Suggested Title:

Electronic Techniques in Electromyography.

A LINE OPERATED ELECTROMYOGRAPH

L. A. Geddes

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FIGURE LEGEND

PREFACE

Early in the War (1939-45), the value of Electromyography for the diagnosis of the extent of nerve injuries was recognized by Dr. Herbert H. Jasper who gained the support of the Associate Committee on Army Medical Research and the Subcommittee on Traumatic Injuries of the Nervous System. This organization supported the research and development under his directorship at the Montreal Neurological Institute. After initial research and development had progressed, a report was presented in April 1945[1] to the Associate Committee describing the techniques and apparatus in use. These events marked the emergence of Electromyography from a research investigation to that of a clinical procedure. In the hands of a trained clinician, the value of this technique has proven itself sound and of genuine diagnostic value.

During and after this period, the instrument described in this report was put into limited production and designated as the Royal Canadian Army Medical Corps Electromyograph Mark II, the original pilot model instrument having been designated as Mark I. The production was carried out under the direction of Dr. Herbert H. Jasper at the laboratories of the Montreal Neurological Institute. The personnel engaged in the assembly were provided by the Royal Canadian Army Medical Corps.

The various instruments were assigned to selected military centers for diagnostic purposes. Personnel were selected and instructed in the techniques and operation of the instruments. A training course was given at the Montreal Neurological Institute covering the neurophysiology and electronics.

The success and value of the first series of instruments was recognized and additional support was gained. The Royal Canadian Electrical and Mechanical Engineers provided the technical and production personnel to further development of instrumentation in electromyography. Accordingly a military sub-department under Captain W. O. Fordse was established at the Montreal Neurological Institute. Working with, and under the direction of Dr. Herbert H. Jasper, this team designed a larger and more flexible instrument for electromyography which was designated as the RCAMC Electromyograph Mark III.[2-3] This instrument embodied the best techniques known at the time.

The instrument was physically larger and classed as mobile rather than portable like the Mark II. The Mark III was more pleasing in appearance with a greater ease of operation and mobility. It was built mechanically stronger and able to withstand higher humidity and temperature variations.

The principal electrical improvement over the Mark II, was in the audio amplifier system used to aurally monitor the electromyographic potentials. The stimulator was improved to the extent of providing more voltage. Later, an external ground-balancing stimulus-artifact-suppressor unit was supplied.

The Mark III unit was put into production and four units fabricated. These also were released to the specially trained personnel throughout the various military hospital treatment centers in Canada. The use of the instruments was not limited to Army establishment, Navy and Air Force units availed themselves of the facilities afforded by these instruments.

Substantially, all of the electromyographic work, during the war, in Canada,was performed on the Mark I, II, III units. These instruments, in the hands of trained personnel,provided valuable diagnostic information in nerve injury cases admitted to the various military hospitals.

At the end of the war, these assets became the responsibility of the Department of Veterans Affairs. With the cessation of active hostilities, and the consequent demobilization, many of the service personnel returned to civilian life. Consequently, a sharp reduction in the number of nerve injury cases occurred and the demand for electromyography lessened considerably in the military hospitals.

Meanwhile the value of the diagnostic information provided by electromyography began to be recognized by civilian hospitals. Inquiries were received by the Montreal Neurological Institute about the availability of the electromyographic apparatus. To make the equipment available commercially, Philips Industries of Eindhoven, Holland and Toronto, Canada, secured the services of W. O. Forde on his demobilization, with a view to producing a limited number of the Mark III electromyographs. Arrangements were accordingly completed between Philips Industries and the Montreal Neurological Institute for joint cooperation to permit these units to be constructed.

A production run was started and an initial quantity of instruments was made. The finished units were designated as Mark IV Electromyograph. One of the units was submitted to the Montreal Neurological Institute for their approval and testing.

The instrument was an electrical duplication of the Mark III with considerable economy mechanically. It resembled the Mark II unit in style, portability, and appearance but had the main features of the Mark III. These units were offered for sale by Philips Industries throughout the world.

In the immediate post-war period, attention at the Montreal Neurological Institute was being focussed on the more practical as well as the theoretical aspects of electromyographic apparatus. The early models Mark I, II, III, although well executed, required attention at inconvenient times, particularly since the preamplifier was battery operated. The batteries employed were the standard B-type radio batteries and a six volt storage battery. The storage battery was kept charged by a built-in manually controlled charger. Although the drain on the batteries was light, there were often periods of disuse during which they became neglected and run down.

It was for these reasons that the author under the direction of Dr. H. H. Jasper, undertook a program of research and development to eliminate the batteries. The ultimate aim was to operate the instrument entirely from the power line. This program was completed for the Mark III instruments constructed by the electronics development group at the Montreal Neurological Institute.

Consideration was also given to modernizing the stimulator features to permit newer measurements to be made. In addition, it became evident that more voltage, a stimulus delay and additional pulse durations were required. However, by this time, the War had terminated and pressure on the equipment was somewhat lessened. It was therefore, decided not to modify the existing units any further, but to consider the replacement of the present ones should the demands increase for electromyographic studies in the Department of Veterans Affairs.

With these original developments and operational experience as a background, requests were received practically simultaneously from the Royal Victoria Hospital in Montreal and the St. Vincent's Hospital in Los Angeles for electromyographic apparatus embodying the latest in developmental features, for versatility and ease of operation known at this time. The author accordingly accepted the responsibility of carrying out the design and construction of these units in his capacity as a consulting engineer.

The instrument herein described is a single channel model. St. Vincent's Hospital required a two channel unit which was constructed containing circuits identical with the single channel model.

The actual design, construction, wiring and testing of the electronic equipment was carried out by the author. The cabinet enclosing the various units was constructed by Mr. L. Katz, graduate student at McGill University.

The various circuits described and the techniques of construction were developed over several years by the author. Some were originated during the course of his work as a Consulting Engineer. Others were developed as a result of investigations and needs of the Montreal Neurological Institute. Many of the circuits herein described have been incorporated as basic circuitry for the various recording and stimulating devices now used at the Montreal Neurològical Institute.

ACKNOWLEDGEMENTS

The help and encouragement of Dr. Herbert H. Jasper of the Montreal Neurological Institute is gratefully acknowledged. It was he who brought the author into contact with the bioelectric measurements and techniques which has been a constant fascination and stimulus. Through his efforts, funds and laboratory facilities were provided so that these investigations could be carried out.

Dr. F. S. Howes of the Electrical Engineering Department at McGill, who authorized the subject material for thesis presentation, is to be thanked also. It is from his teachings that the author gained proficiency in the methods of applying electronics to the various medical problems.

Dr. H. E. Hoff, formerly Professor of Physiology at McGill University and now Professor of Physiology at Baylor University Medical College, Houston, Texas, is to be thanked for his reading of the first section on the theory of Electromyographic potentials and his general interest and suggestions in the presentation of this paper.

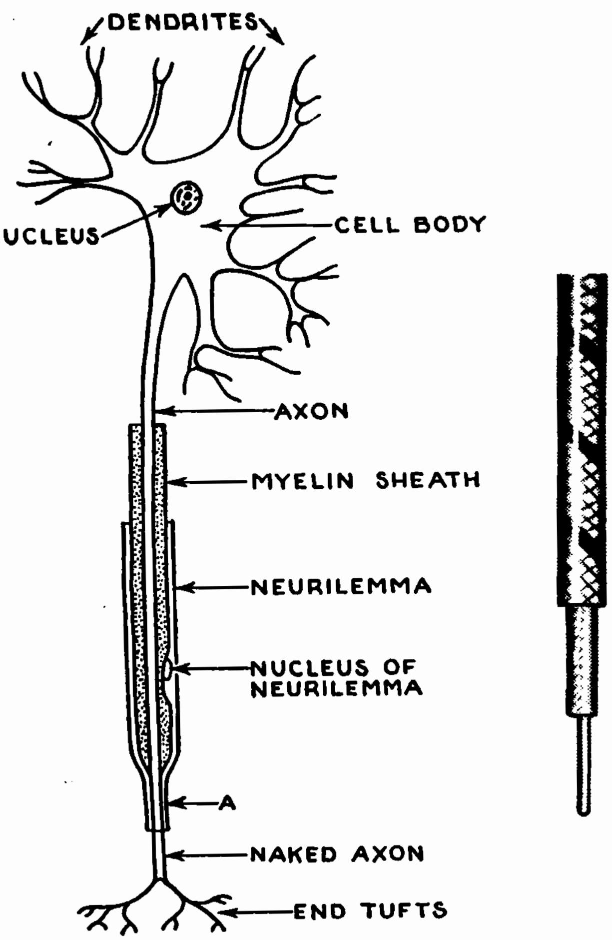
Dr. C. L. Li of the Montreal Neurological Institute is to be thanked for taking the records showing the electrical activity of the various muscles. He is also to be thanked for the surgical procedures carried out which were necessary to exhibit the muscle potentials found when nerve injury has occurred.

ELECTROMYOGRAPHY

The Science of Electromyography deals with the study of the electrical potentials generated within muscle fibers. An important part in the production of these potentials lies in the satisfactory transmission of the impulse along the nerve which supplies the muscle. This study, combined under the heading of Electromyography, is of great practical use in the diagnosis of various nerve-muscle disorders due to the disease or other agencies. In order to understand the principles involved, it is useful to review the membrane theory on the mechanisms involved in the transmission of an impulse along a nerve and into a muscle.

Membrane Theory.

The nerve, or more properly the nerve trunk, is made up of a bundle of nerve fibers. Each of these fibers consists of an axon (or axis cylinder) which is an extension or process of the nerve cell body. The axon is surrounded by a myelin sheath which in turn is surrounded by a thin membrane called the neurilemma. The neurilemma is an independent living structure, whereas the myelin sheath is an integral part of the axis cylinder. A structural comparison exists between the nerve fiber and a coaxial cable wherein the axon is the inner conductor, the myelin sheath corresponds to the dielectric and the neurilemma to the outer shield. (See Fig. 1). However, all



AXON

COAXIAL CABLE

FIG. 1.

(FROM ZOETHOUT-TEXTBOOK OF PHYSIOLOGY 10 ED. P.79)

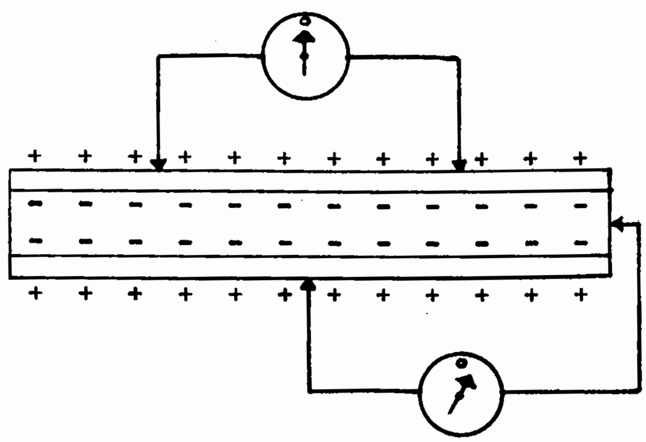
(STANDARD RG59U RADIO CABLE)

nerve fibers do not have a distinct myelin sheath. Those without myelin form a part of the autonomic system which is concerned with the maintenance of activity in the internal organs of the body.

The function of the nerve fiber is to conduct the nerve impulse from the point of origin to the structure terminating it. To do this the nerve is said to possess the property of irritability and conductivity. The fiber membrane itself has the property of electrolytic semipermeability in which the end result is that a prolonged state exists in which the outer surface is positive and the inner core or axis is negative in the normal resting nerve.

When the nerve conducts an impulse, a wave of depolarization travels along the nerve. It is interesting to note that the impulse is conducted along the fiber without attenuation. During and after the impulse has passed along the nerve, there is refractory period during which no impulse can be transmitted.

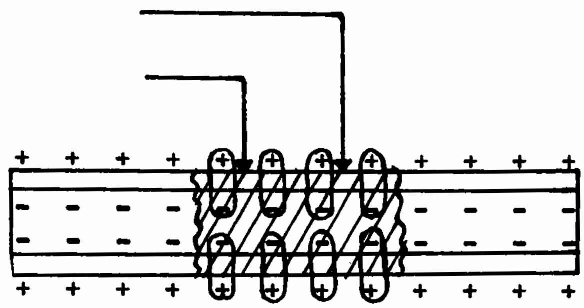
To illustrate these factors, measurements have been made on isolated nerve fibers. If, as in Fig. 2, electrodes are placed on the outer surface of the fiber, in the resting state, no potential difference is observed. On the other hand, if electrodes are placed with one on the outer surface and the other on the exposed end, the outer surface is found to be positive with respect to the inner axis and current flows through the indicating instrument. In summary the charge conditions resemble those of a condenser arranged cylindrically.



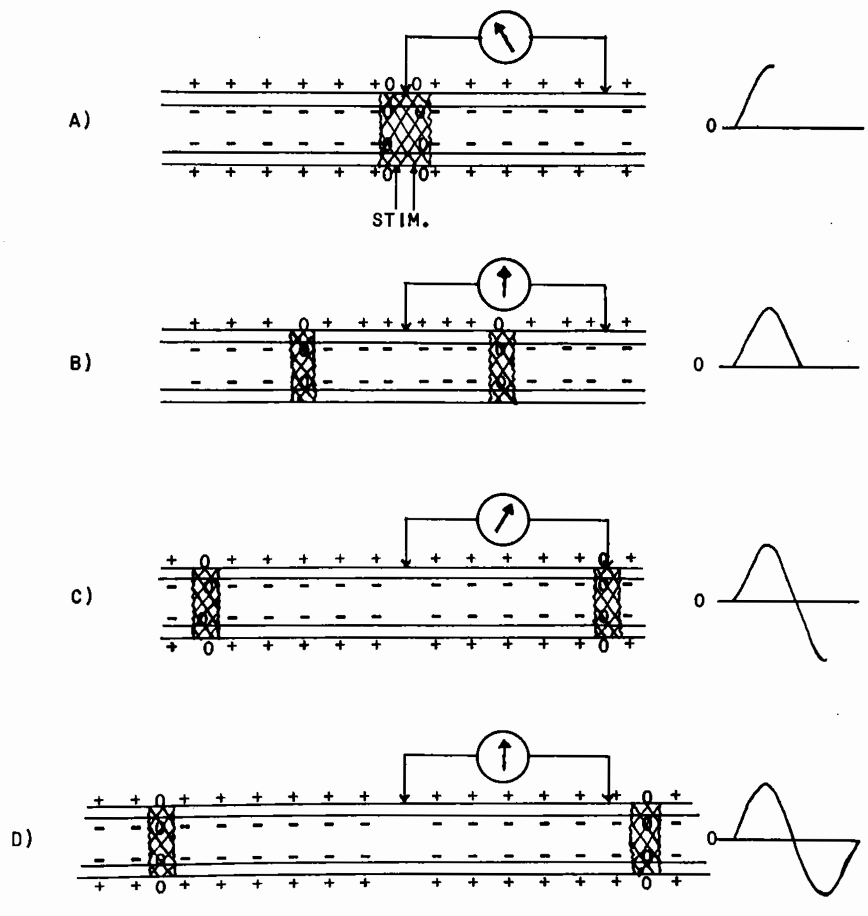
POTENTIALS OF
AN ISOLATED NERVE FIBRE.
FIG. 2.

Until now, consideration has been given only to the static isolated nerve fiber. If one examines the fiber in situ, at rest, the polarized state exists along the nerve fiber. If now an electrical stimulus is applied as in Fig. 3, physical and chemical changes are elicited which result in a change of the permeability of the membrane and flow of ions takes place at the point of stimulation. This results in a local depolarization and causes a difference of potential along the outer surface between the point of stimulus and all other points on the surface of the nerve fiber. However, this state of depolarization does not remain local in character. The state of depolarization with the associated ion flow liberates energy, similar to the discharge of a condenser. The liberated energy acts as a stimulus on adjacent areas of the nerve fiber and the wave of depolarization travels outward in both directions from the point of stimulation. Placing pick-up electrodes on the nerve and applying a stimulus will cause a potential change wave to travel along the nerve such that the potentials will be at first surface negative then positive as shown in Fig. 4 abcd. This potential wave is called the action potential. After it has passed, reconstructive forces restore the polarization of the membrane in readiness for the next impulse. The time taken to repolarize is referred to as the refractory time, during which no impulse can be conducted.

The nerve impulse, now having been generated, is conducted to its terminating organ. On entering a muscle, nerve fibers distribute themselves among hundreds of muscle fibers. The



STIMULATION OF
AN ISOLATED NERVE FIBRE.
FIG. 3.



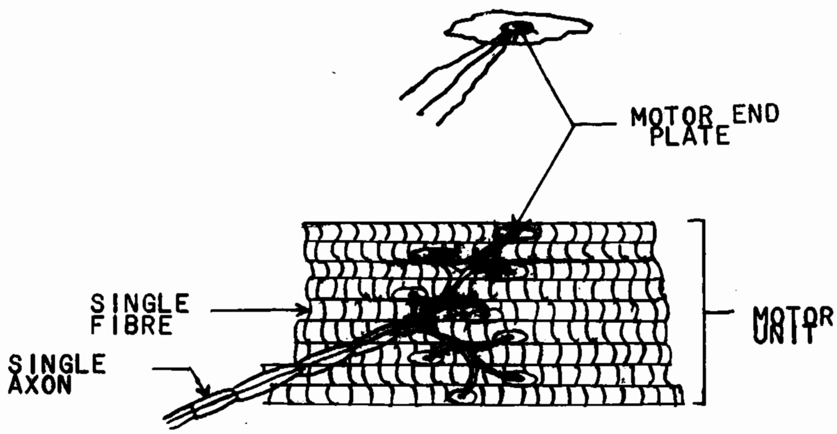
THE ACTION POTENTIAL
FIG. 4.

muscle fibers themselves are elongated groups of fused cells which have the property of contraction when stimulated. In addition, like nerve fibers, they produce a characteristic voltage when excitation takes place.

Motor End Plate.

At the junction between the nerve ending and the muscle fibers is a very important structure called the motor end plate. This structure is shown in its position in the innervation of muscle as shown in Fig. 5. It is an area of extreme physiological importance. In a sense it is a one way transmission site (like a rectifier) and is the weakest link in the neuromuscular chain. It is in this area that fatigue and many diseases have their effect. The end plate responds also to the action of drugs in a dramatic way. For example, the transmission across the motor end plate can be abolished by a drug called curare and in many cases can be restored or enhanced by another drug called prostigmine. It was, indeed, the study of the abolition of the transmission of the nerve impulse across the end plate in the curarized preparation that provided much of the early knowledge of muscle physiology.

In the curarized preparation, the nerve can be stimulated giving rise to the nerve action potential, but no muscle contraction occurs. The muscle fibers themselves can be stimulated directly and contraction occurs showing the property of contraction by stimulation. When the nerve is stimulated and normal physiological conditions exist, the nerve impulse travels along the nerve fiber across the motor end plate to the muscle fibers.



THE INNERVATION OF MUSCLE
FIG. 5.

(After a sketch from "The Rate of Innervation of Muscle Following Nerve Injuries in Man as Determined by the Electromyogram" Trans. R.S.C. Sec. V. 1946 by H. H. Jasper-presented by Wilder Penfield)

The muscle fibers in turn contract and produce their own wave of potential called the motor unit potential. However, the process is not instantaneous. Each of the structures, the nerve fiber, the end plate and the muscle fiber has a refractory period during which no response can be obtained from a subsequent stimulus. Each has associated with it a time of conduction which varies with disease and other physiological conditions. Such conduction times can be computed, and in turn, the actual conduction velocity of the nerve fibers obtained.

The Use of Electromyography.

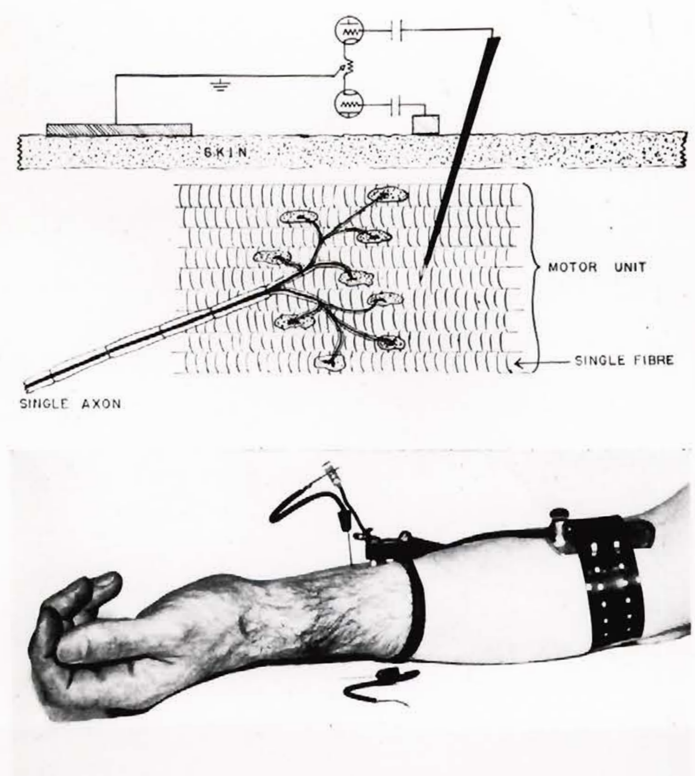
The diagnostic information in the electromyogram is considerable. One of the principal uses of the apparatus has been the study of the reinnervation of muscle following nerve injuries in man. During the War (1939-45), many nerve injury cases were to be found in military hospitals. Toward the end of the War the electromyograph was used on these cases to record the electrical activity of the muscle and to estimate the recovery rate of the muscle group studied. In the denervated muscle, spontaneous electrical activity exists and has a definite and recognizable pattern. On the other hand, a normal muscle is electrically silent when at rest. However, on voluntary contraction, the normal muscle is electrically active with a recognizable and considerably different pattern from that of the nerve injury state.

