The Bell System Technical Journal

Vol. XXV *January, 1946* *No. 1*

Early Fire-Control Radars for Naval Vessels

By W. C. TINUS and W. H. C. HIGGINS

Introduction

FOR a number of years before the war a very intensive development effort was under way in the Army and Navy laboratories, and in several commercial laboratories, on the application of radio methods to the location of objects at a distance. The equipment which resulted was eventually called "Radar" equipment by the Navy and this term is now almost universally used. The urgent needs of the war have resulted in the very rapid development and extensive application of this new science during the last few years.

Radar equipments of many different types have been designed to perform specific functions on land and sea, and in the air. These equipments have had an important part in the winning of the war and the recent relaxation in secrecy regulations now permits publishing some of the story. In this present article a description of the Mark 3 and 4 Fire-Control Radars for Naval Vessels will be given, together with a little of the history that preceded their development.

Historical Background

When the Bell Telephone Laboratories began active radar development work early in 1938 an effort was made to set technical objectives for this work that would avoid duplication of the intensive work then under way in the Army and Navy laboratories, and that would advance the art toward the solution of some of the recognized basic problems. The general objectives were to increase the accuracy of radar measurement of location and to increase as much as possible the operating carrier frequency. The reasons for these objectives are discussed in the following paragraphs.

The state of the art at the time under discussion has been partially described in a recent paper by Maj. Gen. R. B. Colton.[1] The work he described and directed was carried out at the Signal Corps Laboratories at Fort Monmouth, New Jersey and was directed principally toward solving

[1] "Radar in the U. S. Army" by Maj. Gen. Roger B. Colton, published in the *Proceedings of the I. R. E.*, November, 1945.

the ground forces' problems of aircraft warning and searchlight control. At the same time intensive work was being pursued at the Naval Research Laboratory at Anacostia, D. C. under the direction of Dr. A. H. Taylor, Dr. R. M. Page and Mr. L. C. Young. Their work was directed primarily toward developing radar equipment that would be useful aboard ship, and it was from them and from the engineers of the Navy Department that the principal inspiration and guidance for the work described in this paper were obtained.

The first military application in which radar equipment proved its usefulness was in the detection of approaching aircraft. For this kind of application the radar is not required to locate the approaching planes with very great accuracy and the experimental radars of 1938 and 1939 performed this function in quite a useful way. The fact that the first application of radar was a strictly defensive one may account in part for the great interest and support given radar work in England and in this country, while apparently much less radar work was done before the war by the scientists of Germany and Japan. Thus, when radar later became a powerful and versatile aid to offense, the enemy nations found themselves years behind in development.

Very early in their work the men of the Naval Research Laboratory recognized the potential ability of radar to help solve the fire-control problem. Since this problem determined the design of the radar systems to be described later in this paper a brief general discussion of fire control is given here. The term *fire control* refers broadly to the means by which a gun or other weapon is aimed and fused so that, when fired, the projectile will hit or burst near the intended target. A fire-control system includes two major parts: first, a locating device for determining the present position of the target; and second, a computing device which analyzes the present position data, computes the target's course and speed, and the position the target will occupy at the future time when the projectile arrives at that point, and finally furnishes the correct aiming and fusing information to the guns. A modern fire-control system does these things in a continuous manner so the guns remain correctly aimed and can be fired at any time during the engagement.

Before the war the present position of the target was ordinarily determined by optical instruments. Operators tracked the target by controlling their telescopes in such a way that the target remained on the crosshairs in their eyepieces. Thus the azimuth and elevation angles were found. Another operator measured the range to the target with an optical range finder, or indirectly estimated range from the angular extent of the target and its estimated size.

The accuracy of this optical system in determining azimuth and elevation angles is very good provided the target can be seen clearly. This proviso is a serious limitation under many typical operating conditions. It is frequently difficult to see a target at a range of several miles on account of haze even on a relatively clear day, and at night or in fog or smoke screen the usefulness of a telescope is almost nil. The optical range finder is subject to the same limitations as the telescope and in addition leaves much to be desired in the matter of accuracy and continuity of data even under the best visibility conditions. This is due to the fact that optical range finders are triangulation devices which inherently have accuracy limitations. The need for a long and very stable base line between the prisms of an optical range finder is difficult to meet aboard ship, and the principle of operation makes inevitable a rapidly decreasing accuracy with increasing range. Thus, as the effective range of guns increased, the need for more accurate means for measuring range became more acute.

In its earliest forms radar offered at once a potential means for measuring range with much better accuracy than that of the optical range finder. This was due to the different principle on which radar works. A pulse of radio frequency energy is sent out to the target and the echo signal is received back at the source. The velocity of the waves en route is the same as that of light, and is one of the basic physical constants. To measure range accurately with radar required only the development of techniques for producing short transmitted pulses and for measuring accurately the short intervals of time between the transmitted pulse and the returning echo pulse. Both of these were the kind of problems which yield readily to electronic solutions. The early work in Bell Telephone Laboratories thus included the production of shorter transmitted pulses than were being commonly used, and the development of improved range measuring means.

