the audio spectrum. When the measured noise spectrum has its energy fairly evenly distributed over the audible range, higher amounts of harmonic distortion can be tolerated without affecting the results of these measurements. The amount of distortion present in an instrument is generally a strong function of the amplitude of signal being handled by the instrument.

All of the instruments used in work under this contract were found to have negligible distortion throughout the part of their dynamic range in which they are used. The harmonic distortion in each instrument was obtained by applying pure tones of various frequencies and amplitudes and measuring the amplitudes of the various harmonic components at the output of the instruments being tested. The General Radio narrow band frequency analyzer or the Bruel and Kjaer one-third octave filter were used to measure these harmonic components. The one-third octave filter analysis was much faster and generally gave sufficient detail. The test set-up is like that shown in Fig. 25. The output of the instrument under test with pure tone excitation was analyzed through the one-third octave filter and presented on the graphic level recorder. The one-third octave filter automatically steps through all of the filter bands in the audio spectrum at the rate of approximately one band every two seconds. Measurements are made with the oscillator set at two or more.

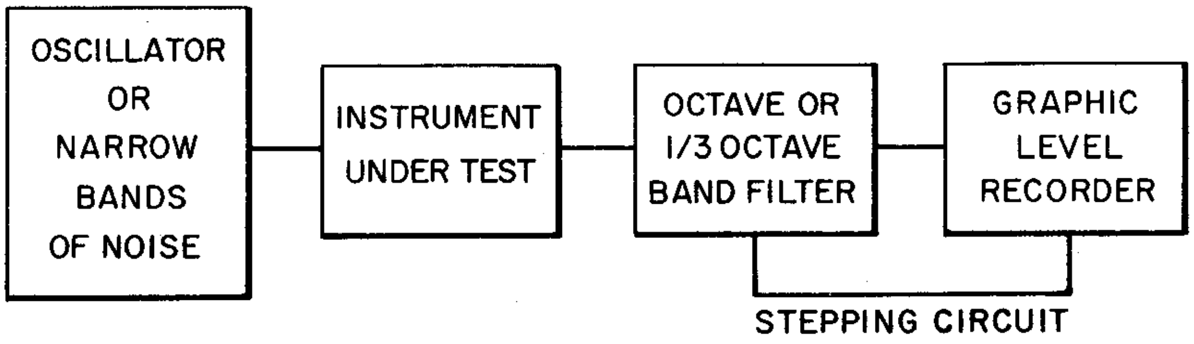


FIG. 25 HARMONIC DISTORTION TEST FOR ELECTRONIC INSTRUMENTS

different frequencies and several different amplitudes at each. The result of such a test for a Magnecord recorder is presented in Fig. 43 where the pure tone input frequency was 100 cps. Sometimes the tests are performed by using narrow bands of noise in place of the oscillator test signal. The result of such a test is shown in Fig. 43 in which the instrument being studied is the Magnecord tape recorder.

Dynamic Range. In addition to knowing the maximum signal handling capabilities of each instrument, it is important to know the minimum signal as a function of frequency. The lower limit is set by the noise generated in the equipment itself. This "noise floor" is obtained by a method similar to that described above in Fig. 25. However, in this case the pure-tone input signal is removed and an appropriate impedance is placed across the input terminals to the instrument being tested. The level of the noise floor is compared in each frequency band to the maximum usable output level of an instrument in that band. The difference is the dynamic range and it usually varies with the frequency band. Sound measuring apparatus should have a useful dynamic range in excess of 60 db in all frequency bands if it is intended for general sound measurements. Figure 41 shows the signal-to-noise ratios for the electronic noise of a Magnecord tape recorder, tested in octave bands.

Stability. The accuracy to which acoustic measurements can be obtained is directly related to the stability of the measuring apparatus. Unintentional variations in gain and frequency response must be kept to a minimum. The next section in this report deals primarily with the methods developed, and the procedures followed, for improving the stability of the noise measuring apparatus under this contract.

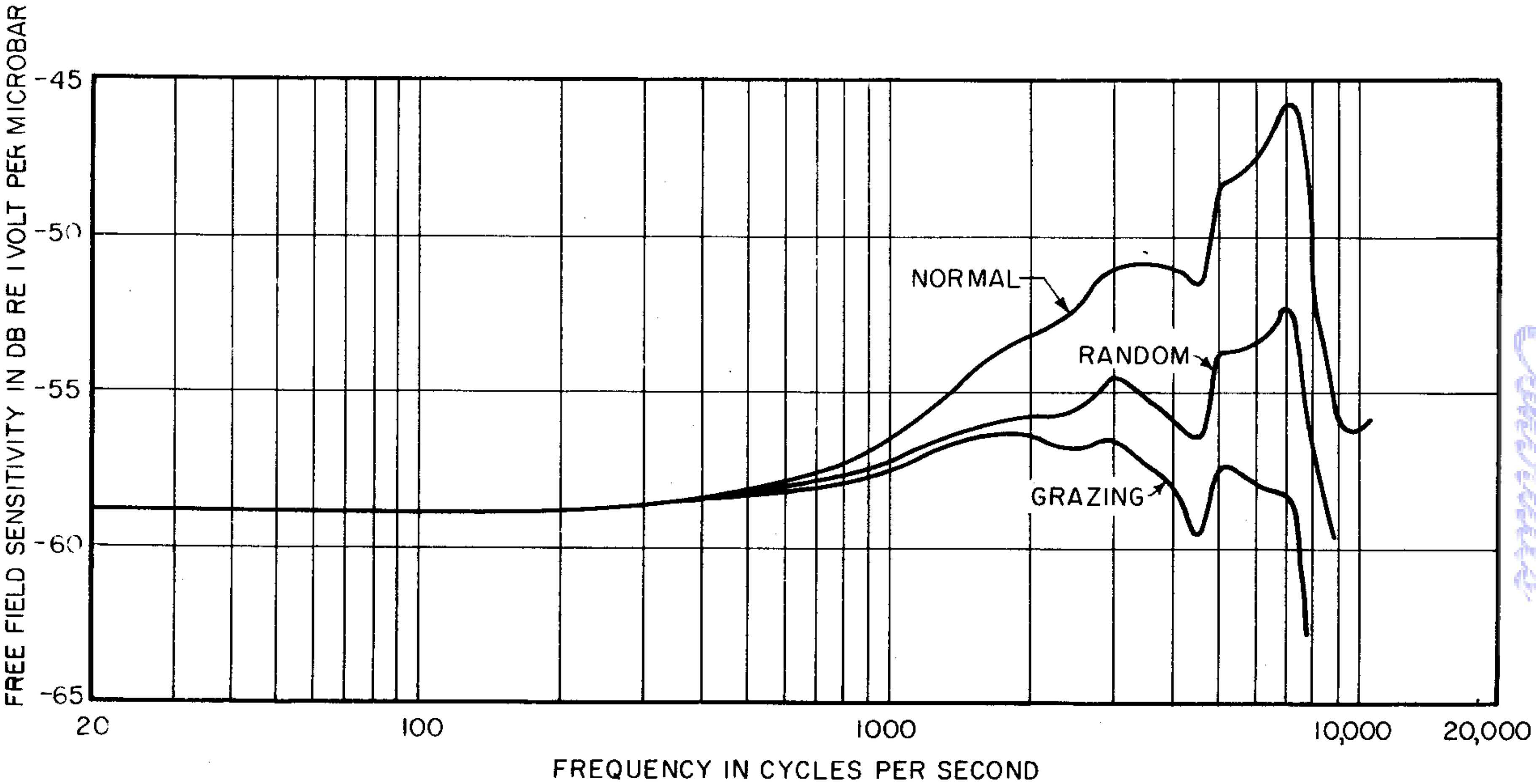


FIG. 26 FREE FIELD SENSITIVITY OF SHURE MICROPHONE TYPE 9898, SERIAL NUMBER 19, FOR NORMAL, RANDOM AND GRAZING INCIDENCE. 16 AUG. 1954

SECTION VII

MODIFICATIONS AND LIMITATIONS OF EQUIPMENT

Some of the limitations of sound measuring apparatus are so subtle that they go undetected even by an experienced observer. Nearly every piece of apparatus involved in the work under this contract has been altered to render it more useful for our specific needs. Some of the alterations were required solely for improving the reliability of an instrument. In other instances it was necessary to extend the dynamic range of an instrument. The important modifications and limitations of all the equipment are discussed here in detail. The discussion will start with the microphones and then proceed through the various items of apparatus in an order similar to that experienced by a measured noise signal.

The microphones used for the work under this contract are three varieties of pressure transducers: (1) diaphragm Rochelle salt crystal; (2) diaphragm barium titanate ceramic; and (3) condenser.

A. Diaphragm Rochelle Salt Crystal Microphones

Frequency Response. The diaphragm Rochelle salt crystal microphone is a general purpose transducer. The units selected were manufactured by Shure Brothers and are their Type 9898. The microphone is normally supplied with a connector which fits the commercial version of the General Radio sound level meter. The Cannon XL series connector has been found to be a more durable type of connector and so the regular connectors have been replaced with male Cannon XL connectors.

An ideal microphone for making general noise measurements should be reliable, rugged, have a flat frequency response throughout the audio spectrum, low distortion at high amplitudes of signal, a sufficiently high output voltage to exceed the self-noise of the amplifier when measuring low sound levels, a low output impedance, and a small temperature coefficient. At the present time there is no simple and inexpensive microphone which is capable of meeting all of these requirements. When used with a specially designed preamplifier, the Shure Type 9898 crystal microphone most nearly meets all of these requirements. Open-circuit voltage vs frequency responses of a typical Shure 9898 Rochelle salt crystal microphone at normal, grazing and random wave incidence are shown in Fig. 26. The responses are essentially flat below 1000 cps. Above 3500 cycles the response becomes irregular up to a frequency of approximately 7000 cps. Above 7000 cps the microphone sensitivity falls off rapidly with increasing frequency. The majority of these Shure crystal microphones have response curves very similar to those shown in Fig. 26.

The free-field, normal-incidence, frequency response is measured for each microphone prior to every major field trip. The calibration procedures have been outlined earlier in Sec. VI.

Temperature Behavior. There are two serious drawbacks to the use of Shure 9898 microphones. The first is its irregular frequency response above 3500 cps and the second is its variation in sensitivity due to change in temperature. The temperature coefficient can be resolved into two separate effects. The first effect is the increase in open-circuit voltage with increasing temperature as shown for various frequencies in Fig. 27. The temperature coefficient is the same for the frequencies 600, 1000, 2000, and 4000 cps.

The second temperature effect is due to the change of capacitance of the microphone with temperature changes. The electric impedance looking back into the microphone is nearly a pure capacitance. Figure 28 shows how widely the microphone capacitance varies with temperature. The capacitance change is particularly severe at the Curie points of 0^{o}F and 75^{o}F. This second temperature effect is nearly independent of the first effect. If the microphone is operated into near open-circuit the second effect is avoided. However, with the microphone connected to a cable there is a voltage division between the microphone capacitance and the capacitance of the cable. The longer the cable, the greater the percentage of the microphone signal that is lost in the cable. The serious problem is that the voltage delivered by the cable to the sound level meter changes rapidly with varying temperature of the microphone when the temperature of the microphone is near one of the Curie points. An example will indicate the magnitude of this change in output voltage. Suppose the microphone is connected to a 50 ft cable which in turn feeds into a sound level meter. The microphone cable has a capacitance of 30 micro-microfarads per foot yielding a total capacitance of 1500 micromicrofarads. Let us assume a change in microphone temperature from 60^{o}F to 77^{o}F. From Fig. 27 it is seen that the

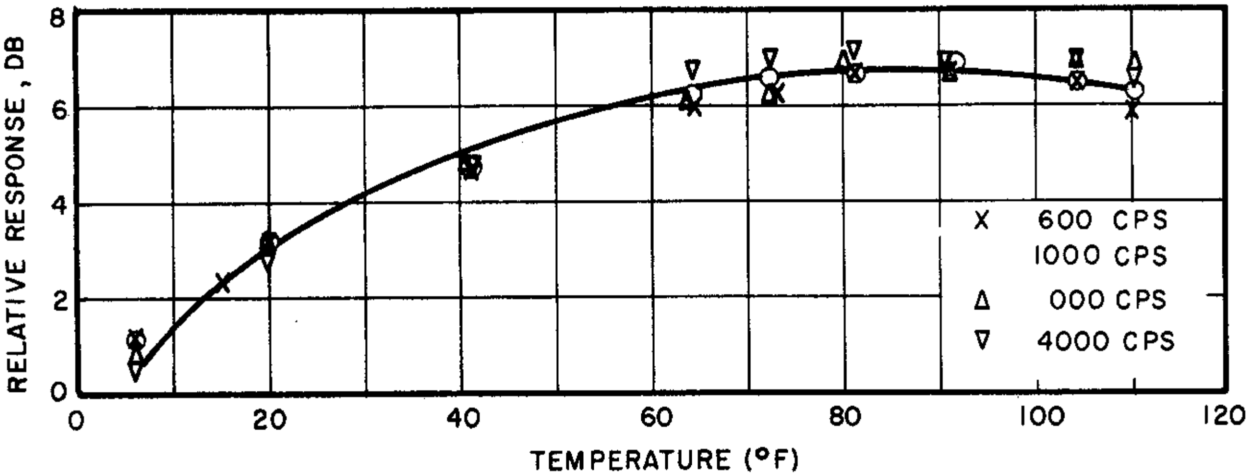


FIG. 27 RELATIVE CHANGE OF OPEN-CIRCUIT SENSITIVITY WITH TEMPERATURE AT DIFFERENT FREQUENCIES. ROCHELLE SALT MICROPHONE SHURE TYPE 9898. SERIAL NUMBER D-5824.

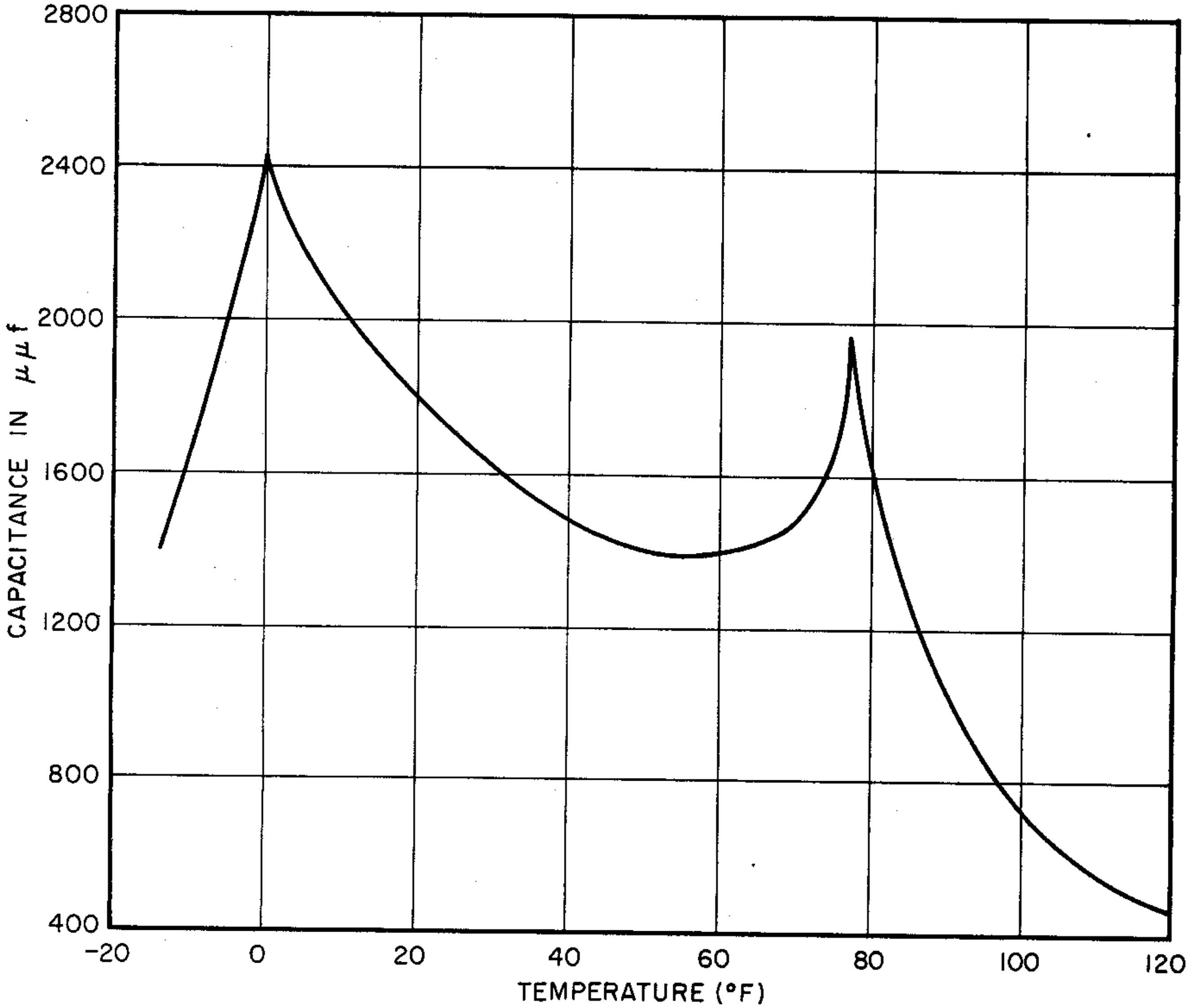


FIG. 28 TYPICAL VARIATION OF CAPACITANCE WITH TEMPERATURE FOR SHURE TYPE 9898 ROCHELLE SALT MICROPHONE

microphone sensitivity in this 17° temperature drop will decrease approximately 0.5 db. From Fig. 29 the nominal microphone capacitance at 77°F is 1960 micro-microfarads and at 60°F it is only 1400 micro-microfarads. At 77°F with a microphone capacitance of 1960 micro-microfarads and a cable capacitance of 1500 micro-microfarads, there will be a 4.9 db loss in the voltage delivered to the sound level meter due to the cable. At 60°F where the microphone capacitance is only 1400 micro-microfarads, the voltage loss due to adding the cable is 6.3 db. From this it can be seen that due to the addition of the 50 ft cable alone only a 17°F change in temperature can cause a 1.4 db change in the voltage supplied to the sound level meter. When the 0.5 db change in open-circuit sensitivity is added, a total change of 1.9 db is obtained.

Two methods have been devised for combating the effects of the change in capacitance of the microphone whenever long cables are necessary between the microphone and the magnetic tape recorder. The method most often used is to employ a preamplifier very near the microphone. This preamplifier is a small self-contained, battery-operated, cathode-follower discussed in detail in Sec. VII F, Crystal Microphone Preamplifier. With the microphone connected directly to the very high impedance input of the preamplifier, capacitance changes in the microphone have no effect upon the voltage delivered to the sound level meter. Cable lengths up to several hundred feet may then be used to feed the signal from the preamplifier into the field-data magnetic tape recorder or other equipment.

Under certain conditions it is not feasible to have a preamplifier located at each microphone. An illustration of this is in aircraft engine test cell measurements. Here, five or six microphones are positioned symmetrically in a grid across the opening to an acoustical treatment. The electric output signal from these microphones is then connected to a switchbox by relatively short cables usually 5 or 10 ft, always under 25 ft in length. The signal from any one of the microphones is selected electrically by remote control. The output signal from the microphone switchbox is fed directly into a microphone preamplifier and then to the data recording system outside the test cell through long cables. This typical set-up is shown in Fig. 29. Although the cables carrying the signals between the microphones and the switchbox are relatively short,

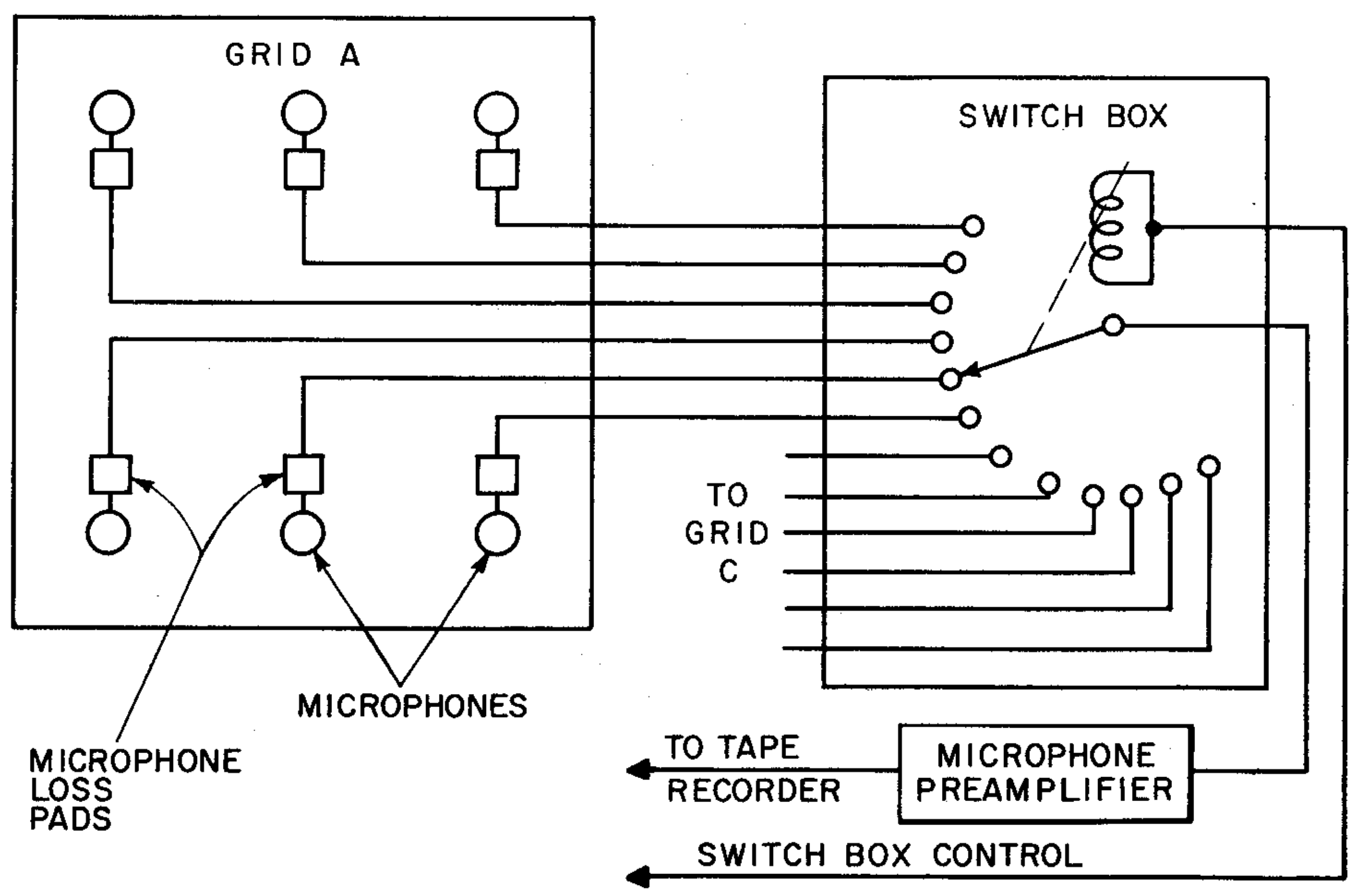


FIG. 29 TEST CELL SET-UP FOR REDUCING EFFECT OF TEMPERATURE CHANGE ON SIGNAL RECEIVED FROM ROCHELLE SALT MICROPHONE

their capacitance produces a sufficient load on the microphone to cause variations in the output voltages due to changes in the temperature of the microphone. The air temperature surrounding these microphones in an engine test cell often changes greatly after the engine starts operating.

When cables are necessary as in the case just stated, and when the sound levels to be measured are high, a second method of reducing the effects of temperature change is employed. By placing an appropriate loss pad at the microphone, the voltage variation due to temperature can be reduced by factors of as much as 10°. This loss pad is a capacitance divider as shown in Fig. 30. From this figure it can be seen that the capacitance added to the output of the microphone can never exceed 100 micro-microfarads. Hence, variations in microphone capacitance due to temperature will cause very small changes in the voltage produced at the output of the loss pad. The loss pad has a nominal attenuation of 20 db depending upon the capacitance of the cable connected to its output. Note that this attenuation is independent of frequency. This device, including the input and output connectors, is cylindrical in shape and is approximately 6 in. long and 5/8 in. in diameter.

Figure 27 shows the change of open-circuit sensitivity with temperature for a Shure Brothers 9898 crystal microphone after the microphone has stabilized at each temperature shown on the abscissa. We see that if the microphone temperature changes only a few degrees during the period of the noise measurements, its sensitivity varies by a small fraction of a decibel. Wide variations in microphone temperature may cause errors of large and unknown amounts because the microphone temperature does not follow rapid changes in the surrounding air temperature. We have determined empirically how fast the microphone assumes a new temperature condition by measuring the open-circuit output voltage as the microphone warms up. For a large change in temperature, the change in open-circuit voltage sensitivity for the Shure Brothers Type 9898 Rochelle salt crystal microphone, is:

$$\Delta M = 0.002\ t \quad \Delta T \text{ db}$$

where ΔM = change of 9898 microphone open-circuit sensitivity

t = time in minutes

ΔT = change of temperature in Fahrenheit degrees.