The electromyograph is also of service in the diagnosis of nerve and muscle disease. It can be used as an instrument to record the electrical activity of other parts of the nervous system such as the spinal cord and brain potentials. As a physiological research tool, much basic information can be obtained on nervous propogation and to study the effects of drugs on the nervous system. Since, in many diseases, specific parts of the nervous system are attacked, the extent of the ddisease can be studied as well as the effectiveness of the applied therapy.

Technique.

The actual connection to the muscle can be conveniently made by an arrangement as shown in Fig. 6, (in which is shown the input connections). This technique, was devised by Dr. Herbert H. Jasper of the Montreal Neurological Institute. The actual pick-up electrode is a very sharp steel needle about $2\frac{1}{2}$ inches long coated with a plastic insulating varnish called Tygon 109. Due to surface tension action during the coating procedure, only the very tip of the needle is exposed for a distance of about 50-75 microns. This allows a highly localized exploratory recording to be made within the muscle. The reference electrode consists of a strip of silver about 3 cm. by 1 cm., and is held to the member under examination by a rubber band. It is placed above the muscle group under examination. The grounding electrode which is another silver plate about 3 cm. by 6 cm., is located distant to the recording pair. Both the grounding electrode and reference electrode are lubricated with electrolytic jelly to insure good electrical connection to the subject.

With these input connections and subsequent amplification,



Schematic diagram of innervation of muscle by a single motor nerve fibre or axone, with illustration of method of recording muscle action potentials by the use of a single small sharply pointed needle electrode insulated except at the tip. The electrodes attached to the arm are shown in the photograph below.

FIG. 6.

(FROM "THE R.C.A.M.C. ELECTROMYOGRAPH MARK III–FIG.1 BY HERBERT H. JASPER AND WILLIAM O. FORDE." CAN. JOUR. RES. E25:100–110 APRIL 1947) the wave forms are displayed on a cathode ray tube and fed to a loudspeaker. The wave forms can be recognized by sound as well as sight which allows the operator freedom to explore the muscle for the electrical activity sought without watching the cathode ray tube face. When the characteristic sounds are heard, detailed wave form examination and permanent recordings are made on the cathode ray tube. The electrical activity from the area immediately in the neighborhood of the needle electrode is sharp in sound, while that of distant muscles is a muffled rumbling. When the exploratory electrode is placed in a denervated muscle, a spontaneous activity called fibrillation is observed which consists of condenser discharge-like waves having a duration of 1 to $1\frac{1}{2}$ miliseconds and amplitude of 50 to 100 micro-volts. These potentials produce a sharp crackling sound in the loud-speaker. The electrical activity of a normal muscle at rest is nil. However, during response from a single nerve impulse from a single axon, a normal motor unit wave of duration of 5 to 8 miliseconds and amplitude 1,000 to 6,000 micro-volts is obtained and produces a sharp knocking or rumbling sound in the louspeaker. These wave forms are sketched in Fig. 7.

In the regenerating electromyogram, both individual wave forms are observed and the resultant wave is very complex in character. As reinnervation proceeds, the wave forms develop from a condition of less and less spontaneous fibrillation to organized normal motor units. Hence, a chronological study of the process can be made to estimate recovery time.

With this knowledge of wave forms and amplitudes, derived

NAME OF WAVE	WAVE FORM	AMPLITUDE	CHARACTERISTIC SOUND HEARD
NORMAL MOTOR UNIT		2000 UV.	KNOCKING OR RUMBLING
FIBRILLATION		100 UV.	SHARP CRACKLING
TIME SCALE 1000 CYCLES PER SECOND		---------	PURE TONE

WAVE FORMS.
FIG. 7

from the laboratory experiments of many research investigators, the problem resolves itself into one of design of adequate apparatus to measure these potentials. Accordingly, the overall characteristics of the apparatus are such that a true reproduction of these wave forms must be possible.

DERIVATION OF REQUIREMENTS

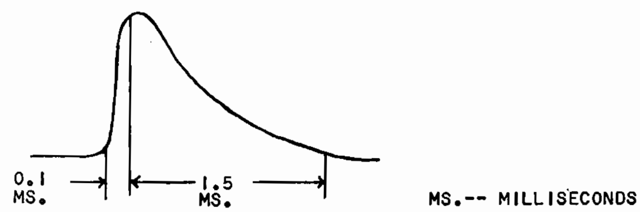
In summary, the apparatus must record the smallest voltages which are fibrillation potentials and the largest which are motor units. These must be displayed on the cathode ray tube for visual study and through a loudspeaker for aural recognition. The sharpest waves will dictate the high frequency response needed and the waves of longest duration determine the low frequency response required in the amplifying system.

High Frequency Requirements.

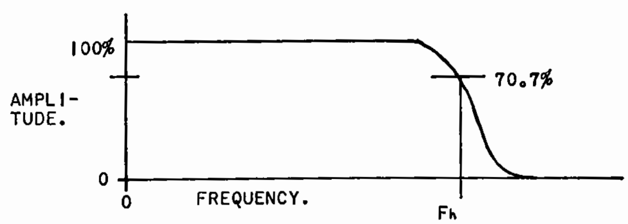
The fibrillation potentials are of the order of 50 to 100 micro-volts in amplitude and are of condenser discharge form with a duration at the base of about 1 to 1½ miliseconds. The rising phase, or steepness of the front of the wave, is of the order of $\frac{1}{10,000}$ of a second. This wave is dimensioned in Fig. 8a. From these quantities one can impose operating requirements on the amplifier stages.

From the Sampling Theory[4] the relationship between frequency response and rise time can be used as a starting point. Fig. 8b shows the identical frequency response of a linear system. Such a system would respond to a step function as shown in Fig. 8c. The rise time is defined as the time for 10-90% amplitude response and is given by the relationship $T = \frac{1}{2Fh}$, where Fh is the usual 70.70% high frequency cut off point.

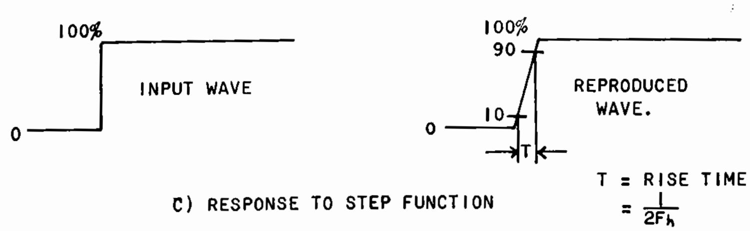
By applying this relationship to the present case, $T = \frac{1}{10,000}$ second $= \frac{1}{2Fh}$. Therefore Fh = 5,000 cycles. From this, the



A) FIBRILLATION WAVE



B) FREQUENCY RESPONSE



C) RESPONSE TO STEP FUNCTION

HIGH FREQUENCY REQUIREMENTS
FIGURE 8

minimum high frequency response can be set at 5,000 cycles. A higher Fh would permit the reproduction of shorter transients than fibrillation waves of $\frac{1}{10,000}$ second rise time.

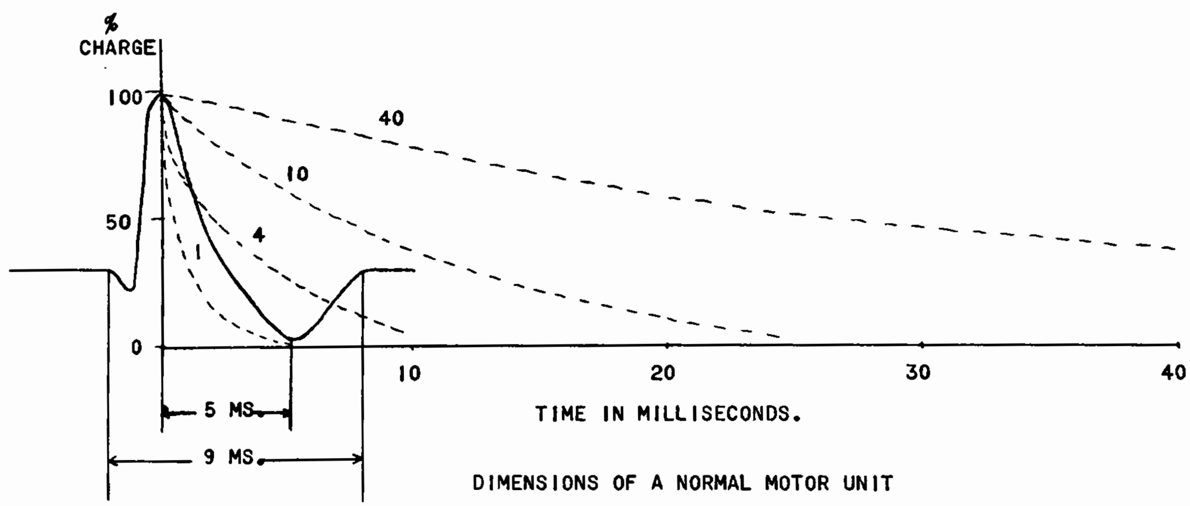
Low Frequency Requirements.

To examine the low frequency requirements, one must consider the longest duration wave which is the normal motor unit. This wave form is dimensioned on Fig. 9. The total duration of the wave is 9 milliseconds. The rising phase occupies about 1 millisecond and the falling phase about 5 milliseconds. The return to zero potential requires about 3 milliseconds. Frequently these waves are polyphasic but in general, there is no single component with a width greater than 5 milliseconds.

The shape of the wave resembles a half sine wave with a steeper rising phase than falling phase. This falling phase resembles an exponential curve decay but a simple time constant cannot be readily deduced, as it is not a true exponential. A Fourier analysis would give frequencies components ranging from zero to infinity due to asymmetrical shape of the wave.

As a practical attack to the problem, the wave was dimensioned (solid) along with various time constant curves (dotted) in Fig. 9. Assuming various time constants of 1, 4, 10, 40 milliseconds, it is seen that a time constant longer than 4 milliseconds and less than ten milliseconds would give the desired low frequency response to reproduce the wave form falling phase.

In some instances the waves are accompanied by a slower



DIMENSIONS OF A NORMAL MOTOR UNIT

FIG. 9

after-potential which is important diagnostically. This then would require a longer time constant than one between 4 and 10 milliseconds. To reproduce these and longer duration transients which might be of importance in the future, a time constant of 40 milliseconds was decided upon. With such a margin of safety of low frequency response, motor unit waves of longer durations will be faithfully registered.

Amplitude Requirements.

For the amplitude characteristic, the smallest potentials of the order of 50 to 100 micro-volts must be displayed about $\frac{1}{2}$ to 1 inch in amplitude on the face of the cathode ray tube. Most standard cathode ray tubes of 5 inches in diameter with about 1500 volts accelerating potential, have a deflection sensitivity of about 50 volts per inch. By simple computation, 50 micro-volts must be amplified to $\frac{1}{2}$ inch or 25 volts. Therefore, the amplification needed is of the order of $\frac{25}{50 \times 10^{-6}} = \frac{1}{2}$ million.

To summarize, the amplifying channel must have a minimum high frequency response of better than 5,000 cycles at 70.7 percent amplitude and a time constant of at least 40 milliseconds. The approximate minimum gain required from input to cathode ray tube deflection plates is of the order of one-half million.

Input Considerations.

Another of the operating conditions inposed on the apparatus is the high resistance of the subject across the input leads with inherent tendency to pick up hum and other external interference. This calls for not only a push-pull amplifier, but one with very high degeneration to inphase signals, so that the output is a true differential of the input. Interference signals will be picked up equally by both input leads with respect to ground. If the amplifier has a high in-phase discrimination, these signals will not appear across the push-pull deflection plates.

Balance Ratio.

It is customary to call the in-phase discrimination characteristic the "balance ratio" and is defined as the ratio of the push-pull gain to the parallel gain measured across the push-pull output. The usual technique employed to measure this ratio is to apply a push-pull signal to input and note the output. The two input grids are then joined together and the signal applied between these grids and the negative return of the cathodes. The input is increased until the output is the same as it was under the push-pull conditions. The ratio of these two inputs determines the balance ratio. Care must be taken not to block or overdrive the amplifier when the parallel input signal is applied. Usual balance ratios run from several hundred to twenty thousand. A ratio of about five thousand is onsidered excellent for biological amplifiers.

Cathode Ray Presentation.

The cathode ray tube used for viewing the amplified signal must be swept by a time base in such a way that photography as well as visual observation will be possible. This imposes the requirement that the sweep have single stroke action, initiated by the camera as well as being capable of repetitive operation.

If the sweep were arranged to run freely, as in standard oscilloscopes, synchronization of the sweep would not be possible, as the biological signal is transient in nature. With no synchronization, the transient biological potentials would shift back and forth depending upon the sweep velocity and their own repitition rate. The addition of synchronization to such a system would cause the sweep to shorten and the effective sweep velocity would vary with the amount of synchronizing voltage, which is the signal under investigation. These difficulties are overcome by triggering the sweep by a separate oscillator. This means that the sweep will be repeated at some convenient number of times per second. Depending upon the sweep speed and the sweep repetition, there may exist a dead time in which the potentials can occur without being visible on the cathode ray tube face. Here is where the loudspeaker and audio amplifier are of practical value. With a little experience, the aural recognition of the motor units and fibrillation potentials becomes easy. The loudspeaker channel, of course, listens continuously and hence misses none of the potentials. It is also very useful in placing the pick up electrodes because the operator can concentrate on the insertion technique, rather than watching the cathode ray tube. Since the loud speaker handles the same signals as the cathode ray tube vertical deflecting plates, the same frequency response characteristics are required. The characteristic sounds heard for fibrillation potentials resemble the rustling of cellophane. The motor units, on the other hand, have their characteristic knocking or thumping sound.

It has been found practical to run the sweep repetition rate at about 10 per second. The range of sweep velocities that is of value extends from 20 to 2.5 milliseconds per inch, measured on the cathode ray tube face. This permits enough range to show detail in the normal motor units and to spread out the fibrillation potentials for close observation. When photography is required, the sweep repetition oscillator is turned off and the camera shutter contacts are arranged to trigger the time base for a single excursion of the tube. Several photographic exposures are usually taken. When one sees a wave appear on the cathode ray tube face, with this technique, it is photographically recorded. The fibrillation potentials are semi-transient in nature. However, when one occurs, usually a volley follows shortly thereafter. The motor unit potentials in the normal nerve-supplied muscle are elicited by voluntary contraction. During the voluntary contraction several photographs can be obtained with ease.

Stimulator.

It is often advantageous to employ a stimulator in conjunction with electromyography to stimulate various nerve and muscle groups. There is considerable diagnostic information in the strength-duration test of a muscle and in the conduction velocity of a nerve. The strength-duration test is carried out by stimulating the muscle with various duration waves from very short to very long and noting the voltage for each duration necessary for a response. A curve is plotted called the strength-duration curve and is shown in Fig. 10 in which the typical shape for a normal muscle and a denervated muscle are shown. There are two main points of importance on the strength-duration curve. One is that theshold or value of stimulus intensity necessary to obtain a response when the current flows for an infinitely long time. This threshold is called the Rheobase. The other point on the curve is called the Chronaxie and is defined as the time that the stimulus must last at an intensity of twice rheobase in order to be an effective stimulus.

The value in the strength-duration test lies largely in the great difference existing between the values of chronaxie obtained in normal muscle and denervated muscle. When the technique is used to follow destructive degenerative changes in muscle nerve supply, the chronaxie remains unaltered a short period following the destruction. Chemical and other changes take place within the muscle resulting in the lengthening of the chronaxie. Later the chronaxie becomes so long that the muscle becomes inexcitable with brief (Faradic) stimuli, although still excitable by currents of long (Galvanic current) duration. This sequence of events is often called the reaction of degeneration and is particularly well suited to measurement with the electromyograph.

Conduction Velocity Technique.

The conduction velocity of a nerve or conduction time of a nerve-muscle response is also well suited to measurement with the electromyograph. These latencies vary widely with physiological conditions and disease. The conduction velocity of nerve

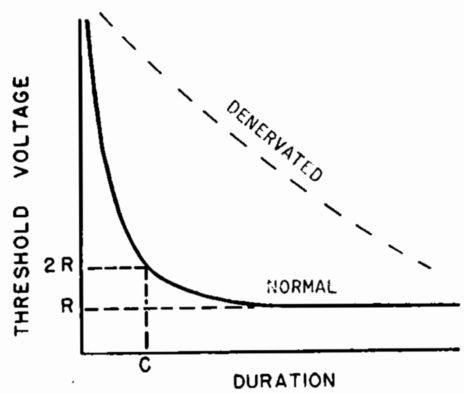


Fig 10 Threshold voltage for current pulses of various durations. Rheobase at R; chronaxie at C.

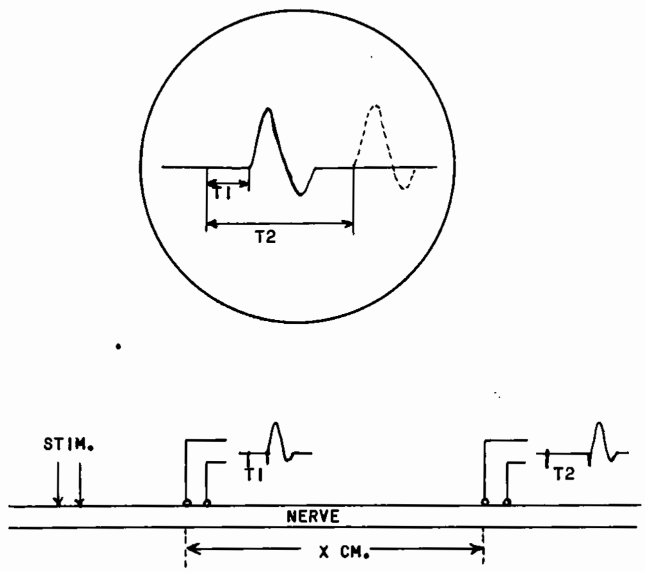
(After a sketch from "Medical Physics" p.799 fig.3-Glasser Copy. 1944) fibers also depends on their physical dimensions. Coarse large diameter fibers have a high velocity of conduction (about 30 meters /second) whereas fine filamentary fibers conduct much more slowly (a few meters/second).

To measure the conduction velocity of a nerve, or conduction time of a nerve-muscle response, a stimulator, synchronized and delayed with the sweep, is necessary. The stimulus excites the nerve and the response or impulse wave travels along the nerve. It is picked up by the recording electrodes and displayed on the cathode ray tube. The time between the stimulus and the response can be scaled off the tube. This is the time taken for the stimulus to activate the nerve, initiate the nerve impulse and the time taken in its propogation along the nerve to the recording electrodes.

The conduction velocity can be computed by making two measurements as in Fig. 11. A first stimulus response time (T1) is computed. The recording electrodes are then moved along the nerve a distance of x centimeters and another stimulus response time (T2) is measured. The conduction velocity will then be given by $\frac{x}{T2-T1}$ and will be in centimeters per second.

Since the sweep is triggerable from the camera shutter, and the stimulus is triggered from the sweep, it will then be possible to initiate a stimulus and response by depressing the camera shutter release. In so doing, the complete picture will be photographed by a single procedure.