The second important general objective for the early work at Bell Telephone Laboratories was to devise equipment which would operate at frequencies much higher than had been previously used. The need for higher-frequency operation arose from the fact that for a given size of antenna the beam width decreases with increasing frequency while the gain increases. Narrow beams are required to obtain accurate angular data while increased gain is desirable since it obviously provides increased range for a given transmitter power and receiver noise figure. These factors are illustrated by the curves of Figs. 1A and 1B which show the relationship between beam width, antenna gain and antenna size expressed in wavelengths. The curve labeled "uniform illumination" yields maximum gain and minimum beam width for a given antenna size but produces unwanted side lobes of undesirable amplitude. For this reason the illumination is usually graded over the antenna aperture to reduce minor lobes. The gain

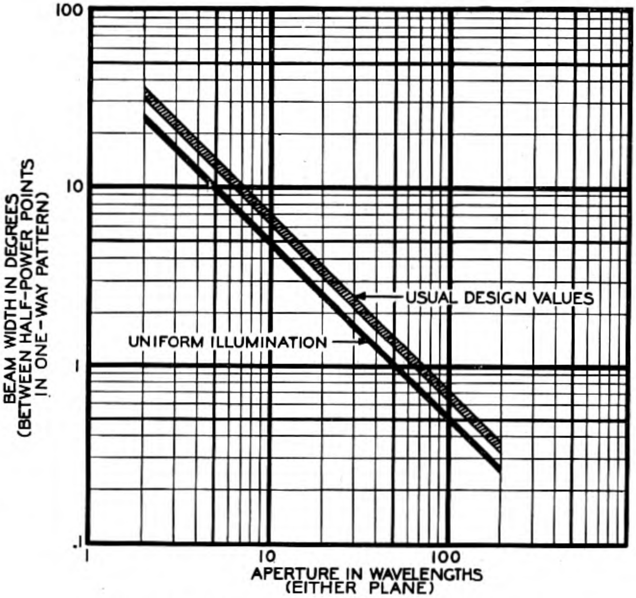


Fig. 1A—Antenna beam width vs. aperture

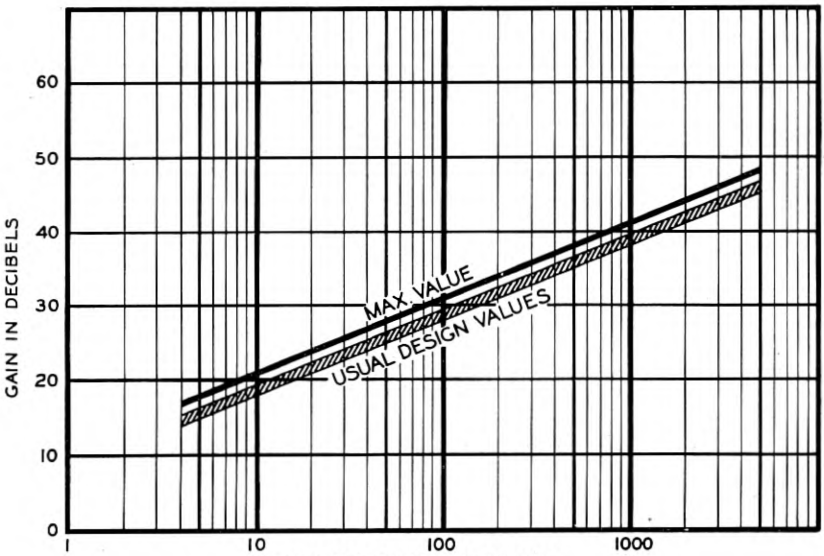


Fig. 1B—Antenna gain vs. aperture

and beam width obtained in this manner are shown by shaded area labelled *usual design values.* The need for higher frequency or shorter wavelength was apparent to all of the early experimenters since physical limitations restricted the size of antenna which could be installed conveniently aboard ship. However, development effort along these lines had previously been hampered by lack of suitable vacuum tubes.

In spite of the vacuum tube difficulties the Laboratories work was started in the range from 500 to 700 mcs, a region several times that then in use at the Army and Navy laboratories. The best tubes available were those of the *doorknob* type which have been described in the literature by A. L. Samuel[2] and are illustrated in Fig. 2. The smallest of these was used in the receiver input circuits and two of the middle sized ones were used in the tramsmitter oscillator. These triodes operated at quite high frequencies by virtue of the very small spacing between their electrodes, a feature which made them fragile and demanded the development of plate modulation. Earlier radars had generally used grid keyed oscillators, i.e., the plate voltage was applied to the oscillator continuously together with a high grid bias voltage. The bias was removed momentarily by the keyer to emit a pulse. In order to obtain a useful pulse output from the doorknob oscillator tubes it was found essential to remove all stress from them except during the pulse. This was accomplished by using a direct coupled pulse amplifier or modulator, effectively in series with the oscillator and the power supply. Here again in 1938 no really suitable tubes were available for the modulator service since it also demanded a highly intermittent duty. However, since the modulator duty did not require the tubes to operate at very high frequency it was possible to use rugged high-voltage triodes which had been designed for continuous service, and to obtain the required pulse current capacity by paralleling a number of tubes. The earliest radar modulators used in the Laboratories employed a group of Eimac 100-TH tubes. Later, in the CXAS and Mark 1 Radars, six tubes similar to the W. E. 356A were used in parallel.