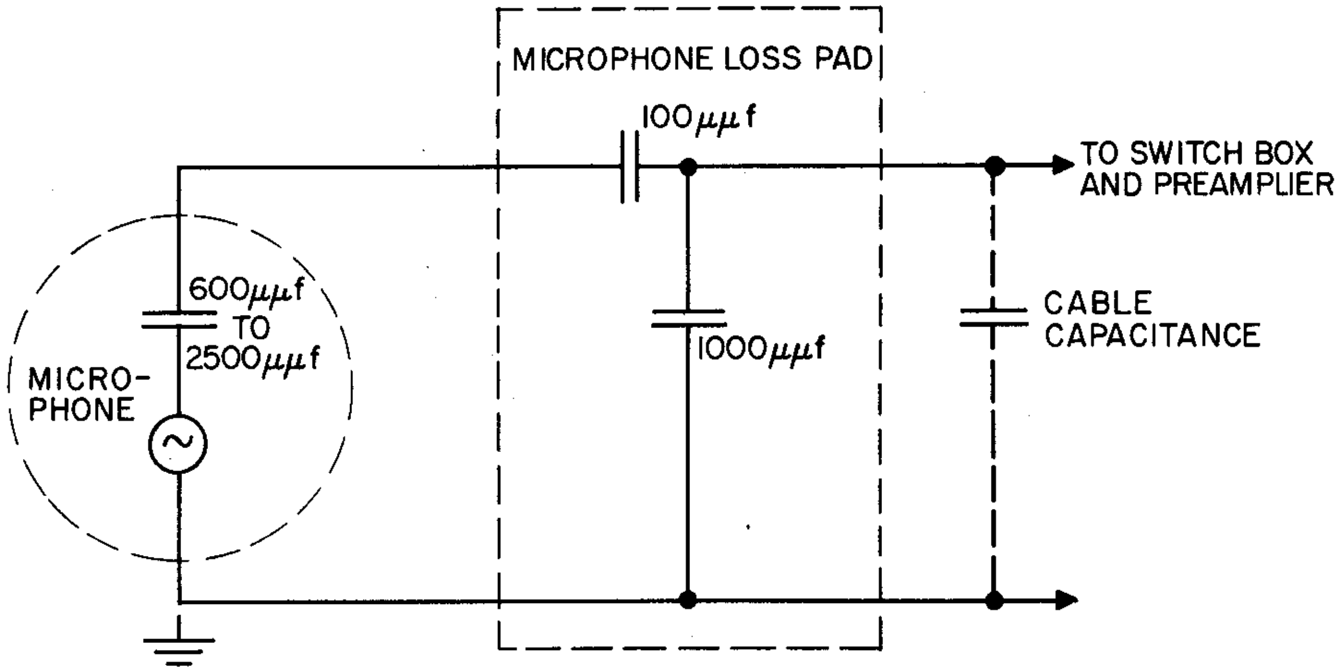


FIG. 30 MICROPHONE LOSS PAD USED TO REDUCE EFFECTS OF VOLTAGE VARIATION DUE TO TEMPERATURE CHANGES

This formula says that if the microphone has previously been stabilized at a temperature of 80°F and then suddenly is subjected to a constant air temperature of 40°F the microphone sensitivity will drop 1 db in approximately 12 minutes. This formula assumes little or no wind conditions about the microphone during the period when its temperature is changing.

It is apparent that acoustical calibrations should be performed, at least, just prior to and immediately after a test run. It is important to know the rate of change of microphone sensitivity with time and temperature when it is not feasible to use the acoustic calibrator periodically during the measurement tests. Such a condition exists during jet engine operation in test cell measurements. When possible, the jet engine is operated at a particular power setting several minutes before acoustic measurements are made in an attempt to stabilize the temperatures of the microphones in the test cell. Immediately after the engine is shut off the air temperatures inside the test cell may either rise or fall. The magnitude of the temperature change in the vicinity of the various noise measuring microphones determines the rate of change of their sensitivity with time. This rate of change of microphone sensitivity then dictates the swiftness with which acoustic calibration must be made at various microphone positions after the engine has been shut down.

Stability. The primary advantage of the Rochelle salt crystal microphone is its ruggedness and reliability. The Shure Brothers Type 9898 is capable of withstanding severe mechanical shocks, such as unintentional dropping, without noticeable affects on its frequency response and sensitivity. If the shock is very intense, the microphone diaphragm may rupture or the crystal may fracture, thereby leaving no doubt that its operating characteristics have changed. Because this microphone is inexpensive, it is possible to sacrifice it to obtain certain measurements.

The chief disadvantages of the Rochelle salt crystal microphones for making aircraft engine test cell measurements are its upper temperature limit and its maximum sound pressure level limit. The Rochelle salt crystal is completely destroyed if it is allowed to reach a temperature of 130°F. Valid acoustical measurements can be made only to a temperature of 110°F. Sound pressure levels in the field of greater than about 160 db will frequently rupture the microphone diaphragm, although it maintains its linearity up to 170 db during laboratory tests.

The frequency response of these microphones is very stable over a long period of time. As a matter of course, a complete frequency response is measured for each microphone before and after every field trip on which it is used. Comparing several of these calibrations for any particular microphone reveals no significant difference in their relative frequency response even over long periods of time.

High humidity conditions may sometimes reduce the low frequency sensitivity of these microphones. After several hours of exposure in a very humid atmosphere, moisture collects on the electrical terminals inside of the microphone case. Occasionally there is sufficient moisture condensation to produce a harmfully low leakage resistance across the output terminals of the microphone. The microphone then looks like a high pass R-C filter. This deficiency in low frequency sensitivity can be determined by acoustically calibrating the microphone or measuring the electrical impedance across the microphone output terminals with an ohm-meter. An internal resistance lower than approximately 20 megohms will affect the normal low frequency response of the microphone. Caution must be exercised when measuring the internal resistance with an ohm-meter. If the voltage present at the test leads is more than 30 volts it may fracture the Rochelle crystal in the microphone.

B. Diaphragm Barium Titanate Microphones

Diaphragm barium titanate ceramic microphones (Shure Type 98100) are similar to the Shure Brothers Type 9898 Rochelle salt crystal microphones except that barium titanate is substituted for Rochelle salt as the active element. These units have been constructed on special order for the purpose of making sound measurements in aircraft engine test cells where temperatures are too high for Rochelle salt. The useful upper temperature range of these microphones is 200°F, compared with 110°F for the Rochelle salt microphone. The internal electrical capacitance of barium titanate with lead titanate additive varies less than that of Rochelle salt as a function of temperature. The variation of dielectric constant, with temperature for barium titanate with lead additive is shown in Fig. 31. At the present time these microphones are in the development stage at Shure Brothers and are not available as a production item. Figure 32 shows a typical free field, normal incidence response curve for a diaphragm barium titanate microphone.

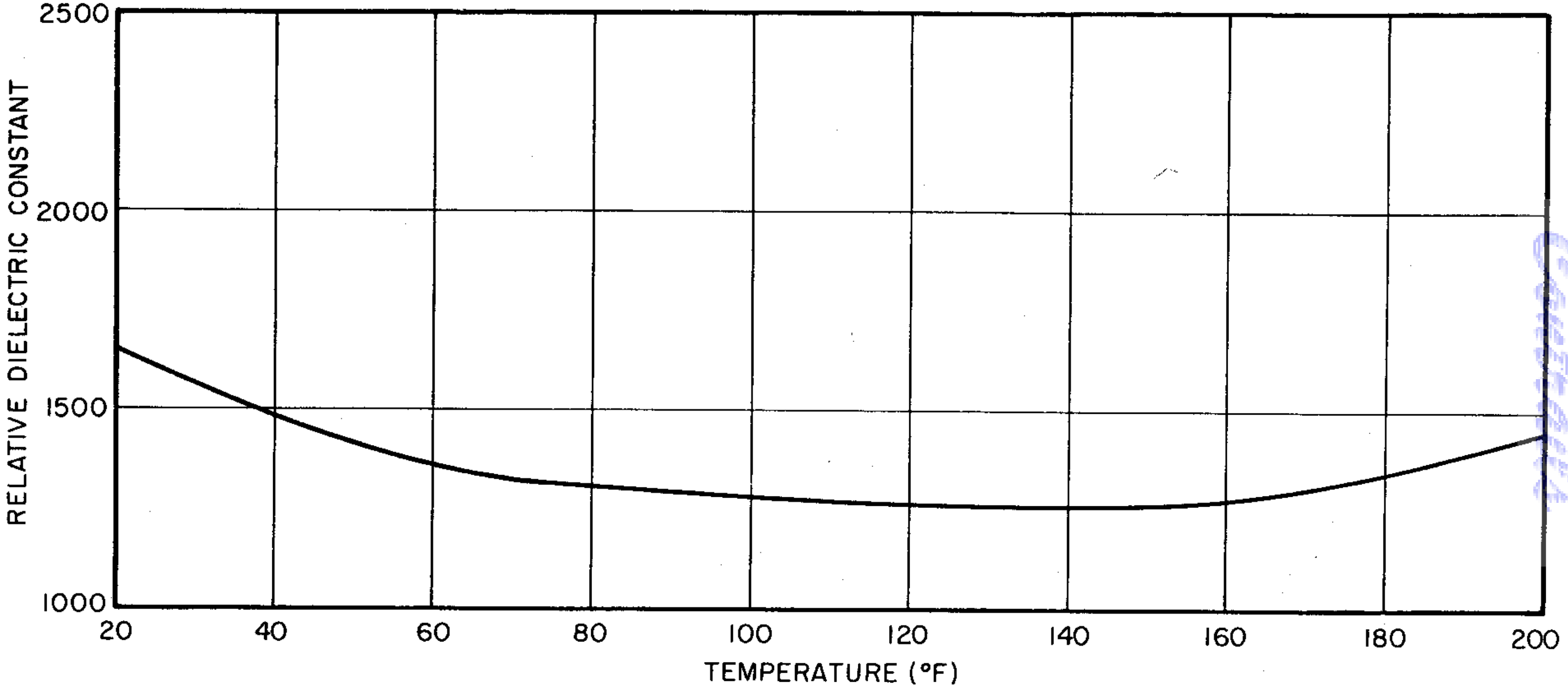


FIG. 31 TYPICAL VARIATION OF DIELECTRIC CONSTANT WITH TEMPERATURE FOR BARIUM TITANATE WITH 4% LEAD TITANATE ADDITIVE SUCH AS USED IN ELEMENT OF SHURE TYPE 98100 MICROPHONE

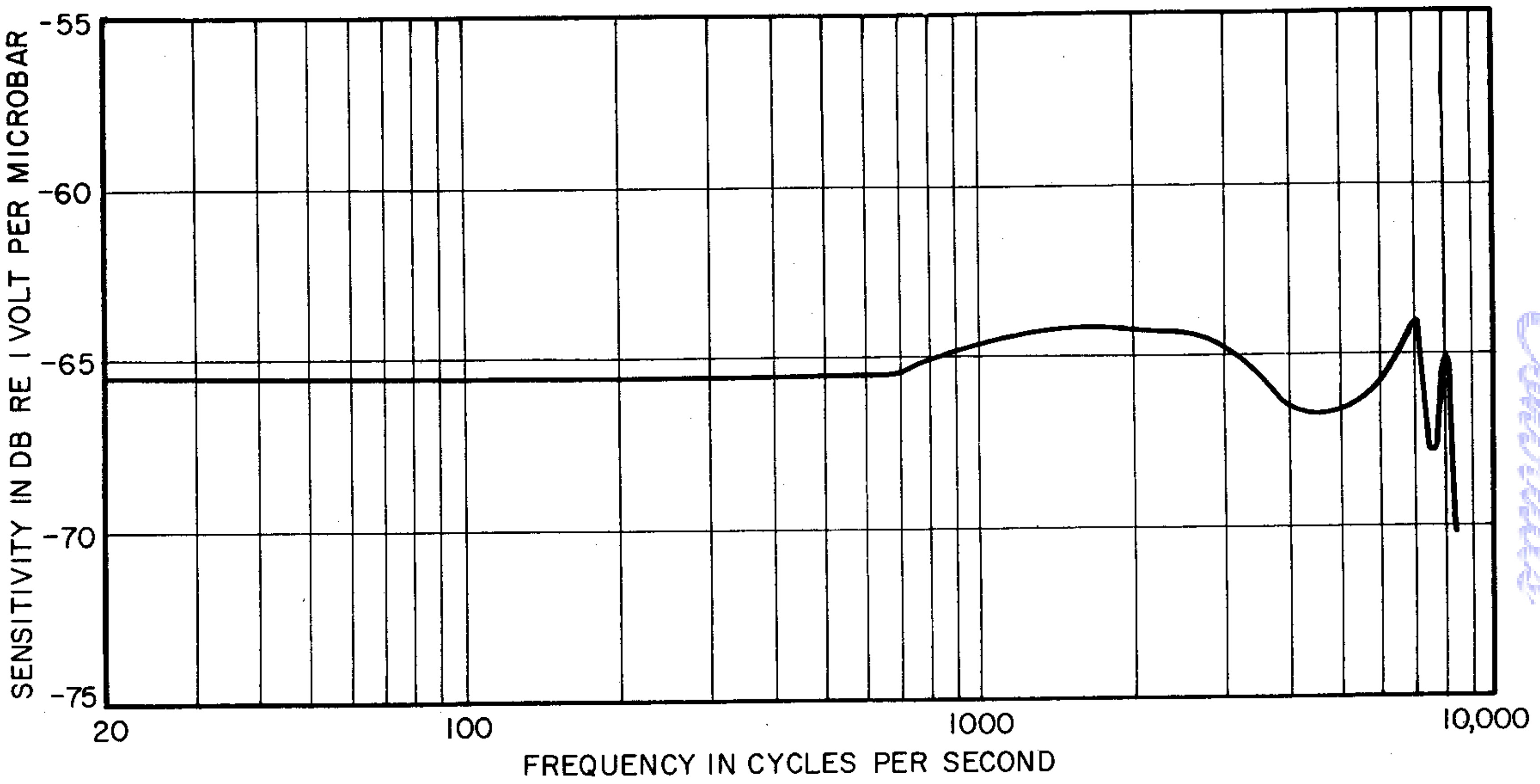


FIG. 32 FREE-FIELD NORMAL INCIDENCE SENSITIVITY OF SHURE MICROPHONE TYPE 98100, SERIAL NUMBER 107. 5 JAN. 1955.

C. Barium Titanate Cylinder Microphones.

Study and evaluation of a barium titanate cylinder microphone is now going on in our development section. Such a microphone is expected to have several advantages in high sound pressure level work.

Being relatively insensitive, the output voltages will not overload electronic equipment when the microphone is subjected to high sound pressure levels. There will be no diaphragm subject to splitting. The upper limit of measurable sound pressure will be of the order of hundreds of atmospheres. The temperature variation of capacitance is relatively slight, as shown in Fig. 31.

Limitations to the use of the barium titanate cylinders include the usable temperature range which extends up to 200°F and the previously-mentioned low sensitivity which puts a lower limit on the sound pressure detectable by the microphone.

D. Condenser Microphones

The Altec Type 21BR150 condenser microphone has been found useful for two special applications in evaluating jet engine test cells. With this microphone it is possible, under certain conditions, to make sound pressure level measurements at temperatures as high as 500°F. A special battery operated preamplifier for this microphone is a product of the General Radio Company. The preamplifier assembly and power supply is designated as Type 1551-P1. The preamplifier is approximately 3/4 in. in diameter and 3 in. long and contains a one-tube cathode follower. It is separated from its battery-operated power supply by a 10 ft cable.

The microphone and preamplifier can be operated continuously at temperatures below 225°F. By changing the tube in the preamplifier to a heavier duty tube such as a Raytheon Type CK5975, the preamplifier and microphone assembly can be operated satisfactorily to temperatures of 500°F. It should be noted that the heavier duty tube in the preamplifier requires an increased filament supply voltage. The free-field frequency response at normal incidence for a typical 21BR150 is presented in Fig. 33. In Figure 34 is shown the variation of microphone sensitivity with temperatures up to 325°F when used with the modified General Radio

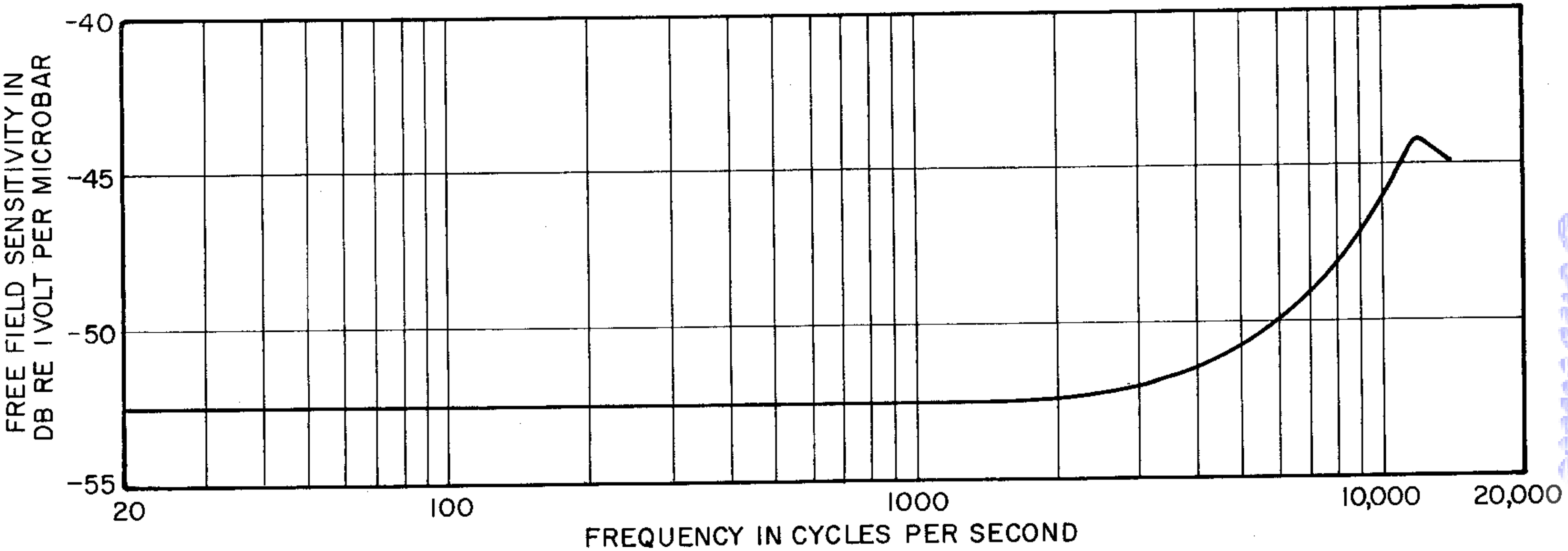


FIG. 33 FREE FIELD SENSITIVITY AT NORMAL INCIDENCE FOR ALTEC TYPE 21BR150 SERIAL NUMBER 7081. DEC.1954.

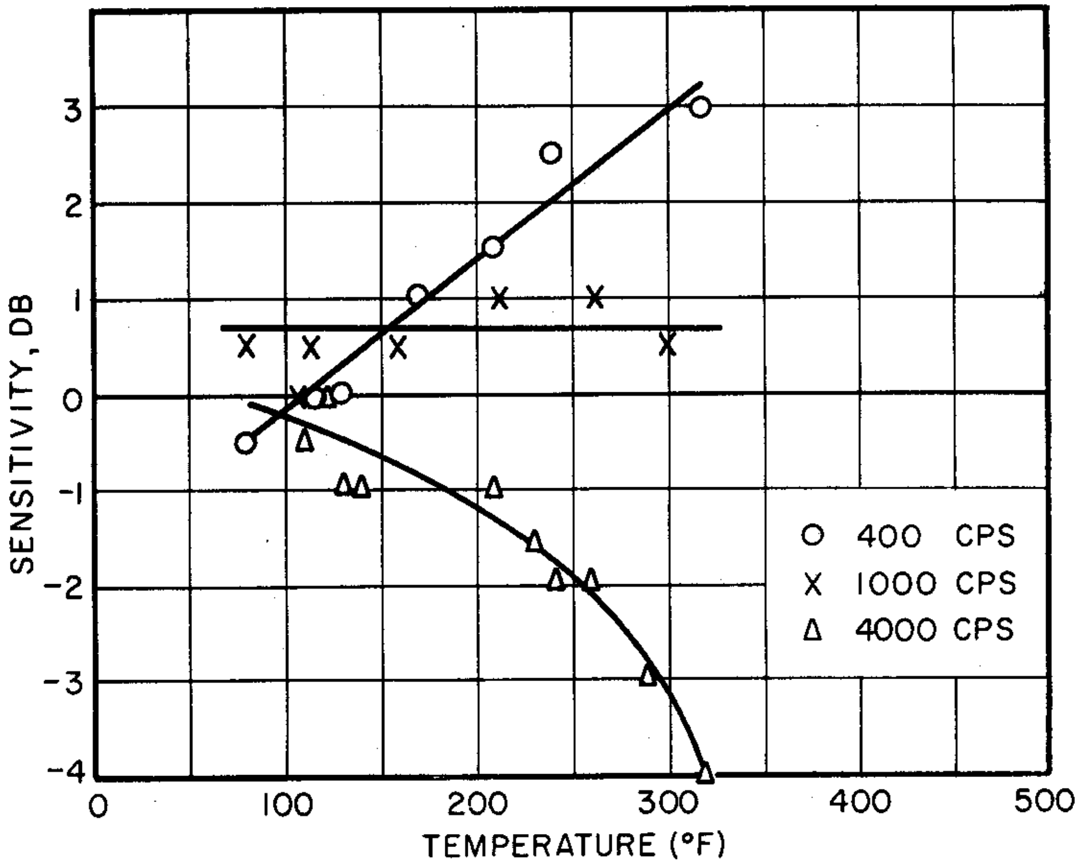


FIG. 34 VARIATION OF SENSITIVITY WITH TEMPERATURE FOR ALTEC 21BR150 MICROPHONE

preamplifier. This curve was obtained after cycling the microphone several times from room temperature to 325°F.

In addition to its satisfactory behavior at elevated temperatures, the Altec condenser microphone has a relatively flat frequency response (Fig. 33). Its disadvantages are: (1) It becomes noisy and even shorts out in only moderately humid weather. This problem is essentially eliminated by using a preamplifier whose tube filament dissipates sufficient heat to keep the microphone temperature above the surrounding air temperature and thereby prevents moisture condensation in the microphone. (2) It requires a much more elaborate preamplifier circuitry than does the crystal microphone. (3) Its cost is several times that of the Shure Brothers Rochelle salt crystal microphone Type 9898.

E. Acoustic Calibrator

The accuracy of all field measurements is based upon an acoustic calibrator as a secondary reference standard. The device which we use is a modified version of the General Radio Type 1552A, 400 cps acoustic calibrator. The transducer in the calibrator has been replaced by a Shure Brothers controlled reluctance microphone cartridge, similar to the Shure Brothers Type R5 unit but with a special low impedance winding. This transducer has greater stability and is capable of a much greater acoustic output than the transducer normally supplied with the General Radio calibrator.

The 400 cps acoustic calibrator is operated in conjunction with the General Radio Type 1307-A transistor oscillator and is physically attached to the oscillator as shown in the photograph of Fig. 5. The front face of the transistor oscillator contains an output voltmeter, an output level adjustment and a combined off-on switch and frequency control. The oscillator can be operated at two fixed frequencies, 400 and 1000 cps. At the present time the acoustic calibrator is used only at 400 cps. When the output level control is adjusted to a meter reading of exactly 2 volts, the acoustic calibrator produces a sound pressure level of 100 db at the diaphragm of a Shure Brothers 9898 microphone that has been properly positioned in the calibrator. Special adapters are used for calibrating other microphones having different physical dimensions.

A minimum of three acoustic calibrators are taken on each field trip and they are intercompared frequently. In addition, their absolute calibration is checked prior to each major field trip. By inter-comparing the three units frequently, any change in the calibration of one of the units is readily detected.

The absolute level of the 400 cps acoustic calibrator is set in the laboratory by the following procedure. A Western Electric 640AA condenser microphone and preamplifier are positioned in the low frequency microphone calibration duct in the laboratory. A 400 cps tone is applied to the duct loudspeaker and is adjusted to produce a sound pressure level of 100 db re 0.0002 microbar at the reference microphone.

After the 100 ± 0.1 db sound pressure level field has been established at a point in the duct the standard microphone is removed and a Shure Type 9898 crystal microphone is carefully positioned in exactly the same place. It is to be noted from the duct calibration curve of Fig. 14 that, at 400 cps, a standing wave ratio of only 0.7 db exists between adjacent pressure maxima and minima. Therefore, the variation in the acoustic pressure level is less than 0.1 db within 3 in. of the pressure anti-nodes at this frequency. The output of the crystal microphone is observed on a meter. The duct sound source is turned off and a 400 cps acoustic calibrator placed over the same microphone. The acoustic calibrator output is then adjusted to give the same reading on the meter as did the 100 db sound field in the duct. This adjustment is made by means of a calibration control inside the transistor oscillator. During the adjustment, the electrical output of the transistor oscillator is held at exactly 2 volts. The same procedure is then repeated for all of the acoustic calibrators. Usually more than one crystal microphone is used for this calibration procedure.