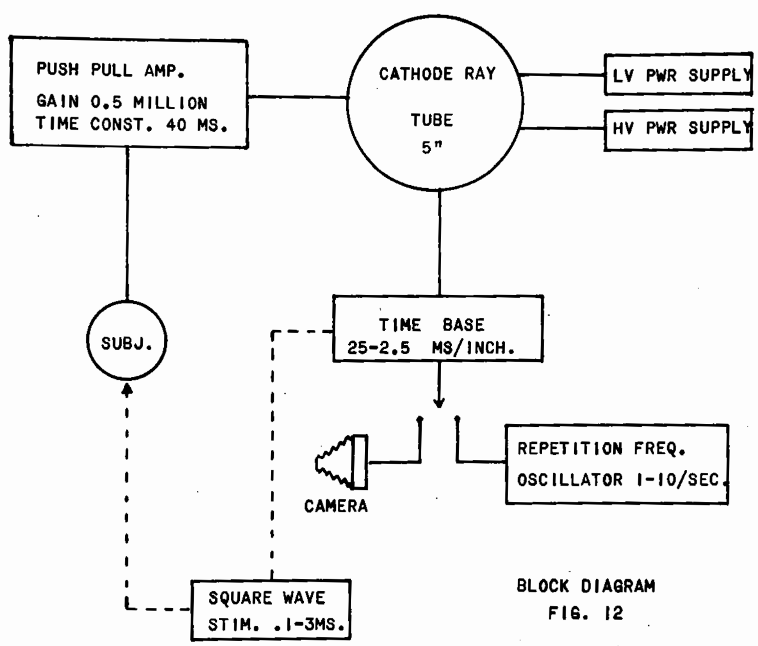
From the foregoing theory and techniques, it is now possible



CONDUCTION VELOCITY = $\frac{X}{T2 - T1}$ CM./ SEC.

CONDUCTION VELOCITY TECHNIQUE
FIG. 11.

to draw up a block diagram of facilities required to accomplish the recording and eliciting of the nerve-muscle potentials. Fig. 12 shows a graphical summary in a black diagram.



BLOCK DIAGRAM
FIG. 12

DESIGN OF COMPONENT PARTS

Preamplifier - General Consideration

In order to suppress the pick-up of stray interference by the input stages, it is useful to contain them in a separate shielded cabinet, usually called the preamplifier. In addition, if the filaments are operated on direct current there need not be any alternating current carrying conductors, other than the signal leads, in the preamplifier. By following this procedure the desired signal can be boosted in amplitude so that its magnitude is large compared to the extraneous interfering fields present in usual amplifier stages. This would result in uncritical placing and wiring of the components in the various stages.

Since high frequency response is of paramount importance, all practices toward the attainment of this goal must be carried out. Obviously shielding, in addition to all its other benefits, adds shunt capacitance. This must be avoided as must all capacitive loading procedures. Furthermore, with a gain of half a million to be attained, many stages in cascade are required, making the high frequency problem even more difficult.

From both theoretical and practical considerations, a factor worthyof considerable attention is the location of the gain or sensitivity control in the amplifying channel. For example, if the gain control were placed late in the amplifier, the dynamic amplitude range of the apparatus would be seriously limited because the early stages would block on large signals. If, in the other extreme, the gain control is located at the input, all of the internal noise of the amplifier would be present at very low gain. This would result in a very low signal to noise ratio for large signals. In addition, switching transients would be very severe due to thermals and contact potentials. For these reasons, therefore, a compromise must be made to give the best overall characteristics.

From the operational standpoint, it is useful to locate the preamplifier close to the subject. By so doing, the length of the subject input cable with its shunt capacity is its shortest. To add facility in operation, the gain control should be located within easy reach of the operator who is generally at the subject adjusting or inserting electrodes. The only disadvantage to this arrangement is that the power supply cable and the signal output cables would be lengthy.

One of the first things to do before splitting the amplifying channel into its pre and later amplifying stages, is to decide on the number of stages and the tube types necessary to meet the requirements. Since the amplifying channel has high gain, the input stage tube will have to be selected for low noise and anti-microphonism. It would be good design procedure to use as many of the same type of tubes in the apparatus. With this feature, the tubes rejected in the selection of an input tube could be used further back in the less critical stages of the amplifier.

Another choice that must be made is that of pentodes versus triodes. Briefly, pentodes are charactericized by high transconductance, plate resistance, amplification factor and noise, but with low input capacitance. Triodes, on the other hand, have moderate transconductance, low plate resistance, amplification factor, and noise but with high input capacitance. Using pentodes would apparently require fewer stages if gain were the only consideration. Such an amplifier would have few stages, high noise, and poor high frequency response due to the high output impedance; which comprises the plate resistance and load resistance. On the other hand, using triodes to construct the amplifier would require more stages but give a better high frequency response over all and per stage. The use of more stages to obtain the required gain would tend to make the overall high frequency response a little more difficult to attain.

Choice of Tubes.

Since biological amplifiers are balanced push-pull in design, the use of double tubes would be a very practical choice to conserve space and lessen wiring capacitance. Of all the double voltage amplifying tubes, there exists only one twin pentode with the heater type cathode which bears the number 12L8GT. However, this tube is relatively unavailable and is not on the R.M.A.[5] standard stock replacement list. It also draws rather more plate current than is needed for the voltage swings of an input stage. This then tends toward the discarding of this tube and consequently pentodes due to the very limited choice.

The choice then must be made on the various twin triodes on the basis of plate resistance, amplification factor, transconductance, interelctrode capacitance, plate current, and any practical experience covers such points as anti-microphonism, noise, similarity, tendency toward hum pick-up, hours of life, and any other miscellaneous factors. Another choice must be made on the individual merits of glass, metal or miniature tubes.

Past experience of the author has shown that in spite of the ruggedness of the minature tubes for their size, they tend to be rather microphonic. Another factor against the use of miniature tubes is the instability of the pin-socket contact. This shows up as noise that disappears when the tube is rocked in its socket. Recently, however, there have been developed specially constructed Silver-plated Beryllium-Copper contact spring sockets for miniature tubes which should remedy this situation.

Experience with metal tubes has shown then to be rather microphonic in the mid-frequency range and to produce a long-lasting or ringing type of microphonism. One additional characteristic was that the apparent excellent shielding offered by the metal envelope caused the tube to be sensitive to hum pick-up by induced pulsation fields which entered the shield.

Using this experience, as a background, one would favor the glass twin triode in spite of its apparent lack of shielding. However, the following table (Fig. 13) was drawn up as a survey of the tubes from which a choice was made.

A survey of the table, bearing the preceding facts in mind, leads to the preference of the 6SL7 for its standard octal base, glass, moderately good gain, low plate current, and plate resistance characteristics. Although the input capacitances with a shield are higher than the metal 6SC7, the lower plate resistance

Tube Type	U	Rp	Ip	Approx. Gain	Input Cap.	Remarks
6SC7 (12SC7)	70	53k	2	45.7	Cgk 2uuf Cgp 2	Common cathode, double triode, metal, used in pre-amps for phono - tendency toward microphonism and select - ability fair - octal - hi gain.
6SL7 (12SL7)	70	44k	2.3	48.6	Cgk 2.8 Cgp 3.2	Hi gain twin triode - separate cathodes - octal glass - 3 matched selectable from 12 - Previous experience good.
6SN7	20	7.7k	9.0	17.7	Cgk 2.9 Cpk 3.9	Medium gain - twin triode separate cathodes octal glass - low power tube.
6N7	35	11k	7	31.5	not stated	Common cathode class B power amplifier metal and glass
12AU7	17	7.7k	10.5	15.8	Cgk 1.6 Cgp 1.5	Medium gain twin triode separate cathode glass 9 pin miniature.
12AX7	100	62.5k	1.2	61.7	Cgk 1.6 Cgp 1.7	Hi gain twin triode separate cathode similar to 6SL7 - glass 9 pin miniature - very microphonic
12AY7	100	62.5	1.2	61.7	Cgk 1.6 Cgp 1.7	Non micronphonic 12AX7 - Experience to date has been that it was only <u>slightly</u> better than 12AX7.

TUBE FIGURE

FIG. 13

would tend to offset this fact. The 6SL7 is virtually the only standard heater-type twin triode with a glass envelope. There are, of course, other twin triode tubes with direct current filaments and still others with 7 volt filaments. However, one would hesitate to employ 7 volt tubes due to their obsolesence. Again, the difficulties in obtaining cathode bias when using direct current filaments renders these tubes out of the class of contenders. It is indeed unfortunate, however, that the miniature tube, 12AY7, had to be discarded as it has high gain, low plate resistance, and looks like a very promising amplifier tube for the future.

Having decided that the 6SL7 will be used, it is in order to sectionalize the amplifying channel into its preamplifier and voltage amplifying stages. To do this, assumptions must be made in order to get started in computing the total number of stages. The gain of a triode amplifier is given by

$$A = \frac{URL}{Rp + RL}$$

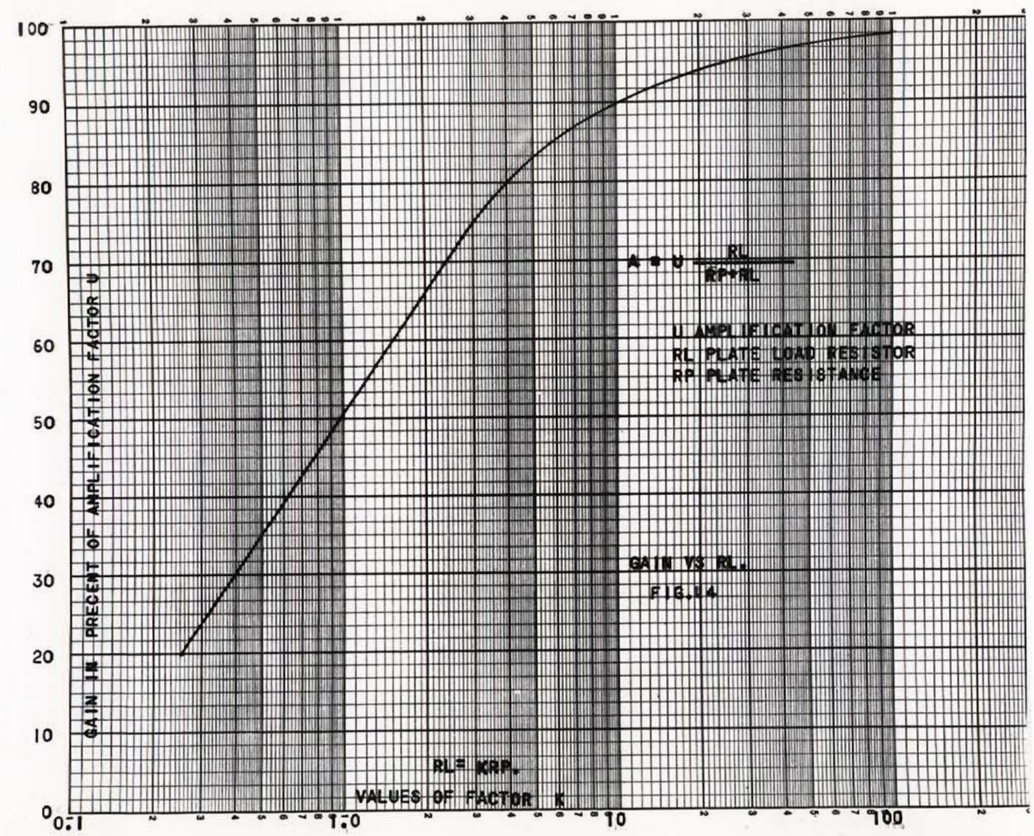
When A = Amplification or gain

U = Amplification factor

RL = Load resistance

Rp = Plate resistance

If one makes Rl equal Rp, the gain reduces to $\frac{u}{2}$. Increasing Rl, of course, increases the gain but not until Rl is much greater than Rp does the gain begin to approach u. This is plotted in Fig. 14. If one considers the gain when Rl equals Rp for the 6SL7, a gain of $\frac{70}{2}$ or 35 per stage is obtained. Two such stages would, of course, give $(35)^2$ or



GAIN VS RL.
FIG.14

1,225 and four would produce $(1,225)^2$ of $1\frac{1}{2}$ million. This is more gain than is required, but allows a margin in design for the variation of components and tube parameters at the operating voltages.

High Frequency Response.

Having chosen Rl equals Rp and in the case of the 6SL7 this is 44,000 ohms, the maximum allowable shunt capacitance per stage can be computed for an overall attenuation of 3db (70.7% response) at 5,000 cycles. With uniformly distributed capacitance, the amplitude response of each stage at 5000 cycles will be $4/\overline{0.707}$ or 0.91. With this figure as a starting point, the maximum shunt capacitance permissable per stage was calculated as follows:

Solution to High Frequency Response.

Triode amplifier gain $= \frac{uZl}{Rp+Zl}$

Zl in this case is the parallel impedance of the load resistance Rl and the shunt capacitance Cs.

$$\frac{Gain}{u} = \frac{Zl}{Rp+Zl}$$

Let $\frac{Gain}{u} = a$

Where u is the amplification factor

Zl " " load impedance

Rp " " plate resistance

Rl " " load resistance

Cs " " Shunt capacitance

$$\frac{1}{Z1} = \frac{1}{R1} + jwCs = \frac{jwCsR1 + 1}{R1}$$

$$Z1 = \frac{R1}{jwCsR1 + 1}$$

$$a = \frac{Z1}{Rp+Z1}$$

Where $w = 2\pi f$

f = frequency

$j = \sqrt{-1}$

$$a = \frac{R1}{jwCsR1+1} \times \frac{1}{Rp + \frac{R1}{jwCsR1+1}}$$

$$= \frac{R1}{(R1+Rp)+jwCsR1Rp}$$

$$\frac{1}{a} = 1+\frac{Rp}{R1}+jwCsRp$$

$$\left(\frac{1}{a}\right) = \sqrt{\left(1+\frac{Rp}{R1}\right)^2 + (wCsRp)^2}$$

$$\left(\frac{1}{a}\right)^2 = \left(1+\frac{Rp}{R1}\right)^2 + (wCsRp)^2 \qquad \text{------------- 1)}$$

Choosing $Rp = R1$, and neglecting the term involving the frequency (w), we get the mid frequency gain as follows:

$$\left(\frac{1}{a}\right)^2 = \left(1+\frac{1}{1}\right)^2 = 4$$

$$a = \frac{1}{2}$$

In particular, the parameters for the 6SL7GT are 44,000 ohms for Rp and 70 for u.

By substituting these values in equation 1, the maximum value of Cs can be computed for an amplitude response of 91% at 5000 cycles. In this case $a = 0.91 \times \frac{1}{2} = 0.455$

$$\left(\frac{1}{0.455}\right)^2 = (1+1)^2 + (2\pi \times 5000 \times Cs \times 44,000)^2$$

$$4.84 = 4 + (440\pi \times 10^6\ Cs)^2$$

$Cs = 0.665 \times 10^{-9}$ or 665 micro-microfarads.

If, on the other hand, Rp is 100,000 ohms at lower voltages, and Rl = Rp, the maximum shunt capacitance under these conditions can be found by substitution as follows:

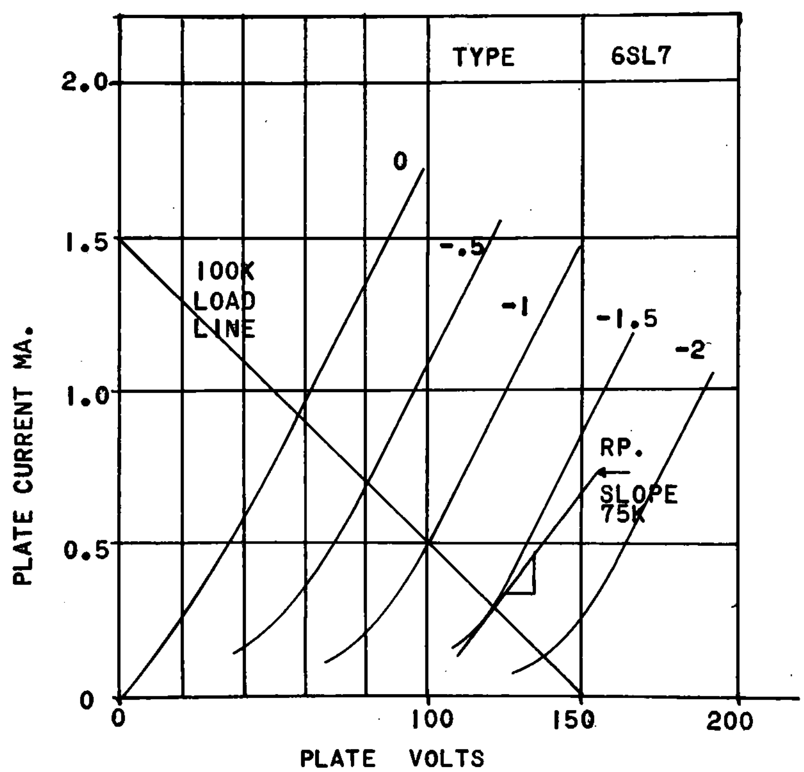
$$4.84 = 4 + (2\pi \times 5000 \times Cs \times 100{,}000)^2$$

$$Cs = 0.292 \times 10^{-9} \text{ or } 292 \text{ micro-cicrofarads.}$$

From this we can permit a shunt capacitance of not greater than 665 uuf for the specified frequency response of -3db at 5 KC with four stages employing 44K as plate load resistors. This capacitance is higher than one would expect wiring strays combined with tube input and output capacitances to run in practice. To take advantage of this fact, the plate load resistance was raised to 100K, permitting less current drain and more gain. With a plate voltage supply of 150 volts, the plate load line was drawn and is shown on Fig. 15. From this one can compute a little more closely the operating characteristics of the stage. At the operating point of -1.5 volts bias, u = 60, Rp = 75K ohms, and therefore the gain per stage will be given by:

$$A = \frac{URl}{Rp+Rl} = \frac{60x100}{100x75} = 34.3$$

This is considerably less than the computed gain on assuming u and Rp were those tabulated by the manufacturer. Actually, the gain was expected to be still less due to the fact that the grid resistor of the following stage shunts and consequently lowers Rl. However, this is only a small loss and the gain expected from the four stages is of the order of $(34.3)^4$ which is approximately 1.44×10^6. This is still more gain than the minimum required.



6SL7GT CHARACTERISTICS

FIG 15.

Division of Amplifying Channel.

From the foregoing considerations the preamplifier was arranged to consist of two push-pull stages, and was expected to give a gain of $(34.3)^2$ or 1200 approximately. This gain is sufficient to raise signals of micro-volts to millivolts and permit standard construction techniques in later amplifying stages. However, the output of the preamplifier must be connected to later amplifying stages by a shielded cable. If this connection is made from the plates of the second stage, the shunt capacitance would be much in excess of the 292 uuf. which could be tolerated to retain the high frequency response. Since a little more overall gain than was necessary was available, the most convenient way of overcoming the problem was to use a push-pull cathode follower, using a 6SL7 in the interests of standardization. Here the use of the 6SL7 for the amplifier stages was a fortunate choice as it has separate cathodes requiring only one tube for the push-pull cathode follower.

The input impedance of a cathode follower is high, and the output impedance is low, although the gain is less than unity. The output impedance of the cathode follower is given by:

$$Zo = \frac{1}{Gm + \frac{1}{Rp} + \frac{1}{Rk}}$$

$$= \frac{1}{1600 \times 10^{-6} + \frac{10^{-3}}{44} + \frac{10^{-3}}{5}}$$

$$= 550 \text{ ohms}$$

<u>For 6SL7GT</u>

$U = 70$

$Rp = 44{,}000$

$Gm = 1600 \times 10^{-6}$

$Rk = 5 \times 10^{-3}$

The gain of a cathode follower is given by:

$$A = \frac{URK}{Rp+Rk\ (1+U)}$$

$$A = \frac{70x5000}{44000+5000(70+1)} = 0.875$$

A = gain

U = 70 = amplification factor

Rk = 5000 = cathode resistance

Rp = 44000 = plate resistance

The loss of gain brings the overall amplification down to 87.5% of $1.44 x 10^6$ or 1.3×10^6 approximately. The low output impedance of 550 ohms allows the possibility of using a very long cable with a large shunt capacitance before serious attenuation occurs. Quantitatively the permissible loading on such a system is calculated. If the response was to be attenuated by 10% at 5KC, then the conditions existing are as follows:

$$\frac{Eo}{Ei} = 0.9 = \frac{\frac{1}{jwc}}{550+\frac{1}{jwc}}$$

Where Eo is output

Ei is input

$$\frac{1}{0.9} = 1 + j550wc$$

If 550jwc is much greater than 1

$c^2 = 41.4x10^{-12}$; $c^2 = 6.44 \times 10^{-6}$ farads

Therefore, the connecting table would have to be very long to have a capacitance of 6 microfarads. Usual cable shunt capacitances are of the order of 5 to 100 uuf. per foot.

In addition, the low output impedance permitted the inclusion of the output cable in the power cable used to supply the heaters and plates of the preamplifier.

Location of Stepped Attenuator.

As a practical and theoretical choice, it was convenient to insert the stepped attenuator control between the second stage and the cathode follower. The cathode follower, having high input impedance does not load the gain attenuator. This results in a uniform frequency response at all amplifier sensitivites. On the practical side, this puts the gain control in the preamplifier within reach of the operator and in a reasonably good position for a large dynamic range of input voltages.

Blocking Voltage.