After a great deal of laboratory work an experimental equipment was assembled and demonstrated to the Army and Navy in July 1939. This early radar was notable in that it operated at what was then considered a very high frequency and also in that it employed a single antenna only about 6 ft. square. The transmitter and receiver were connected to the common antenna by a *duplexing technique* to be described later, which had been applied at lower frequencies by engineers at the Naval Research Laboratory. The results of these first field tests were encouraging and both the Army and the Navy ordered one prototype model equipment to be known as the CXAS. This radar was to operate at 500 or 700 mcs and was to incorporate a number of new features which were designed to make it

[2] *Proceedings of I. R. E.*, Vol. 25, page 1243, 1937—"Negative Grid Triode Oscillator and Amplifier for Ultra High Frequencies." Digest in Oct. 1937 *B. S. T. J.*

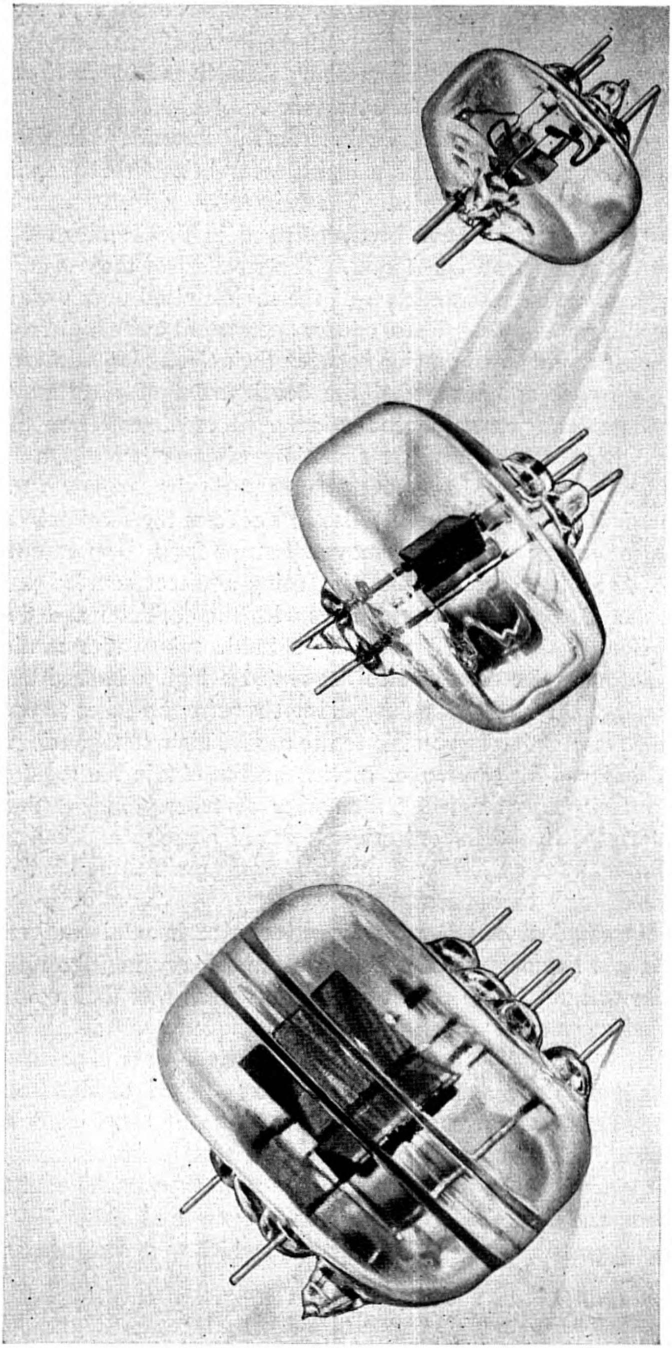


Fig. 2—Vacuum tubes for ultra-short waves

convenient to operate and to provide a range accuracy that would be useful in fire control. Since this early radar is of cosiderable historical importance it will be described in some detail.