Experience has shown that all seemingly identical Shure Type 9898 crystal microphones do not respond exactly alike to the pressure field inside the acoustic calibrator. There appears to be no unique relationship between the microphone's performance in the 100 db sound field of the calibrator and the calibration of the microphone with a plane wave sound source in a free field. The sensitivity of each crystal microphone is accurately measured in the duct using a 400 cps plane wave. Immediately following this, the sensitivity is measured with a 400 cps acoustic calibrator. These tests show the mean deviation between the two methods for a group of 20 to 50 Rochelle salt microphones is ± 0.4 db. Individual microphones that show deviations from the mean of more than 0.4 db are rejected. This test is repeated after microphones have received rough usage on field trips or have been accidentally dropped.

Measurements have been made to determine the temperature dependence of the acoustic output of the calibration system comprising the transistor oscillator (with its indicating meter) and the acoustic calibrator. The results of these measurements are presented in Fig. 35 in which the variation in the sound pressure level generated by the calibrator is plotted as a function of the temperature of the calibration system and the surrounding air. In the region around 70°F the system is seen to have a dependence of about -0.02 db/°F. A calibrator which is correct at 70°F will therefore be subject to a variation of ± 0.5 db over the temperature range 40°F to 100°F.

Actually the effect shown in Fig. 35 is ascribable directly to the variation of air temperature in the calibration cavity and to the temperature of the calibrator transducer. Also shown in Fig. 35 is the calculated theoretical dependence of the calibrator output on the temperature of the air in which it operates. This calculated variation accounts for an appreciable part of the observed variation and implies that the acoustic output of the calibrator depends not only on the temperature of the calibrator itself, but also on the temperature of the air in which the calibrator operates. Figure 35 shows that the error is not great for the range of temperatures considered safe for Rochelle salt microphones.

Another variation of calibrator output pressure with temperature is due to dependence of acoustic output on oscillator frequency. Over a range of several octaves in the vicinity of 400 cps the acoustic output of the calibrator rises uniformly with a slope of + 10 db/octave. Experiments have shown that over the temperature range 0°F to 120°F the frequency of the transistor oscillator varies approximately ± 1% from 400 cps. The variation in acoustic output due to temperature-induced frequency shift is therefore approximately ± 0.14 db over the range of 0°F to 120°F.

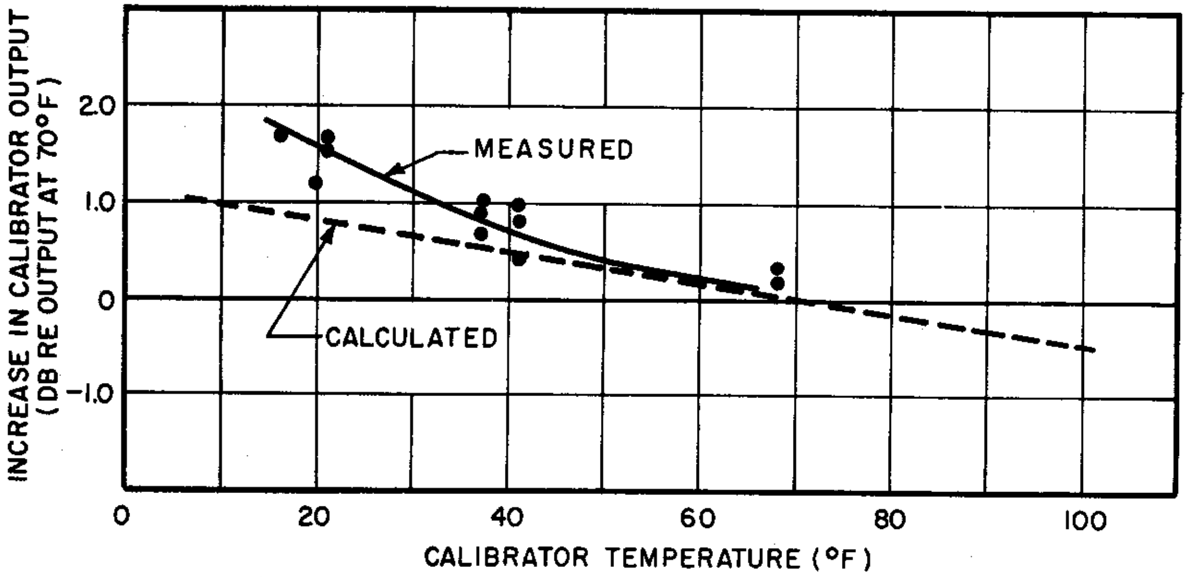


FIG. 35 TEMPERATURE DEPENDENCE OF ACOUSTIC PRESSURE GENERATED BY MICROPHONE CALIBRATOR. (CONSTANT VOLTAGE INDICATED BY THE TRANSISTOR-OSCILLATOR OUTPUT METER)

F. Crystal Microphone Preamplifier

The importance of a preamplifier for use with a Rochelle salt crystal microphone when long cables are necessary was discussed above under Sec. A, Diaphragm Rochelle Salt Crystal Microphones. In addition to the need for temperature stability it is also necessary to avoid the pick-up of voltages induced by acoustical or mechanical excitation of the microphone cable. Such "microphonics" are often a serious problem when using microphones of low internal capacitance. This difficulty is eliminated if a preamplifier is used between the microphone and the cable.

The preamplifier must have a high input impedance (greater than 10 megohms) and a low output impedance. The high input impedance eliminates the effects of temperature due to variation of microphone capacitance. The low output impedance greatly reduces problems due to cable microphonics and pick-up from stray electrical fields. A photograph of the preamplifier is shown in Fig. 6. The microphone is plugged into one end of the unit and the cable into the other end. The unit has a self-contained, battery-operated power supply. The batteries are turned on by plugging in the output cable, which in turn closes the filament circuits of the tubes inside.

A schematic wiring diagram of the preamplifier is shown in Fig. 36. Numerous tubes were tried and the Raytheon Type CK512AX was found to be sufficiently quiet in operation and less subject to microphonics than any other tube. The only disadvantage with this tube as a cathode follower is its low transconductance. With two of these tubes operated in parallel the output impedance of the preamplifier is approximately 2000 ohms. This output impedance is low enough to allow cable lengths up to several hundred feet. When longer cables are necessary, additional preamplifiers are inserted into the line at intervals of 300 to 400 ft of cable length.

The heater current is supplied by a small mercury cell. The two-tube filaments are connected in series and each requires 20 milliamperes at 0.625 volts. The total plate current of the two tubes is approximately 300 microamperes. Because the filaments of the two tubes are in series and the control grids are in parallel there is a slightly different quiescent bias voltage on each tube. This requires one of the tubes to do most of the work at low signal levels. At high signal levels where the power output requirements are more stringent the difference in bias on the

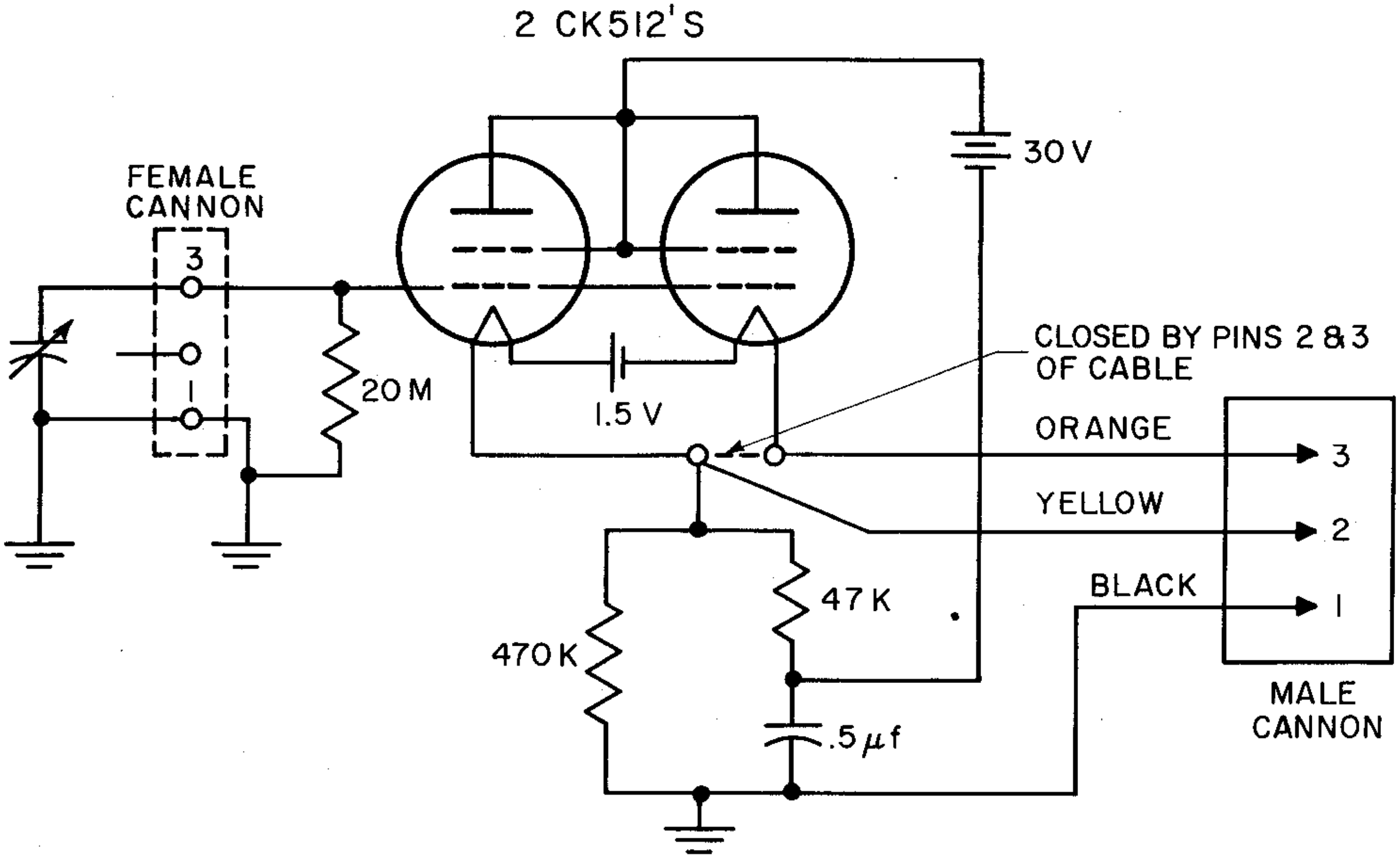


FIG. 36 BATTERY-OPERATED PREAMPLIFIER

two tubes is negligible and the plate loads are balanced. The maximum undistorted output is approximately 6 volts rms into a load whose impedance must be not less than 20,000 ohms. This voltage is about equal to the voltage output from a Type 9898 Rochelle salt crystal microphone in a 150 db sound field. When it is necessary to measure slightly higher sound levels, a 20 db capacitance loss pad (Fig. 30) is connected in series with the microphone. The filament battery and the plate battery have a life span slightly over 100 hours under conditions of continuous operation.

The mercury cell used for the filament supply has the advantage of constant voltage throughout its life. A serious disadvantage is that its internal resistance increases rapidly with decreasing temperature below 40°F. The preamplifier will not function if the temperature of the filament battery is permitted to fall below 35°F. Some electrically heated sleeves have been constructed to fit over the preamplifier. These are operated from a six-volt dry battery and permit operation in sub-zero temperatures. For milder temperatures it is possible to hand-hold the preamplifier and microphone allowing the warmth from the hand to keep the battery temperatures above 40°F. Occasionally the series of sound measurements is so short that the thermal lag, itself, is adequate protection. Normal operation of the cathode follower may be expected for 15 minutes or so at low temperatures immediately after the preamplifier has been removed from a warm room.

G. Microphone Cables

Microphone cables have been used extensively for work under this contract. Field trips may require the use of over 100 separate cables. Five standard lengths are used; namely, 5, 10, 25, 50, and 100 feet. Each cable is terminated with a Cannon XL male cable connector at one end and a Cannon XL female cable connector at the other end. These Cannon connectors are inexpensive, easy to use and maintain, and are very rugged and dependable.

The cables are of the coaxial type with a copper braided shield and either a solid or standard center conductor. The shield is covered with rubber giving the cable a nominal outside diameter of 1/4 inch. All of the cables except the 100 ft length are a Birnbach Type 1872. The 100 ft lengths are made of RG62U cable manufactured by Amphenol Corporation with a nominal capacitance between center conductor and shield of 13.5 micro-microfarads per foot. All other microphone cables have a nominal capacitance of 30 micro-microfarads per foot.

The RG62U cable has a solid copper inner-conductor and is not as easily handled as the other type. Also, it is not recommended for use with crystal microphones without preamplifiers as the cable is excessively microphonic. The metal shell of the Cannon cable connectors must be grounded to the cable shield or to the ground side of the microphone line. The output impedance of the microphone preamplifiers is not sufficiently low to prevent hum pick-up from ungrounded cable connector housings.

H. Remote Control Selection of Microphones

When measuring noise inside test cells, it is often inconvenient or impossible to run a cable for each individual microphone from the microphone to the field-data tape recorders outside of the test cell. Electrical conduit space through the wall between the test cell and its control room is usually limited. Sufficient space can generally be found for running several small microphone cables through the wall but seldom is there enough space for 20 to 50 cables. Even if all of the individual microphone cables were brought in separately to the magnetic tape recorder, some means would be required for switching from the electrical output of one microphone to that of another. The problem is much less complicated if the switching among microphones is done near them. In this way the microphones in a group are individually connected to the switchbox through short cables and only one output cable from the switchbox is necessary from the test cell to the tape recorder in the control room. In addition, another cable is required to control the switchbox. Each switchbox contains an electrically operated 12-position rotary switch. (See Fig. 7). Each of the 12 positions can be used to select the signal from 12 different microphones. The selector switch is a Ledex stepping switch manufactured by the L. H. Leland Company.

The outputs of all microphones connected to the control box except the one that is being sampled are short-circuited. Cross-talk between various microphone signals inside the control box is thereby eliminated. The selector switch steps from one position to the next upon receiving an electrical impulse over its control cable from a pushbutton switch located near the field-data tape recorders. Associated with the pushbutton is an indicator dial which enables the operator to know which microphone is connected to one of the magnetic tape recorders. Each time the push-button is depressed a different microphone output is selected.

I. Spectrum Shaping Filters

The octave bands of one-third octave bands of the noise spectrum near a turbojet engine or near the cannon usually have almost the same (within 10 db) sound pressure levels. The noise spectrum of a jet after it has passed through an acoustical treatment to the outside of the test cell has a very different shape. When the engines are operating near full power the sound pressure levels outside the test cell in the lower bands are much greater than those in the higher bands. Sometimes the levels in the lower bands are over 60 db greater than those in the higher bands. Such spectra can be accurately measured only with acoustic measuring apparatus having an extraordinarily wide dynamic range.

A practical solution to the problem of a very non-uniform spectrum is to discriminate electrically against the low band levels in the output of the noise measuring microphones. A more uniform spectrum from the microphone imposes a less stringent requirement upon the electronic apparatus. The spectrum shaping filters which are used are simple RC high pass filters. A photograph of typical filter units is shown in Fig. 37. One of two types of filters is used depending upon the amount of low frequency attenuation required. The frequency responses of two types are shown in Fig. 38. The filters are designed to have an S-shaped characteristic. The inverse of these filters, a low pass filter, is used at the time the field data are reduced on the automatic data reduction system. The filters are designed to have S-shape characteristics to facilitate the practical realization of the inverse filters. At the time of measurement in the field, the filter is inserted in the microphone line immediately ahead of the magnetic tape recorders. In practice, these filters are used only when the band levels drop more than 40 db between the 20-75 cps and the 4800-10,000 cps bands.

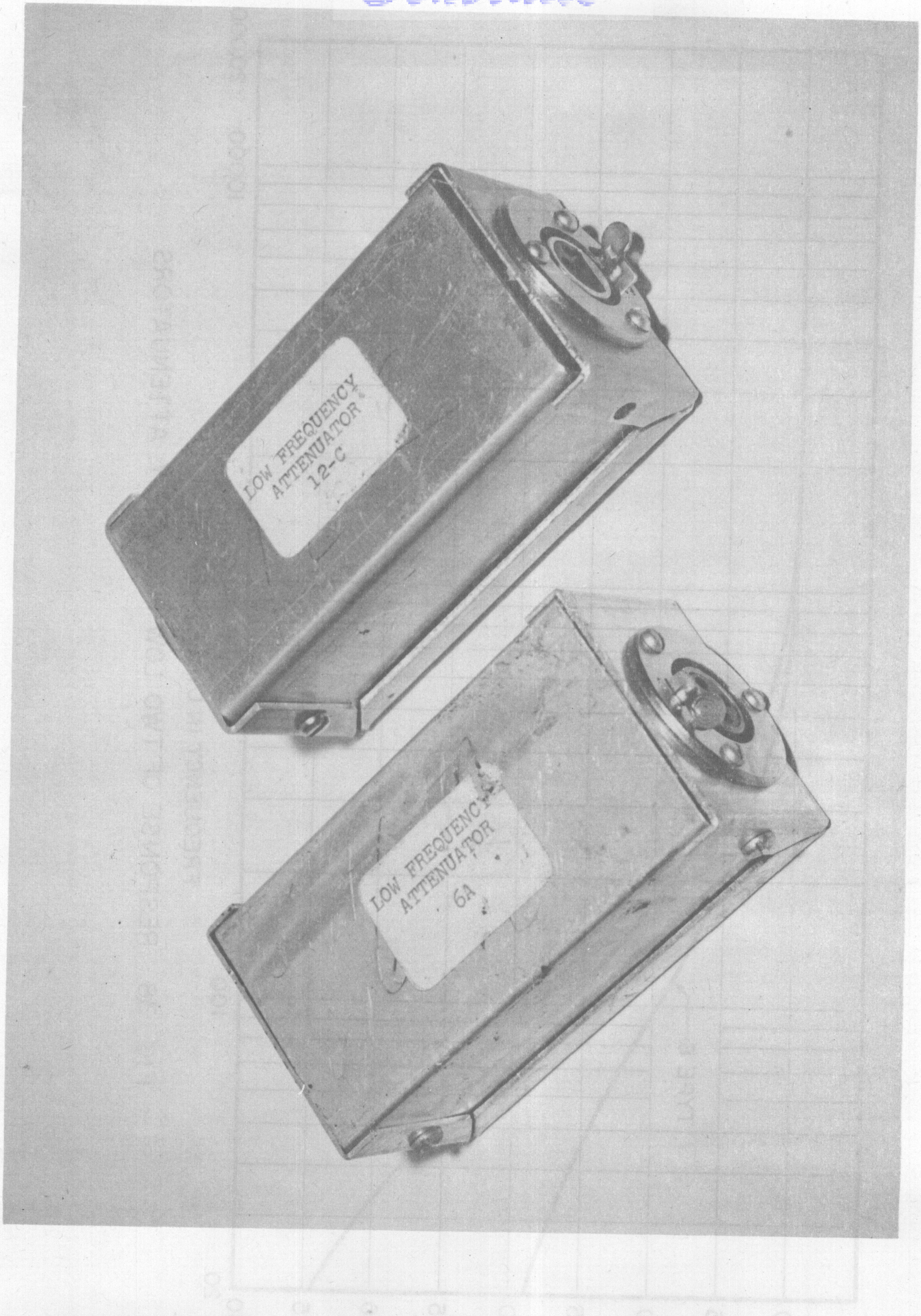


FIG. 37 PHOTOGRAPH OF LOW FREQUENCY ATTENUATORS

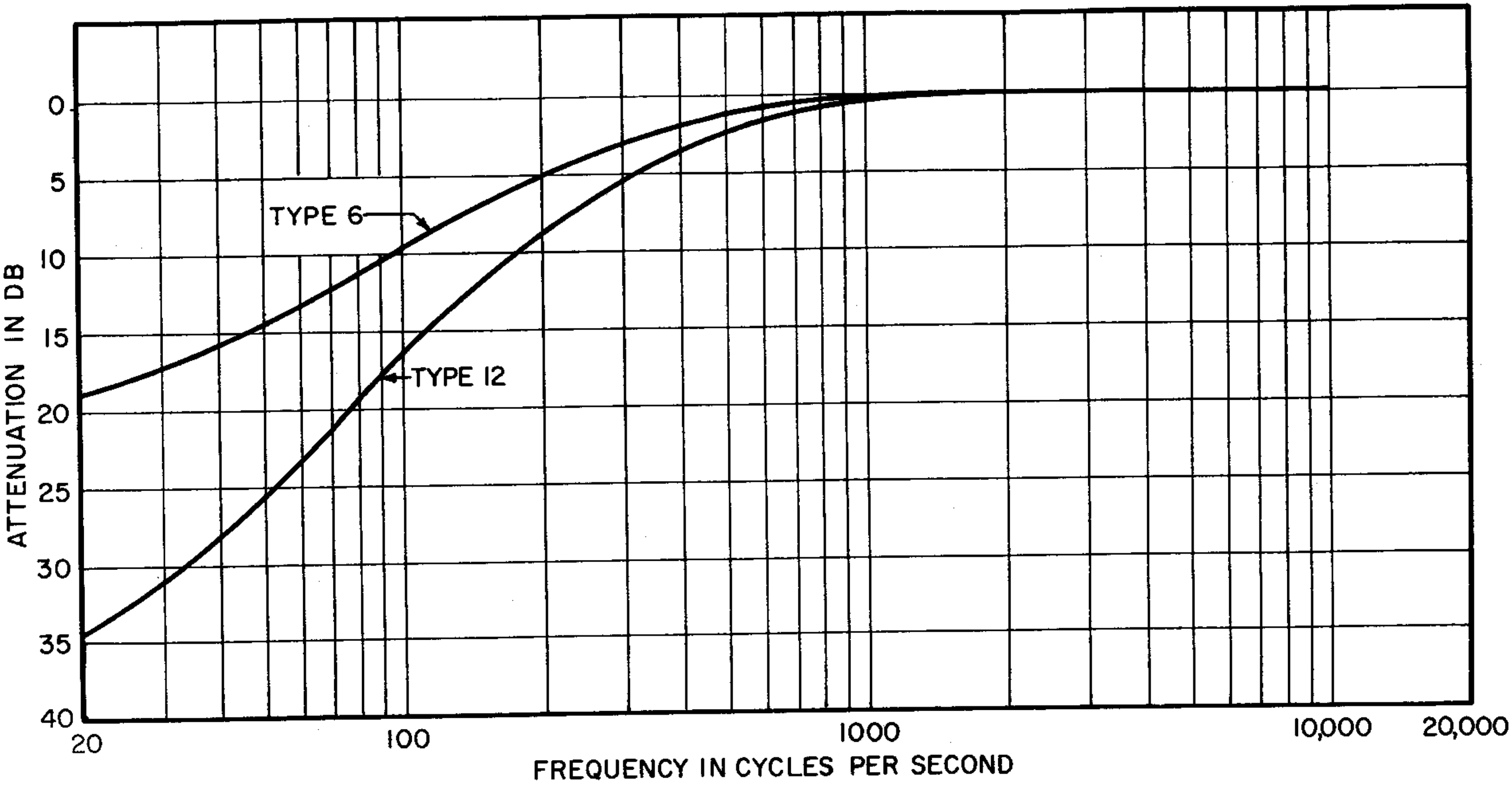


FIG. 38 RESPONSE OF TWO LOW FREQUENCY ATTENUATORS

J. Field-Data Magnetic Tape Recorders

It is our belief that detailed acoustical surveys are most effectively carried out by using magnetic tape recorders. The advent of the magnetic tape recorder greatly simplified many acoustical engineering tasks. The reasons involved in the choice of a particular type of magnetic tape recorder were discussed earlier in Sec. IV, Field Data Taking Systems. The equipment which was chosen is manufactured by the Magnecord Corporation. Each tape recorder records two magnetic tracks simultaneously on one tape. Three of these twin-channel recorders were found necessary to perform the required tasks. They are amplifiers Type PT6BN and tape transport mechanisms Type PT6BAH. A photograph of tape recorder amplifiers and tape transport mechanisms is shown in Fig. 3. These tape recorders required extensive modifications in order to meet the high performance standards required for carrying out the work on this contract. The most important modifications to the equipment are discussed here briefly.

Input Circuits. The nominal input impedance to the microphone amplifiers was 30 ohms. For the majority of our field work an unbalanced line and relatively high input impedance is required. The manufacturer's microphone input transformer was removed from the circuit to permit the microphone signals to pass through a precision input attenuator and directly to the grid of the first amplifying tube.

Precision Attenuators. There is a precision attenuator in the input circuit of each amplifier channel. These are of the precision decade type having an increase of attenuation of 10 db per step covering the range in eleven steps from 0 to 100 db. These attenuators have an error of less than 0.1 db on any and all steps below frequencies of 1000 cps. At 10,000 cps, the error is within 1/2 db at all settings. Each attenuator is split into two sections having 50 db of attenuation in each section. The attenuator section between 0 and 50 db is located between the first and second stages of voltage amplification. The second section of the attenuator, between 50 and 100 db, is across the input to the amplifier, before the grid of the first stage. This arrangement has several advantages over placing one attenuator of 0 to 100 db at the input of the amplifiers. Each of the two 50 db sections of the attenuator has an input impedance of 500,000 ohms. At these high impedance levels an attenuator having a total attenuation of 100 db would have very poor accuracy at the higher audio frequencies. At high input signal levels (with the attenuator setting between 60 and 100 db) the microphonics from the tube in the first stage are reduced by 50 db so that the signal-to-noise ratio of the recording amplifier is improved by approximately 40 db, that is, by the gain of the first stage.