With this arrangement, the maximum single sided signal that can be tolerated without blocking is of the order of

$\frac{1}{\text{gain of 1st stage}}$ x Bias of second stage. This is about $\frac{1}{40} \times 1.5 \times 10^{+3}$ or about 40 millivolts for a bias of 1.5 volts on the second stage of the preamplifier. This is about six times the maximum signal encountered.

Attenuator Steps.

The attenuator steps that have been found practical in the past are $\frac{1}{2}$ gain reduction per step. In this instance, this created a slight problem because with the R.M.A. series, of resistor values, one can not conveniently choose a total resistance and build it up from standard resistors to have $\frac{1}{2}$ ratio steps. To compromise, using standard resistors, the following attenuator was built up. The total resistance is slightly over 1 megohm, but the individual errors on each step are smaller than the tolerances in the resistors themselves. The attentuator was built and the errors tabulated as follows:

Step	Resistance	Error
0	Kilohms	Percent
1	560	0.5
2	270	-2.5
3	150	2.5
4	68	2.2
5	33	-1.25
6	18	0.78
7	8.2	-3.9
8	4.7	3.9
9	2.2	-0.39
10	2.2	off

Low Frequency Response.

For the low frequency response, an overall time constant of 40 milliseconds is required. Since the amplifier now consists of two stages and a cathode follower in the preamplifier, followed by two additional stages of amplification to the cathode ray tube; the actual coupling time constants of each stage are calculated.

Commencing at the input of the preamplifier, there is one coupling condenser from the patient to the first stage, one between the first stage and the second stage, one between the second stage and the cathode follower, one between the cathode follower and the first voltage amplifier of the oscilloscope, one between the first and second oscilloscope voltage amplifiers, with the output of the last stage directly coupled to the oscilloscope deflection plates. This makes five time constants in all, and if uniformly distributed, each would have to be 5x40 or 200 milliseconds to have an overall time constant of 40 milliseconds.

Choice of Actual Values of Time Constants.

The choice of the actual values of coupling condenser and grid resistor is always open to much discussion. Some tubes have a limit for the magnitude of d.c. resistance permissible in the grid circuit. Usual values run from 0.5 to 2 megohms with the lower values being popular when stability is required. Input capacitance shunts the grid resistor and for this reason in the case of triodes, one should use lower values of resistance. In the case of pentodes, one can use higher resistances due to the lower input capacitance.

Standardization was again decided upon to facilitate construction and procurement. Sealed condensers of 0.25 uf with 600 volt ratings were chosen as the standard coupling condensers. Resistances of 0.56 megohms were chosen for grid resistors. The gain attenuator, having 1.116 megohms resistance, tends to increase the time constant of the amplifier. The overall time constant of the preamplifier (to the cathode follower cathodes) is expected to be in the order of

$$\frac{1}{RC} = \frac{1}{R1C1} + \frac{1}{R2C2} + \frac{1}{R3C3}$$

$$= \frac{1}{.56x.25} - \frac{1}{.56x.25} - \frac{1}{1.116x.25} = 17.75$$

$$RC = \frac{1}{17.75} = 56.4 \text{ milliseconds}$$

Choice of Balance of Component Values.

To complete the design of the preamplifier, the plate supply voltage was taken to be 150 volts (obtained from a voltage regulator tube). The plate load resistors were chosen as 100,000 ohms with those in the first stage being non-inductive, wire-wound units. The plate supply was common for the first two stages with the cathode follower operating at a higher voltage supply and decoupled with an RC filter of 22K and 16 uf. This is to insure no self oscillation between the preamplifier stages operating from the same power supply.

In order to obtain high in-phase degeneration or balance, high cathode resistors are necessary. However, high cathode resistors will not permit the correct operating bias voltages to be applied to the tubes. A convenient arrangement was to use high cathode resistors and instead of returning them to the negative of the power supply, which is connected to the grid return; the connection was made to a potential more negative than the plate power supply return. This supply, of course, must have as good regulation as the plate supply and a value of minus 75 volts was chosen (obtained from a VR-75 gaseous regulator tube). With this arrangement operating biases of $1\frac{1}{2}$ volts were obtained at the cathodes of the first two stages of the preamplifier with 100,000 ohm resistors in the cathodes of each stage. The cathode resistor of the first stage was non-inductive wire-wound for stability.

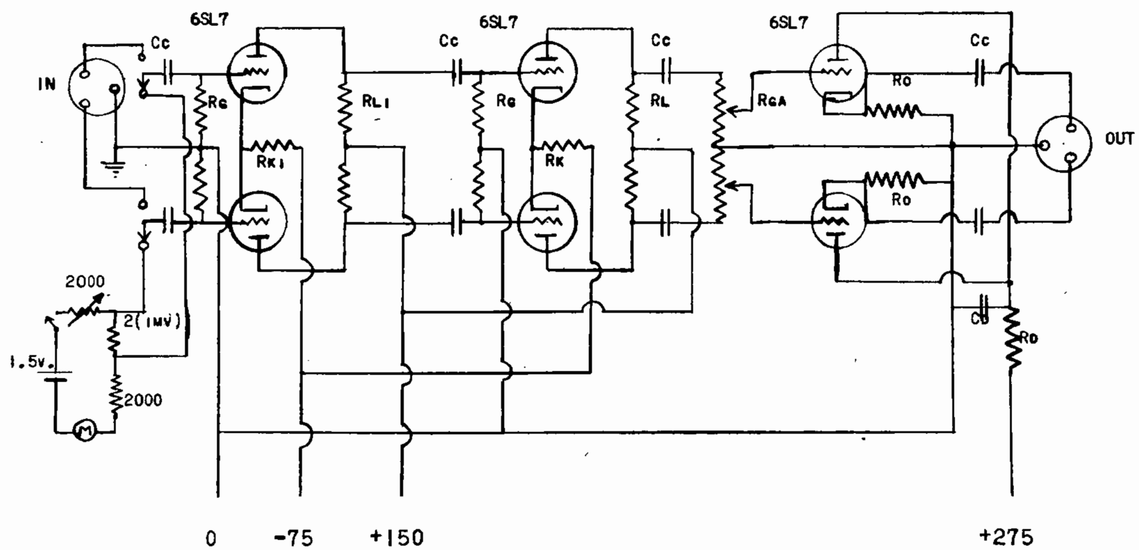
The cathode follower output stage was arranged to operate at a plate supply voltage of 275 volts and the decoupling network dropped this to about 250 volts with about 0.5 milliamperes per section of the push-pull cathode follower. The 0.5 milliamperes flowing through a cathode resistor of 5,000 ohms gave about 2.5 volts bias.

The preamplifier cabinet houses also a calibration circuit to which the amplifier can be switched to permit amplitude calibration. The circuit employed is of the potentiometer type consisting of a 1.5 volt pen-lite cell, two resistors, (one of two ohms and the other of 3000 ohms, made up of a variable and fixed resistor), and a momentary push button. When the push-button is depressed, a signal of 1 millivolt appears across the two ohm resistor when the current is adjusted to a 0.5 millamperes in the potentiometer circuit. This signal provides a voltage reference for amplitude calibration of the instrument.

Figure 16a shows the final circuit of the preamplifier and table 1 gives the component values. Figure 16b shows the front panel view of the preamplifier.

TABLE 1
PREAMPLIFIER COMPONENT VALUES

Cc	0.25 uf 600v.
Rg	0.56 meg. ½w. carbon
Rk	100k. ½w. carbon
Rk1	100k. ww.



PREAMPLIFIER CIRCUIT

FIG. 16A

FIG. 16B - PREAMPLIFIER PANEL.

RL	100k, $\frac{1}{2}$w. carbon
RL1	100 k. ww.
Cd	16 uf. 450 v.
Rd	22k 1w. carbon
Ro	5k. 2w.
Rga	Gain Control 560k, 270k, 150k, 68k, 35k, 18k, 8.2k, 4.7k, 2.2k, 2.2k. $\frac{1}{2}$ per step 1.1163 meg.

Power Supply (Preamplifier).

The role of the power supply is to provide the various plate, filament and bias voltages for the preamplifier. These voltages must be stable and ripple free in order to keep the internal noise of the amplifier as low as possible. In addition, these voltages must be obtained with a minimum of cost consistent with the work to be done by the amplifying system. Standard components were used with a good margin of safety on their operating limits. This insures long life and easy replacement by semi-skilled personnel at the end of the useful life of the components.

To conserve space and keep the number of units down, the audio amplifier was incorporated on to the power supply chassis. The danger hum pick up was not a serious consideration due to the preamplification of the signal and its appearance across the cathode follower output impedance of 550 ohms. This procedure provided another advantage in that no extra cables were required to connect the audio amplifier to the preamplifier. With the appearance of the signal across a low impedance line, the output of the preamplifier was taken along in the power cable.

Voltages Required.

In detail, the voltages required for the preamplifier are plus 275, plus 150, minus 75 and 6 volts for the filaments. The plus 275 supply is required for the cathode follower plates, the plus 150 and the minus 75 taps are required for the plate and bias voltages of the first two stages. The 6 volt supply is needed for the heaters of all the preamplifiers stages. The plate current requirement for the first three stages is small and of the order of a few milliamperes. However, the current needed from the 6 volt supply is of the order of 1 ampere, (3-6SL7 @ 0.3A = 0.9A).

The power required to operate the audio amplifier was provided by a separate power supply also incorporated on the power supply chassis. This was done in order to minimize the"motorboating" which usually occurs when many cascade stages are operated from the same power supply. Another reason for separately powering the audio amplifier was to insure the stability of the preamplifier power supply when large blocking signals appeared at the input. The power requirement of any audio amplifier is usually much in excess of that required to operate voltage amplifying stages. In this case, little regulation was needed as only aural monitoring was required from this section.

Filament Voltage Supply.

Earlier in this report it was stated that some previous research development had been carried out by the author to eliminate the batteries and made the apparatus completely power line operated. These experiments examined the hum and pick-up by input stages when 60 cycle alternating current was used for filament power. The following is a summary of these experiments carried out.

Hum Elimination Studies.

It was found that increasing the balance ratio of the input stages reduced the hum pick-up. A limit was soon reached however, when even infinite balance would not have reduced the hum pick-up to zero. Moreover, it was found that filament hum pick-up varied widely among tubes of the same type. One of the best methods found to reduce this pick-up was to insert a low resistance potentiometer across the filament supply to the input stage. The rotor of the potentiometer was then connected to the negative of the plate supply voltage supply. When the rotor was turned, there usually was found a position where the hum pick-up was a minimum. This device is known by some as a "hum-dinger". However, the best adjustment of the hum-dinger was not satisfactory for the gain capabilities of the amplifier.

From these experiments the author concluded that direct current was needed to energize the filaments of the input stage. The problem then was not how to obtain the direct current, but how much ripple could be tolerated. The "thermal inertia" of the filament or its inability to follow rapid changes in voltage helps suppress any pick-up from transient variations in filament voltage. A high balance ratio also helps suppress the pick-up of filament ripple. For these reasons, as well as the wide variability in the susceptability to hum pick-up of the individual tubes made the problem practically impossible to calculate quantitatively.

As a starting point, an 8 volt filament transformer with a full-wave Selenium rectifier and a 2000 mfd shunt filter condenser was employed in conjunction with a hum-dinger. This arrangement was used as filament power for the input stages. From the outset, in comparison with the previous experiments, excellent results were obtained. However, the hum pick-up from the second stage (which was still on 60 cycle AC) now was greater than that from the first stage due to ripple in the DC supply. Accordingly, the filaments of the first and second stages were paralleled and operated from the same Selenium rectifier supply. In this case, the reduction in hum pick-up was not as good as was expected. This was due to insufficient storage capacity of the 2000 mfd. filter condenser. Increasing this capacitor by a factor of ten improved the situation but not a satisfactory degree. It then seemed that an LC filter would have to be employed to render negligible the pick-up due to filament ripple voltage.

Since the filament current required was not that of two tubes, even a small filter choke would have to be very large physically to have even a small inductance with 0.6 amps filament current. It would also have to be of very heavy wire to keep the voltage drop small. In spite of these drawbacks, the inductor-capacitor filter looked like the only solution to the problem.

After careful consideration, it was recognized that size and expense were more important than efficiency. Accordingly, a rearrangement of the filament supply voltages to the rectifier was made. A standard 12.6 volt filament transformer was used to feed the Selenium bridge rectifier. The output of the rectifier was fed to a 2000 mfd. shunt condenser, then to a series resistor and to another 2000 mfd. shunt condenser. The series resistor was made variable and adjusted under load to produce 6.3 volts at the output of the filter. This arrangement proved to be an excellent solution to the problem. It is, of course, nothing more than a Pi section RC filter similar to those used in many cheaper plate power supplies. The difference is that in the plate supplies, the values are in microfarads and thousands of ohms and in this filter the values are in thousands of microfarads and ohms.

The voltage loss across the filter is, of course, large. The actual drop is of the order of $12.6\sqrt{2}$ volts at the input to 6.3 volts at the output of the filter system and represents a loss of power equal to that which is useful output. However, the physical size of the filter is very small is spite of the 10 watt size of the dropping resistor in the series arm of the Pi. It is unlikely that the inductance of this resistor contributes to the filtering, even though most low value resistors are quite inductive.

The performance of this filter system was so good that the use of the hum-dinger was of no benefit. The hum pick-up with this system was less than the noise level of the amplifier. Tubes no longer had to be selected for filament hum pick-up susceptability due to the exceedingly small ripple in the filament voltage.

This filter circuit was incorporated into the power supply to provide filament power for the preamplifier. In this case, however, all three preamplifier stages were operated from a filament supply very satisfactorily. By doing this, no alternating current power carrying conductors were brought into the preamplifier chassis. Although it was not necessary to operate the 6SL7 cathode follower stage on direct current, the desire to keep 60 cycle current carrying wires out of the chassis justified this procedure. Figure 17 shows the arrangement of the filament power supply and component values.

Plate Voltage Supply.

To supply plate voltage, the standard full-wave rectifier circuit was employed both for the positive and negative supplies. The positive voltage was obtained from a standard twin-diode rectifier (5Y3), connected to the power transformer in the conventional manner. To obtain the negative voltage, a pair of indirectly heated twin-diodes ((6X5GT) were used. The diodes used were of the type with a high heater-cathode voltage rating. This allowed conservation of filament supplies and a consequent saving in space. The standard 6 volt winding on the power transformer was used for the negative rectifiers. To take advantage of the fact that the negative rectifiers each

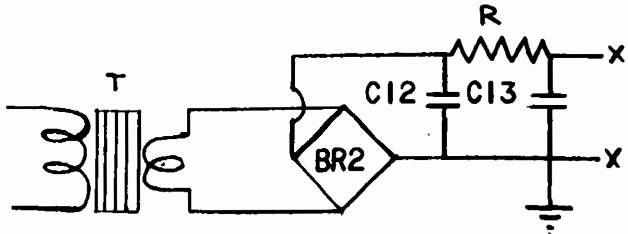


FIG. 17 - FILAMENT VOLTAGE SUPPLY.

R - 10 OHMS (VARIABLE)

C12-13 2000 MFD. 25V.

BR2-2AMP SELENIUM RECTIFIER

T - 12 VOLT FILAMENT TRANS.

had one extra diode plate, a parallel connection was made to the other plate, thus reducing the current per plate and allowing a more even ageing of the tube cathode.

Filtering.

The filter system employed for both the positive and negative supplies was the standard Pi section or "brute-force" type employing 10 mfd. electrolytic condensers and 30 henry chokes. This circuit is a very standard filter used in most power supplies to eliminate ripple voltage from its output.

Choice of Regulator Tubes.

To provide regulation and a low output impedance, gas regulator diodes were used. (Fig. 18 shows the circuit arrangement). The system had proven very satisfactory in the line operation investigation carried out previously by the author. The following is a brief summary of the investigation.

Since the preamplifier current drawn from the power supply is only of the order of a few milliamperes, the use of gas diodes seemed advisable from practical and theoretical considerations. This was the starting point of the investigation and accordingly the operating characteristics of the tubes were sought. The manufacturers however, only supplied data on the striking and operating voltages and the recommended operating current through the tube. Text books went only as far as saying that the output impedance was low. This was inadequate information for use in design, so a survey of the

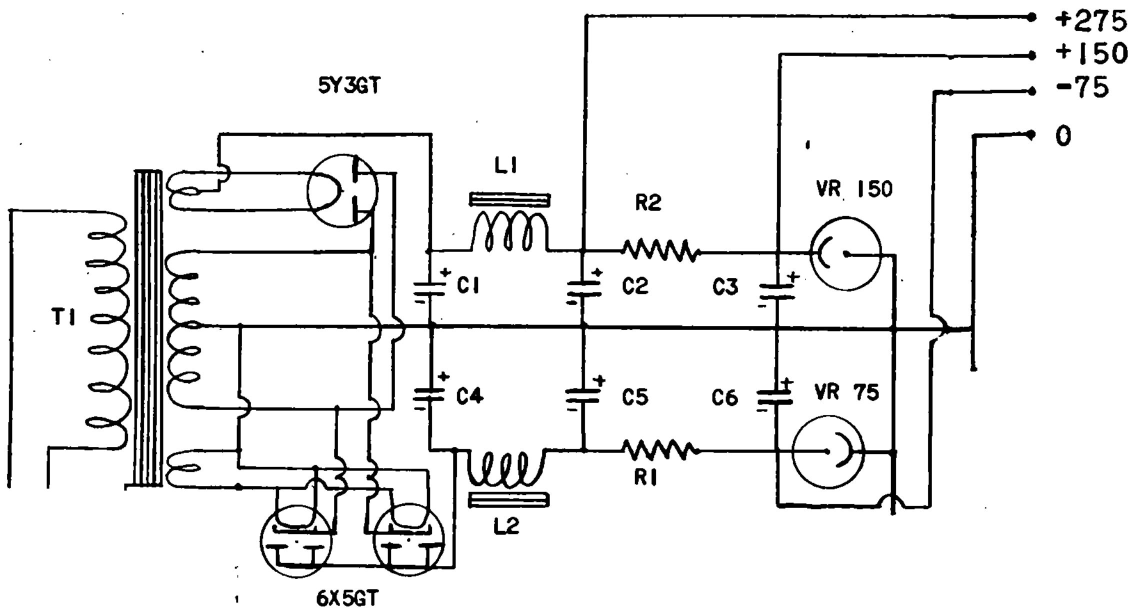


FIG. 18 - PREAMP. POWER SUPPLY

standard gaseous regulators was made to determine primarily the output impedance and any other information that would be of value in the preference of one type over another.

Many voltage regulator tubes of each type were chosen and studied. Those available at that time were the VR75, VR105, and VR150 types. Voltage-current curves were plotted to determine the output impedance over the operating range. From all this data, it was found that the VR75 had the flattest voltage-current curve with the VR-150 second and and VR-105 a poor third. The flatness of the operating portion of the curve, or the voltage change across the tube per unit of current change through the tube was used as a measure of the regulatory ability of the tube. This ratio is also the output impedance of the regulator. The lowest output impedances were found with an average current of 15 ma, d. c. through the tubes and varied from a low of 10 ohms to a high of 200 ohms. The magnitude of variations for the VR75 tube was of the order of 10 to 150 ohms. The variations encountered with the VR150 tube were from about 50 to 200 ohms. In the case of the VR 105 tube, the voltage-current curve was not always reproducible and some tubes tested had a negative slope. For this reason, the VR105 was avoided and the VR75 was used for the negative regulator tube and the VR150 was employed as the positive supply regulator.

Ripple Voltage.

The actual percent ripple of the largest component present at the output of a Pi section capacitor input filter is difficult to calculate exactly. It can, however, be calculated to a good approximation which will give an idea of the order of its magnitude. The following calculation was based on the analysis given in "Applied Electronics"[6].

In this case, with a full wave rectifier, the second harmonic is the largest and is given by:

$$E_2 = \frac{1}{\sqrt{2}} \times \frac{1}{4w^2 LC_2} \times \frac{Idc}{2 fC_1}$$

Where Idc - d.c. output current (amps.) = 0.015

E_2 - r.m.s. ripple voltage of 2f

f - supply frequency 60 c.p.s.

w - $2\pi f$

C_1; C_2 - condenser capacity (farads) = 10×10^{-6}

L - inductance (henries) = 30

$$E_2 - \frac{1}{1.41 \times 3.14} \times \frac{1}{4(2\pi x60)^2 \times 30x10x10^{-6}} \times \frac{15 \times 10^{-3}}{2x60x10x10^{-6}}$$

$= 167.5 \times 10^{-3}$ or 167.5 millivolts.

The filtering in the positive and negative supplies is identical, this voltage represents the 120 cycle ripple component before the voltage regulator tubes in each supply. Since the impedance of the voltage regulator tubes is low, a further reduction in ripple voltage takes place.