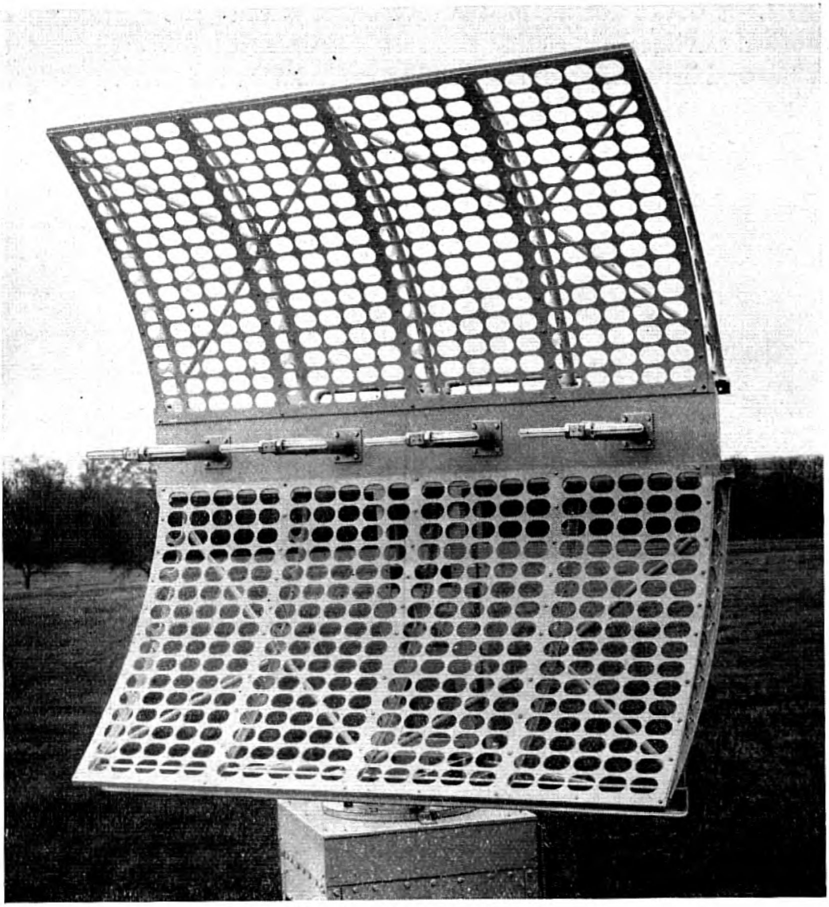


Fig. 3—CXAS—Antenna

The CXAS Radar

This equipment was divided into three major assemblies and the circuits were arranged so the three could be installed at some distance from each other. The antenna (see Fig. 3) consisted of a cylindrical parabolic reflector about 6 ft. square with an array of eight half-wavelength dipoles along the focal line. With shipboard use in mind the reflector was perforated to minimize wind resistance and the dipole and coaxial line feed system was made weatherproof, which was accomplished by making the line system pressure-tight and filling it with dry gas. The gas-line system was extended to include the radiating elements by covering the latter with pyrex test tubes sealed to the support with a packing gland as shown in Fig. 4. A device was included in each dipole assembly for supplying the two half-wavelength radiating elements with balanced voltages from the unbalanced line, while a coaxile line harness including impedance matching

Fig. 4—CXAS—Dipoles

transformers was used to connect the several dipole assemblies and provide a matched load to the single transmitter-receiver line. A schematic diagram of this arrangement is shown in Fig. 5. The contemplated use of this radar was for surface targets or low-flying planes and rotation was provided only in azimuth. A gas-tight rotary joint was developed to carry the $\frac{7}{8}''$ coaxial line through the azimuth axis (Fig. 6).