Regulated Power Supply. The two amplifiers in the twin-channel recorder are completely independent except for a common power supply. It was found that line-voltage fluctuations of 10% produced a change in gain of about 1 db in the recorder amplifiers. This instability was virtually eliminated by installing voltage regulator tubes to stabilize the plate supply to all amplifying tubes except the power output stage.

Recording Bias Meter. Changes in amplitude of the high frequency bias current in the tape recording heads will alter both the level and the frequency response of the tape recordings. A means for easily monitoring this bias current is desirable even though the high frequency bias current is normally very stable. The 50 kc bias current in the bias winding of the record head is sufficiently high to induce a signal of several volts across the recording winding in the recording head. This induced bias signal appears across the output of the recording equalizers. The VU meters on the front panel of the recording amplifiers are connected through a front panel switch for monitoring this bias current. Any changes in the output level of the bias oscillator are readily detected by a slight change in the meter reading. As an example, a bias current change equal to a meter reading of 0.5 db on the VU meter represents a change in the recording sensitivity of less than 0.5 db at any frequency.

Recording Overload Indicators. The VU meters on the recording amplifiers are intended as a means for monitoring the signal level being fed to the recording heads. The standard VU meter responds to the mean value of the rectified signal. The meter ballistics are intended to monitor the amplitude level of human speech. On the other hand the maximum signal which can be recorded on tape for a given distortion is directly related to the peak value of the incoming signal. A peak-reading VU meter would be of greater value on a magnetic tape recorder than the average-reading VU meter. The standard VU meter is adequate for monitoring pure tones and noise having near gaussian characteristics but it is of little value for monitoring signals of high peak to average value or impulse type sounds. The use of an explosive noise source (the cannon) made a peak indicating meter for the field-data tape recorders mandatory. For the purposes of this program it is not necessary to be able to read the peak value of the signal directly, but one must know when a pre-determined recording level is exceeded.

To supplement the VU meters on the tape recorder amplifiers, a front panel warning lamp was added for each channel. Each lamp lights and stays lit whenever its respective recording channel is overloaded. Reset buttons mounted next to lamp are pushed to put the lamps out. The primary use of these lamps is to aid in recording cannon data. When recording cannon shots the attenuators on the Magnecord amplifiers are set to the highest permissible gain setting without lighting the overload lamps when the cannon is fired. The VU meter is helpful in establishing the correct attenuator settings. Cannon shots that are just sufficiently high in level to trigger the overload lamps produce a maximum swing of the VU meter needle across 1/4 of its scale face to about a -7 VU reading. After some experience with the sound pressure levels to be expected from the cannon shots, the precision attenuators on the tape recorder amplifiers are readily set to the nearest 10 db step to produce the highest recorded signal level without overloading.

The overload circuits are very simple and reliable. A Raytheon cold-cathode type thyratron having two trigger grids serves both as the triggering device and as the glow lamp. The two control grids are connected through current limiting resistors directly to the plate circuits of the push-pull power output stages of one of the recording amplifier channels. A DC bias voltage appears across the thyratrons so that when sufficient voltages appear on either of the trigger grids the thyratron will fire and remain glowing until the reset button is pushed to remove the DC bias temporarily. A positive potential on the trigger grids is required to fire the thyratron. With the trigger grids connected push-pull across the output stage, whether the signal impulse from the microphone is positive or negative becomes unimportant. The operation of the trigger grids does not distort the output signal of the recording amplifier. The overload indicators are adjusted to trigger on a signal having a peak value of approximately 15 db above the average value of a steady tone giving a reading of zero on the VU meter. Experimentation showed this to be the best compromise between maximum recording level and distortion.

Loudspeaker Loading. The Magnecord amplifiers have a built-in loudspeaker for monitoring the output of the record amplifiers. The load presented by the loudspeaker to the amplifiers is sufficient to reduce the output of the amplifiers as much as 3 db when the monitor speaker is turned on. A simple resistance loss-pad and dummy load were installed so that the recording amplifier always looked into the same load impedance whether or not the loudspeaker was turned on.

Recording Head Assembly. The recording head assembly on the tape transport mechanism is flimsy and can lead to gross errors due to head misalignment. It was found to be necessary to strengthen this assembly with machined aluminum brackets.

Tape Guide Rollers. Another shortcoming of the tape transport mechanism is the inadequate method for accurate alignment of the magnetic tape as it is fed through the recording head assembly. Carefully machined and aligned guide rollers have provided a satisfactory solution to this problem.

Playback Frequency-Response. The frequency response of the record playback system is the most frequently checked of all response curves. It is checked indirectly each time the machine is used for the reduction of data because the field-data tape recorder is included as one of the components in the automatic data reduction system each time the entire system is being calibrated as described in Sec. V-C above. For this reason it is never necessary to know the exact frequency response of the field data tape recorder. However, it is very important that the frequency response of the recorder should not change during its operation on a field trip. The frequency response of each tape recorder is measured before and after each field trip as a precautionary measure.

The frequency responses of the three twin-channel tape recorder systems are shown in Fig. 39.

Signal-to-Noise Ratio. The useful dynamic range of the tape recorder is determined by the signal-to-noise ratio of the playback system. Figure 40 shows the self-noise level of the Magnecord tape recorders at 0 db input attenuator setting. The noise is plotted in octave bands of equivalent sound pressure levels in db relative to 0.0002 microbar (assuming a microphone of sensitivity equal to that

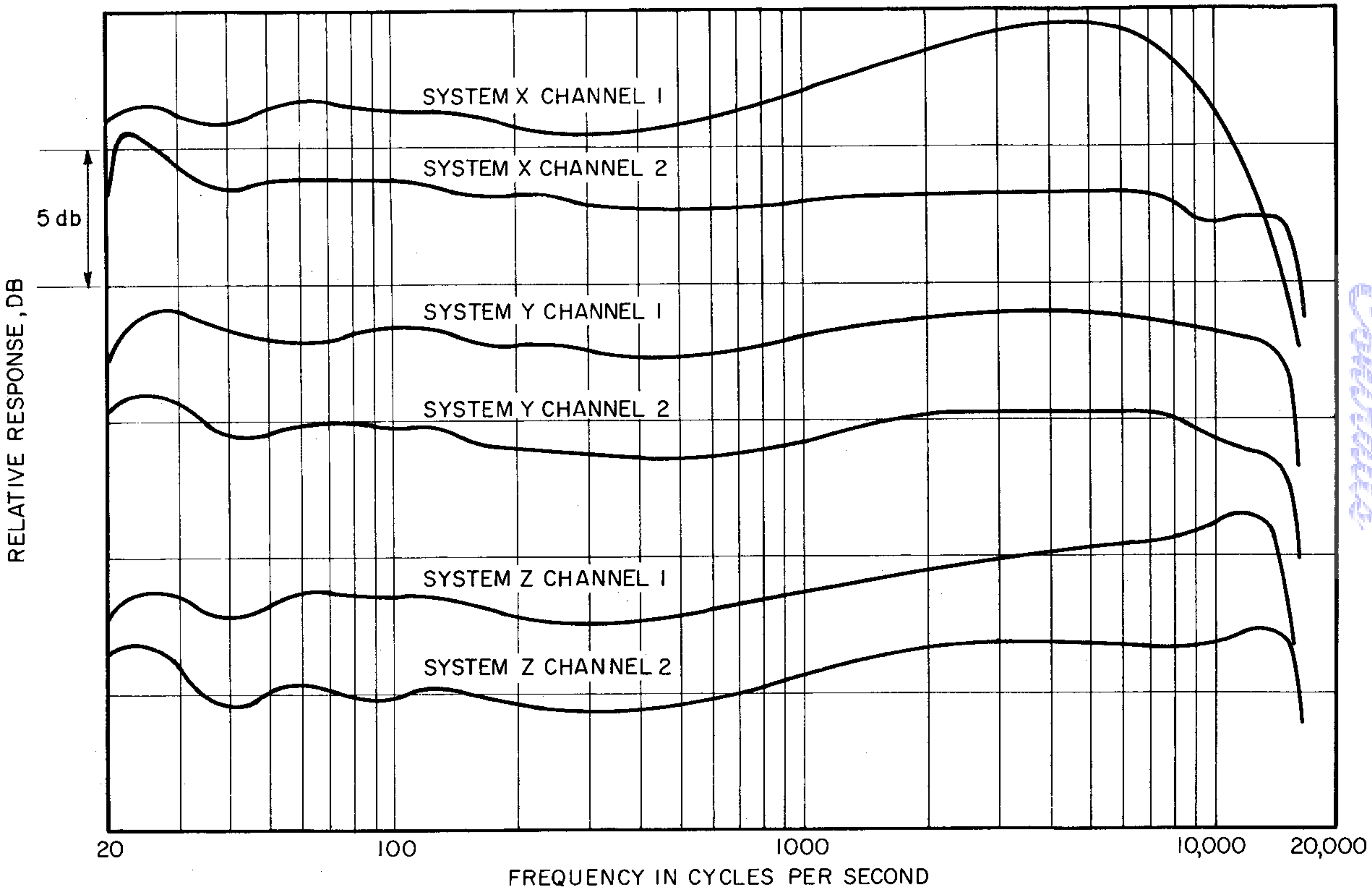


FIG. 39 FREQUENCY RESPONSE OF TAPE RECORDERS

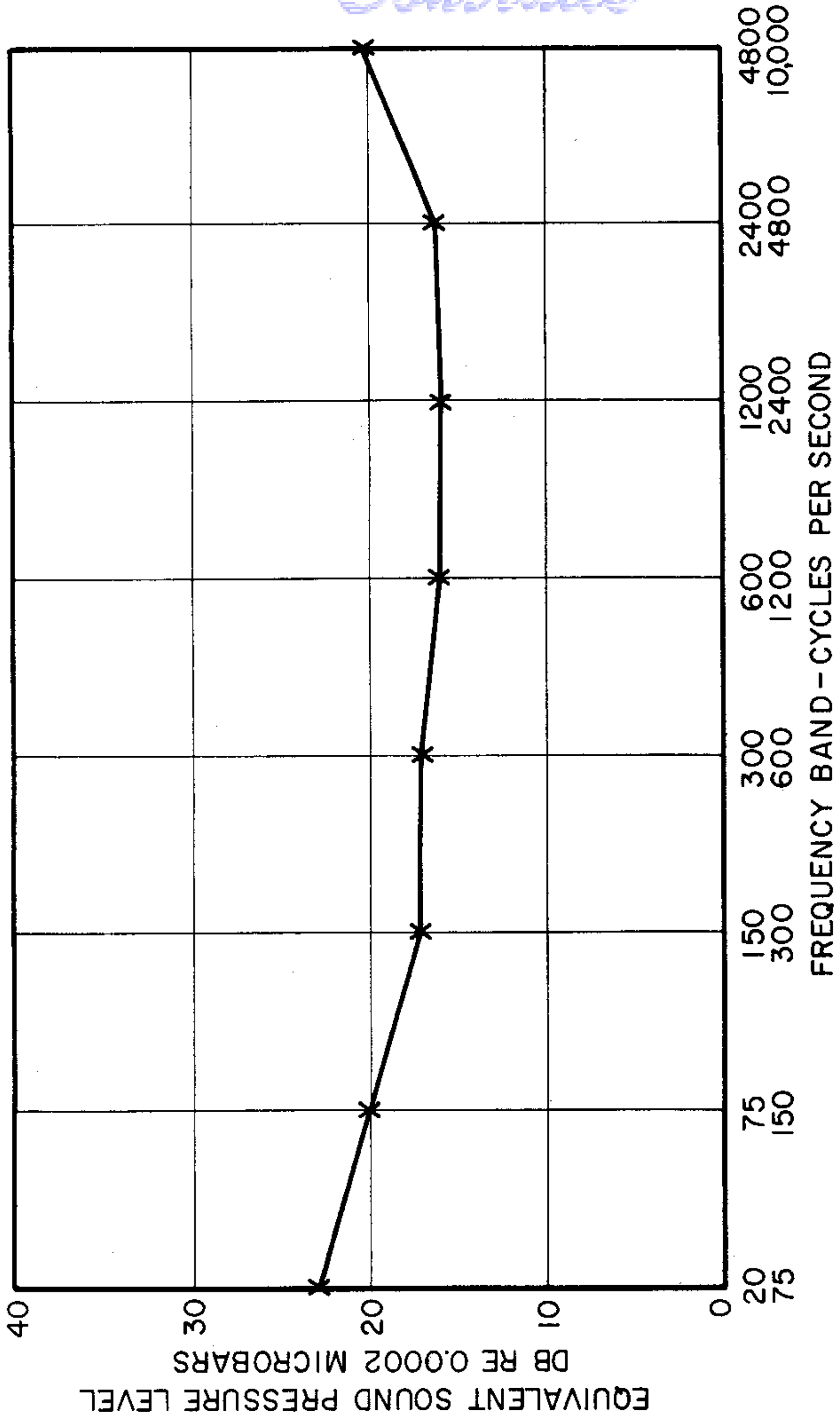


FIG. 40 SELF NOISE OF MAGNECORD TAPE RECORDER AT ZERO DB INPUT ATTENUATOR SETTING

of the Shure 9898). These data are supplemented by Fig. 41 which presents octave band signal-to-noise ratios in db for Magnecord input attenuator settings of 0 db and 30 db to 100 db. The graph shows how far the noise floor lies below a recorded level of zero VU meter reading. The useful dynamic range above zero VU record level will be discussed in the section entitled "Distortion" which follows immediately. For these self-noise tests the amplifier input was connected to the output of a microphone preamplifier because that is the procedure when making sound recordings. A dummy microphone was plugged into the input of the preamplifier in place of the normal microphone. The 60 cycle power line frequency predominates in these curves. This is from hum pick-up in the playback head induced by the tape transport driving motor.

Distortion. Harmonic distortion is generally the only type of distortion that becomes important when working with broad bands of noise. With some types of noise spectra even large amounts of harmonic distortion will not alter the accuracy of measurement. If, on the other hand, the spectrum level decreases rapidly with increasing frequency the requirements on harmonic distortion become very stringent. Figure 42 shows the level of harmonics generated through Magnecord distortion when a 75 cps to 150 cps band of random noise is fed into a Magnecord tape recorder at different VU meter readings. The increased generation of harmonics at higher VU meter readings is clearly evident. In all cases shown the harmonic generation is down at least 25 db at the octaves.

The effect is shown again, perhaps more clearly, in Fig. 43 in which a pure tone of frequency 100 cps is sent into the recorder and the one-third octave band analysis of the output signal is presented for VU meter readings -5 db, 0, +5 db and +10 db.

Stability. Under conditions of continuous operation no important changes in the performance of the amplifiers or the recording heads have been observed. There is, of course, a gradual decrease in the high frequency response due to normal wear of the recording heads. The recording tape tension controls and the tape transport mechanism have to be continually adjusted for changing relative humidity.

Cross-Talk. There is serious cross-talk between the two channels of the twin-channel Magnecord tape recorder.

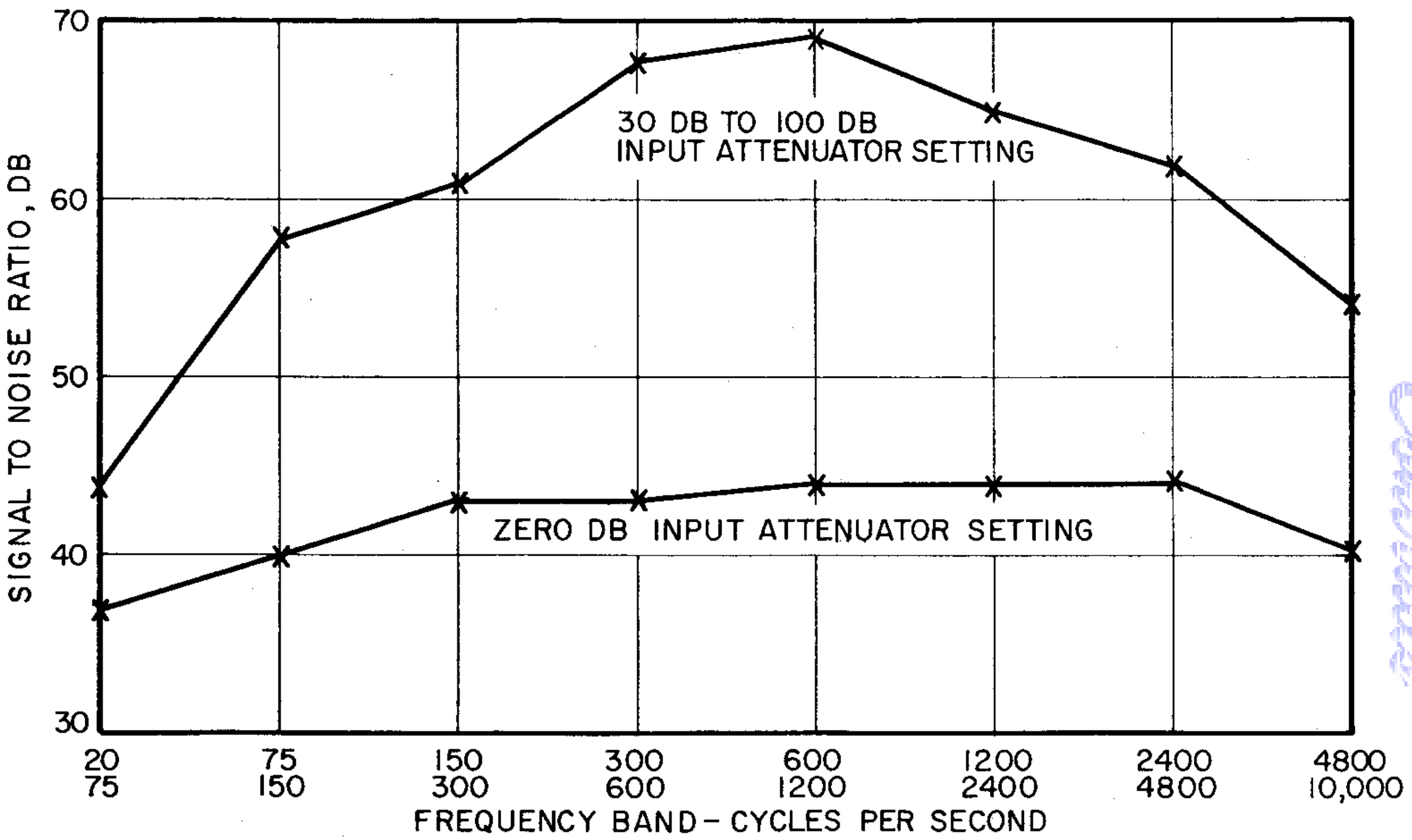


FIG. 41 SIGNAL TO NOISE RATIOS FOR SELF NOISE OF MAGNECORD TAPE RECORDER

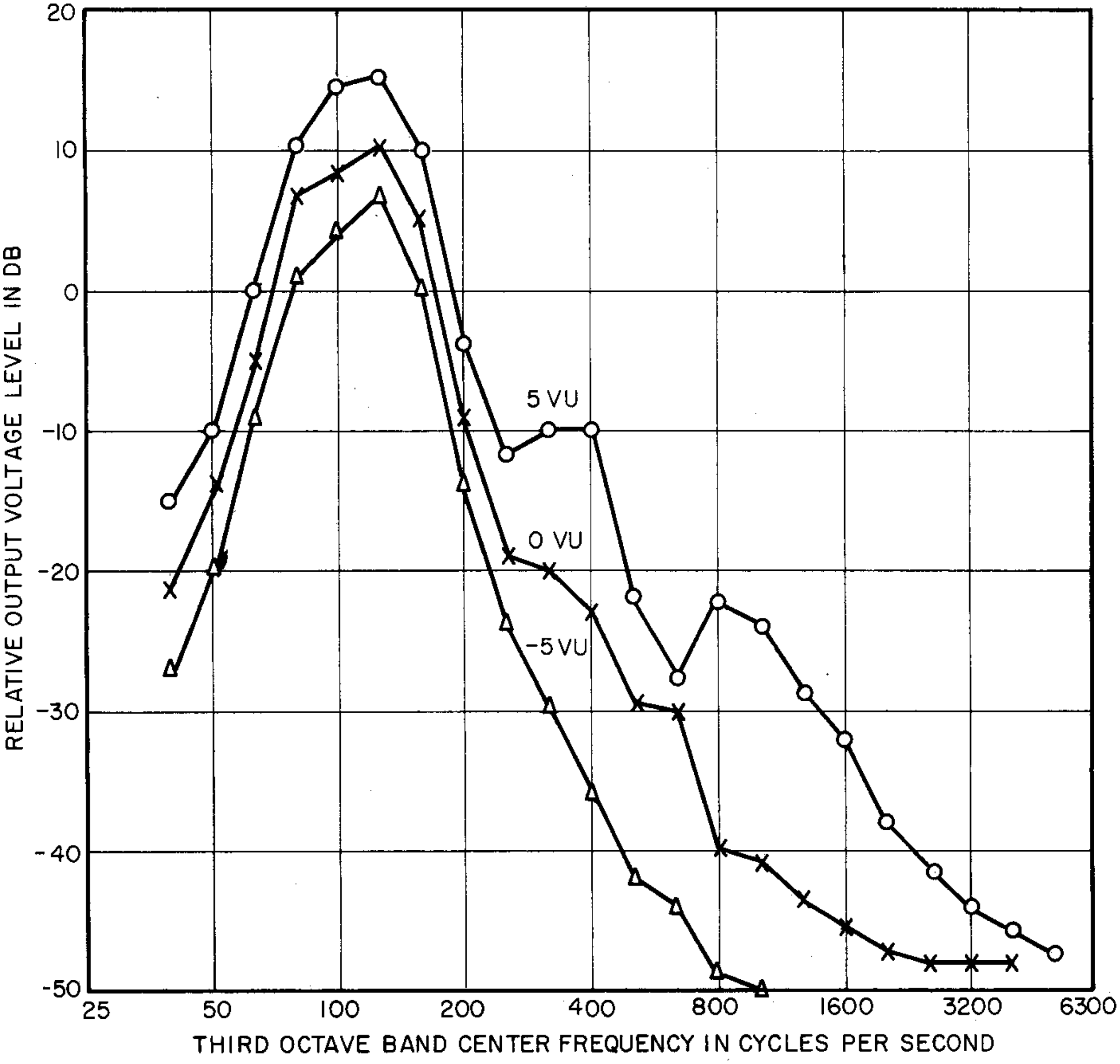


FIG. 42 ONE-THIRD OCTAVE BAND ANALYSIS OF HARMONICS GENERATED BY MAGNECORD DISTORTION FOR A 75 CPS TO 150 CPS BAND OF RANDOM NOISE INPUT.