The series resistors for the regulators were determined experimentally, The values chosen were those to permit the operation of each regulator tube on the mid-point of the plateau of the voltage current characteristic. The actual resistors necessary were 10,000 ohms for the VR150 to provide a current of 15 ma. through the tube and 15,000 ohms for the VR75 to allow a current flow of 10 ma. through it. No calculation of loading due to the amplifier was deemed necessary as the drain of a few milliamperes is negligible in comparison to 10 to 15 milliamperes standing current through the regulators. However, the power dissipation in these series resistors is a point of consideration and is computed as follows:

VR150 - 15 ma. and 10 kilohms

$$P = I^2R = 15^2 \times 10^{-6} \times 10 \times 10^{+3} =$$

2.25 watts.

VR75 - 10 ma. and 15 kilohms.

$$P = I^2R = 10^2 \times 10^{-6} \times 15 \times 10^{+3} =$$

1.5 watts.

In order to provide long life and low operating temperatures, ten watt resistors were used. Low temperatures were desired to keep the thermal drifts down to a minimum.

Gas tubes themselves are known to be good noise generators so large condensers were shunted across them to short circuit any self generated noise. There is always the possibility of creating a relaxation ocillator when this is done. In this case, the regulator series resistors were too low to permit oscillation. The addition of these condensers also lowered the output impedance and consequently the ripple voltages in addition to shorting out any internal noise in the regulator tubes themselves.

Calculation of Output Ripple Voltage.

To obtain an idea of the actual magnitude of the second harmonic ripple voltage in the regulated output, an equivalent circuit of the regulator was drawn up and is shown in Fig. 19. The derivation of the reduction of ripple follows and the quantities defined.

$$\frac{e2}{E_2} = \frac{Z}{Z+R}$$

$$\frac{1}{Z} = \frac{1}{Rd} + jwC$$

$$= \frac{1 + jwCRd}{Rd}$$

$$Z = \frac{Rd}{1 + jwCRd}$$

Substituting:

$$\frac{e_2}{E_2} = \frac{Rd}{Rd + R(1+ jwCRd)}$$

E_2 = Second harmonic voltage after filter at input to regulator = 167.5 m.v.r.m.s.

R = Series Resistor
For VR150 = 10K
VR75 = 15K

C = Shunt condenser = 10mfd.

f = Ripple frequency = 120 cycles/second

w = $2\pi f$

E = Voltage of Regulator tube
For VR150 = 150 volts
VR75 = 75 volts

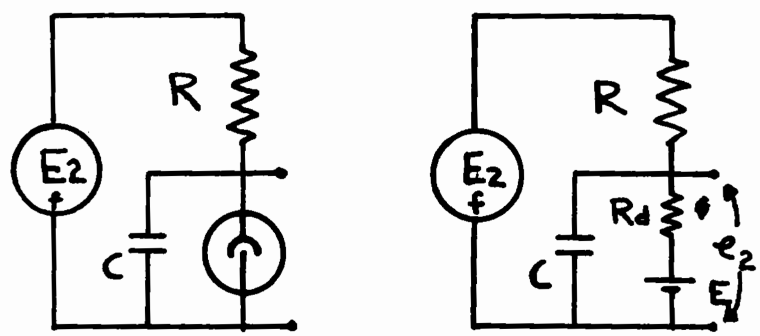


FIG. 19.

EQUIVALENT CIRCUIT.

e_2 = Ripple voltage at output of regulator.

Rd = Regulator output impedance
For VR150 = 200 ohms max.
VR75 = 150 ohms max.

In the case of the positive regulator using the VR150 the value of R = 10,000 ohms and Rd, the gas diode impedance varied from 50-200 ohms. In all cases C was 10mf. and F the frequency is 120 cycles. Under the worst conditions for the VR150 is Rd equal 200 ohms, the reduction of ripple is calculated by substitution in the above equation:

$$\frac{e_2}{E_2} = \frac{200}{200 + 10^4 \left(1 + j2\pi \times 120 \times 10 \times 10^{-6} \times 200\right)}$$

$$= \frac{1}{50\,(1 + j1.5)}$$

$$\frac{E_2}{e_2} = 50\,(1 + j1.5)$$

$$\frac{E_2}{e_2} = 50\sqrt{1 + (1.5)^2} \cong 90$$

$$\text{Reduction} = \frac{1}{90}$$

$$\text{Ripple output} = \frac{1}{90} \times 167.5 = 1.86 \text{ millivolts}$$

of VR150 side.

Under the worst conditions, the ripple voltage present in the VR75 negative rectifier would also be obtained with the highest regulator impedance which was 150 ohms. The series resistor employed was 15,000 ohms. With the other quantities the same as for the VR150, the ripple voltage present is as follows:

$$\frac{e_2}{E_2} = \frac{150}{150 + 10^3 \times 15\ (1+j7.54\times10^{-3}\times150)}$$

$$\frac{E_2}{e_2} = 100\ (1+j1.03)$$

$$\frac{E_2}{e_2} = 100\ \sqrt{1+(1.03)^2} = 144$$

$$\text{Reduction} = \frac{1}{144}$$

$$\text{Ripple output of VR75 side} = \frac{1}{144} \times 167.5 = 1.15 \text{ millivolts}$$

Effects of Ripple Voltage.

Although these maximum ripple voltages of 1.86 and 1.15 millivolts seem large, they are superimposed on a direct voltage which supplies a push-pull balanced amplifier. If the balance were perfect (possible only with identical tubes with linear characteristics and in circuits with matched components) no ripple would appear in the out put of the amplifier. Such a condition can only be a theoretical supposition and never a practical reality. However, the amount of ripple voltage developed in the output can be estimated by making conservative assumptions.

If the amplifier has a balance ratio of 1000 to 1, this would mean that a signal impressed on both grids simultaneously would give the same output as a signal 1/1000th as large as when applied push-pull. (It was stated earlier that the minimum balance ratio tolerable in a biological amplifier is of the order of 1000/1.) The ripple voltage in the power supply is such a signal.

All push-pull grids, cathodes and plates have a common return connection. In the case of the grids, the return is to the common negative. In the case of the cathodes, the return is to -75 volts with a maximum of 1.15 millivolts ripple appearing across the 150 ohm impedance of the gaseous regulator. Assuming the impedance looking into the cathode is high, (which is not actually the case), the signal of 1.15 millivolts is being fed into the amplifiers via the input stage cathodes, would look like a signal of 1/1000 of 1.15 millivolts or 1.15 microvolts applied push-pull. This, is of course, much less amplitude than the smallest signal of diagnostic value. It also is below the measureable noise consistent with the band width of the amplifier.

In the case of the positive regulated supply, the maximum ripple voltage of 1.86 millivolts is superimposed on 150 volts DC appearing across a maximum of 200 ohms impedance. Considering this voltage as modulation of the cathode current, a very large attenuation would be encountered before reaching the cathodes due to the high plate load resistors and plate resistance which are both in the hundreds of thousands of ohms. Therefore, the ripple contributed by the plate voltage supply would be immeasurably small in comparison to that fed into the cathodes by the negative supply.

Audio Amplifier.

The audio amplifier incorporated on the power supply chassis was of conventional style. It was designed to have good low frequency response and a medium power output. A 12 inch loud speaker was used with the reflex baffle recommended by the manufacturer for the loud speaker. No tone compensation was incorporated as the role of the audio amplifier was to give a flat frequency response. This is desireable so that wave forms once recognized, would not be lost by the mis-setting of controls. The only control provided on the audio amplifier is a volume or intensity control.

Operating Limits.

The input to the audio amplifier was taken directly from the output cathode follower of the preamplifier. With the minimum signal from the subject being of the order of 100 microvolts, (fibrillations) the output of the preamplifier is 900* x 100 microvolts = 90 millivolts. This signal must be boosted to an amplitude sufficient to operate the power stage driving the loud speaker. The actual output power required is that amount necessary to drive the loud speaker at what would be called "normal" listening volume. This may be assumed to be of the order of 1 watt peak of audio power. It was also decided to provide a minimum of 10 watts of audio capability so that should a small fast transient appear on a large slower wave, the system will respond linearly and faithfully reproduce the complex wave.

The most standard tubes in use as power amplifiers to deliver 10 watts of audio output are the 6V6GT tubes. These

* Overall Preamp. gain = 87.5% x 34^2 = 1050
Allowing 10% margin, minimum gain = 900.

were chosen and operated in push-pull, driving a transformer to match the plate impedance to the voice coil.

A single voltage amplifier stage was employed to boost the signal of 90 millivolts sufficiently to obtain a minimum of 10 watts of peak audio power from the output stage. The 6V6 tubes have a transconductance of the order of 5 ma. per volt. One watt output requires an oscillating current in the push-pull plate impedance of 15,000 ohms (for 6V6 tubes) as follows:

$$P = I^2R$$

$$1 = I^2 \times 15,000$$

$$I = \sqrt{\frac{1}{15,000}} = 8.14 \text{ ma.}$$

I = Current amperes

R = Resistance in ohms

P = Power in watts.

The 8.14 ma. can be produced by $\frac{8.14}{5}$ or 1.63 volts change in the grids of the 6V6 stage. The voltage amplifier then must provide at least an amplification of the ratio of $\frac{\text{output}}{\text{input}} = \frac{1.63}{90 \times 10^{-3}} = 18.1$ The type 6SL7GT was chosen to provide this gain in the interests of standardization. A 6SN7GT could have been used the gain obtainable with this tube would just have been sufficient as shown in Fig. 13. From this table, the 6SL7 tube is capable of giving a gain of about 48 which is much in excess of the minimum required. However, since a volume control was included, the additional amplification is controllable and available if desired.

Component Values.

The actual component values chosen were those listed in the Resistance Capacity coupled amplifier chart tabulated in the RCA Receiving Tube Manual.[7] Smaller coupling condensers than those used in the preamplifier were employed as the limits of audibility do not extend much below 40 cycles. The limit of the low and high frequency response of the audio amplifier as was considered to lie in the output transformer's capabilities. The transformer used was good quality 10 watt size recommended by the manufacturer (Hammond) to match push-pull 6V6GTs to a voice coil of 6 ohms which was the nominal impedance of the 12 inch loud speaker.

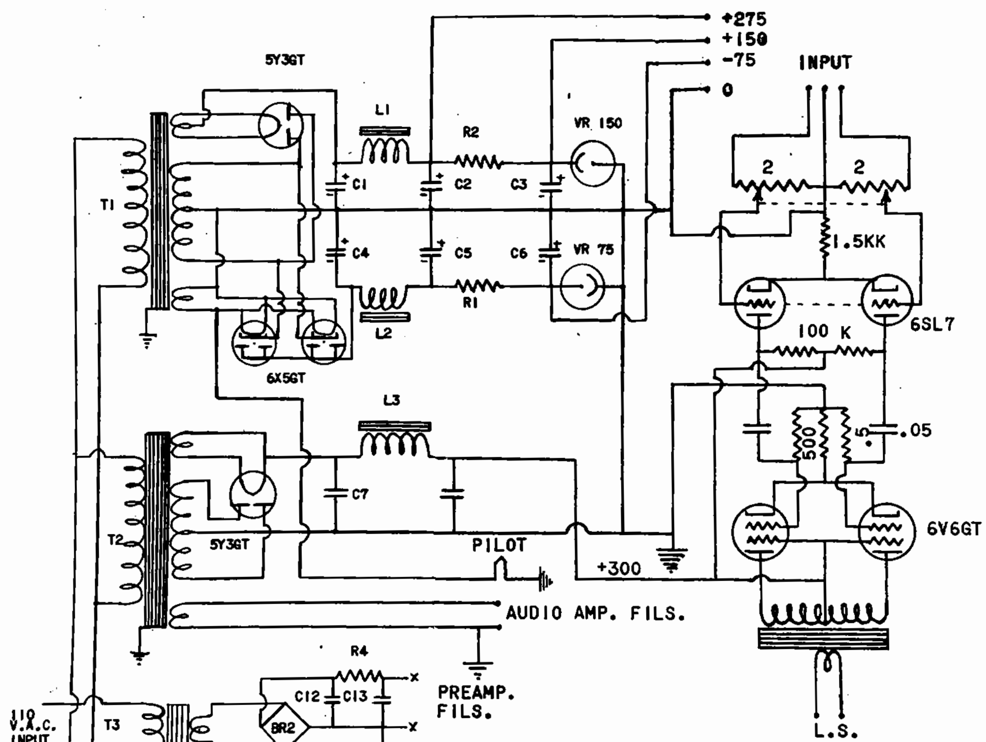
Gain Control.

The gain or volume control was placed at the input of the audio amplifier. It was made a double-gang 2 meg. potentiometer with an audio (logarithmic) taper. By means of this control, the listening volume can be varied to suit the amplitude of the wave forms encountered.

Power Supply.

The power supply for the audio amplifier was the standard full wave rectifier type with a Pi section filter similar to that used for the preamplifier but with higher current output. The 6V6 tubes require about 30 milliamperes each and the 6SL7 a few millamperes. A 75ma. transformer was used to feed a 5Y5GT tube as full wave rectifier. The filament windings on the same power transformer were used to energize all the audio tubes.

The complete audio-amplifier with its own power supply and the preamplifier power and filament supplies are shown on Fig. 20. All these circuits are incorporated into the same chassis.



PREAMPLIFIER POWER SUPPLY
AND AUDIO AMPLIFIER
FIG. 20

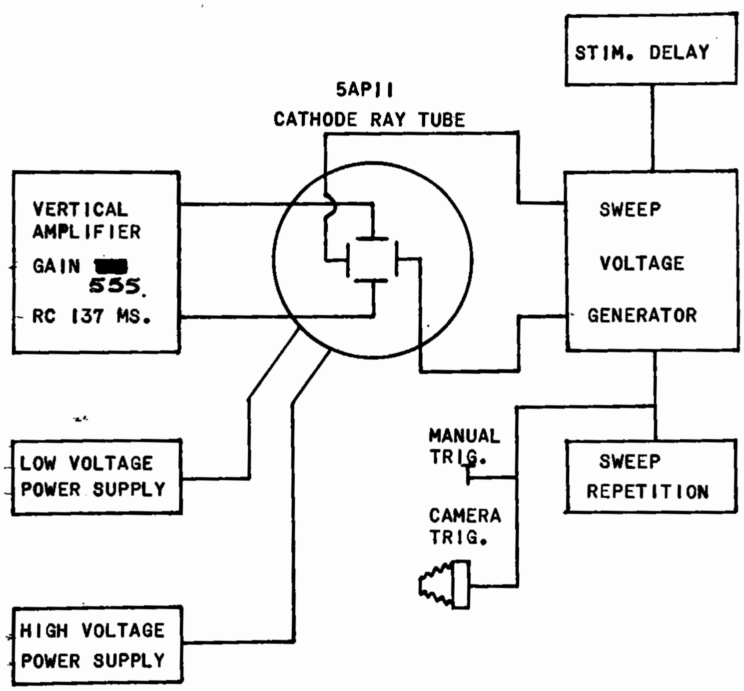
OSCILLOSCOPE

From the block diagram of Fig. 12, the facilities required in the oscilloscope were examined and the unit designed. The block diagram of Fig. 21, shows the arrangement of the various sections as they were combined to form the oscilloscopic apparatus. The various units are tabulated and their requirements were set forth and are described in the following paragraphs.

Vertical Deflection Amplifier (General).

Using the conventional system, the vertical deflecting plates were used to display the signal under investigation. The additional amplification needed to raise the preamplified signal to a level suitable to deflect the cathode ray tube beam, was incorporated into the oscilloscope unit. The actual overall minimum amplification required was calculated previously to be 1/2 million. The signal has already been amplified 900 times by the preamplifier, leaving an amplification of $\frac{0.5 \times 10^6}{900} = 555$ to be provided by the oscilloscope amplifier.

The overall time constant in the amplifying channel was stated previously to be 40 milliseconds. The time constant from the input of the preamplifier to the output of the cathode follower is 56.4 milliseconds. Therefore, the overall time constant from the input of the oscilloscope unit to the cathode ray tube deflecting plates cannot be less



BLOCK DIAGRAM OF OSCILLOSCOPE
FIG 21

than the following:

$$\frac{1}{\text{Over all RC}} = \frac{1}{\text{RC preamp.}} + \frac{1}{\text{RC oscilloscope}}$$

$$\frac{1}{40} = \frac{1}{56.4} + \frac{1}{RC}$$

$$RC = 157 \text{ milliseconds.}$$

Time Base (General).

The time base or sweep was connected to the horizontal deflecting plates in the usual manner. The beam velocity requirements were tabulated previously and range from 2.5 to 20 milliseconds per inch. The most useful repetition rate was previously stated to be 10 per second, but on occassion slower repetitions of 1 per second have been of value in research investigations. A repetition rate variable from 1 to 10 sweeps per second was considered necessary with provision for single sweep operation initiated either manually or by the camera shutter.

Stimulator Trigger.

In order to allow the maximum use of a stimulator, a very careful study of techniques was made, particulatly in regard to the delay required to display the stimulus on the cathode ray tube face at various sweep velocities. The sweep velocity range of 20 to 2.5 milliseconds per inch is approximately a ten to one ratio. If, for example, a fixed delay time were chosen such that the stimulus appeared 1/2" from the left hand side of the tube at the slowest sweep velocity, the delay marker would be approximately 5 inches from the left hand edge of the tube at the fastest sweep velocity. This would not leave space on the tube face for viewing the response to the stimulus.

The apparent solution would have been to provide a variable delay, either manually controlled or automatically switched, when the sweep velocity was changed. This however would involve the critical adjustment of component values in the sweep and delay circuits to meet this condition.

It was recognized that in order to maintain a marker at the same position on the sweep, regardless of sweep velocity, the delay marker would have to be derived from a fraction of the sweep voltage and not a function of velocity. Therefore, a circuit that triggers and supplies a marker pulse when a critical voltage is reached was a very logical choice. With the critical triggering voltage variable, the delay marker can be set anywhere on the sweep. With such a system, the marker will always remain in the same position on the sweep, regardless of sweep velocity. This, of course, pre-supposes that the sweep voltage is well regulated and remains constant in amplitude with varying sweep velocity. With the employment of gaseous discharge tubes and a stabilized bias, this is easily accomplished. The actual circuit chosen to generate the marker used to trigger the stimulator is a form of the direct coupled "flip-flop". This circuit is often called a Schmitt Trigger[8] and has the unique property of quickly switching (or flips) from one stable condition to another when the input voltage is raised beyond a critical value. When the input voltage is reduced below this critical potential, the circuit quickly returns (or flops) back to its original condition.

The input to the flip-flop was derived from the sweep voltage. As the sweep voltage builds up and the cathode ray tube beam traverses the tube, the flip-flop transforms from one condition to the second when the critical voltage is reached. When the sweep voltage reaches its maximum and drops back to zero on the retrace of the sweep, the circuit quickly resumes its original condition. The "flip" wave of the flip-flop was differentiated and used as a triggering pulse to initiate the stimulus wave.

A receptacle labelled "accessories" was installed on the front panel which provides filament and high voltage connections as well as the stimulus triggering pulse. A stimulator can be connected to this outlet and obtain the necessary voltages an d delayed triggering wave.

Power Supplies.

Careful thought was given to the power supplies for the oscilloscope. The susceptibility of cathode ray tubes to pick-up hum from stray magnetic fields is tremendous. In the past, the author has had considerable difficulty eliminating this source of interference. The effect is not seen on many standard oscilloscopes, due to the fact that the sweep velocities usually provided are not slow enough to see multiple 60 cycle waves on the trace of the tube. Magnetic shielding helps but does not entirely eliminate the pick-up. In one instance, after resorting to extensive magnetic shielding, hum pick-up was traced to the magnetic field surrounding a glass vacuum tube. The field came from the flow of 60 cycle alternating current through its filament. Although no 60 cycle modulation appeared in the output of this tube, the field was stong enough, and the tube was located sufficiently close to the cathode ray tube electron gun to modulate the beam.

With this danger in mind, a new design approach was made. The aim was to separate the various tubes and transformers from the cathode ray tube by as much distance as possible. If the intervening space were filled or partially filled with magnetic material, the effáctive distance would be even greater. In addition, orientation and placing of the power transformers below and behind the cathode ray tube gun was considered essential. With a magnetic shield surrounding the cathode ray tube, it seemed very unlikely that appreciable hum modulation would be picked up.

In order to supply voltages for the various circuits, two power supplies were decided upon. One was a 2000 volt low current output supply for the focus and accelerating voltage of the cathode ray tube. The other was a standard full-wave 400 volt DC supply with both negative and positive voltages. The negative voltages were provided to bias the various pulse circuits. A voltage regulator tube was incorporated to stabilize the bias supply. The positive supply energized all the amplifying and wave generating circuits.

Controls.

As an overall aim, the controls available on the front panel were only those essential and were grouped as to importance. Primary controls were provided with standard size pointer radio knobs. Secondary controls, or those which were not used after warm-up and calibration, were made either screw-driver set or provided with small button knobs. In this way, the danger of accidentally changing the wrong control was minimized.