The operator's cathode ray oscillograph indicator and all of the essential

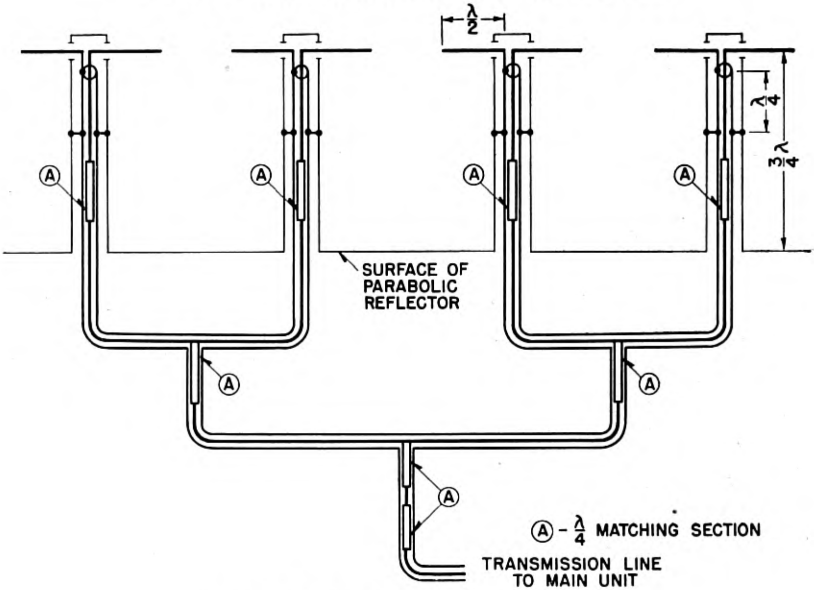


Fig. 5—CXAS—Antenna schematic

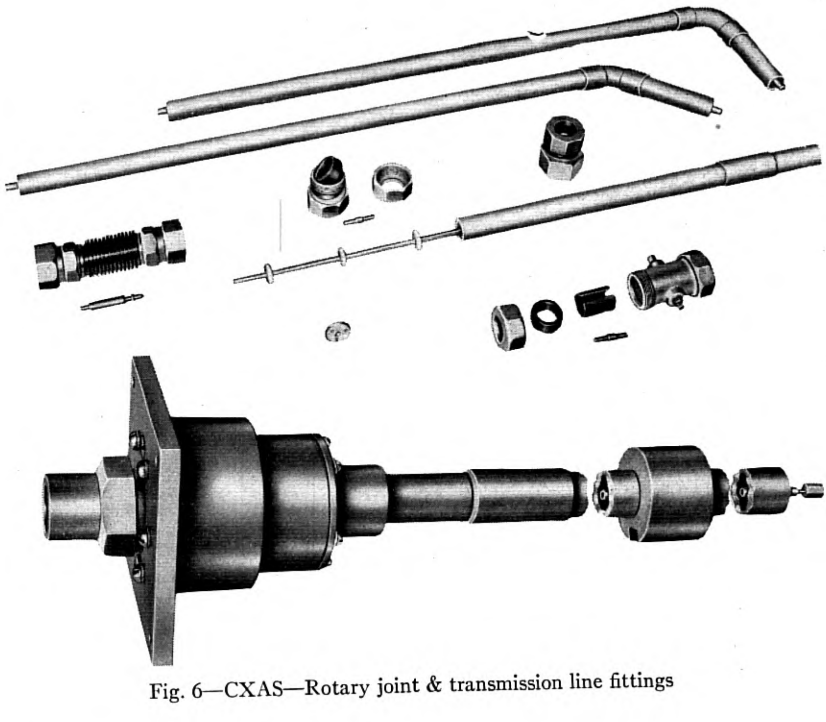


Fig. 6—CXAS—Rotary joint & transmission line fittings

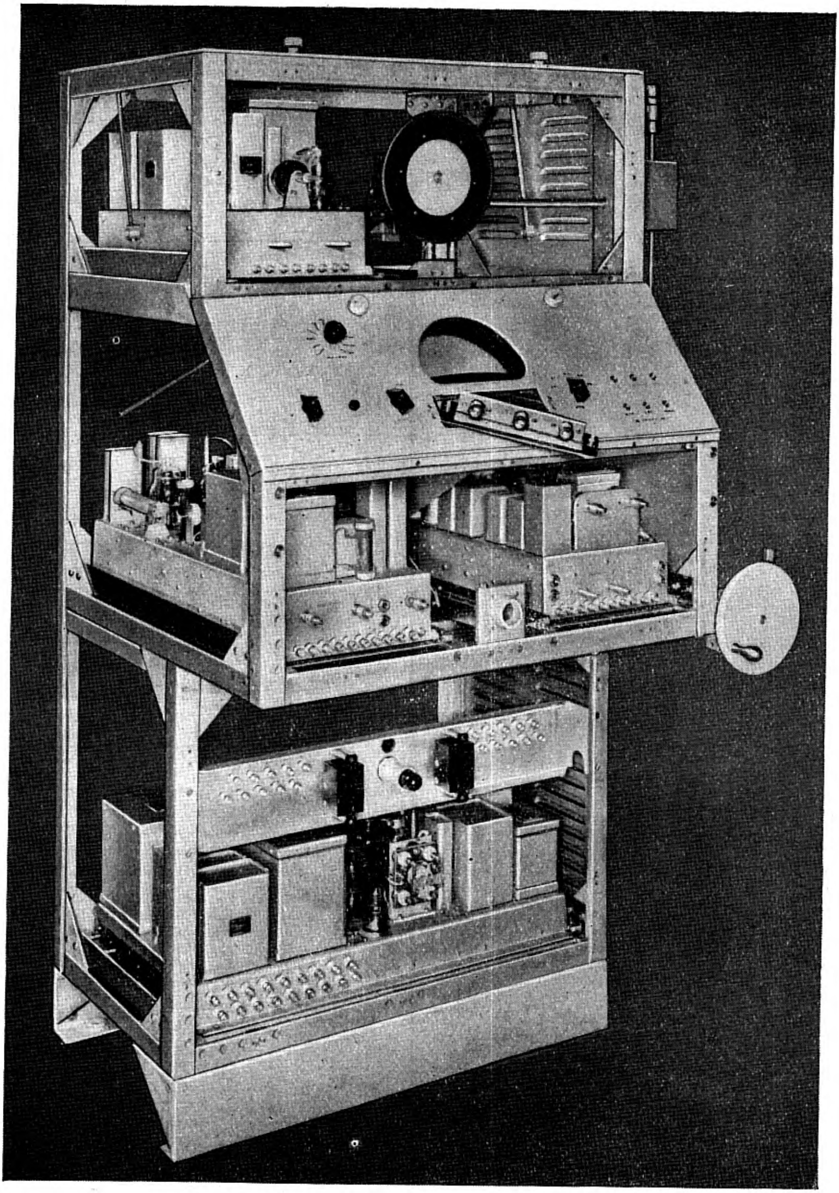


Fig. 7—CXAS—Indicator desk—covers removed

operating controls were combined into an assembly called the Indicator Desk, a photograph of which is shown in Fig. 7. This was intended for indoor mounting below the antenna in such a position that the azimuth hand wheel on the desk could be connected to the antenna turntable by a shaft. The indicator employed a 7″ cathode ray tube and displayed the radar signals by what is now known as a Class A sweep with a full scale of 100,000 yards. A pioneering feature of this indicator was the provision of a series of electronic range marks to increase the accuracy with which target range could be read. Earlier indicators had used a ruled mask for the range scale and had suffered in accuracy due to parallax, sweep non-linearity, drift of sweep position, etc. The CXAS provided sharp pulses to mark the 10,000-yard intervals along the sweep line, and smaller pulses to mark the intervening 2,000-yard intervals. This system was free from the errors of the ruled mask and permitted range readings accurate to ±200 yards throughout the 100,000-yard scale. Provision was also made to expand any desired 20,000-yard segment of the scale to fill the entire tube screen so that signals could be examined more closely. The ranges corresponding to the 10,000-yard intervals were designated by illuminated

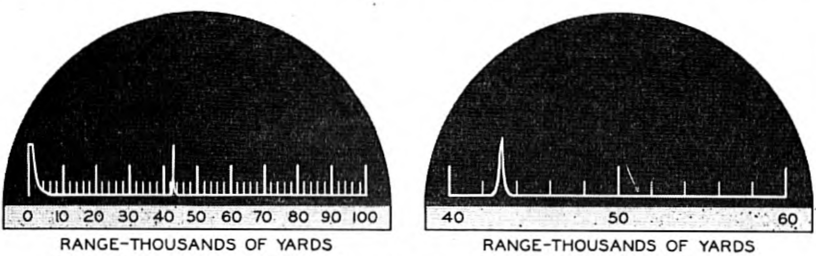


Fig. 8—CXAS—Range mark system

numerals located directly below the electronic scale. The presentation obtained with this arrangement is indicated in Fig. 8 which shows the electronic calibration marks, transmitted pulse, and an echo at 43,000 yards on both the full and expanded scales.

The third part of the CXAS equipment was an assembly known as the Transmitter-Receiver or Main Unit. It was designed to be unattended in normal operation and contained the Pulse Generator, Radio Receiver, Power Control Panel, Radio Transmitter, and H.V. Rectifier, which were all built as removable *drawer type* units. A side compartment in the Main Unit also housed the duplexing circuits, gas equipment for the transmission line, and some built-in test equipment, including a wavemeter and monitoring rectifier. The Main Unit and its sub-units are shown in Figs. 9 to 14, respectively. A single $\frac{7}{8}''$ coaxial transmission line provided connection from the Main Unit to the antenna.