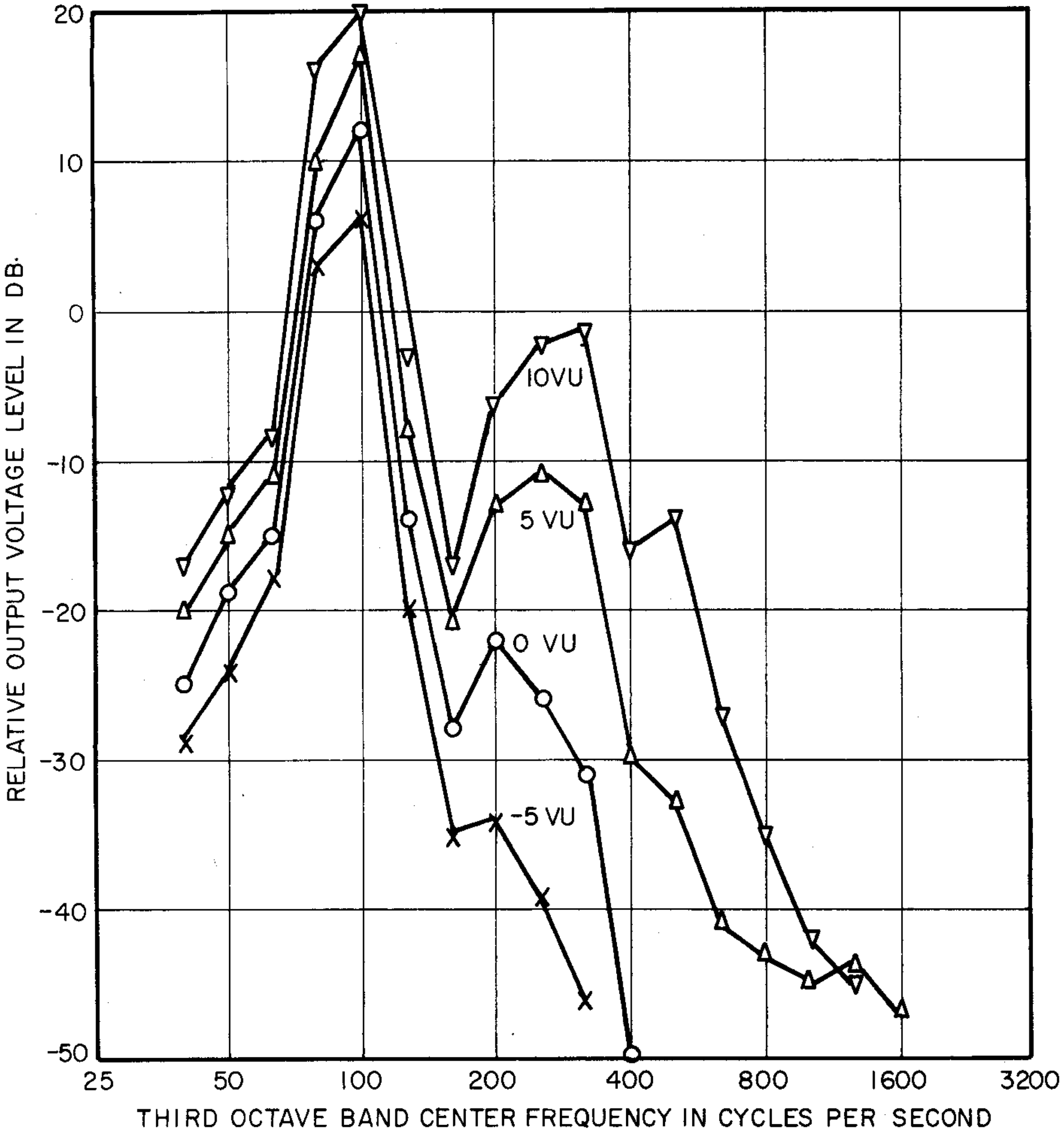


FIG. 43 ONE-THIRD OCTAVE BAND ANALYSIS OF HARMONICS GENERATED BY MAGNECORD DISTORTION FOR A PURE TONE INPUT SIGNAL OF FREQUENCY 100 CPS

The cross-talk is sufficiently bad to make it impractical to record acoustical data on the two channels simultaneously. The difficulty has been avoided in this work by using the second channel for verbal comments only. Figure 44 shows the magnitude of the cross-talk between adjacent channels as a function of frequency. In the test used to obtain Fig.44 a fixed amplitude signal was recorded on channel 2 for frequencies 20 cps to 20,000 cps. Channel 2 had its input attenuator set at 30 db and the VU meter was 0 db; a dummy microphone was connected to a cathode follower which fed into the input of channel 1. Both channels 1 and 2 of this tape were then played back on the same Magnecord.

Tests run on the amplifier alone show that amplifier cross-talk is down at least 60 db in audio frequency range. Much of the phenomenon presented by Fig. 44 occurs at the time a recorded signal is reproduced. The signal on one-half of the tape induces a signal into the unshielded playback head sharing the other half of the tape. Other manufacturers have been successful in greatly reducing the cross-talk between channels by placing a "mu" metal keeper in contact with the recording tape adjacent to the reproduce head and thereby shunting out the adjacent channel. For the present, the cross-talk at low frequencies is minimized by using low frequency attenuators, (which perform as shown in Fig. 38) between the"talk" microphone and the channel 2 Magnecord input.

K. Data Storage Loop Recorder

The loop recorder is an Ampex Type 350-R, Serial No.53K89, rack-mounted tape recorder. It is a standard full-track machine with the modifications which are discussed below.

Modifications. The input and output gain controls were changed in the recorder amplifier. Two precision 600 ohm T-pads replace the input gain control. One is a coarse control having 5 db per step while the other is a fine control having 0.5 db per step. These precision controls each have an accuracy of better than 0.1 db at all audio frequencies. The recorder output-level control was moved to the back of the amplifier. This control is adjusted to give a VU meter reading on the recorder amplifier and is adjusted to a predetermined gain setting. The remainder of the modifications of this tape recorder are primarily in the control circuits for the tape transport mechanism. These circuits are connected with the automatic controls for the data reduction system.

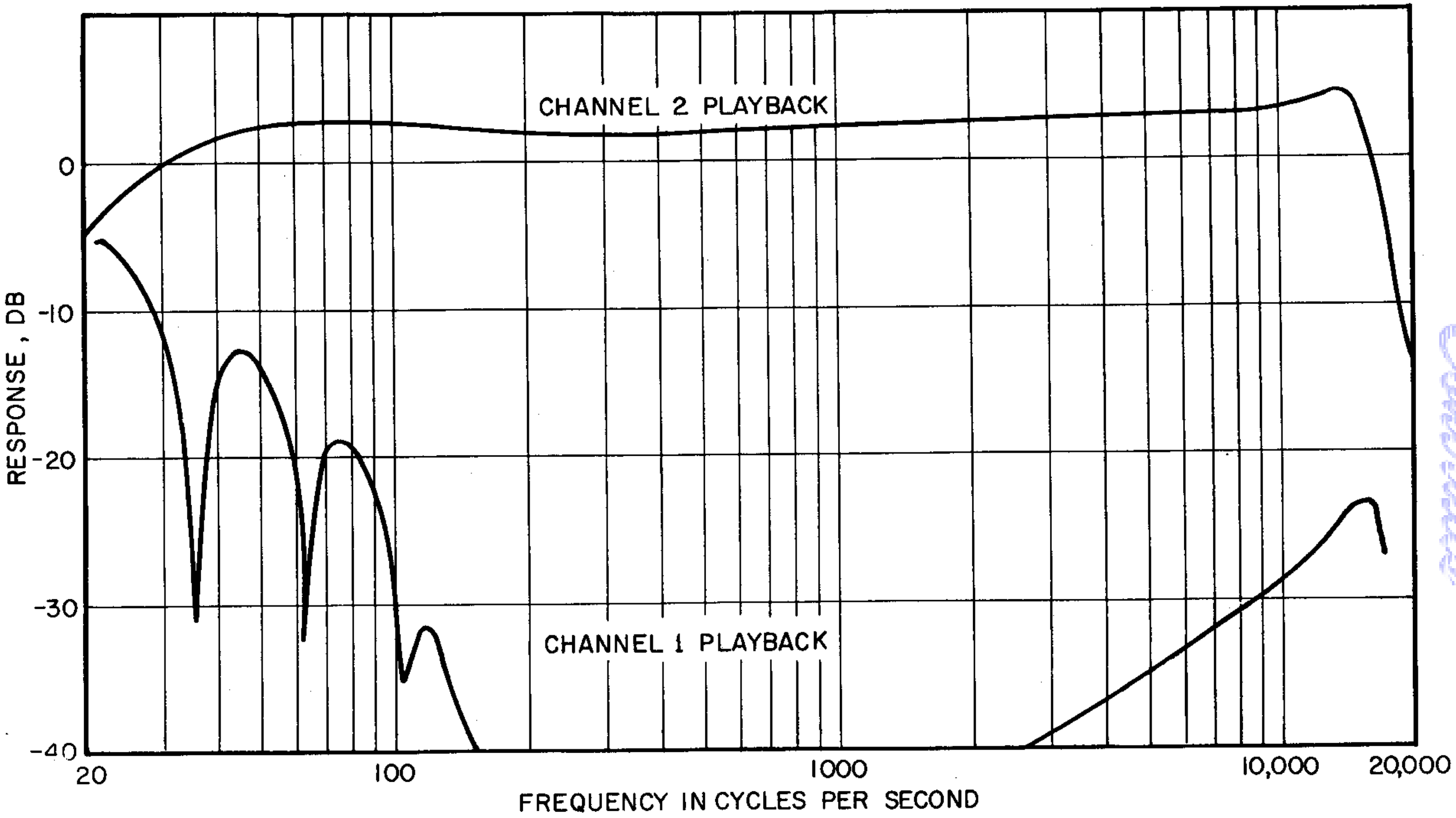


FIG. 44 MAGNECORD CROSSTALK TO CHANNEL 1 FOR SIGNAL RECORDED ON CHANNEL 2

Frequency Response. A typical response of the loop storage recorder is shown in Fig. 45. It should be pointed out that this response is a strong function of the tension on the tape loop and the amount of wear on both the tape loop and the recording heads. Whether the frequency response is flat or not is only of secondary interest provided that the slope is not too great and so long as the response remains constant over the period of a few hours. Although the frequency response of the data reduction system can be adjusted to a flat response in bands, it is important that the response of the entire system should not deviate too greatly from a flat response. A sloping response in the electronic circuits before the band-pass frequency analyzer would produce errors in a measured noise spectrum which is also sloping, especially if the band-pass filters are wide.

Signal-to-Noise Ratio. The VU meter on the amplifier in the tape recorder is adjusted to read zero for a signal level 8 db below the input voltage which would produce a 3% total harmonic distortion. Figure 46 shows how far the noise "floor" of this instrument lies below the zero VU meter reading.

L. Frequency Analyzers.

Three types of frequency analyzers are incorporated into the data reduction system. They are: (1) General Radio octave band analyzer Type 1550-A, Serial No. 101; (2) Bruel and Kjaer Frequency Spectrometer (one-third octave filters) Type 2109, Serial No. 7074; and (3) General Radio Wave Analyzer Type 736-A, Serial No. 1650.

Only the passive filter section of the General Radio octave band analyzer has been utilized. The associated battery-powered amplifier equipment was replaced with a conventional decade voltage amplifier. The selection of the eight filter bands is performed with an electrically-operated solenoid stepping switch. The Bruel and Kjaer one-third octave filter is also actuated by an electrical solenoid. The General Radio wave analyzer has only one band pass filter which is continuously tuned through the audio spectrum. The frequency dial obtains its drive from the Sound Apparatus Company Type FRA graphic level recorder, Serial No. 138. The wave analyzer as received from the manufacturer has an output indicating meter but it has no electrical output to enable the analyzed signal to be recorded. A cathode follower output stage was added so that an analyzed signal can be presented on the graphic level recorder. The output signal is a 50 kc amplitude modulated suppressed carrier.

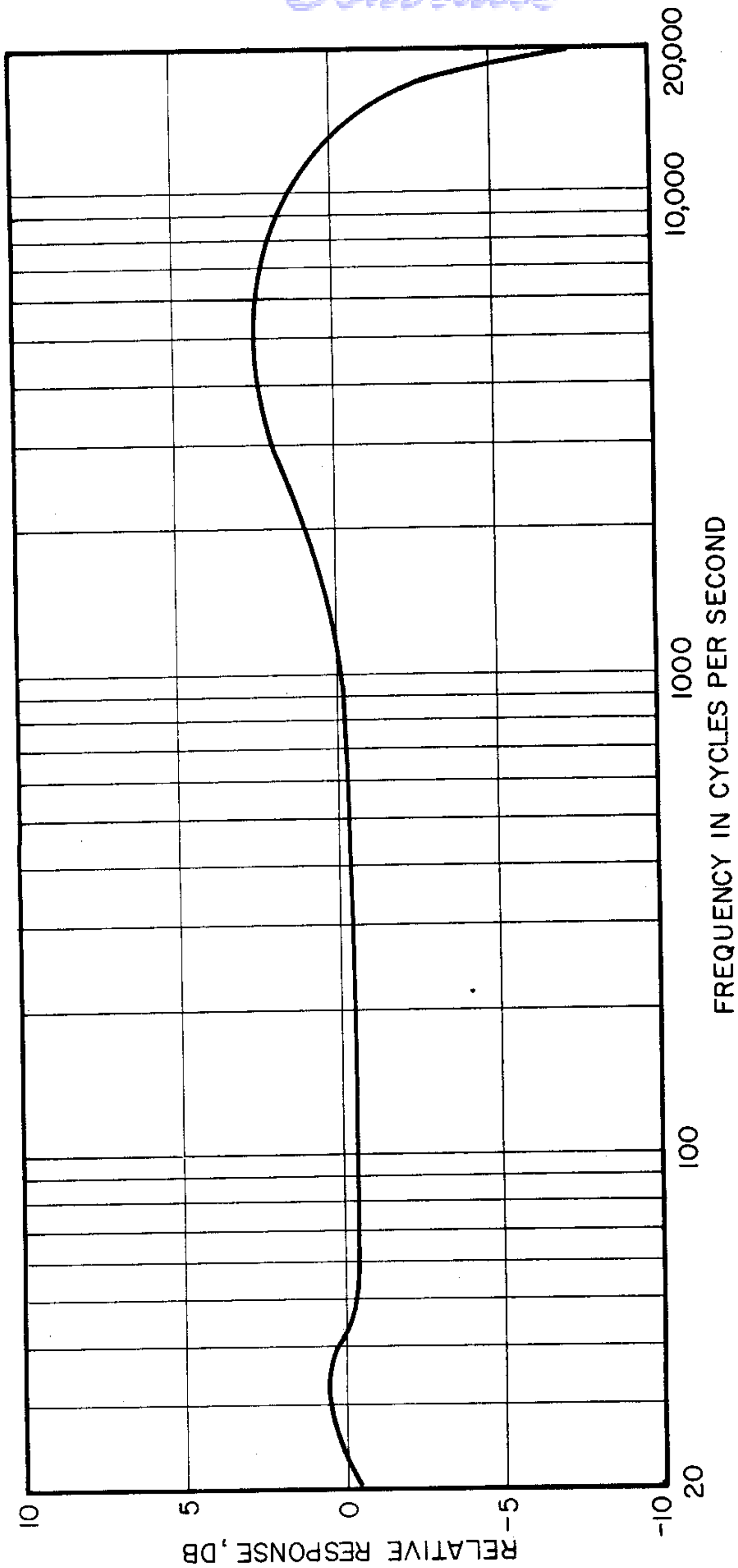


FIG. 45 FREQUENCY RESPONSE OF AMPEX TYPE 350-R LOOP STORAGE RECORDER
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The three analyzers are very different electrically. Each of the six middle filters in the General Radio octave band analyzer (75 through 4800 cps) contains three M-derived filter sections. The first filter (below 75 cps) is a two-section low-pass type. The highest filter (above 4800 cps) is a two-section high-pass type. Each of the 27 band-pass filters in the Bruel and Kjaer one-third octave analyzer contains three K-section filters. The General Radio wave analyzer achieves its narrow pass band from one three-section 50,000 cps band pass filter. The actual frequency response of these three different analyzers are shown in Figs. 47, 48, and 49.

M. System-Response Band-Correction Attenuators

The purpose of the band correction attenuators was discussed in Sec. V, "AUTOMATIC DATA REDUCTION SYSTEM". The attenuator control panel contains 30 identical rotary selector switches, one switch for each one-third octave band from 40 cps through 16,000 cps plus three "stand-by" switches. Each switch has 19 positions. Position one on all switches is tied to a common lead. Position two on all switches is tied to another common lead. The situation is the same for all 19 positions. Each of the individually paralleled 19 switch positions is connected to a different tap on a single 10,000 ohm precision wire wound resistor. The taps of the resistor are at 1 ± 0.1 db intervals so that the 19 positions on each switch control the attenuator from 0 to +9 db and 0 to -9 db, in 1 db steps. By this means the 30 rotary switches determine the amount of the precision resistor used and thereby control the attenuation in the 30, or less, one-third octave bands. The 30 switches are mounted as a group on the front panel of a rack adjacent to the one-third octave filter as shown in the lower center of Fig. 11.

A feed-back-stabilized voltage amplifier is incorporated into the attenuator switch panel to recover a portion of the insertion loss caused by the attenuators and to act as a load isolation stage at the output of the attenuators. The attenuator panel has an input impedance of 10,000 ohms.

N. Noise Integrator

The design objectives and operation of the noise integrator have been discussed earlier in Sec. V-A. The