Power Supply Design Tests.

The actual design of the oscilloscope was begun with construction of the power supplies and in particular with the high voltage power supply. In order to ascertain whether the power supplies could be included in the same cabinet with the cathode ray tube, tests were made using the precautions already discussed to avoid hum modulation. The cathode ray tube and high voltage power supply were mounted in the oscilloscope cabinet. The component values used were those recommended by the manufacturer of the cathode ray tube and transformer. The cathode ray tube and its power supply were mounted in the most convenient manner to satisfy minimum hum pick-up theory. The deflection plates were tied to zero potential with respect to the cathode ray tube final accelerating anode. The circuit was checked carefully and the apparatus turned on.

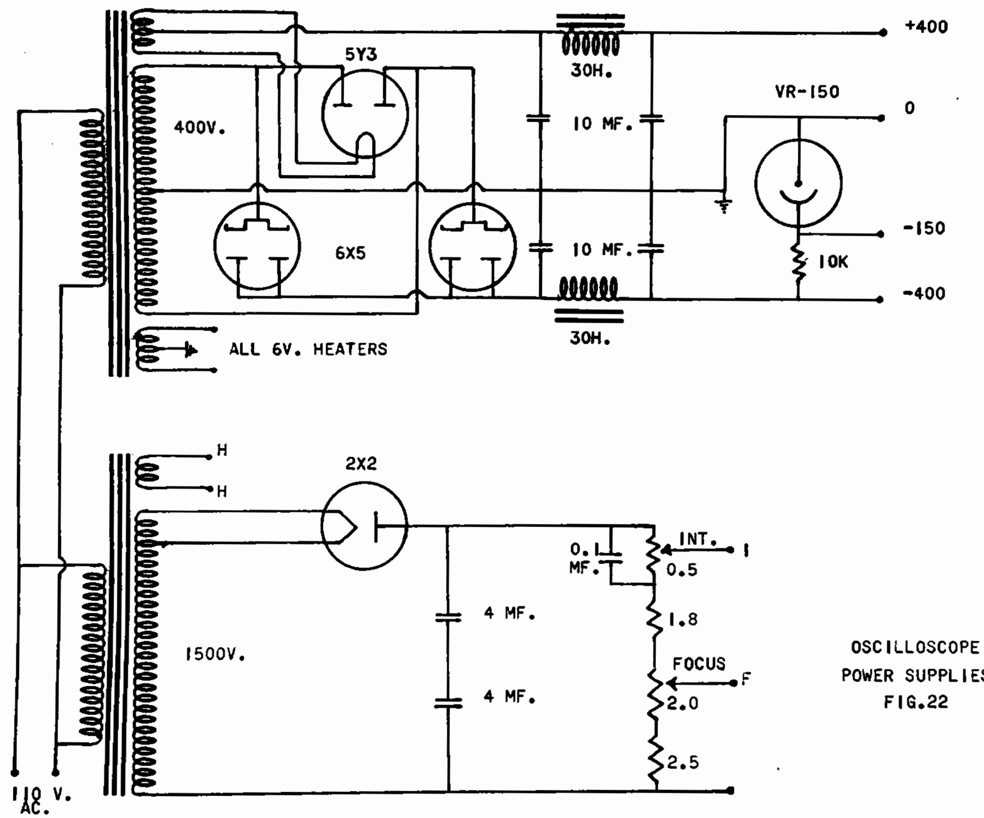
After a warm-up, the luminous spot appeared centrally on the face of the cathode ray tube. Both the focus and intensity controls affected a control over the cathode ray tube in the usual manner.

One pair of deflection plates was then disconnected from the accelerating anode and energized by a variable frequency sine wave oscillator. This produced a single line on the face of the tube. The oscillator voltage was increased so thatthe line just filled the tube. The frequency of the oscillator was varied slowly from 20 to 300 cycles with particular attention given to observing the trace of the tube when 30, 60, 120 and 180 cycles were passed. No beats were observed and the procedure was repeated with the other pair of deflection plates with the same result. Both pairs were then tied to the oscillator and a diagonal line was then observed. The procedure was repeated and the pattern again was free of beats, showing that the hum modulation was absent or present in negligibly small amounts.

The positive and negative supplies were next mounted and wired. They were loaded to the capacity of the power transformer and the foregoing procedure was carried out. Again no hum modulation was observed on the cathode ray tube face, showing that it was feasible to mount the power supplies and the cathode ray tube in the same cabinet when the foregoing precautions were taken.

Figure 22 shows the wiring diagram of the two power supplies. A gaseous regulator (VR150) was incorporated into the circuit of the negative supply to provide a stabilized source of voltage for biasing the various pulsing circuit.

The detailed design of the various sections comprising the oscilloscope was then commenced. The vertical amplifier was designed and assembled. This was followed by the sweep and and delay circuits.



OSCILLOSCOPE
POWER SUPPLIES
FIG.22

Vertical Deflection Amplifier.

Tracing the signal from the cathode follower to the cathode ray tube plates, there are two resistance capacity couplings, A pair of 0.25 mfd. condensers isolate the bias of the cathode follower from the input grid of the first oscilloscope amplifier. Another pair of interstage coupling condensers connects the first and second oscilloscope amplifier stages.

In the interest of standardization, the interstage coupling condensers were also made 0.25 mfd. The output of the second stage was connected directly to the cathode ray tube deflecting plates.

To make the input resistance of the cathode ray oscilloscope high, a dual two meg. potentiometer was used as the grid resistor of the input stage. This allows the freedom of using the cathode ray unit independently as a general purpose oscilloscope with the usual high input impedance.

With the first amplifier grid resistor chosen, only the second stage grid resistor need be determined to provide the oscilloscope amplifier with an overall time constant of 137 milliseconds. The calculation of this resistor is as follows:

$$\frac{1}{\text{Overall RC}} = \frac{1}{\text{RC Stage}_1} + \frac{1}{\text{RC Stage}_2}$$

$$\frac{1}{.137} = \frac{1}{2 \times 0.25} + \frac{1}{R \times 0.25}$$

$$7.3 = 2 + \frac{4}{R}$$

$$R = 0.755 \text{ megohms.}$$

A 1 megohm resistor was used. The overall time constant of the amplifying channel is summarized and calculated herewith.

$$\frac{1}{RC\ Overall} = \underbrace{\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_3C_3} + \frac{1}{R_4C_4}}_{\text{Preamp.}} + \underset{\uparrow \text{ Oscilloscope.}}{\frac{1}{R_5C_5}}$$

$$RC = \frac{1}{0.56x.25} + \frac{1}{0.56x.25} + \frac{1}{1.2x.25} + \frac{1}{.25x2} + \frac{1}{0.25x1}$$

$$= 7.14 + 7.14 + 3.34 + 2.0 + 4.0$$

$$= 23.62$$

RC = 42.3 milliseconds.

In order to keep the input capacitance of the cathode ray unit to a minimum value, push-pull pentodes were used for the input stage. The tube types chosen were the 6SJ7's. Plate load resistors of 220K were used which is a typical value with a 400 volt plate supply. This leaves about 150 volts on the plate as a quiescent voltage, assuming a plate current of about 1 milliampere. The remainder of the values (cathode and screen resistor) were taken from the RCA Receiving Tube Manual.[9]

The gain listed for these operating conditions is of the order of 167. To obtain the balance of the amplification, a double triode was decided upon. The overall gain required of the oscilloscope amplifiers is 555. The push-pull 6SJ7 stage provides 167 leaving a balance of 555/167 = 3.3 to be provided by the push-pull triode stage. To obtain this gain, any double triode could have been used. The choice, however, was narrowed down by an additional practical consideration.

The coupling leads from the vertical amplifier to the cathode ray tube socket would of necessity be long, due to the dimensions of the cathode ray tube. These leads also require shielding. Shielding is antagonistic with good high frequency response because of the shunt capacitance introduced. Therefore, a low plate resistance double triode was used to preserve the high frequency response. A survey of all of the common double triodes shown in Fig. 13 indicates that the 6SN7 tube has sufficient gain as well as very low plate resistance. It accordingly was employed for the final oscilloscope amplifier stage.

The component values in this stage were dictated partly by convention, but mainly by the necessity of providing shift voltages. From Fig. 14, any plate load greater than ten times the plate resistance yields a stage amplification of ninety percent of the amplification factor of the tube. Therefore, a plate load resistor of 77,000 ohms would be expected to give a gain of 18. This gain is far in excess of the 3.3 required, but can be reduced by the dual 2 meg. input control. However such low resistance would require the tube to draw a large plate current even at high bias voltage. The actual plate load values chosen were 330K and were made by inspection of various load lines on the tube plate characteristics. With a plate supply voltage of 400, a convenient quiescent voltage would be 200 volts. This would give a 4 inch deflection of the beam if one half of the double tube were driven to cut off (assuming 50 volts per inch deflection sensitivity of the cathode ray tube). The plate current necessary to drop 400 volts to 200 volts through 330K ohms is approximately 0.625 milliamperes. The bias necessary to create these conditions is approximately 14 volts (from the tube characteristics). This requires a cathode resistor of

$$E = I \times R$$

$$14 = 0.625 \times 10^{-3} \times R$$

$$\text{or} \quad R = 22,400 \text{ ohms}$$

for a single tube. With two tubes connected push-pull, a cathode resistor of half this value or 11,200 ohm provides the operating bias. The stage could be expected to give a deflection of 8 inch maximum or + and -4 inches from the center of the tube with each half tube being driven to cut off. This is more than adequate to satisfy the size of the tube and insures a good linearity of the reproduced wave over the face of the cathode ray tube which is $\pm 2\frac{1}{2}$ inches.

Vertical Centering Control.

The foregoing pre-supposes that the characteristics of the 6SN7 amplifier tube and components are identical. If such a condition existed, no shift control would be necessary for the vertical deflecting amplifier as the conventional method of viewing the trace is with it centered on the tube face.

However, it is rare that twin tube characteristics are identical even over a normal operating range. It is also practically difficult to obtain matched components that have equal thermal drifts. Therefore, a vertical centering control was added to always insure the ability to position the trace in the center of the cathode ray tube.

The most convenient method of accomplishing this is to feed a biasing signal into the deflection amplifier. This would alter the quiescent potentials in a tilt fashion and deflect the mean position of the beam. A convenient way to provide this feature is to connect a small potentiometer between the cathodes of the amplifier with the rotary arm connected to the bias resistor. A potentiometer value of 10% of the cathode resistor would not seriously unbalance the two sides of the push-pull amplifier. A 1000 ohm potentiometer was installed and the operation of the control was satisfactory, but its range was limited. To get a wider range of centering, the potentiometer would have to be an appreciable fraction of the bias resistor. This would upset the balance of the amplifier if the rotor of the potentiometer were off the mid-position. To avoid this, and preserve the balance, the circuit was rearranged. The cathode resistor return was removed from the common power supply return and made to the 400 volt negative supply. The value of the resistor was increased to 330K to consume the negative voltage and bring the cathode up to approximately 15 volts. At 0.625 ma. per tube, the cathode current is 1.25 ma. The drop across the 330K resistor would be 1.25 x 330K or 415 volts. A 25K potentiometer was inserted with its ends between the cathodes and its rotor connected to the 330K resistor.

The conditions existing now are those of a phase inverter. The cathode resistor is high (330K) and in comparison to the plate resistance (7700). With this situation, the output will be balanced by phase inverter action even if one input grid signal is zero. This means that the centering control can be moved far off the mid-position and the signal voltage output will remain balanced.

The arrangement was tested and the cathode bias was found to be about 15 volts. The shift or centering capacity of the circuit was very adequate and no variation in signal output from either plate to ground could be noticed on ratation of the centering control. Figure 23 shows the circuit arrangement of the vertical deflecting amplifier.

Astigmatism Considerations.

To prevent astigmatism in the cathode ray tube, it is necessary to operate the deflection plates at the same mean potential as the final accelerating anode. To accomplish this, an 0.5 megohm potentiometer (with a series 0.5 megohm dropping resistor) was shunted from the positive supply voltage to the chassis negative return. The positive of the cathode ray tube high voltage supply was connected to the rotor of the 0.5 megohm potentiometer. This rotor was adjusted then to the same potential as the plate voltage of the vertical deflecting amplifier tube which,on no signal,is about 200 volts.

Time Base.

To display the potentials under study with their original time distribution is the function of the sweep or time base.In order to accomplish this, the cathode ray tube luminous spot must be deflected linearly across the face of the tube. Assuming that symmetry exists in the electron optics of the cathode ray tube, a linearly rising (or falling) voltage when applied to the horizontal deflection plates; will produce a linear time display of the signal

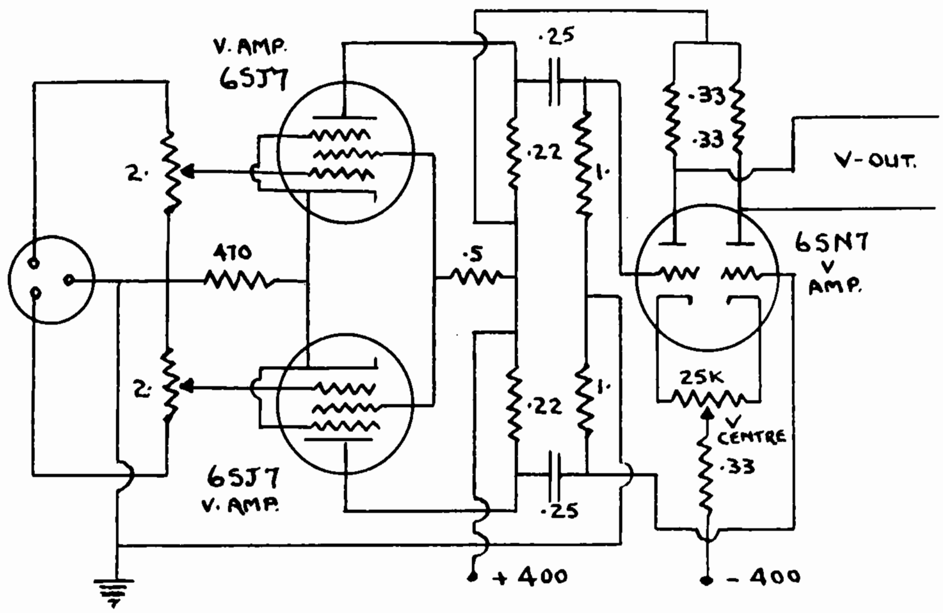


FIG. 23 - VERTICAL AMPLIFIER.

connected to the vertical deflection plates. The features necessary in the sweep circuit are such that the velocity of the luminous spot be controllable, independent of the repetition rate of the sweep. In other words, single or multiple stroke action is required, with the sweep velocity remaining constant at any of the repetition rate settings.

The velocity ranges necessary to display electromyographic potentials are 20 to 2.5 milliseconds per inch measured on the face of the cathode ray tube. The repetition rate of the sweep must be variable between 1 and 10 sweeps per second. To photograph a single trace on the cathode ray tube, the sweep must be initiable by the camera shutter. It is also convenient to have a manual push-button so that a test sweep can be made.

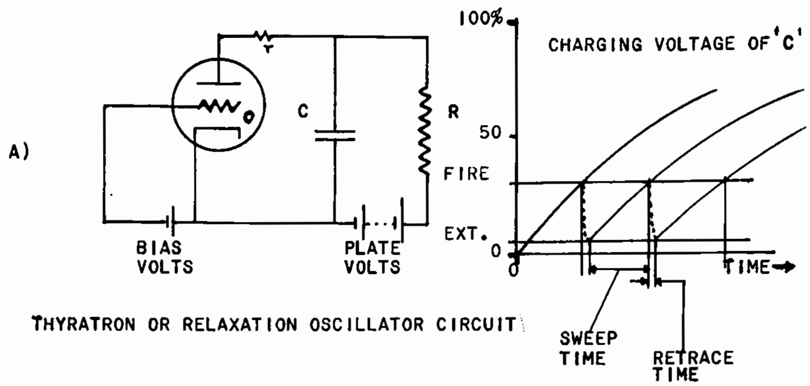
Using a 5 inch cathode ray tube, the time required for one sweep at the slowest sweep velocity is 5 x 20 or 100 milliseconds. It will not be possible to drive this sweep velocity at a repetition rate of 10 per second because of insufficient time for recovery of the sweep generating circuit.

Choice of Sweep Circuit.

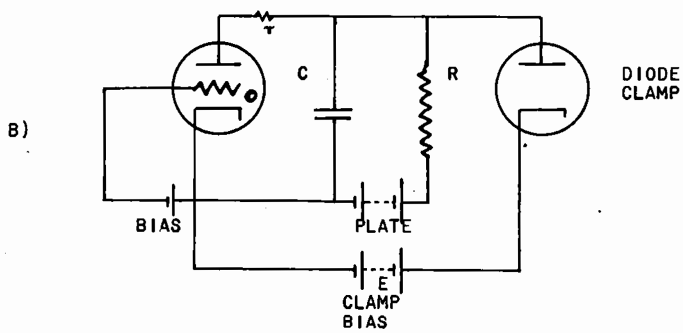
Of all the circuits that are used to generate linearly rising (or falling) sweep voltages, the large majority depend directly on the charging of a condenser. Sweep circuits furthermore are divided into two categories, namely "hard" and "soft" tube circuits. A hard tube circuit is one which employs a vacuum tube, whereas a soft tube circuit is one using a gas tube. Broadly the vacuum tube time bases are more complicated, and when arranged for single stroke operation, tend to have a long recovery time after executing one sweep cycle. The gas tube (or more commonly thyratron) sweep circuit is a freely running circuit whose linearity is poor when arranged for single stroke operation. It has, however, a short recovery time.

The basic sweep circuit decided upon was a modification of the gas tube sweep circuit. The circuit (Fig. 24a) is basically a thyratron or relaxation oscillator. The condenser, C, charges up through R, the resistor, heading for the plate supply voltage. When the voltage on the condenser reaches a critical value (depending upon the bias of the thyratron tube) the tube discharges or "fires" becoming a very low resistance. This discharges the condenser almost completely. The lack of completeness of discharge depends upon the extinguishing voltage of the thyratron. When the thyratron extinguishes, the condenser starts to charge again. In order to limit the discharge current through the thyratron to a safe value, a small limiting resistor r is inserted in series with the plate.

The frequency of the oscillator depends primarily upon the charge time constant RC and secondarily on the discharge time constant rC. The shape of the plate voltage wave depends upon the bias of the tube. If the bias is large and negative, the condenser voltage can approach the plate supply voltage. This would give an exponential voltage wave at the plate. If, however, the bias were low and negative, the plate voltage would not rise to an appreciable fraction of the supply voltage. The onset or early rising phase of an exponential wave is very linear



THYRATRON OR RELAXATION OSCILLATOR CIRCUIT



MODIFIED RELAXATION OSCILLATOR SWEEP GENERATOR

FIG. 24

and is sometimes used as a sawtooth wave. By keeping r small, the discharge time can be made very short so that the voltage wave is linearly rising and immediately dropping, then linearly rising again. It is this type of circuit that is used in many standard oscillographs.

In order to provide the circuit with single stroke capabilities, a clamp was added to hold the plate voltage from rising to the critical firing voltage. The clamp used is shown in Fig. 24b and consists of a biased diode. The operation of the circuit is described as follows.

The condenser C starts to charge up through the resistor R. It would tend to charge toward the plate supply voltage if it were not for the firing point of the thyratron and the diode characteristics. The series voltage E holds the diode from conducting until the potential across the diode exceeds E. The value E is made slightly lower than the firing voltage of the thyratron. By doing this, the voltage on the condenser (after connection to the plate supply) rises to approximately E then stops. This would generate one wave having a linear front when the proper voltage adjustments are made. If this wave were connected to the horizontal deflection plates of a cathode ray tube one sweep would be executed.

However, nothing more can occur in the circuit until the condenser is discharged. In order to discharge the condenser, the thyratron must be fired. By feeding the sweep repetition pulse into the grid of the thyratron, a discharge can be elicited. The voltage on the condenser drops a nearly zero and starts to charge again. It charges up through R, heading again for the plate voltage but is stopped short at a value of E. This executes another sweep of the spot across the tube.

The discharge of the thyratron is accomplished by feeding a brief positive triggering pulse (larger than the thyratron bias) into the grid. Thus, for each positive trigger pulse fed into the grid circuit, the sweep executes one cycle. This positive trigger or repetition pulse was derived from a conventional RC relaxation oscillator using an 884 tube and a circuit identical with that shown in Fig. 24a. The plate voltage was differentiated by passing it through a short RC network. This differentiated pulse was amplified (and inverted) so that it became a large amplitude short duration triggering wave. It was then applied, as described, to the thyratron sweep generator.

Practical Version of Sweep Circuit.

The practical version of the sweep circuit uses an 884 thyratron and a 6SN7GT tube. In order to preserve the linear wave shape generated, direct coupled amplifiers were used to apply the sweep voltage to the cathode ray tube deflecting plates.