In order to use a single antenna for both transmission and reception, means had to be provided to effectively disconnect the receiver during the

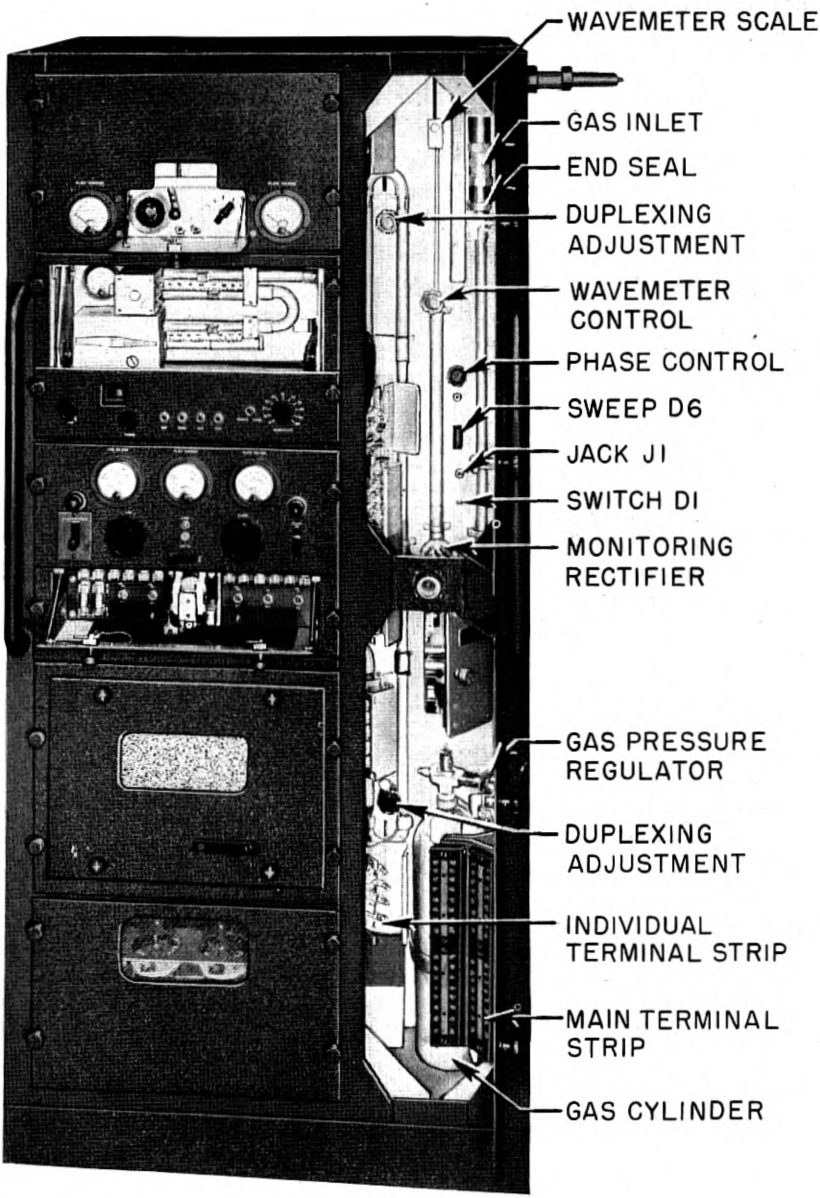


Fig. 9—CXAS—Main unit

transmitted pulse and to effectively disconnect the transmitter when the echo is received. If this were not done, a large part of the transmitted energy would be dissipated in the receiver. Also, the minute received energy would be partially lost in the transmitter output circuit thus reducing the maximum range. Because of the extremely short time intervals between transmitted and received pulses, ordinary switching methods cannot be used. A *duplexing technique* mentioned earlier was therefore developed to provide this function. In the CXAS Radar this switching was obtained by connecting the transmitter and receiver to the antenna transmission line through adjustable lengths of coaxial line which were preset for a given operating frequency to be effectively an odd multiple of

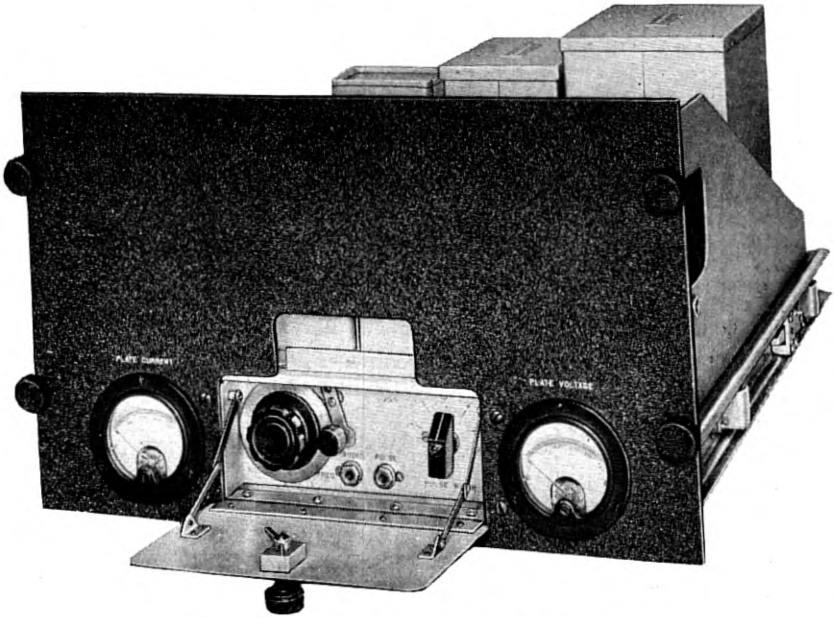


Fig. 10—CXAS—Modulation or pulse generator

one-quarter wavelength long. During the transmitted pulse, a small amount of the transmitted power overloaded the first tube in the receiver and provided a low impedance at that point. Due to the line length between receiver and junction point this low impedance is reflected as a high impedance at the junction point with the result that very little power is lost in the receiver line. At the end of the transmitted pulse the output impedance of the transmitter consists only of the small inductance of the output coupling loop and this impedance is reflected by proper choice of line length as a very high impedance at the junction joint with the receiver line. Thus, most of the received echo is directed to the receiver input