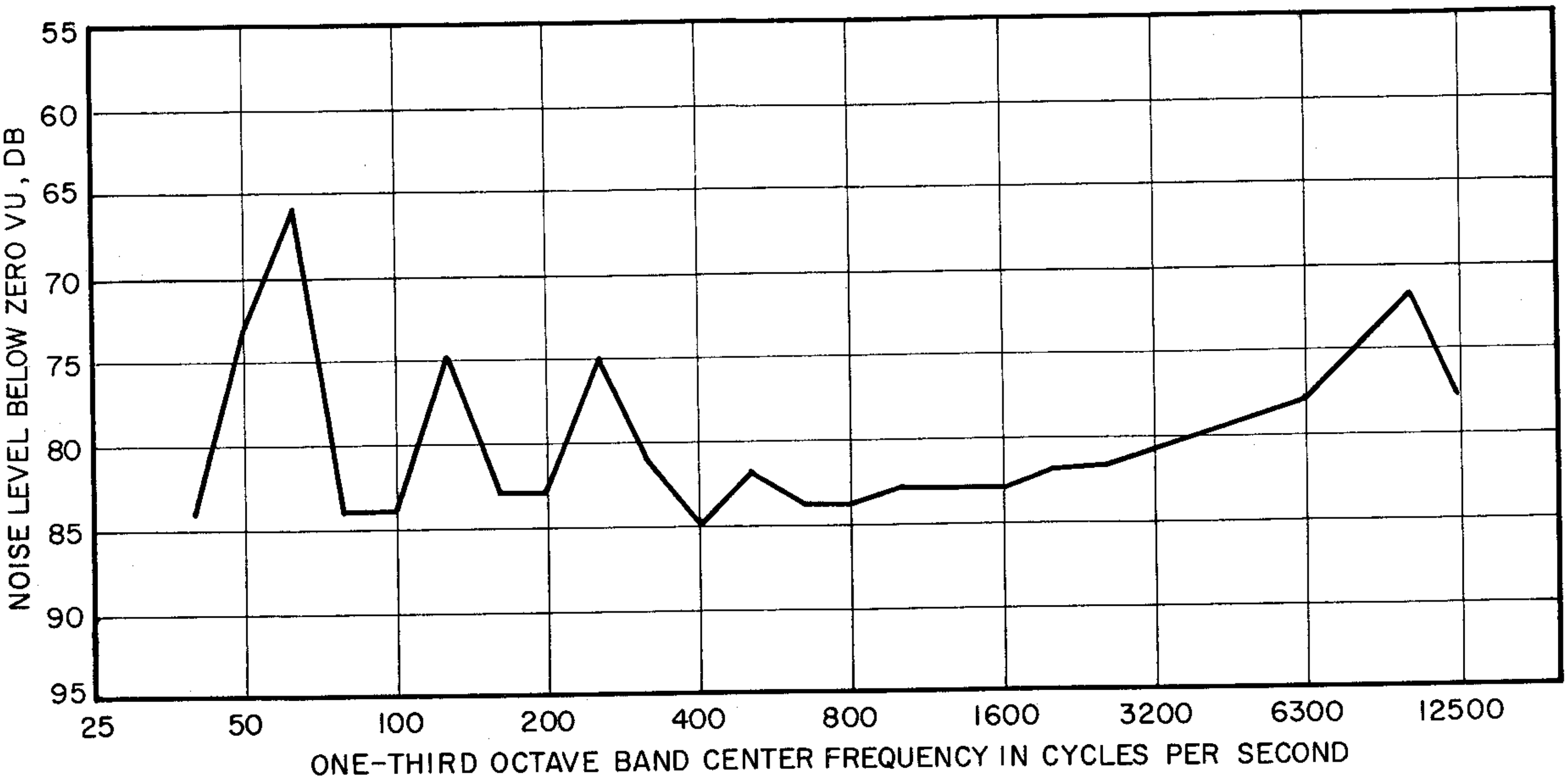


FIG. 46 AMPEX STORAGE LOOP RECORDER NOISE LEVELS BELOW ZERO VU METER READING

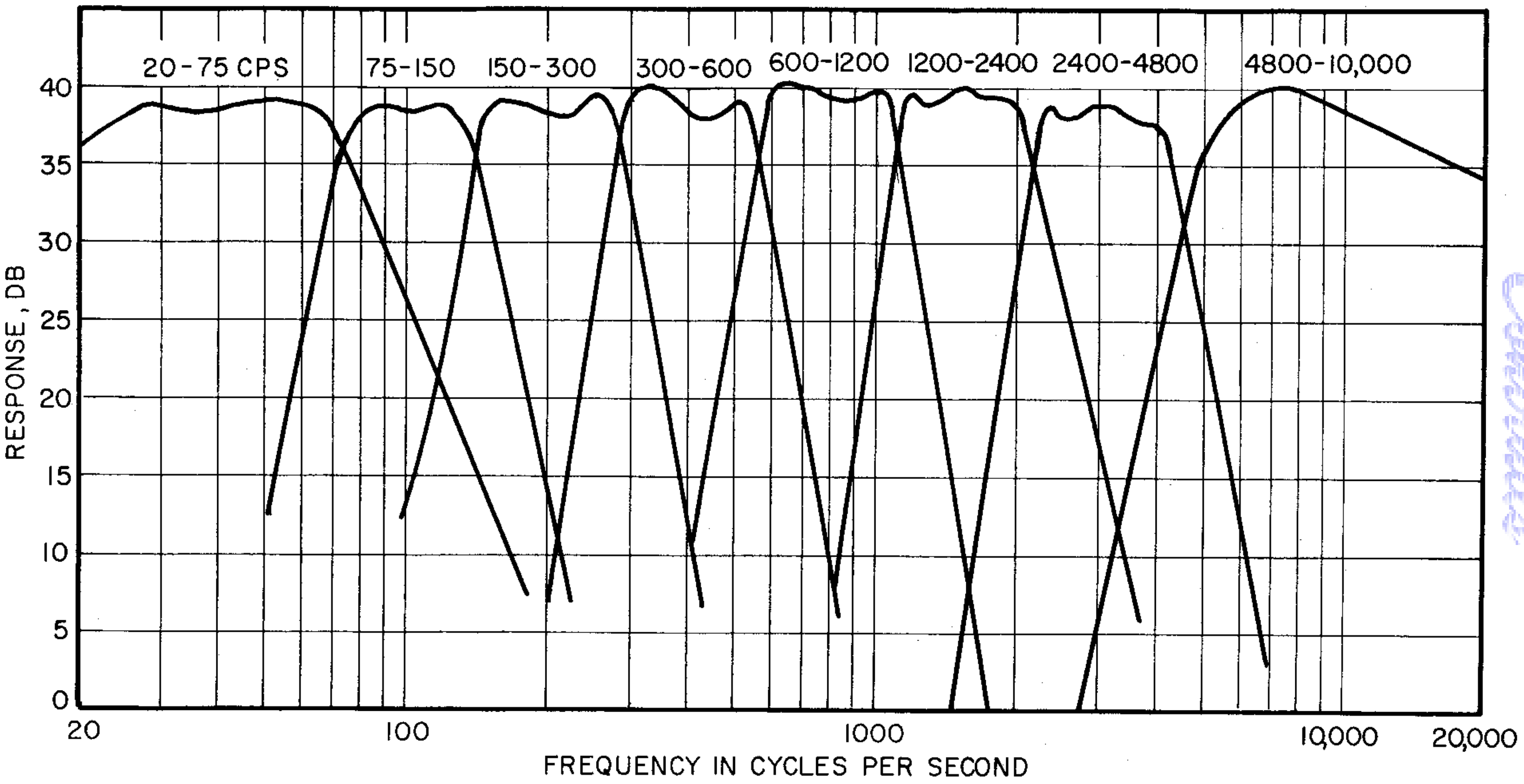


FIG. 47 FREQUENCY RESPONSE OF GENERAL RADIO OCTAVE BAND ANALYZER TYPE 1550-A SERIAL NUMBER 101

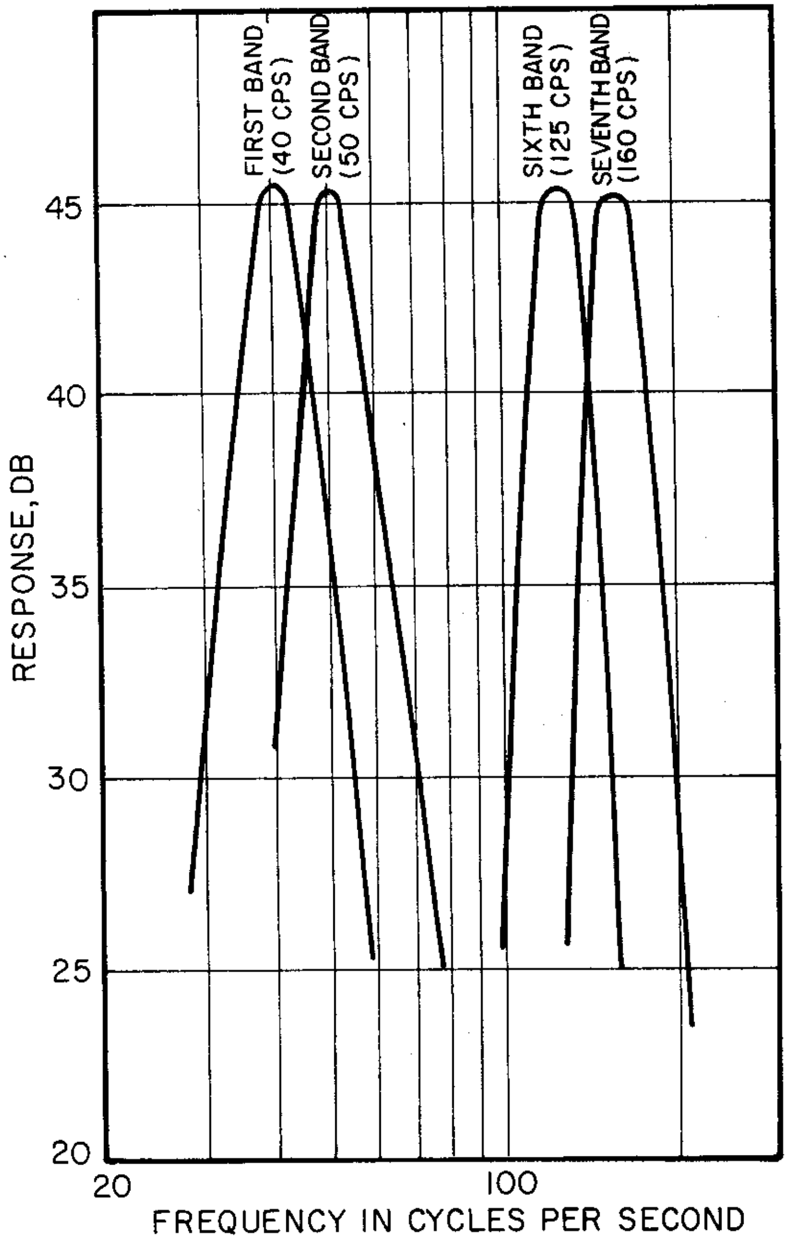


FIG. 48 TYPICAL FREQUENCY RESPONSES OF BRUEL AND KJAER ONE-THIRD OCTAVE BAND ANALYZER TYPE 2109 SERIAL NUMBER 7074

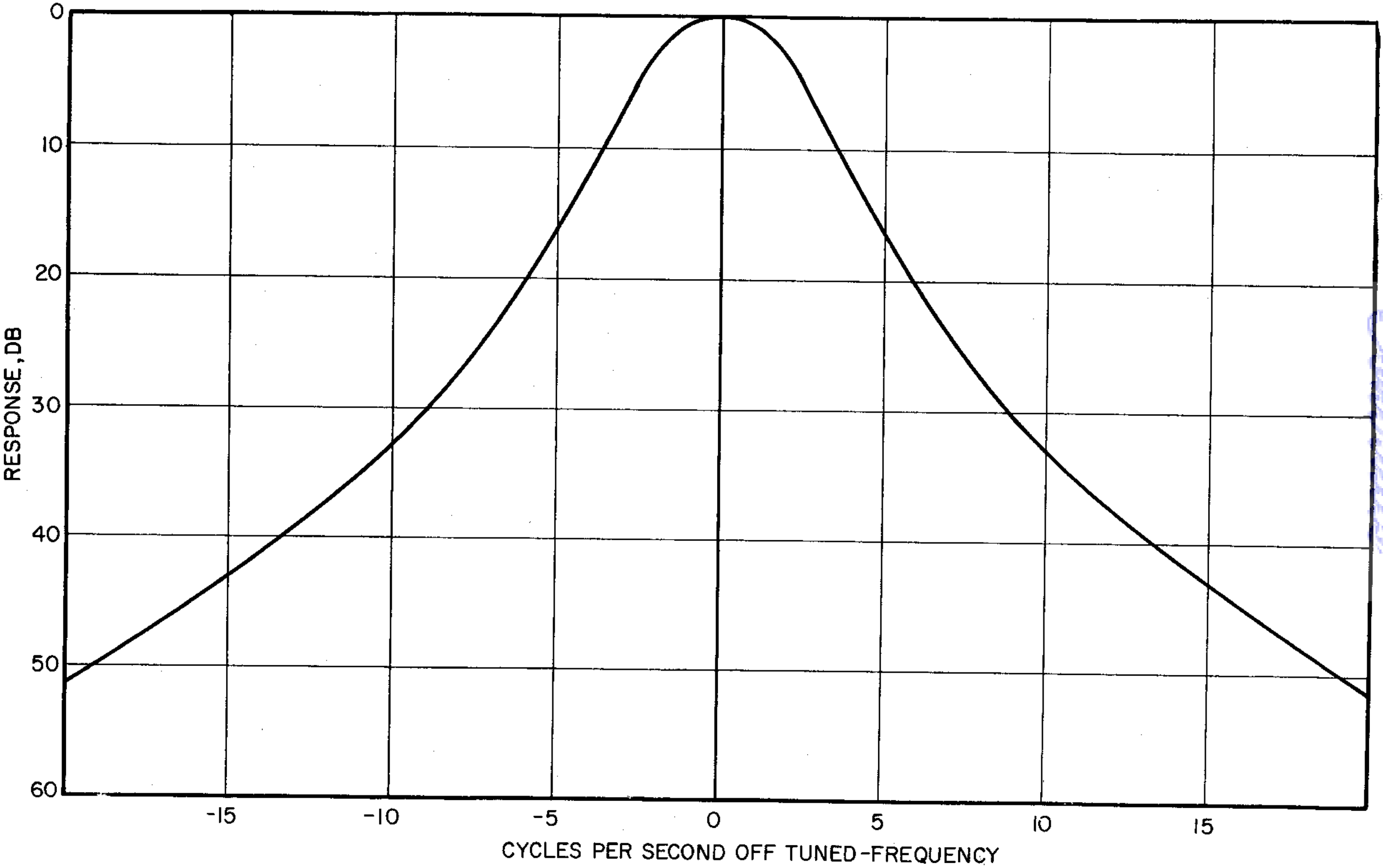


FIG. 49 FREQUENCY RESPONSE OF GENERAL RADIO WAVE ANALYZER TYPE 736 A

voltage amplifiers and the Miller integrator circuits have a flat frequency characteristic (± 0.2 db) from 20 to 10,000 cps. Satisfactory performance of the noise integrator requires a power supply regulation to better than 0.1%. The stability and accuracy of the signal output is also dependent upon the signal input level. The noise integrator has a dynamic range greater than 60 db for pure tones. The dynamic range for random noise signals is less because of the peak factor in the noise signal. The integrator accuracy with random noise signals is 0.25 db at the full undistorted output level. For noise signals 30 db below this level the accuracy is within ± 0.5 db. At 40 db below full output the accuracy decreases to ± 1 db for random noise signals.

O. Graphic Level Recorder

The signal from the noise integrator is presented on a Sound Apparatus Company Type FRA graphic level recorder, Serial No. 138. This level recorder writes with ink on a 4 in. wide graph. This machine was selected primarily for its easily read chart.

The recorder has required major modifications and an excessive amount of maintenance. Sixty cycle hum induced into the precision input attenuator from the amplifier power transformer necessitated an external power supply for the amplifier. The pen writing mechanism which is intended to follow the variations in the input signal level, is driven by a non-linear system which easily becomes unstable. The accuracy of the level recorder is not limited to the resolving power of the precision input attenuator. Rather, unbalanced frictional loads on the slipping clutch of the pen carriage mechanism are the primary sources of inaccuracies. This error was reduced by changing the power output stage and increasing the pen driving force by a factor of four. This modification required that phase shifting networks be added to the amplifier to increase its stability. Under careful maintenance the accuracy of the graphic level recorder can be held within ± 0.05 inches. This number can be translated into decibels for various input potentiometers. For the 5 db per inch potentiometer, ± 0.05 inches corresponds to ± 0.25 db, for the 10 db per inch potentiometer and the 20 db per inch potentiometer, the tolerances are ± 0.5 db and ± 1.0 db respectively.

P. Sound Level Meter and Octave Band Analyzer

A sound level meter and octave band analyzer are needed on field trips to supplement the data taken by the magnetic tape recorders. The particular instruments used are General Radio Company sound level meters Type 1551-A, and General Radio Company octave band analyzers, Type 1550-A. These pieces of equipment have self-contained battery-operated power supplies. The frequency response of a sound level meter is shown in Fig. 50.

The signal-to-noise ratio of most battery-operated sound-level meters, including this type, is inadequate for the needs of the program. To improve the signal-to-noise ratio, the impedance of the input attenuator was lowered and 20 db of amplification was sacrificed. Figures 51 and 52 show the effects of these modifications on the internal noise of the sound-level meter.

In Figure 51 the internal noise is plotted as the equivalent sound-pressure levels in octave bands for sound level meter attenuator settings of 50 and 90. The equivalent sound pressure levels are for use with a microphone with the sensitivity of a Shure Rochelle salt Type 9898. These measurements were made by using a dummy microphone input. As is noted in the figure, for attenuator settings above 90 the difference between modified and unmodified instruments remains constant. For each instrument the equivalent sound pressure levels rise 10 db for each 10 db increase in attenuator setting above 90. Figure 52 shows the average improvement in signal-to-noise ratio (i.e. reduction in internal noise) over the eight octave bands as a function of attenuator setting.

These figures show that the modification of the sound level meter resulted in a reduction of internal noise for all attenuator settings above 50, the improvement reaching 20 db for settings greater than 80. The average increase of 4 db in internal noise shown for an attenuator setting of 50 occurs in the lower frequency bands. This noise increase is from the external cathode follower preamplifier. For the measurement of the downward-sloping spectrum typically observed at low levels, the limitations of the sound level meter with the attenuator set at 50 are practically unchanged by the modifications. Far more important, however, is the consistent improvement of 20 db for attenuator settings above 80, where the great

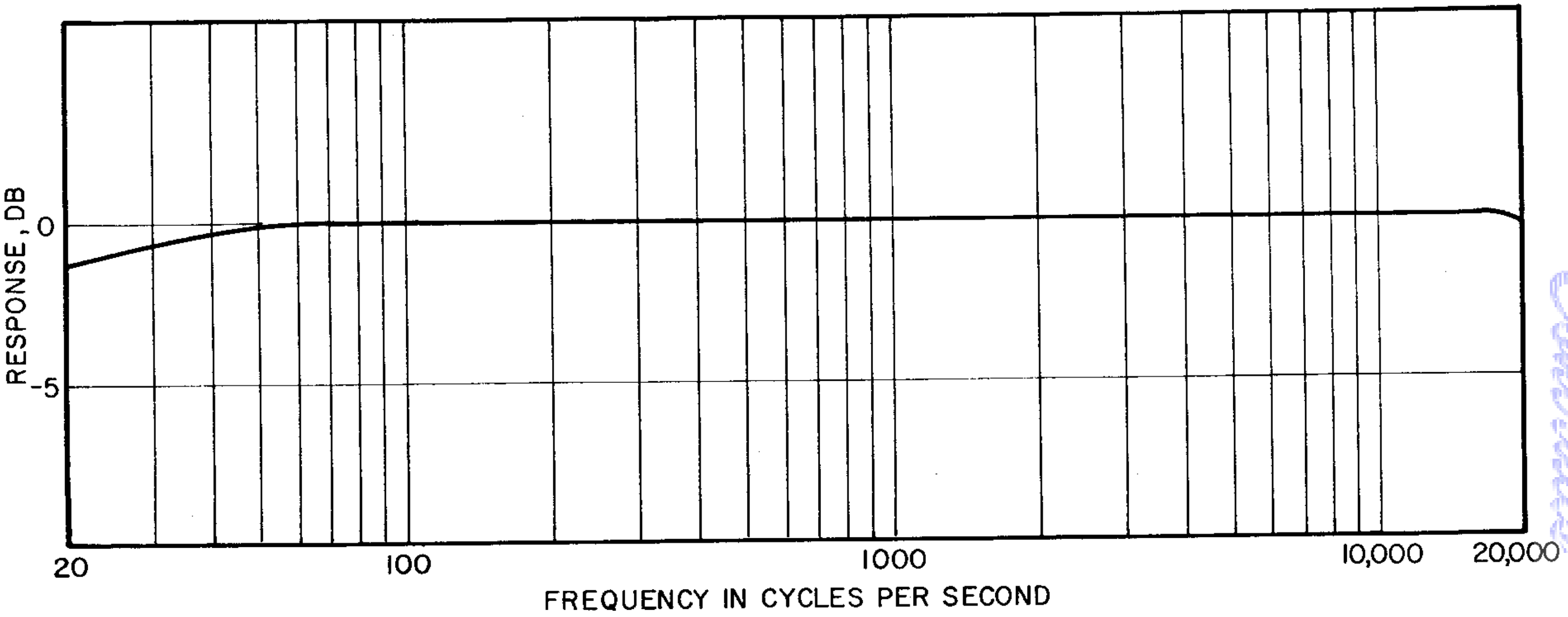


FIG. 50 FREQUENCY RESPONSE OF GENERAL RADIO SOUND LEVEL METER TYPE 1551-A SERIAL NUMBER 312 (WEIGHTING SELECTOR SWITCH AT 20 KC)

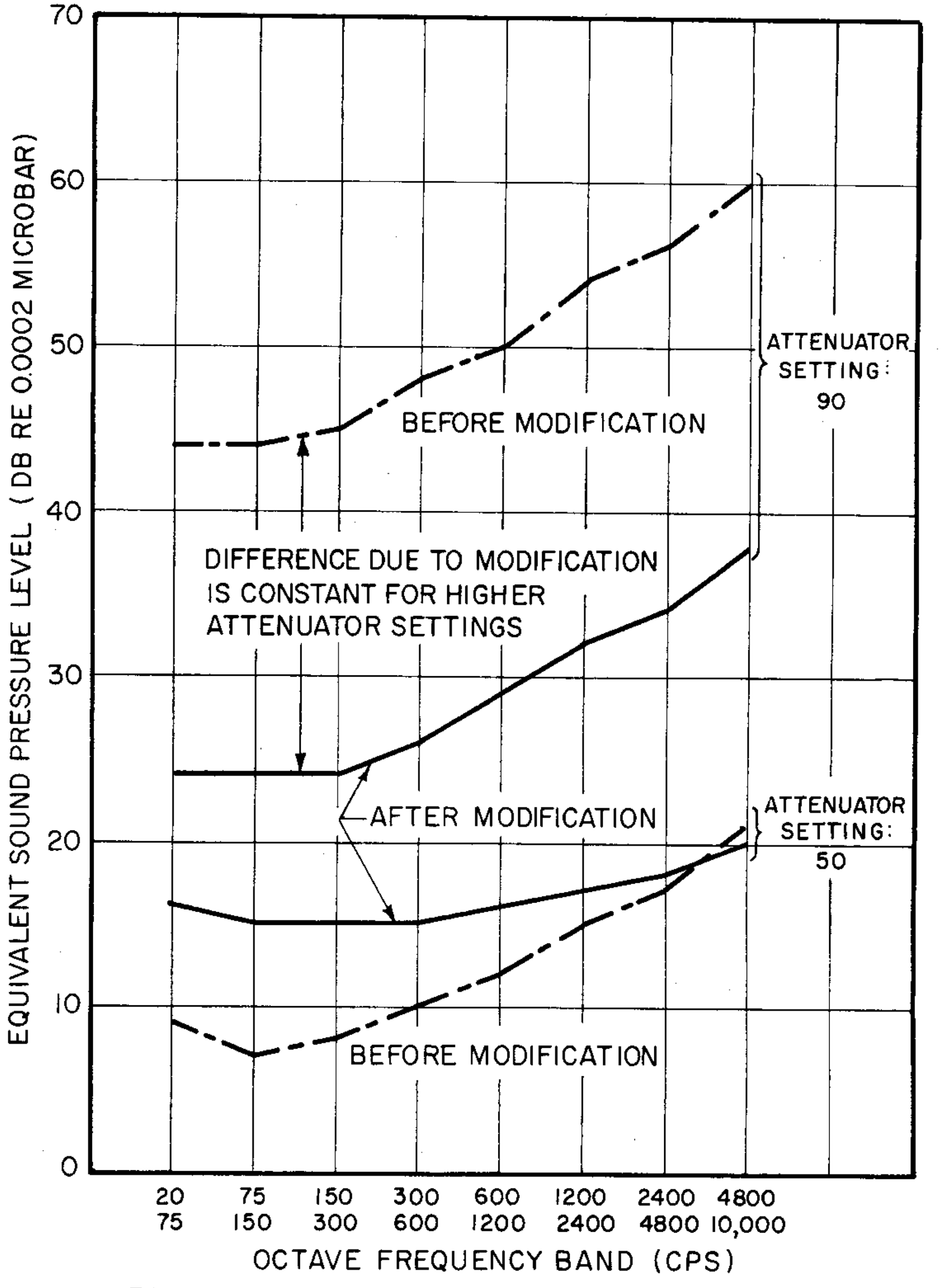


FIG. 51 INTERNAL NOISE OF SOUND LEVEL METER (G.R. TYPE 1551-A) BEFORE AND AFTER MODIFICATION, EXPRESSED AS EQUIVALENT SOUND PRESSURE LEVEL

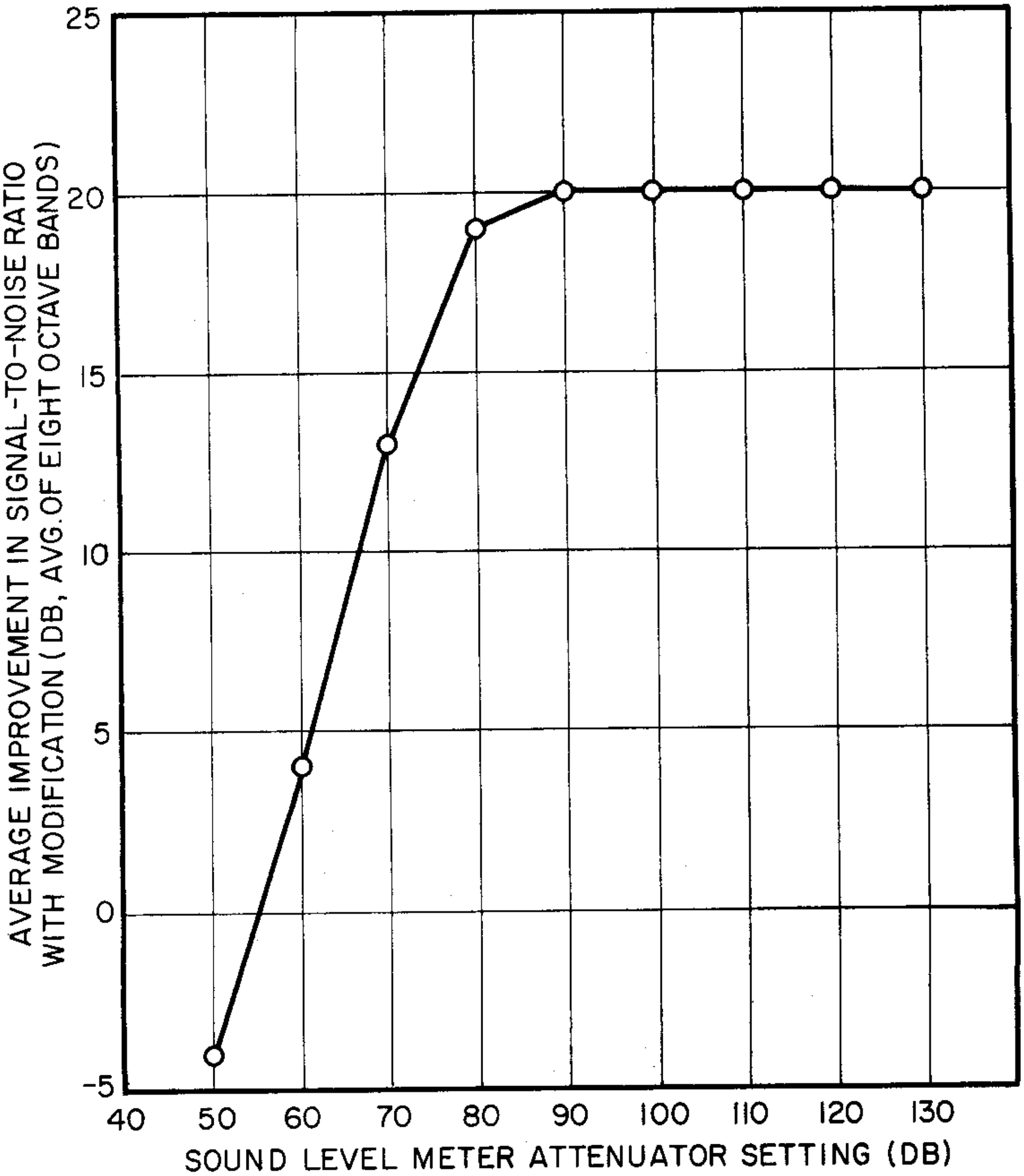


FIG. 52 AVERAGE IMPROVEMENT IN SIGNAL-TO-NOISE RATIO IN OCTAVE FREQUENCY BANDS DUE TO MODIFICATION OF G.R. TYPE 1551-A SOUND LEVEL METER

majority of measurements are made with the equipment described here. The operation of the sound level meter is the same except for the absence of the 30 and 40 db settings on the attenuator and a lower input impedance which requires the cathode follower preamplifier described in Section VII-F. The 20 db loss in sensitivity is of no consequence when the sound level meter is used in conjunction with the octave band analyzer.

The harmonic distortion of both modified and unmodified sound level meters is less than 1% up to full scale on the indicating meter. A signal level of + 10 db corresponds to a full scale meter reading on the sound level meter. At full scale the distortion reaches 1%, and it is 5% at levels 10 db above full scale.

The stability of this sound level meter is considered good for a portable battery-operated instrument. Under conditions of continuous operation its sensitivity does not generally drop more than 0.25 db per hour. The octave band analyzer, however, is not as stable. This instrument has no feedback in its amplifier circuits so that its sensitivity decreases approximately 1 db per hour of continuous operation. Also, the tube in the first stage of the octave band analyzer amplifier is excessively microphonic. This difficulty was remedied by replacing the tube in the first stage with a specially built assembly of two low microphonic, Raytheon CK512AX's, so mounted that the assembly could simply be plugged into the same first stage tube socket of the octave band analyzer. The microphonics were decreased by at least 40 db by this modifications.

Q. Vibration Pick-Ups, Filter and Meter

To evaluate the various sources of noise radiated from an aircraft engine test cell it is sometimes helpful to measure the vibration amplitude of the wall structures. With this information it is possible to deduce the amount of noise radiated by a surface, assuming that it behaves as a simple diaphragm. Two types of vibration pick-ups have been used in this work: the General Radio Rochelle salt Crystal Accelerometer Type 759P35, and the Vibration Pick-Up Type 126 made by the MB Manufacturing Company which has an electrical output proportional to velocity. The General Electric crystal accelerometer may be connected to a tape recorder in the same manner as microphones for measurements between 20 cps and 1000 cps. The MB pick-up is a low impedance device (approximately 500 ohms) and so it is desirable to use an impedance matching transformer for it to operate into the same equipment as that used for microphones. It then may be used for the frequency range 20 cps to 5000 cps. In both cases, the lower frequency limit is imposed by the tape recorder and the upper frequency limit is caused by the response of the pick-up.

When it is desirable to obtain data below 20 cps it is necessary to employ additional low frequency analyzing equipment. For measuring in the frequency range between 5 cps and 2000 cps the MB pick-up may be fed into a Krohn-Hite variable band pass filter. The General Radio Vibration Meter Type 761 is then connected to the output of the filter and is simply used as an indicating instrument. The lower frequency limit of this system is fixed by the resonance frequency of the critically damped MB pick-up, which is 4.75 cps. The upper frequency limit is determined by the Krohn-Hite filter.

A second method, usable for frequencies down to 1 cps, employs the General Radio Accelerometer feeding into a cathode-follower. The output of the cathode follower is filtered by the Krohn-Hite filter and then read on the General Radio vibration meter.

The Krohn-Hite filter and the two vibration pick-ups are shown in Fig. 8.

SECTION VIII

REVIEW AND SUMMARY OF POSSIBLE ERRORS

It is now possible to summarize the errors which are incurred in the various calibrations, and to express the total standard deviation of the absolute sound pressure level finally presented on the graph which is automatically plotted by the level recorder.

Errors at 400 cps

In Table II below there are tabulated the estimated errors in the various measurements and calibrations for a 400 cps tone. For each type of measurement the spread of error listed is assumed to be exceeded in no more than 5% of a series of measurements of that same quantity. That is, 95% of a series of measured values of a given quantity fall within the error listed.

It has been observed[1] that if one assumes that (1) a Gaussian distribution of errors obtains and, (2) 95% of the errors fall within the "spread" of the measured values of the error, then the standard deviation*[2] is approximately equal to one-half the "spread". Therefore, the total standard deviation can be calculated from:

$$\text{Total standard deviation} = \sqrt{\Sigma\ (\text{Individual deviations})^2}$$

Using this method,

$$\text{Total standard deviation at 400 cps} = 0.67 \text{ db}$$

Still using the assumption that the standard deviation is half of the "spread", then the maximum total error for 95% of work at 400 cps = ± 1.3 db.

---

* The standard deviation, σ, is defined as the square root of the mean square deviation

$$\sigma = \left[\left(\int_{-\infty}^{\infty} x^2 y_x dx\right) / \left(\int_{-\infty}^{\infty} y_x dx\right)\right]^{1/2}$$

TABLE II

SUMMARY OF ERRORS AT 400 CPS

Item	Description of Measurement or Calibration	Error (db)
1.	Reciprocity calibration of the Western Electric 640AA condenser microphone	± 0.2
2.	Establishment of a 100 db absolute sound pressure level at 400 cps in the low frequency duct using the WE640AA, a precision thermocouple voltmeter and a precision attenuator	± 0.1
3.	Comparison between 100 db free field calibration and the calibration in the adjusted acoustic calibrator due to physical variations in a group of Shure Type 9898 microphones	± 0.5
4.	Reading of voltmeter scale on the acoustic calibrator	± 0.1
5.	Output stability of the calibrator over a time interval of one month between adjustments	± 0.2
6.	Variation of sound output due to temperature coefficient of acoustic calibrator over a temperature range of ± 20°F near 75°F	± 0.4
7.	Variation in SPL from acoustic calibrator due to positioning of calibrator over microphone during field calibration	± 0.5
8.	Variation in microphone sensitivity due to temperature coefficient of the Shure Brothers' microphone Type 9898, over a temperature range of ± 20°F centered at 75°F	± 0.3
9.	Stability and reproducibility of the field data magnetic tape recorders and recording tape	± 0.2

TABLE II (cont.)