One 6SN7 operated as a conventional push-pull amplifier directly coupled to the horizontal deflecting plates. The connection here is similar to the vertical deflection amplifier with the exception of the arrangement for horizontal centering and gain control. The horizontal centering voltage was inserted in one grid while the sweep signal was fed into the other. A high cathode resistor (returned to the negative supply) provided phase inverter action so that a signal going in one grid appears at both plates with the opposite polarity. The gain control was made screw-driver adjust and served to adjust the length of the sweep to fill the tube exactly.

To connect the sweep generator tube and its clamp to the horizontal amplifier, a cathode follower was used. The cathode follower serves as a low output impedance - high input impedance transformer. It has one other very valuable function in this instance, namely a voltage reference changing device.

The diode clamp and the cathode follower were combined into one tube. A 6SN7 double triode was used with one half connected as a diode and the other half as a conventional triode cathode follower. The clamp voltage was made adjustable in the cathode circuit of the diode. In this way, the clamp voltage can be trimmed very closely to the firing point of the thyratron.

The cathode follower grid was directly connected to the plate of the thyratron. A large cathode resistor was installed and consisted of a potentiometer and a fixed resistor returned to the negative supply. A small series resistor was inserted in the plate circuit of the cathode follower to limit the plate current. With these connections and the take off of the sweep voltage at the rotor of the cathode potentiometer, the reference voltage of the sweep can be chosen at will and set permanently. The reference locates the mean position of the sweep on the cathode ray tube face.

Adjustment and Calibration of Sweep Circuits.

Because of the many variable and interlocking quantities, the sweep circuit was adjusted into operation in a semi-quantitative manner. The following paragraphs outline the procedure on which the chóice of the various critical components was made.

Repetition Oscillator Adjustment.

The circuit of repetition oscillator shown in Fig. 23a contains three main variables. These are the grid bias, the charging condenser C and its associated resistor R. It is assumed that the plate supply voltage is fixed. The frequency of the oscillator depends on the charge time of the condenser through the resistor and consequently inversely on the time constant RC. If the bias is made small, the wave will approximate a linear saw tooth wave on the charge phase. If the discharge path is of low resistance, the frequency then will depend linearly and inversely with the charge time constant. The frequency range required of this circuit is 1 to 10 cycles per second. If the bias were set to such a value that the thyratron fired at 63% of the plate voltage, the wave shape would not be linear, but the time constant required for one cycle per second would be one second. Such a charge voltage on a condenser is far up on the exponential charging curve. The wave shape of the oscillator freely running would not be a linear saw tooth under these conditions.

To know exactly how large the time constant need be when only a part of the exponential charge curve is used, Fig. 24c was constructed. This figure was drawn assuming a time constant of one second according to the formula.

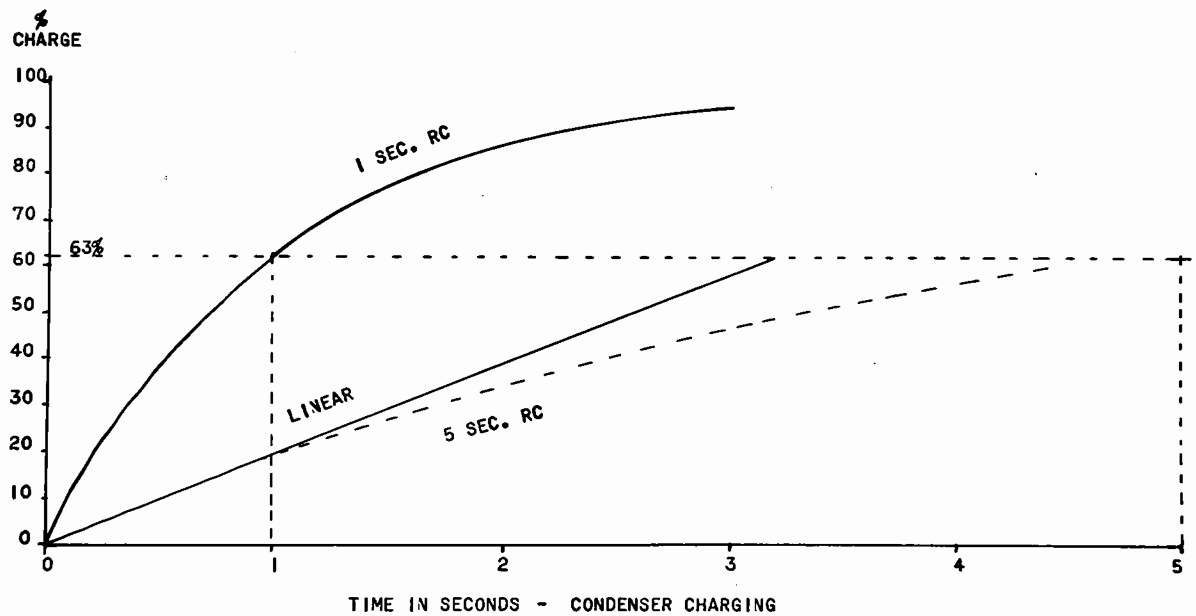

% CHARGE
100
90
80
70
63%
60
50
40
30
20
10
0
1 SEC. RC
LINEAR
5 SEC. RC
0
1
2
3
4
5
TIME IN SECONDS - CONDENSER CHARGING

FIG. 24C

$$E_t = E(1-e^{\frac{t}{-RC}})$$

or

$$\frac{E_t}{E} = 1 - e^{\frac{t}{-RC}}$$

Where t = time

RC = time constant

E_t = instantaneous voltage

E = supply voltage

e = 2.718

where $\frac{E_t}{E}$ is the fractional charge, RC the time constant and t the time. It can readily be seen that if the charge is permitted to reach 63% of its final value, the wave shape is very exponential. The curve starts to depart seriously from linearity when the charge is allowed to exceed 25% of its final value. Therefore, for a linear wave, a time constant of many times the apparent time constant is needed.

In this instance, the time constant chosen to obtain a frequency of 1 per second was 5 times the apparent time constant necessary. The five second time constant exponential wave is shown dotted on Fig. 24c. It is seen that the charge has risen to 20% of final value using this time constant in this time. From the curve, the departure from linearity is of the order of only a few percent under these conditions. The actual RC component values chosen were 5 megohms (variable) and 1 microfarad. To accomplish the 10 cycle per second frequency range, the 5 megohm potentiometer was operated at its minimum resistance and a series 0.56 megohm resistor was installed.

This allows variation of the time constant from 5.56 seconds to 0.56 seconds which is a ratio of 9.95 to 1. The sweep repetition oscillator was adjusted into operation by setting the 5 megohm control to its minimum resistance and adjusting the bias of the thyratron to realize a frequency of 10 cycles per second. With the 5 megohm control at its maximum resistance the frequency was expected to be $\frac{10}{9.95} = 1.005$ cycles per second. By measurement, the frequency was for all purposes was 1 cycle per second.

Sweep Generator Adjustment.

The sweep generator circuit shown in Fig. 23b, also contains many variables. Basically, it has the same variables as the repetition oscillator but with one in addition, namely the clamping voltage E.

The slope of the saw tooth wave must be varied in order to provide the beam velocities on the tube of 20, 10, 5 and 2.5 milliseconds per inch. With the five inch cathode ray tube, the required width of the base of the saw tooth wave is 5 x 20, 5 x 10, 5 x 5, 5 x 2.5, or 100, 50, 25, 12.5 milliseconds respectively. Using the same reasoning for this circuit as for the repetition oscillator, the following conditions exist. Assuming a time constant of five times longer than apparently necessary, time constants of 500, 250, 125 and 62.5 milliseconds were employed. This allows the voltage on the charging condenser C to reach approximately 20% of its value or numerically $\frac{1}{5} \times 400 = 80$ volts. This voltage was then clamped to about 70 volts in order to prevent the sweep thyratron from freely oscillating.

The actual values chosen to provide the time constants were obtained by various selected condensers and a single settable charging resistor. The resistor was made a 5 megohm potentiometer of the screw-driver set type with a fixed 0.56 megohm series resistor. The condensers used to obtain the desired time constants were 0.1, 0.05, 0.025 and .0125 microfarads. The condensers selected were measured on a bridge to have these exact values. With this combination of a fixed resistor and varied capacitors, the DC conditions in the sweep circuit are maintained. Only the charging rate is variable by changing the capacitor in the circuit. The 5 megohm potentiator further gives flexibility to the circuit so that the exact slope of the waves is selectable to provide the sweep velocities necessary.

Calibration of Sweep.

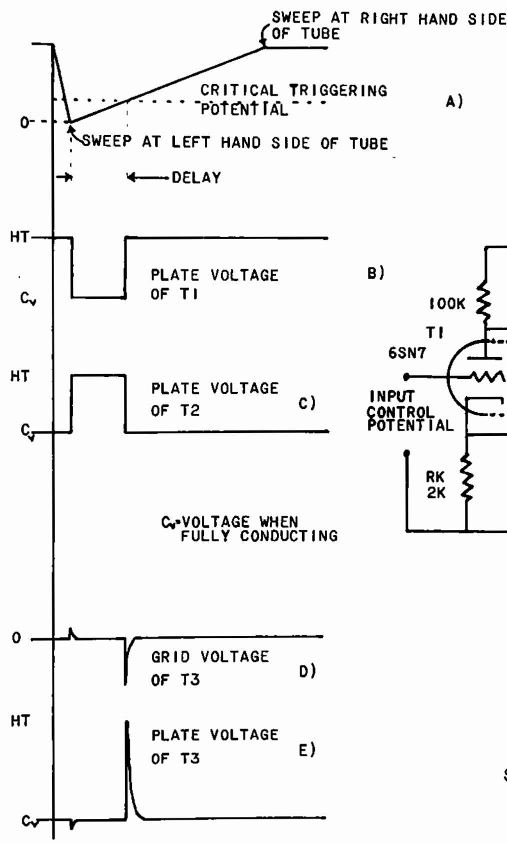
Practically, the circuit was calibrated in the following manner. The sweep frequency oscillator and the clamp tube were removed from their sockets, allowing the sweep oscillator to run freely. The bias of the sweep oscillator was adjusted with 5 megohms as the total charge resistor. The free running frequencies obtained corresponded to the duration of the sweeps. For example, for the 20 milliseconds per inch sweep velocity and a sweep length of 5 inches, the duration of one sweep was 5 x 20 = 100 milliseconds. With the oscillator freely running,this corresponded to a frequency of 10 cycles per second (neglecting flyback or discharge time). The various other sweep velocity positions were checked and the frequency-velocity relationship was excellent.

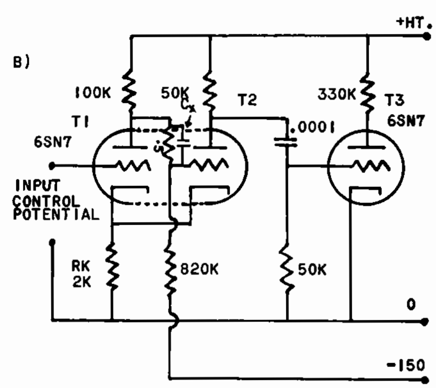
connection is made by inserting the camera plug. This was accomplished by grounding the repetition oscillator plate with auxiliary Jack contacts. An RC network was connected to the camera shutter which, when actuated, momentarily shorts the bias on the sweep thyratron causing a single sweep. A parallel connected push-button was installed to trigger the sweep manually. With these features, the sweep circuit can be initiated at a given repetition rate variable from 1 to 10 per second and manually controlled by the pushbutton or camera shutter contacts when the camera plug is inserted.

Delay Circuit.

In order to generate a triggering pulse for the stimulator, the Schmitt trigger circuit was employed. Earlier in this report, a brief outline was given describing the circuit operation. The following is a more detailed analysis of the practical circuit used to perform the task of providing the delayed pulse.

The tube employed for the Schmitt trigger is a 6SN7 GT. The circuit diagram is shown in Fig. 25. The operation is such that the circuit triggers in one direction when the level of the input potential to T_1 is raised to a critical value. When the input potential is lowered, a return to the original state instantaneously occurs. The two levels may be made to approach one another by reducing the value of the cathode resistor RK. When the input signal to T_1 is zero, the bias conditions are such that maximum current flows in tube T_2. The plate current of the first tube is cut off by the voltage drop across the cathode resistor.





SCHMITT TRIGGER CIRCUIT
FIG. 25

If now the input control potential is increased so that the drop across the cathode resistor RK is reduced by the flow of plate current, the grid potential of T2 will become more negative and reduce the plate current of T2. This will reduce the voltage across the cathode resistor RK which will in turn increase the grid voltage of T1. The effect is a cumulative one and instantaneous triggering occurs from the original condition of T1, non-conducting and T2 conducting fully to the reverse condition. When the input control potential is again reduced to zero, triggering in the reverse direction occurs. The circuit now is in its original condition. (To speed the "flip" from one regime to the other, a small condenser CX was inserted between the plate of T1 and the grid of T2.)

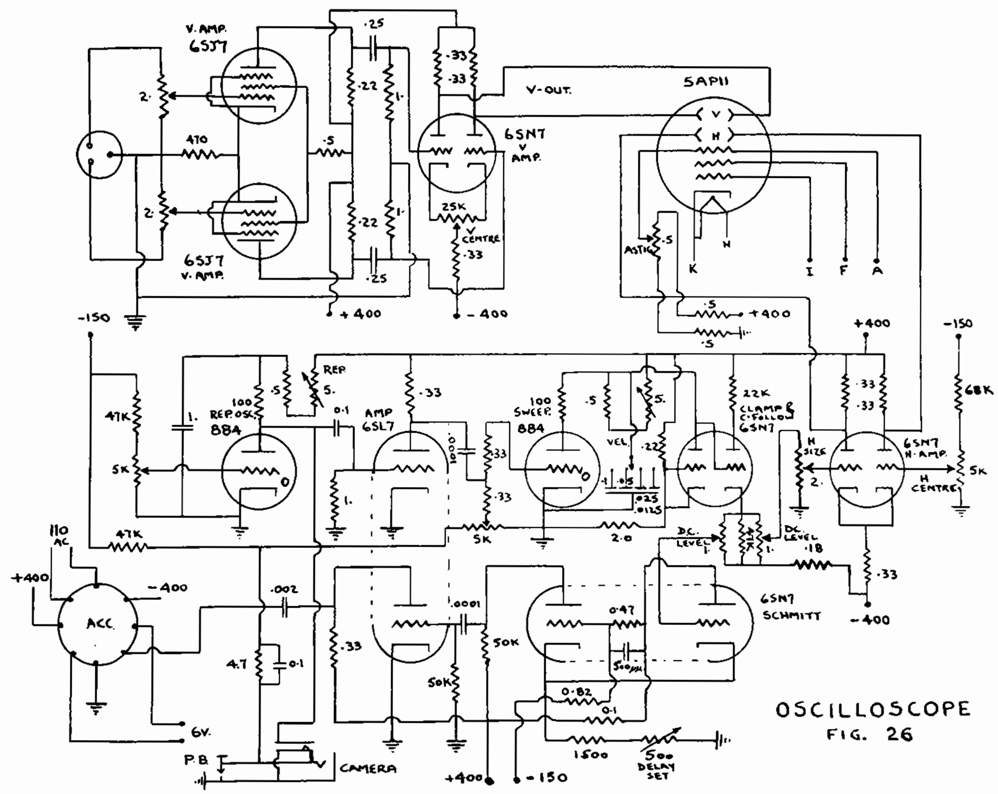
The control potential is derived from the sweep voltage. By means of a parallel potentiometer in the cathode follower sweep output tube, the sweep reference voltage was adjusted. The input requirement of the trigger circuit is a control voltage rising from zero positively. Accordinly, the potentiometer was adjusted so that the sweep voltage rising phase starts at zero and rises positively. This condition is shown graphically in Fig. 25a. When the control potential reaches the critical value, the trigger circuit switches from T1 non-conducting (T2 conducting) to T1 conducting (T2 non-conducting). The plate voltages existing over this cycle are shown in Fig. 25 b and c. HT denotes the supply voltages and C_V the fully conducting plate voltage.

The trailing edge of the plate voltage pulse of T2 was the differentiating amplifier tube was chosen from the tube characteristic curves to allow about 1 milliampere standing plate current to flow. The nearest standard value resistor was 330 kilohms. A .002 mfd. condenser serves as the output coupling condenser to isolate the trigger pulse from the standing plate voltage.

Overall Operation of Sweep and Delayed Pulse Circuits.

In summary, the cathode ray tube spot remains just off the right hand side of the tube between trigger pulses from the sweep repetition oscillator. When a trigger pulse initiates a discharge in the sweep thyratron, the sweep condenser discharges causing the spot to traverse instantly from the right hand side of the tube to the left. The fly-back voltage actuates the Schmitt trigger into its ready state. The sweep thyratron extinguishes and the sweep condenser starts charging moving the spot across the cathode ray tube. When the spot reaches about one quarter of the distance across the tube, the Schmitt circuit quickly switches to its triggered condition because the sweep voltage being fed into it exceeds the critical value. The switch over produces a trigger for the stimulator. Meanwhile, the spot continues to travel to the right hand side of the tube and waits for the next triggering pulse to start another cycle. The Schmitt trigger also remains, in its triggered condition until the next sweep trigger occurs to reset it.

The complete circuit of the oscilloscope embodying the various units is shown (less power supplies) in Fig. 26. The



OSCILLOSCOPE
FIG. 26

various circuits are labelled for easy identification. Figure 27 shows the construction and front panel views of the oscilloscope unit.

Stimulator Connections.

The single channel oscilloscope described here was put into service by the Speech Therapy Department of Royal Victoria Hospital, Montreal, doing routine electromyography in cleft palate cases. For this use, a stimulator is not necessary. It was decided by the Speech Therapy Department that there would probably be no need of a stimulator as long as the present investigation ran. This investigation promises to a permanent part of the function of the department.

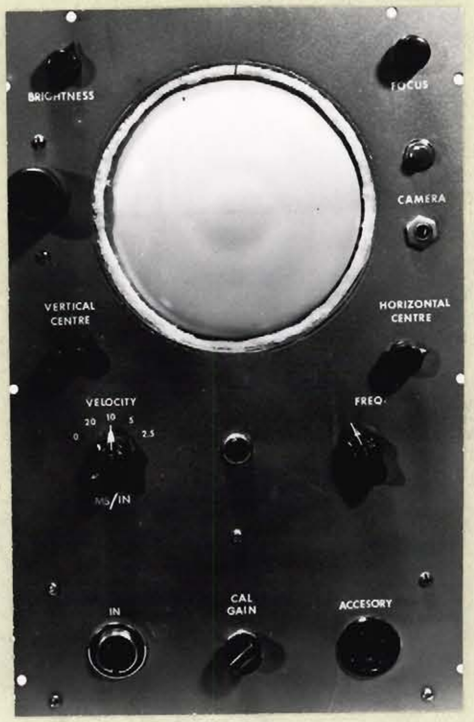
It was agreed to provide a stimulator at a later date or to modify any available model if stimulator studies are required. At the time of writing this report, nearly a year later, the need has not arisen.

The external connections from the oscilloscope for the stimulator are wired to the panel receptacle labelled "Accessory". From this outlet can be obtained the various voltages and triggering pulse necessary to operate a stimulator.

Cabinet Presentation.

The complete apparatus was housed in a heavy plywood cabinet fitted with wheels. Figure 28 is a photograph of the completed instrument. The cabinet finish is pearl gray. The individual units are finished in hammer-tone metal gray.