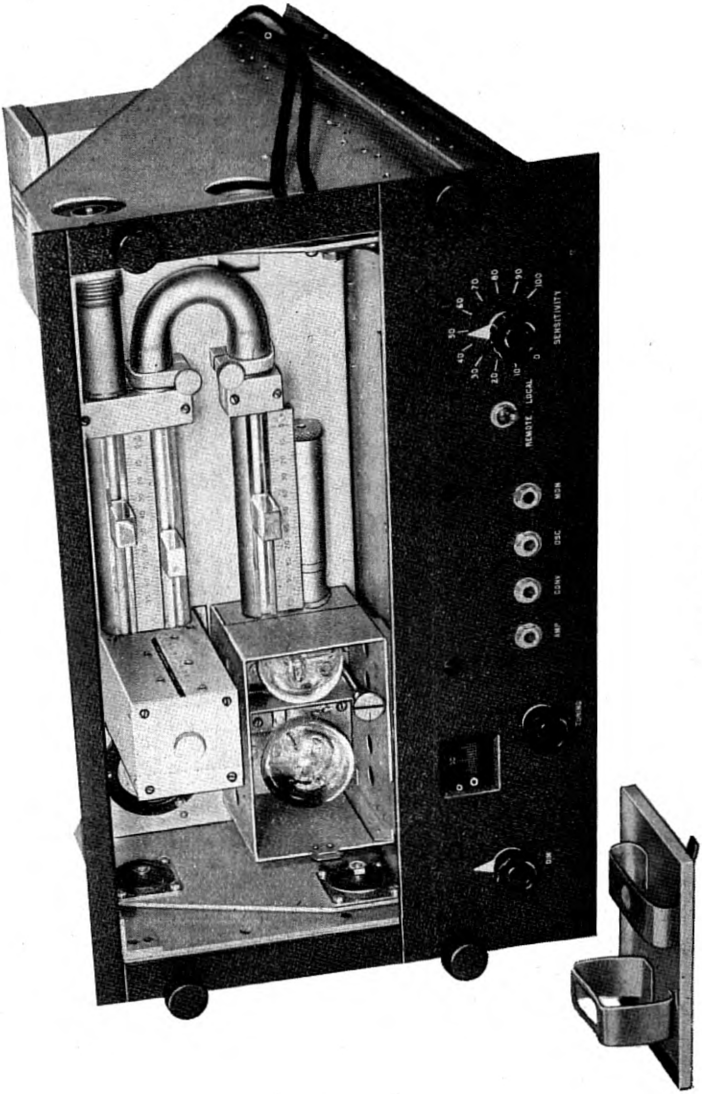


Fig. 11—CXAS—Receiver

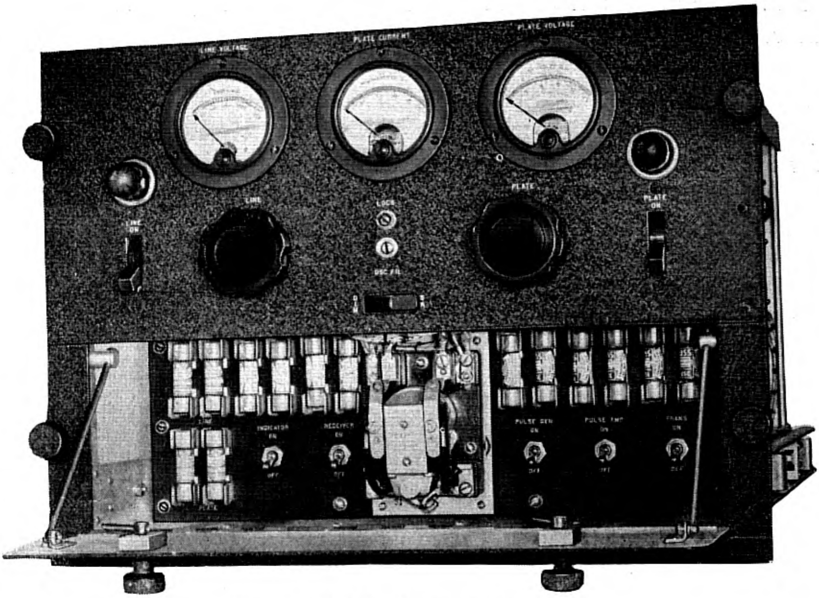


Fig. 12—CXAS—Power control panel

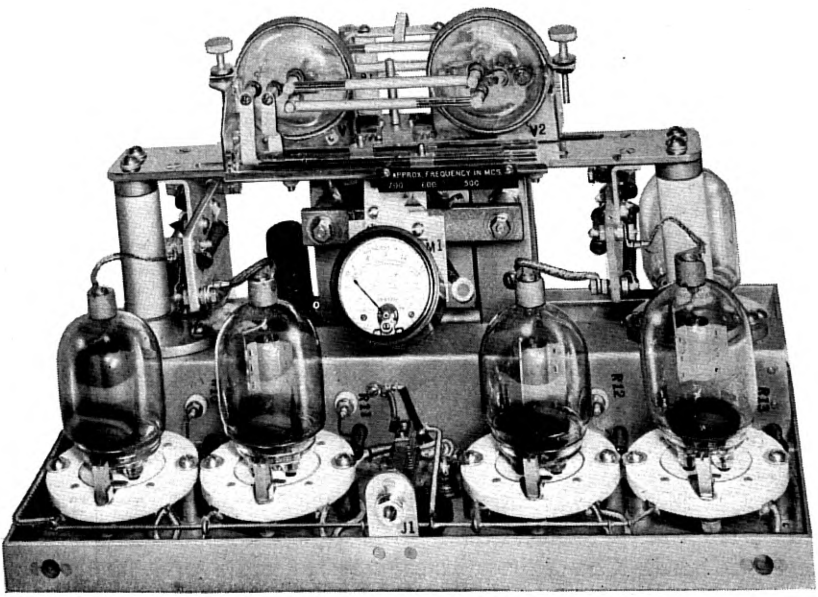


Fig. 13—CXAS—Transmitter

circuit. The adjustable duplexing transmission lines may be seen in the side compartment of the Main Unit on Fig. 9.

The equipment just described could be operated over a small frequency band of about 40 megacycles in the neighborhood of either 700 or 500 megacycles. The transmitter, receiver, and duplexing circuits were tunable over the entire range, but it was necessary to set up the antenna for one band or the other. This was accomplished by installing the proper one of the two sets of dipoles furnished, and installing or omitting a set of wedges

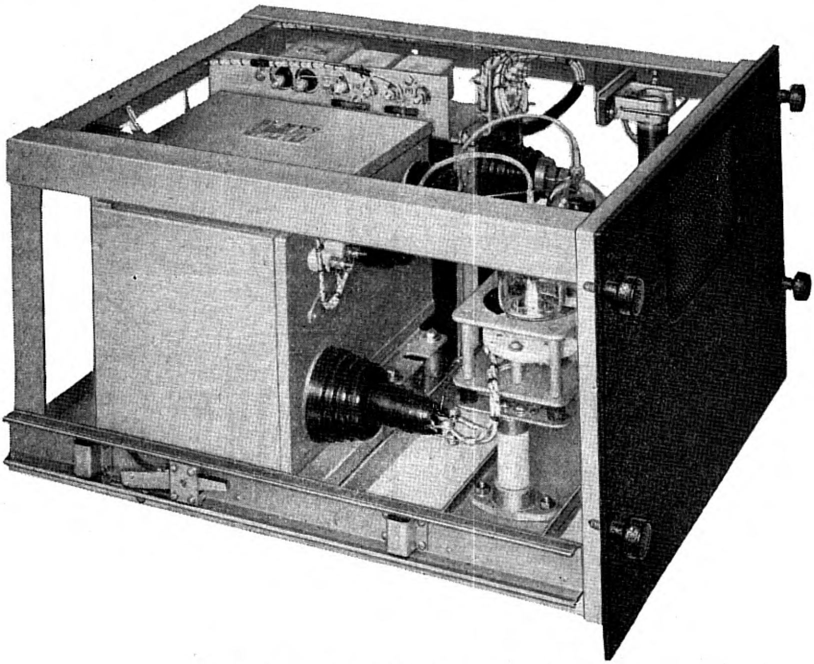
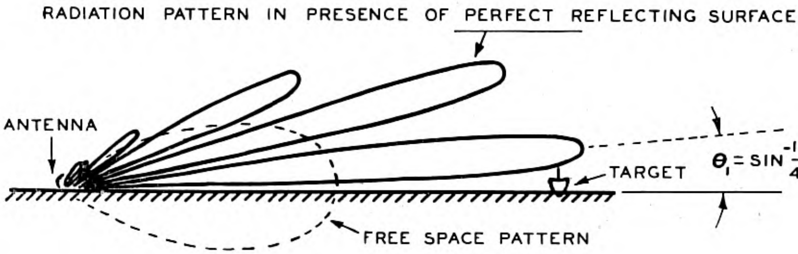


Fig. 14—CXAS—High voltage rectifier

which tilted the reflector wings to change the parabola focal length. This antenna set a precedent in design in that the dipoles and coaxial harness were designed for fairly broadband operation and were entirely free from field tuning adjustments which had been very troublesome in earlier equipment.