Item	Description of Measurement or Calibration	Error (db)
10.	Accuracy of the step attenuators on the tape recorder amplifiers	± 0.1
11.	Gain stability of the field data tape recorders between intervals of acoustic calibration (one hour)	± 0.1
12.	Inaccuracy of the step attenuators in the automatic data reduction system	± 0.3
13.	Inaccuracy of automatic data reduction integrator over a 20 db range	± 0.2
14.	Inaccuracy of the automatic data reduction system frequency response correction attenuators	± 0.5
15.	Variation of integrator response during period between its calibrations	± 0.5
16.	Resolving power of the graphic level recorder used for presenting the reduced data (when using the potentiometer giving 10 db per inch on the chart ordinate)	± 0.5

Errors at Low Frequencies

It is possible to express the standard deviation at other low frequencies (say, below 1000 cps) by considering the additional errors incurred in comparison of the field microphones with the reference microphone. It is estimated that in 95% of the calibrations an error of no greater than 0.5 db occurs due to the variation in geometry of the two microphones as well as the lack of ideal free field in the calibration facilities. If the assumption is made that this is the only additional error (compared with the errors at 400 cps) then:

Total standard deviation at low frequencies other than 400 cps

$$= \sqrt{(0.67)^2 + (0.25)^2 = 0.7 \text{ db}}$$

Maximum total error in 95% of low frequency work = ± 1.4 db

Errors at High Frequencies

At high frequencies (say, greater than 2500 cps), two additional errors come in: The error due to comparison calibration of field microphone is now assumed to incur an error of equal to, or less than ± 0.7 db in 95% of the cases. In addition, the attenuators, throughout the electrical system become subject to capacitive shunting which is estimated to cause a possible error of ± 1.0 db in 95% of the cases. Considering these two new sources of error (compared with the 400 cps calibration) there results:

Total standard deviation for high frequencies

$$= \sqrt{(0.67)^2 + (0.35)^2 + (0.5)^2 = 0.9 \text{ db}}$$

Maximum total error in 95% of high frequency work = ± 1.8 db

One final word should be said about errors at high frequencies. For frequencies at which the microphone size becomes comparable with, or greater than, the wavelength, the microphone response is strongly dependent on the angle of incidence of the sound arriving at the microphone.

Errors would appear in estimating whether the incidence of the sound in the field is random, grazing, normal or at some other angle to the microphone diaphragm. The magnitude of this error depends on the microphone used. Large microphones such as the Shure Type 9898 would show greater differences between grazing and normal incidence than small microphones such as the Altec 21 condenser microphones (see Figs. 4, 26). Consideration of such errors would raise the total standard deviation at high frequencies by an amount depending on the frequency and on the microphone under consideration.

BIBLIOGRAPHY

1. Beranek, L. L. and H. P. Sleeper
   J. Acous. Soc. Am. 18, 140 (1946)

2. Worthing and Geffner, "Treatment of Experimental Data", First Edition, J. Wiley and Sons, N.Y.C. 1943, pp. 157-158

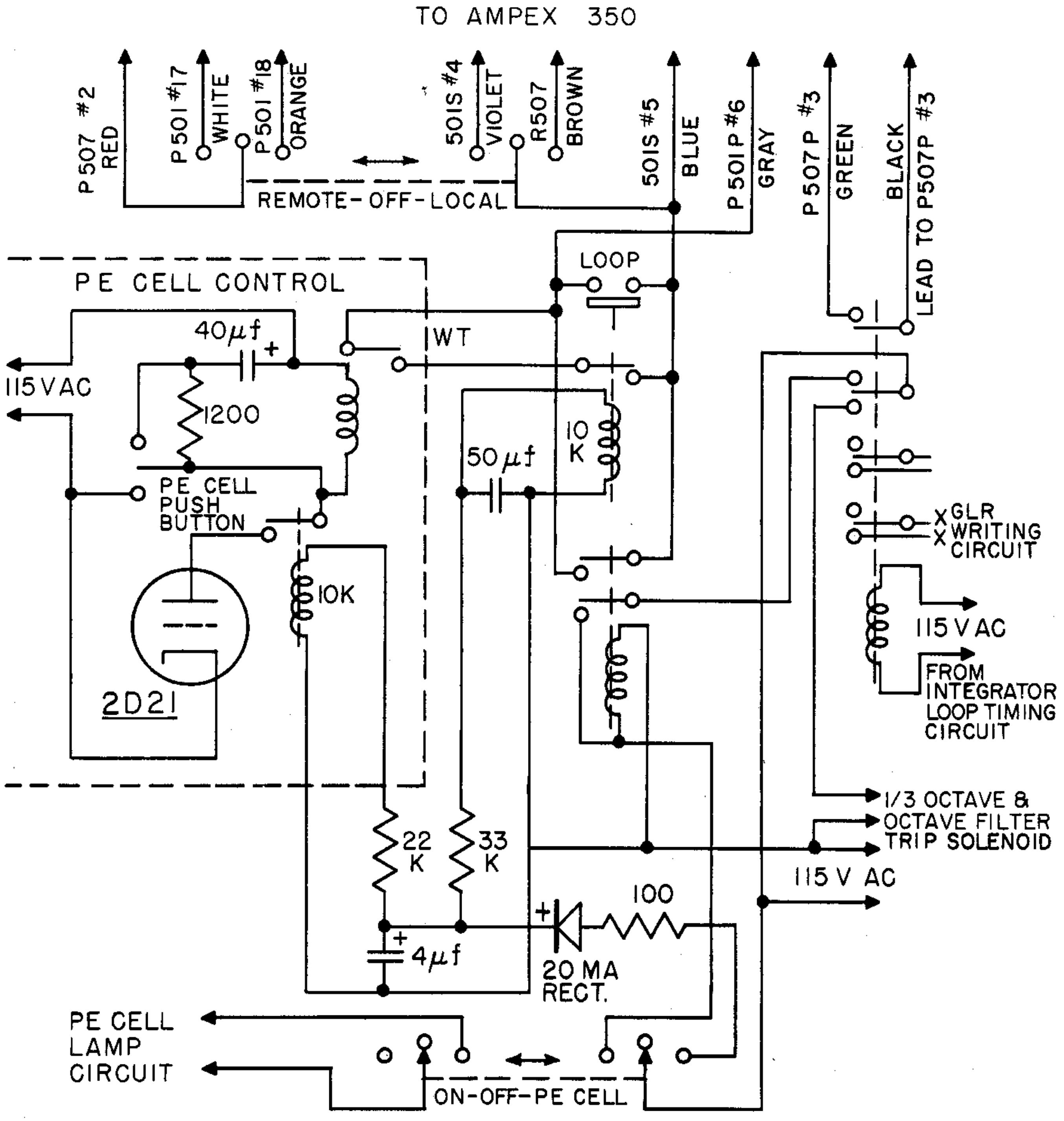


FIG. 53 DATA REDUCTION SYSTEM

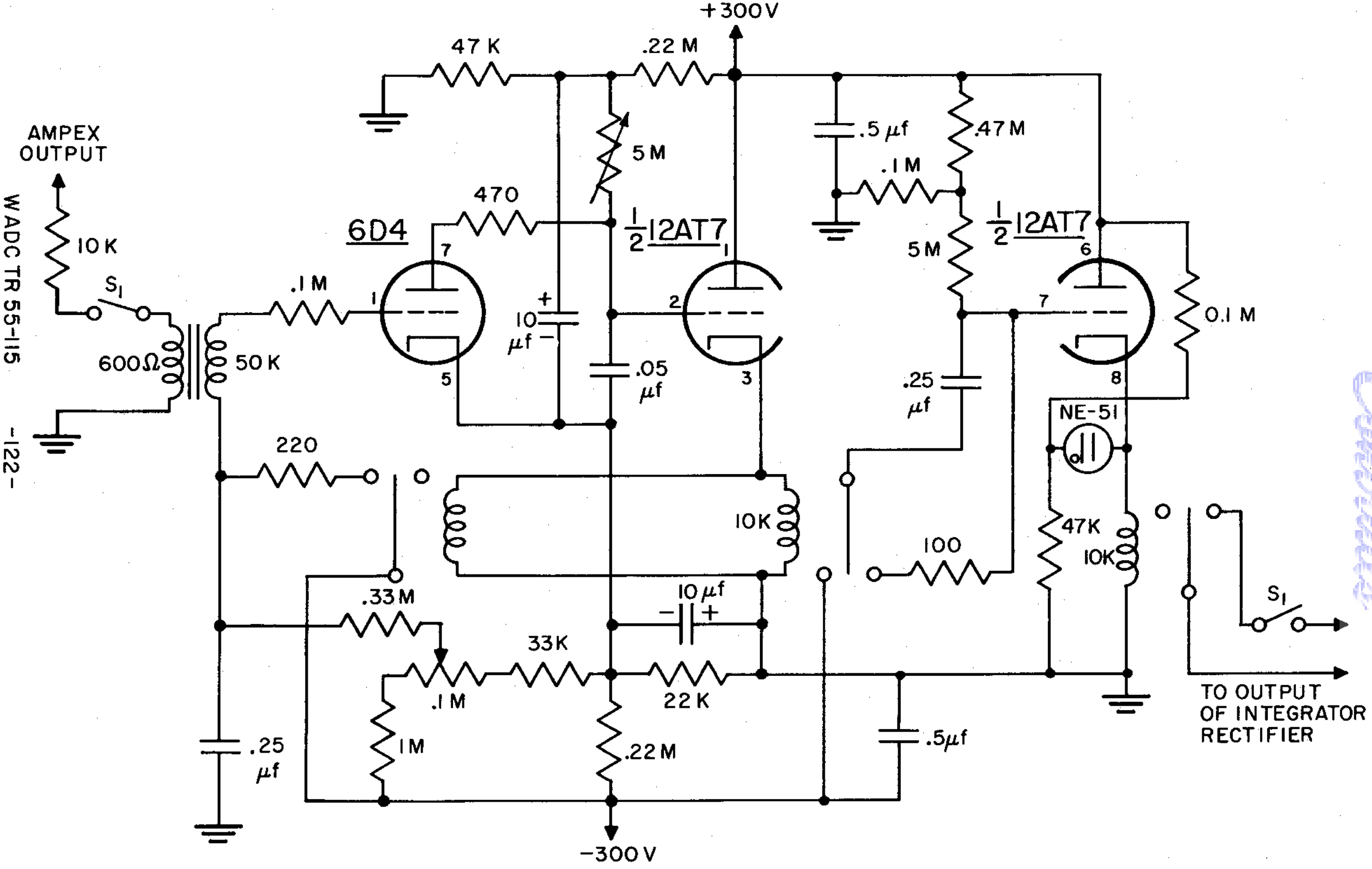


FIG. 54 INTEGRATOR BLANKING CIRCUIT FOR REDUCTION OF CANNON SHOTS IN DATA REDUCTION SYSTEM

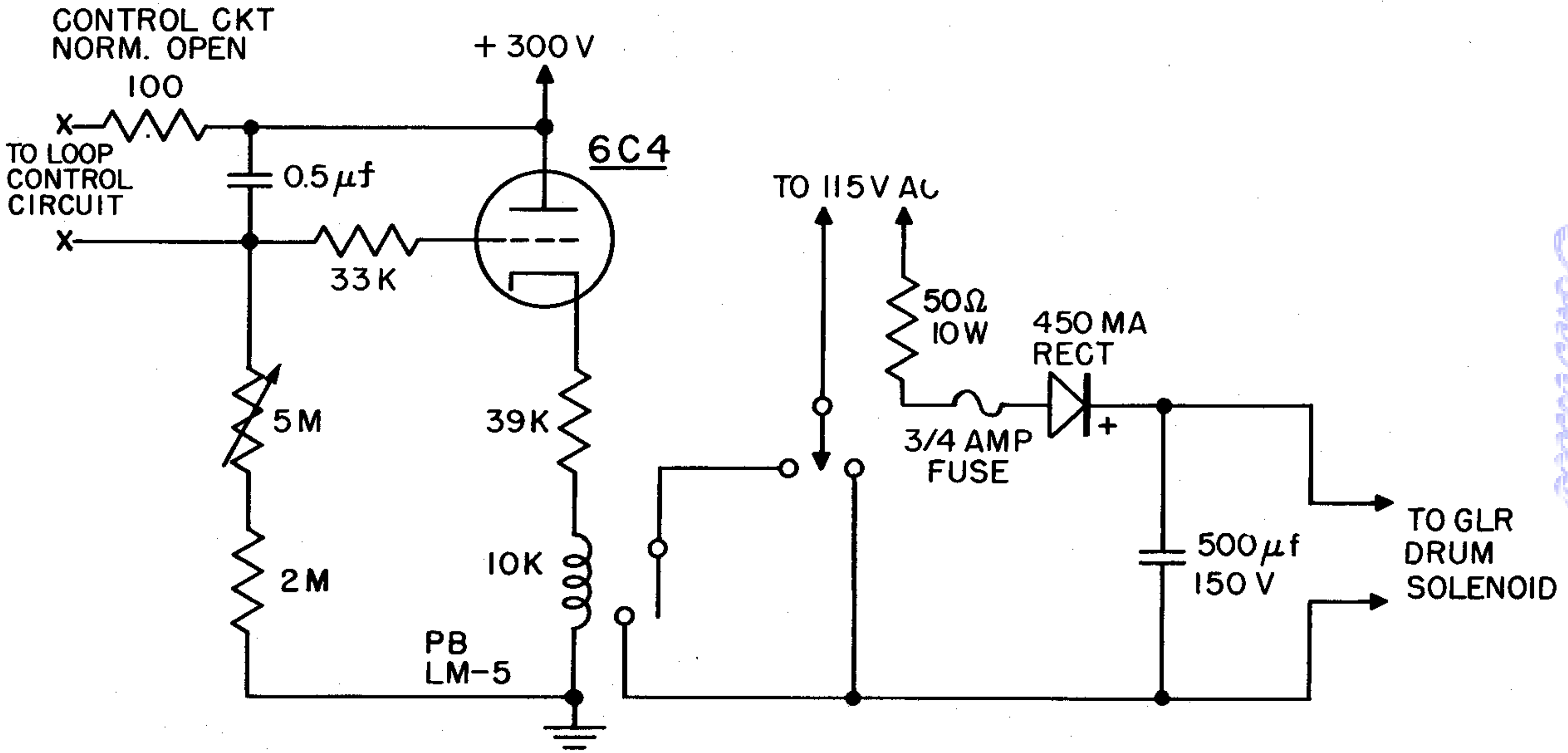


FIG. 55 GRAPHIC LEVEL RECORDER WRITING TIME CONTROL IN DATA REDUCTION SYSTEM

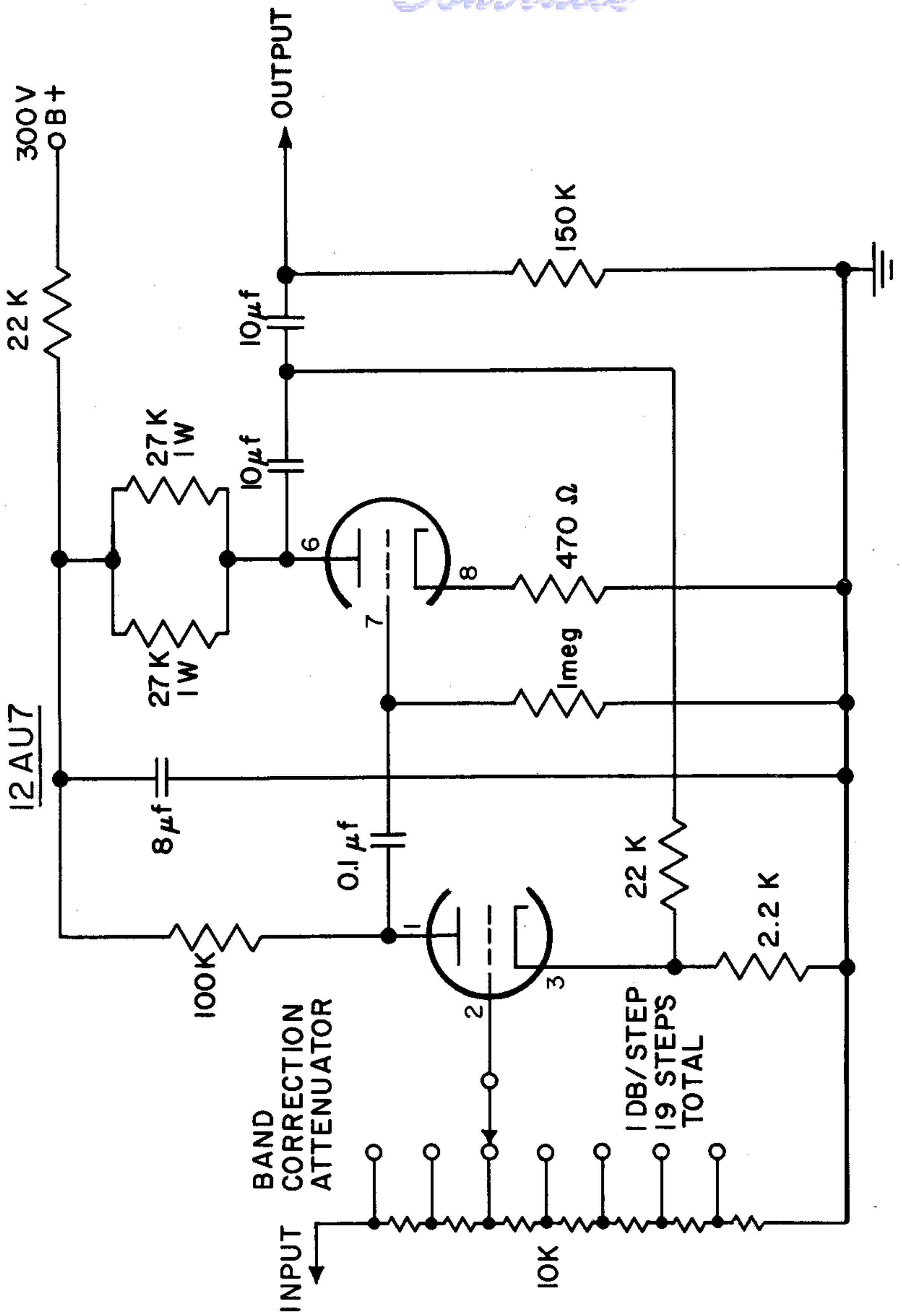


FIG. 56 AMPLIFIER FOR BAND CORRECTION ATTENUATOR SWITCH PANEL

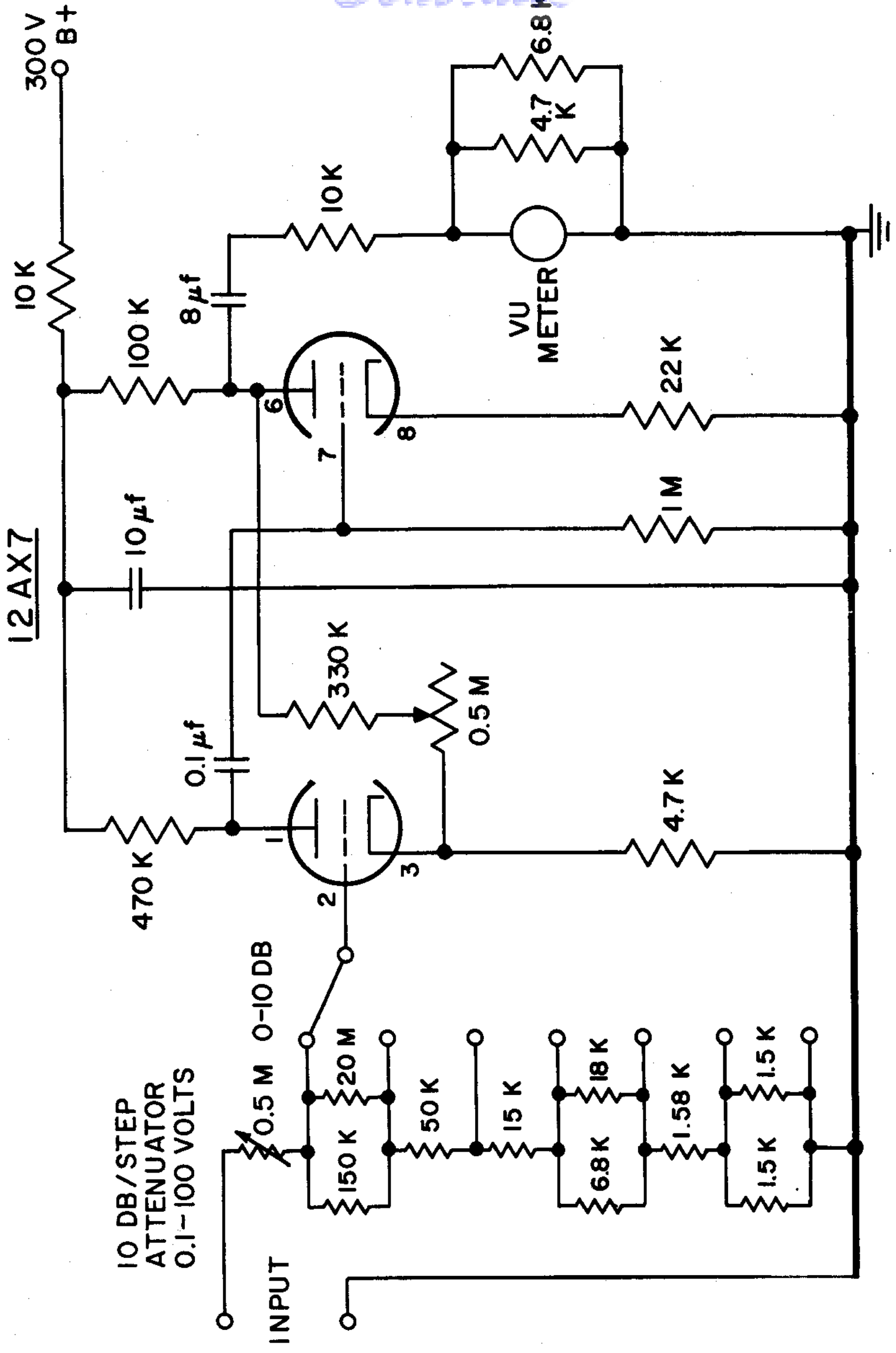
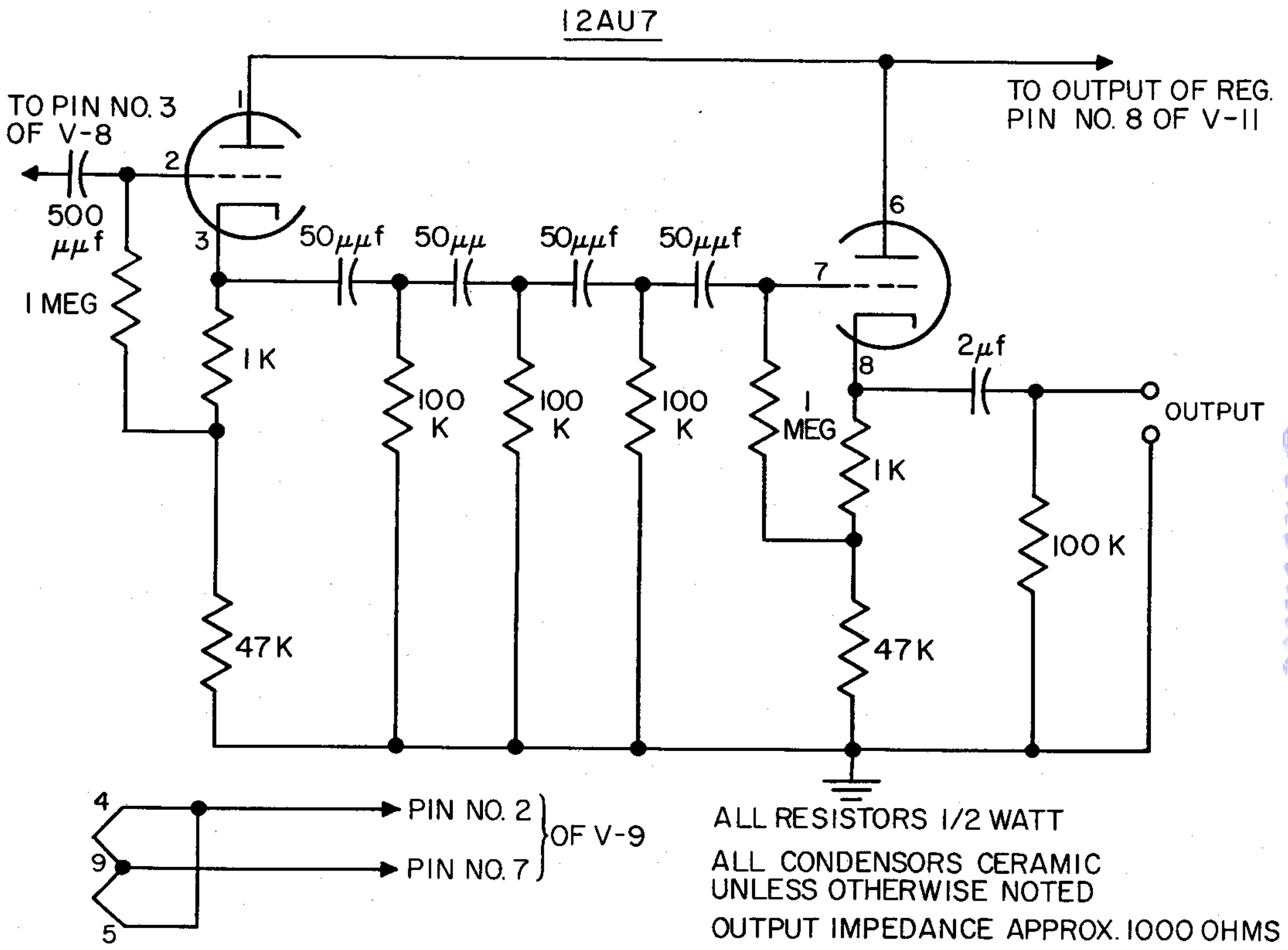