The top left hand compartment is felt lined and holds



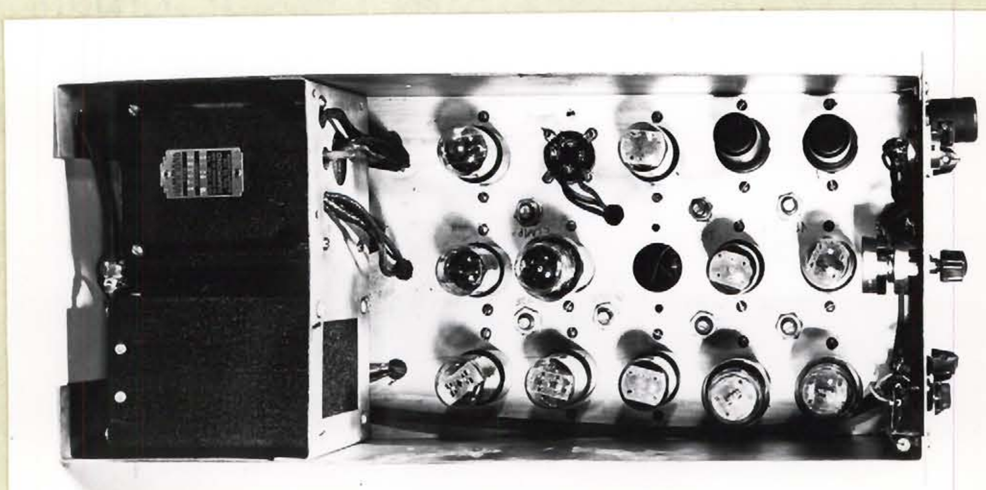


FIG. 27 - OSCILLOSCOPE

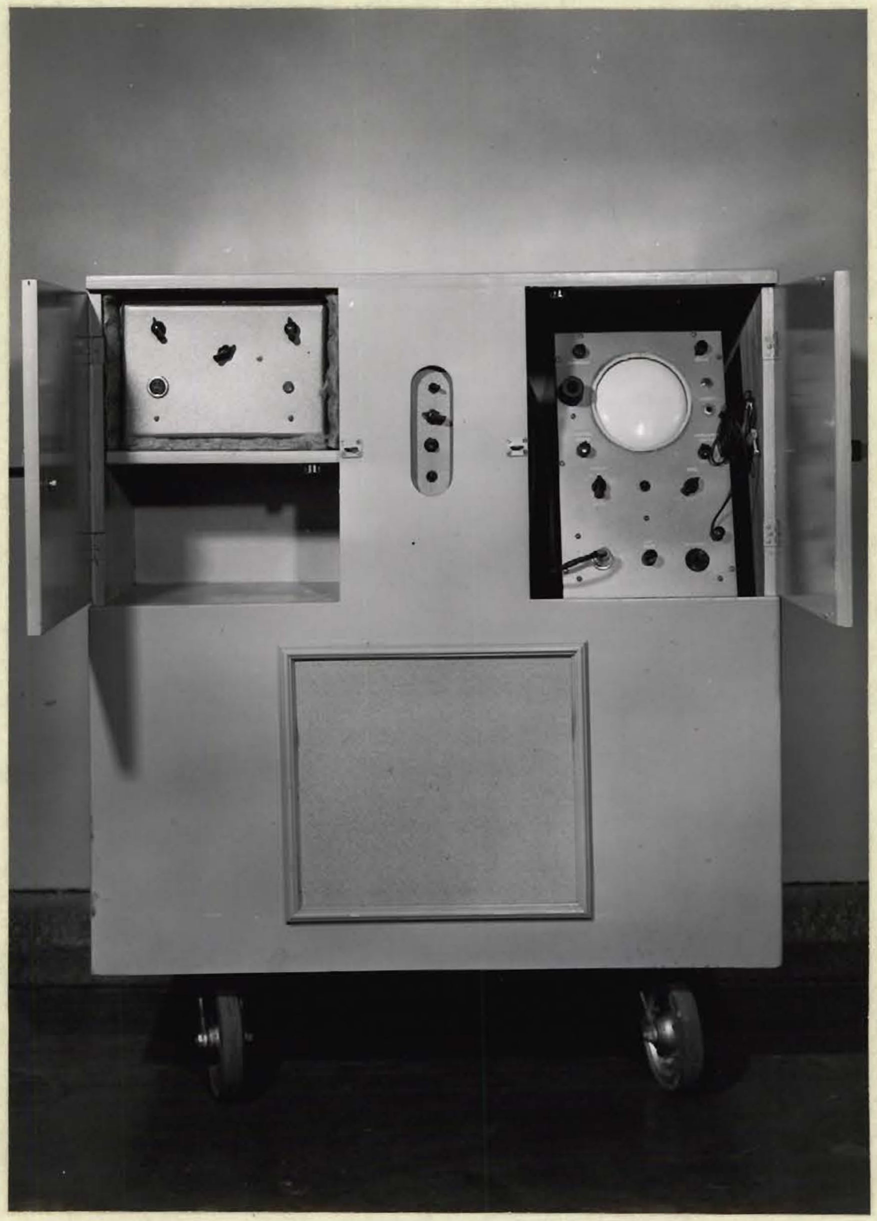


FIG. 28 - COMPLETE ELECTROMYOGRAPH.

the preamplifier. The lower portion of this compartment is storage space for electrodes and supplies. The hinged door conceals the preamplifier and supply shelf when closed.

The top right hand compartment encloses the oscilloscope. The face of this unit is tilted and recessed for easy viewing in an average room without dimming the lights. The hinged door conceals and protects the oscilloscope when the instrument is not in use.

The camera mount is to the left of the cathode ray tube. A 35 millimeter Iloca F 4.5 camera with a portrait lens was used. The portrait lens employed was a plus three which results in the whole cathode ray tube face filling a single 35 millimeter frame.

The preamplifier power supply and audio amplifier unit is located midway between the preamplifier and oscilloscope in the upper part of the cabinet. A slot in the cabinet front provides access to the volume control for the loudspeaker and and main off-on switch.

The bottom half of the cabinet, behind the grille, is used as the loudspeaker enclosure. The rectangular grille covers the circular loudspeaker hole and adds to the general appearance of the unit as a whole.

Performance Tests.

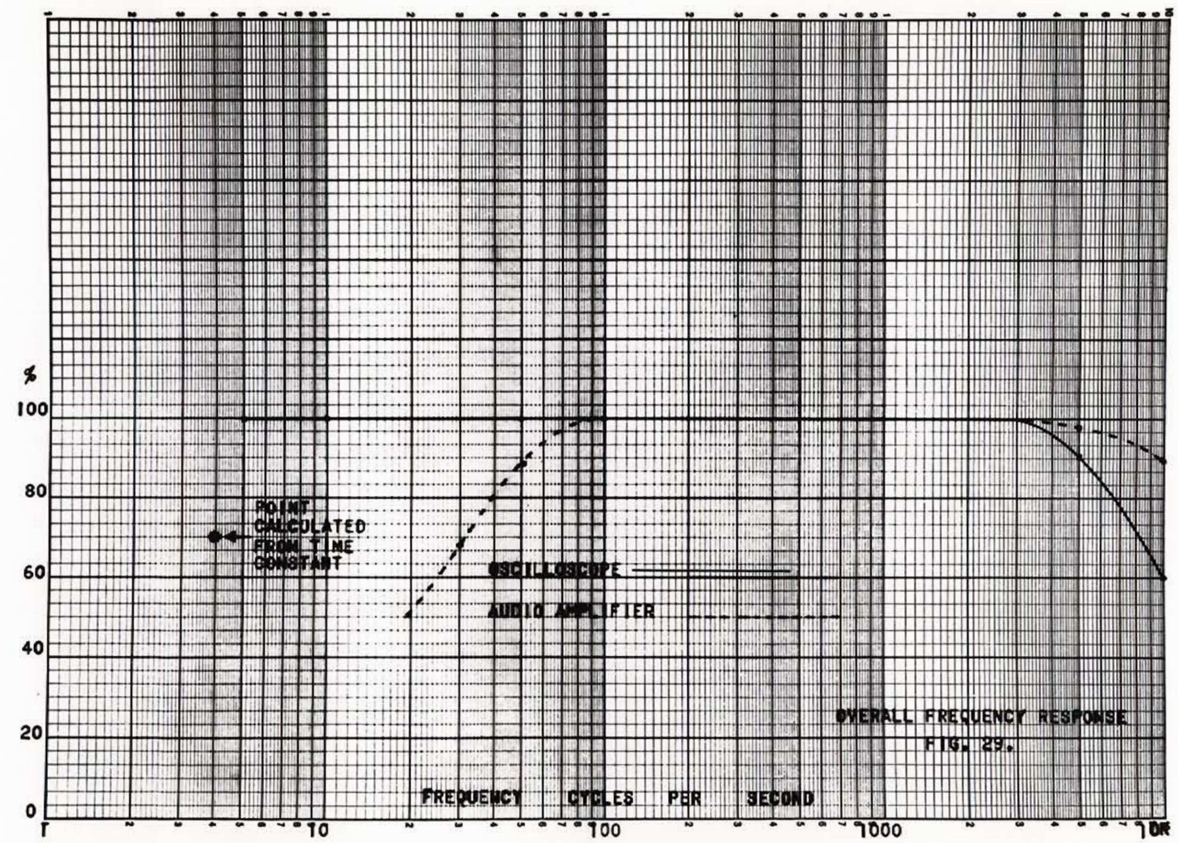
When the apparatus was completed, various tests were carried out. The tests were to ascertain whether the various units were functioning properly and within normal limits.

These tests included frequency response of the amplifying channel and audio amplifier. The time constant was checked and the balance ratio was measured. The sensitivity and noise level were measured with open and short circuited inputs. A heat run test of two days duration was made to check the temperature rise of the various units.

The frequency response from the input to the cathode ray tube and loudspeaker voice coil is shown in Fig. 29. It can be seen that the high frequency response of the audio amplifier (dotted curve) is better than that of the cathode ray tube amplifier. This frequency response probably is not a true measure of acoustic output from the loudspeaker at these frequencies. On the other hand, the low frequency response of the cathode ray channel (solid curve) is far superior to the audio amplifier which is to be expected from the typical characteristics of the output transformer feeding the loudspeaker. A better low frequency audio response would be unusable as these frequencies are close to the lower limit of audibility.

The high frequency response of the cathode ray channel is attenuated by 50% at 8500 cycles. This is better than the maximum requirement at this time and means that the precautions taken to keep shunt capacitance is low were more than adequate. If it were of interest to take advantage of the better than necessary high frequency response, the plate loads of the amplifying stages of the amplifying channel could be increased.

The low frequency response, which was measured flat to five cycles per second, is better than could be expected with



OVERALL FREQUENCY RESPONSE
FIG. 29.

a time constant of 42.3 milliseconds. To obtain roughly what would be expected, the following equivalent circuit and simplified calculation is presented.

Assuming a simple generator feeding a single series RC circuit, the voltage across the resistor would increase with increasing frequency. This is due to the decreasing reactance of the condenser with increasing frequency. With a constant voltage E input, let the output voltage be e., then:

$$\frac{e}{E} = \frac{R}{R + jX}$$

$$\frac{e}{E} = \frac{R}{\sqrt{R^2 + X^2}}$$

Where R = resistance

C = capacitance

X = reactance

$= \frac{1}{2\pi fC}$

f = frequency

$W = 2\pi f$

If we let $\frac{e}{E} = \frac{1}{\sqrt{2}}$

i. e. the response is down to 70.7%

$$\frac{1}{2} = \frac{R^2}{R^2 + \frac{1}{W^2C^2}}$$

$$RC = \frac{1}{W} = \frac{1}{2\pi f}$$

With an overall time constant of 42.3 milliseconds.

$$42.3 \times 10^{-3} = \frac{1}{2\pi f}$$

$f = 3.92$ cycles per second for 70.7% response

The time constant was checked by photographing and measuring a calibration wave. The overall time constant was found to be 40 milliseconds. This is closer than was expected due to the 10% tolerance in the components used, Fig. 30 shows a typical time constant wave.

The balance ratio was measured and found to be approximately 3000/1. This is more than adequate for routine electromyography.

Fig. 31a shows the noise level at top gain when the input was short circuited. The maximum overall peak to peak noise level is approximately 5 micro-volts. The maximum sensitivity was found to be about 30 micro-volts per inch deflection of the cathode ray tube spot.

Fig. 31b shows the noise level at top gain with the input open circuited. Much of this noise in pick up although some is input resistor and tube noise. The peak to peak magnitude of this noise and pick-up is approximately 15 micro-volts.

The heat run showed that the components operated within normal temperature limits. The transformers and various large current carrying resistors operated very far below their rated temperatures. With such a condition existing, it is estimated that the life of the unit will be long and that replacement of electrolytic condensers will not be required for many years.

Electromyographic Potentials.

In order to demonstrate, the use of the apparatus, several electromyographic potentials were recorded from an experimental animal. Figures 32 to 35 illustrate some of the various wave forms encountered in Electromyography. In the following paragraphs,

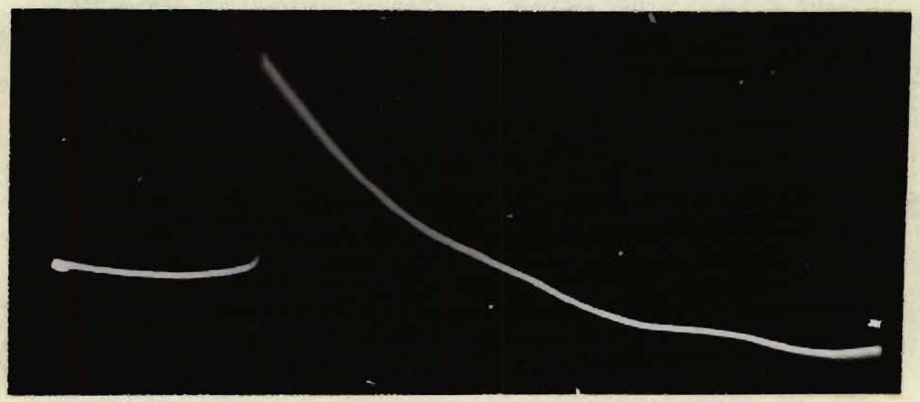


FIG. 30 - TIME CONSTANT WAVE.

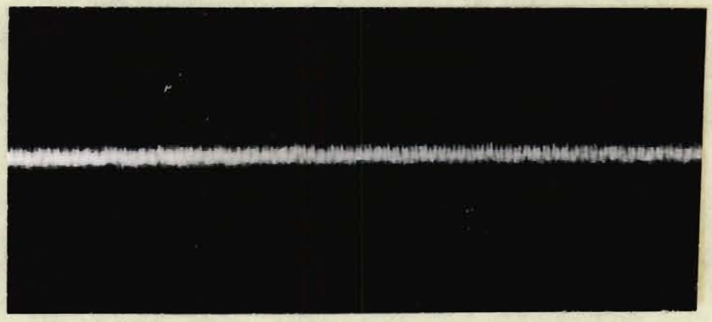


FIG. 31A - NOISE LEVEL (SHORT CIRCUIT)

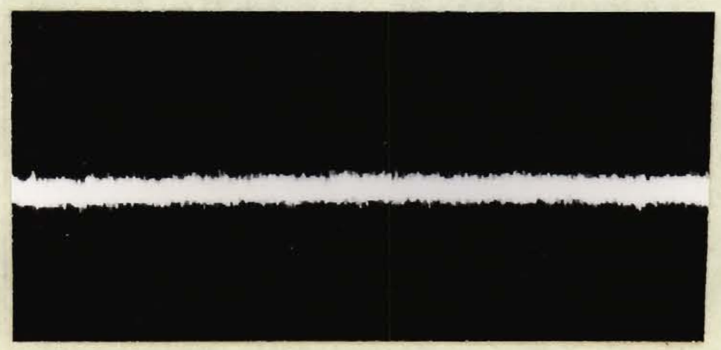


FIG. 31B - NOISE LEVEL (OPEN CIRCUIT)

a detailed description of the waves is given.

Figure 32 shows the almost complete lack of spontaneous electrical activity recorded from the resting gastrocnemius muscle of a white rat. The record was obtained on the apparatus using monopolar needle type electrodes similar to those described earlier in this report.

Figure 33 shows the multiple electrical activity of the quadriceps femoris muscle under voluntary contraction. The amplitude of the voltage waves is in the order of 500 microvolts with duration of about 4 milliseconds. Figure 34 illustrates a single motor unit wave recorded from the hamstring muscle.

In order to demonstrate the electrical activity observed in nerve injury state, a surgical denervation was performed. The procedure consisted of sectioning the sciatic nerve supply to quadriceps femoris using a sterile procedure. Following the operation the animal was permitted to convalesce for four weeks. During this period the outward manifestation was a partially paralyzed limb.

Figure 35 shows the electrical activity recorded from the denervated quadriceps muscle of the same animal after the period of convalesence. The amplitude of the waves is in the order of 150 microvolts with a base line duration of 1 millisecond. These voltage waves are called fibrillation potentials.

The wave forms illustrated by Figures 34 and 35 are what can be called the normal and abvormal unit electrical waves. During muscle reinnervation, the wave forms found consist of both

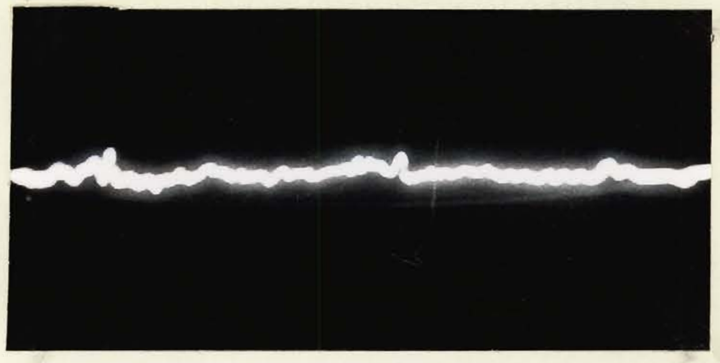


FIG. 32- RESTING MUSCLE (NORMAL)

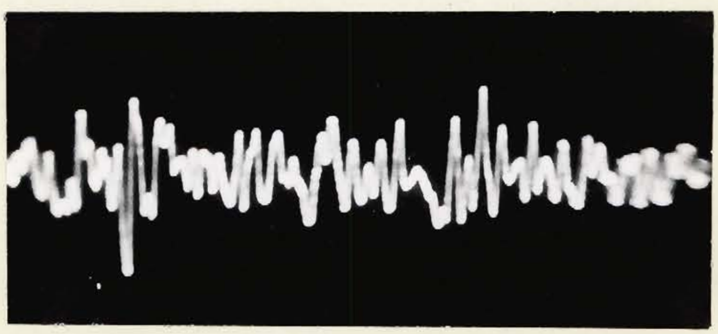


FIG. 33- VOLUNTARY CONTRACTION

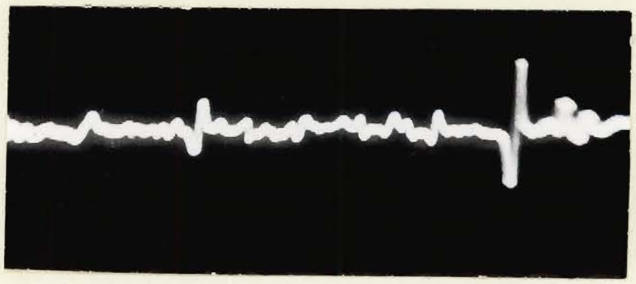


FIG. 34- SINGLE MOTOR UNIT.

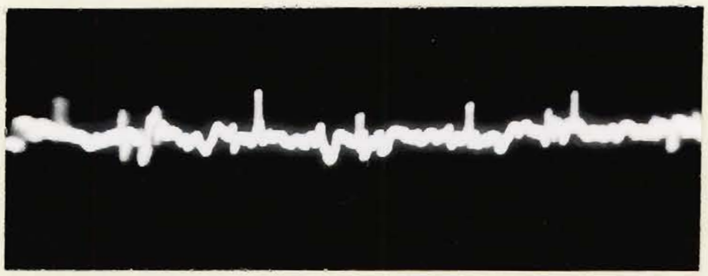


FIG. 35- FIBRILLATION WAVES

types and are very complex in character. With experience, the electromyographer can recognize individual components recorded from various areas of the muscle group and estimate the extent of nerve injury. In addition, with serial observation, of the muscle group, he is able to estimate whether possible recovery of müscle function will occur.

Figure 36 and 37 show the apparatus in use. In Figure 36 the technician on the right is installing the electrodes while the patient is being held by a student nurse. Figure 37 shows the technician operating the controls, preparing to take a picture of the potentials displayed on the cathode ray tube.

FIG. 36 - INSTALLATION OF ELECTRODES BY TECHNICIAN.

FIG. 37 - OPERATING THE ELECTROMYOGRAPH.

CONCLUSIONS

The apparatus herein described was turned over to the Department of Speech Therapy and Plastic Surgery of the Royal Victoria Hospital, Montreal under the directorship of Dr. Hamilton Baxter. A technician was instructed in its use and has since become proficient in utilizing the information contained in the recordings taken. The apparatus has now been in the department about one year. It is a source of valuable diagnostic information for the surgeon in the operations performed on cleft palate cases.

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5- RMA - Radio Manufacturer's Association, now and Radio and Television Manufacturer's Association. During and at the end of the war, industry pooled information and agreed to produce at least a standard minimum number of types and tubes and component values. Each tube manufacturer belonging to the RMA (RTMA) lists these items in his own data sheets in bold face type. This means that one is assured of a continued availability of a tube or component which will not become obsolete.

6- E. E. Staff M. I. T. "Applied Electronics", 4th printing, p. 305. Technology Press, John Wiley, New York.

7- R. C. A. Receiving Tube Manual, Copyright 1947, p. 200, Fig. 7, Radio Corporation of America Tube Department. Harrison, N. J.

8- Schmitt, O. H. "A Thermionic Trigger". Jour. Scientific Instruments, p. 24, 1938

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10- Puckle, O. S., "Time Bases", 2nd Edition, pp 81-83, Wiley, 1951.