FIG. 57 VACUUM TUBE VOLTMETER IN DATA REDUCTION SYSTEM

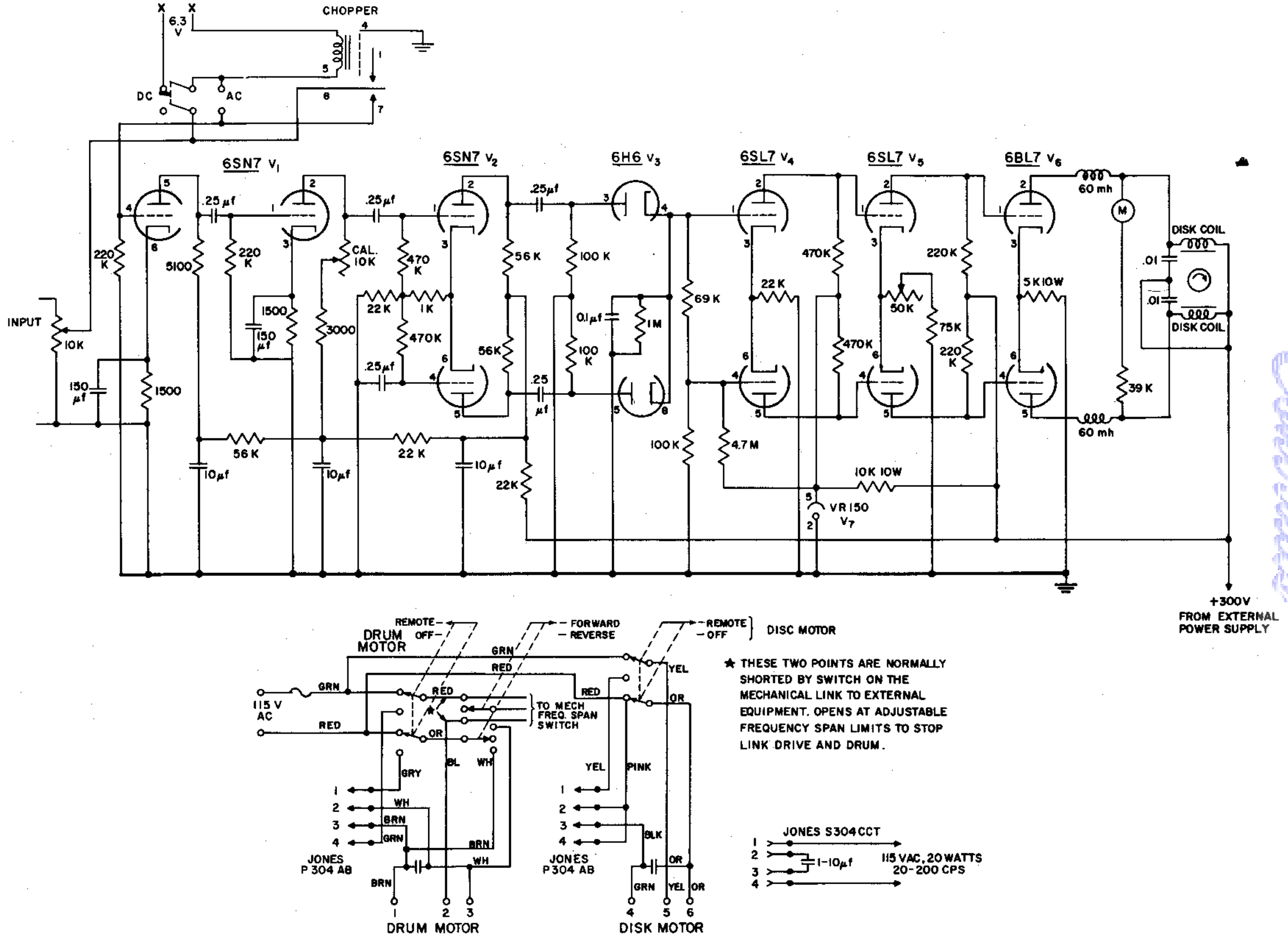


ALL RESISTORS 1/2 WATT

ALL CONDENSORS CERAMIC
UNLESS OTHERWISE NOTED

OUTPUT IMPEDANCE APPROX. 1000 OHMS

FIG. 58 SIGNAL OUTPUT CIRCUIT ADDED TO GENERAL RADIO WAVE ANALYZER TYPE 736-A IN DATA REDUCTION SYSTEM



★ THESE TWO POINTS ARE NORMALLY SHORTED BY SWITCH ON THE MECHANICAL LINK TO EXTERNAL EQUIPMENT. OPENS AT ADJUSTABLE FREQUENCY SPAN LIMITS TO STOP LINK DRIVE AND DRUM.

ADJUSTABLE PEN WRITING AND CHART SPEED CONTROL FOR SOUND APPARATUS GRAPHIC LEVEL RECORDER TYPE FRA

FIG. 59 SOUND APPARATUS GRAPHIC LEVEL RECORDER TYPE FRA

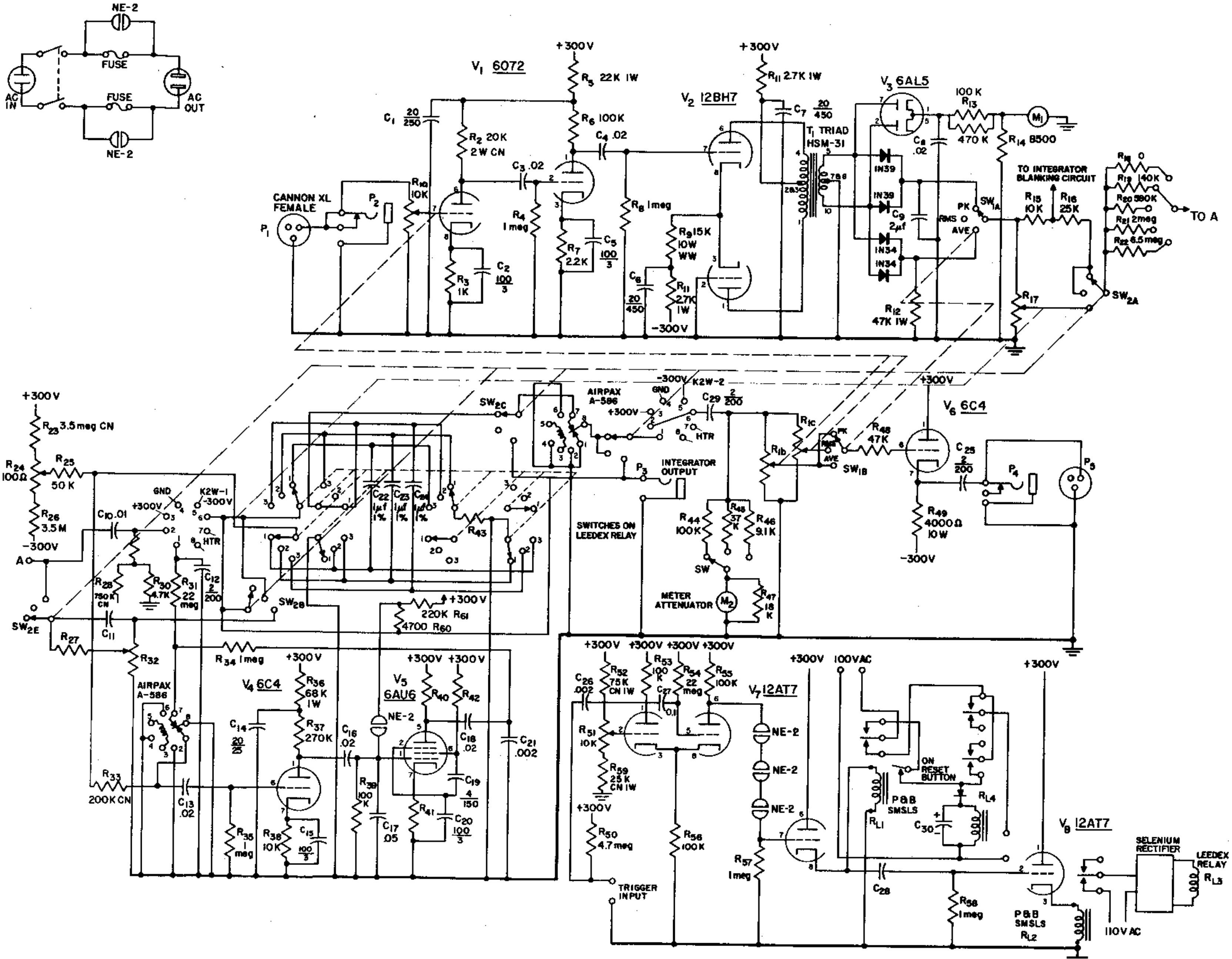


FIG. 60 INTEGRATOR IN DATA REDUCTION SYSTEM

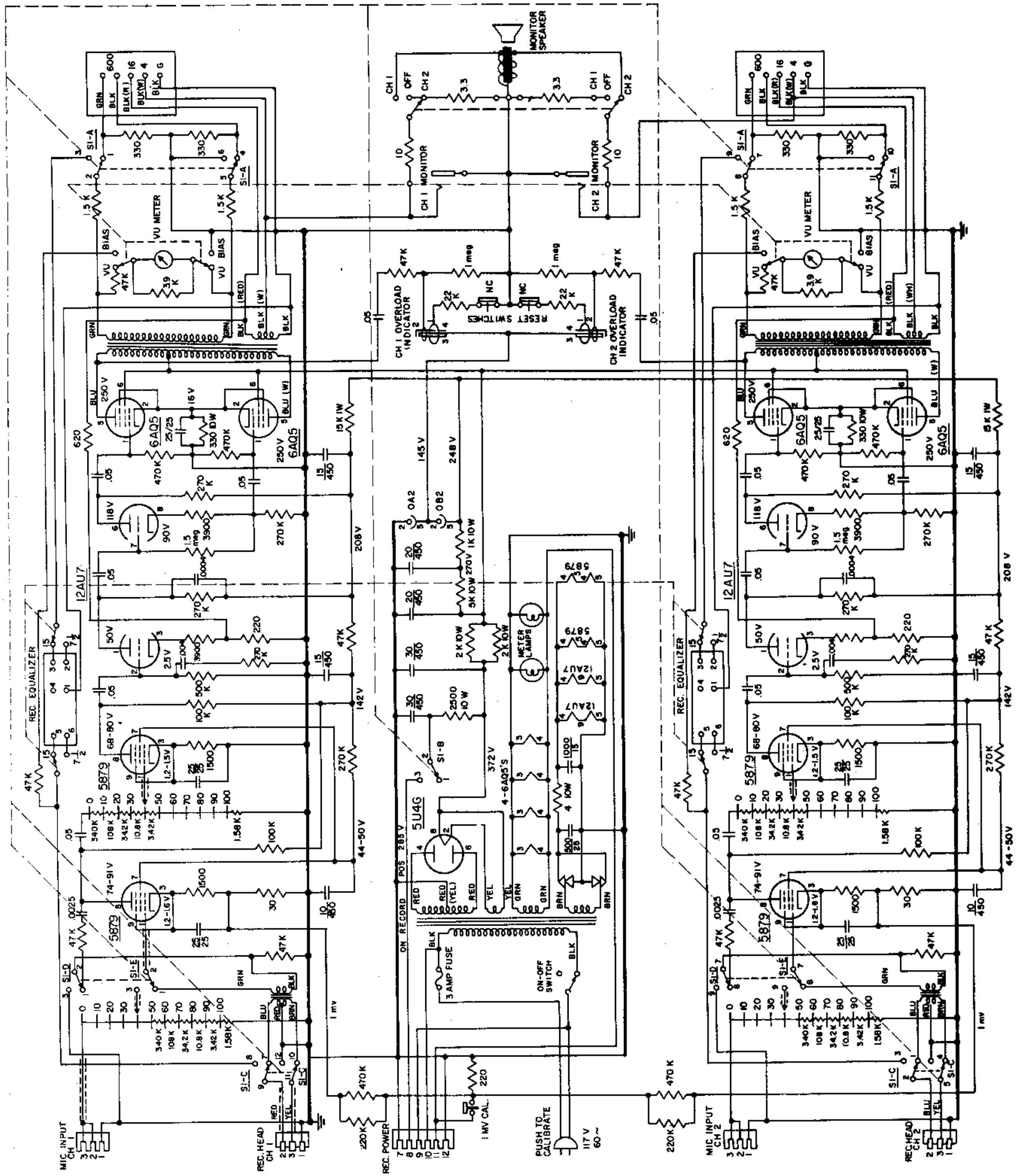


FIG. 61 MAGNECORD AMPLIFIER TYPE PT6-BN

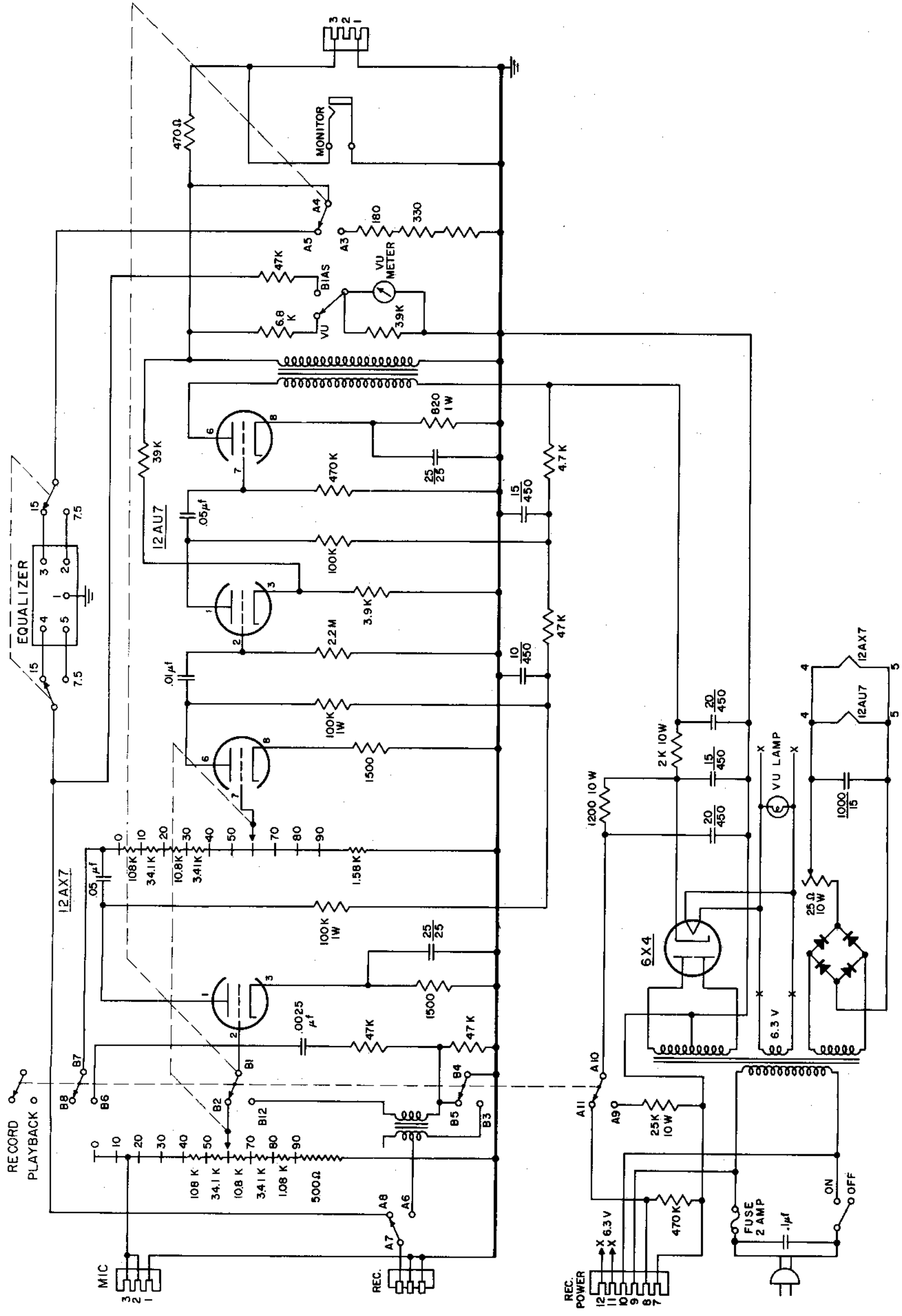


FIG. 62 MAGNECORD AMPLIFIER PT6-V

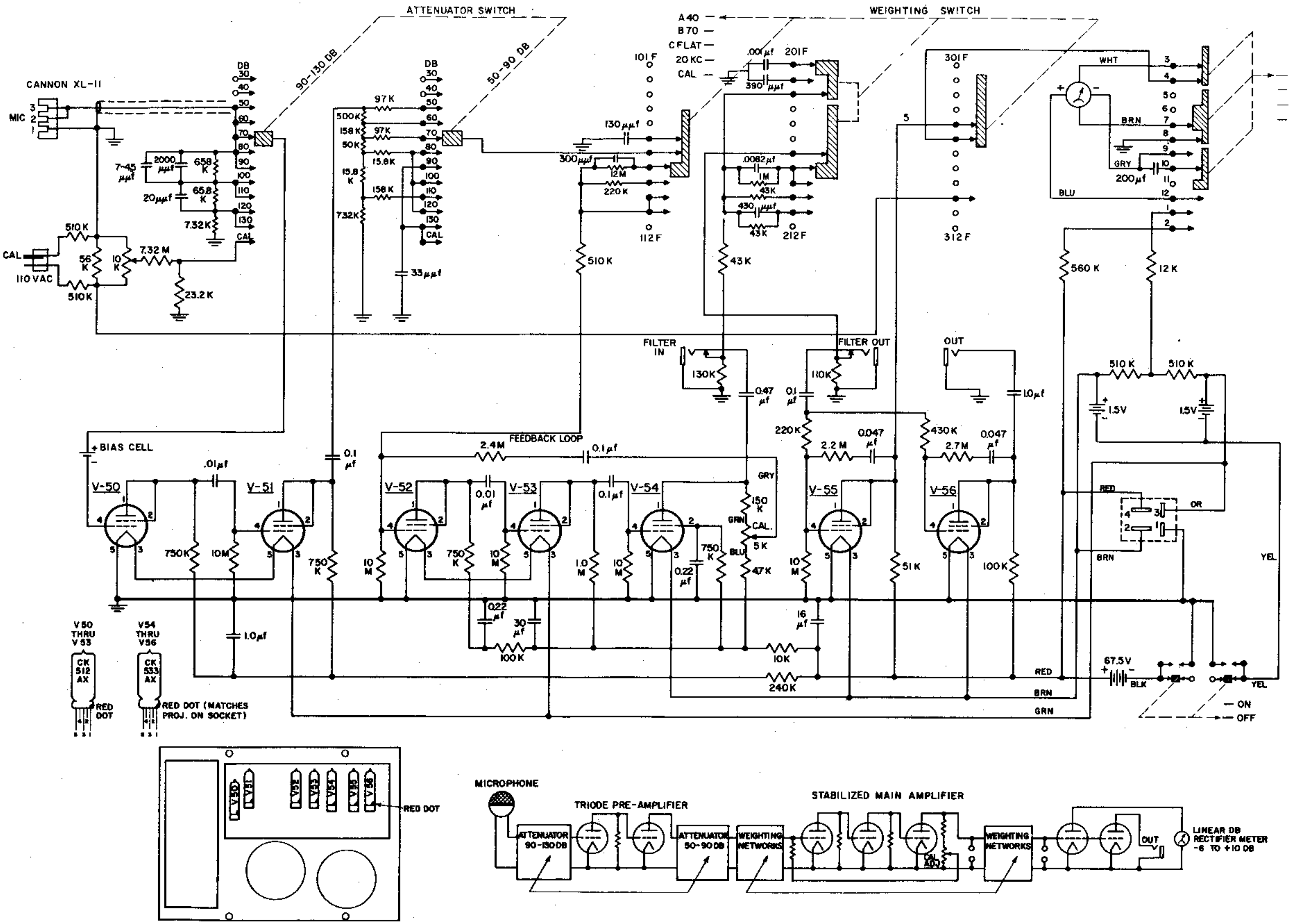
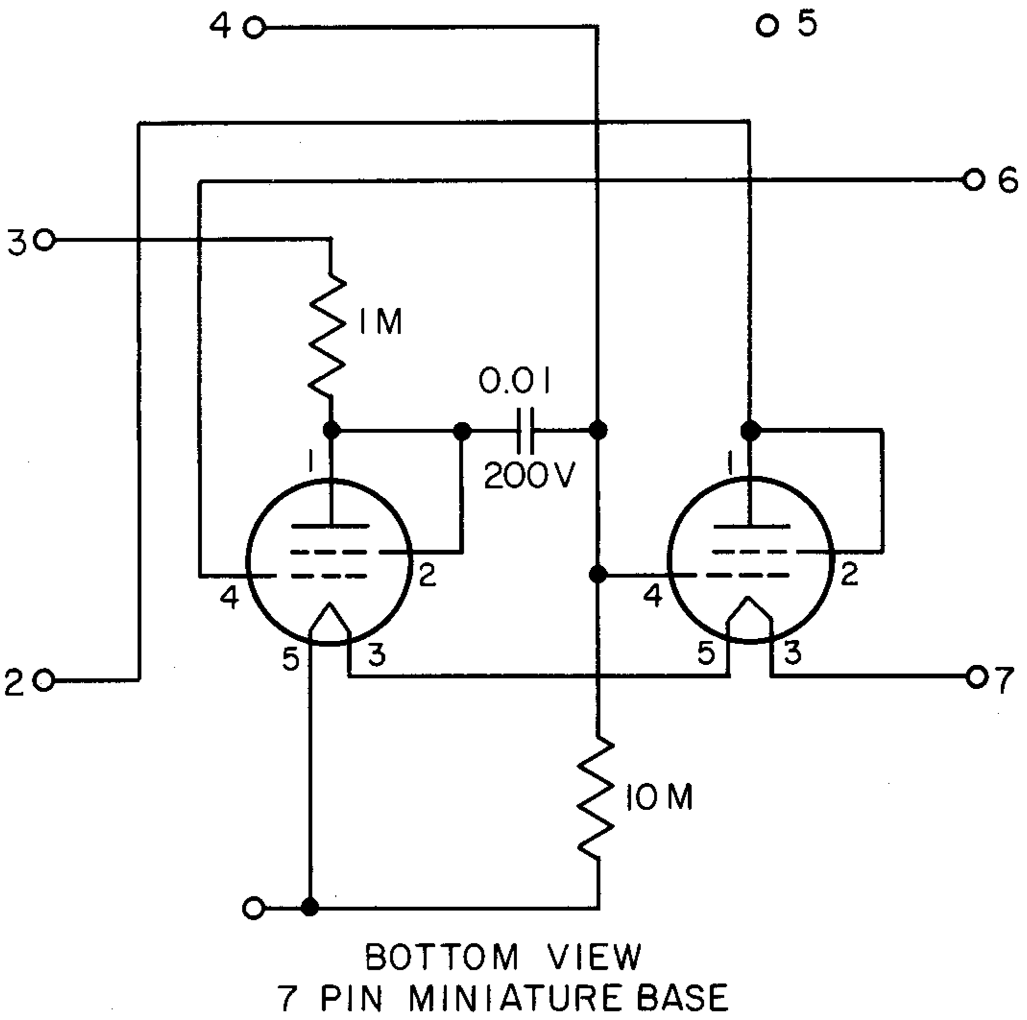


FIG. 63 GENERAL RADIO TYPE 1551-A SOUND-LEVEL METER



ALL RESISTORS 1/2 WATT
5% CARBON
TUBES 2 EA CK512AX
SMALL NUMBERS NEXT TO TUBE
ELEMENTS ARE PIN NUMBERS

FIG. 64 SPECIAL INPUT STAGE FOR GENERAL RADIO TYPE 1550-A OCTAVE-BAND ANALYZER