The CXAS Radar was demonstrated to the Navy in December 1940. After a few tests it was decided by the Navy to standardize on the 700-megacycle band. One of the principal reasons for this was that the tests had proved the superiority of shorter waves for surface target work; the

CXAS having regularly out-performed much higher powered equipment operating at 100 or 200 megacycles for this service. The reason for this can best be uuderstood by reference to Fig. 15 which illustrates what happens when a radio beam is directed horizontally over water. The beam breaks up into an interference pattern of several rays due to reflection from the surface; the position of the lowest ray depending only upon the height of the antenna measured in wavelengths above the water. Since the mount-



$$e = 2 \sin\left(2\pi \frac{H}{\lambda} \sin \theta\right) \times \left[\text{FREE SPACE ANTENNA PATTERN}\right]$$

WHERE H = ANTENNA HEIGHT

λ = WAVE LENGTH IN SAME UNITS AS H

θ = ELEVATION ANGLE IN DEGREES

e = RELATIVE FIELD STRENGTH

Fig. 15—Effect of surface reflection on elevation beam

TABLE I

Operating Frequency	Tunable 680–720 mcs.
Antenna	Dipole array of 8 half-wave radiators, reflector 6′ x 6′, beam width 12 degrees, gain 22 db.
Transmitter Pulse Power	Approximately 2 kw.
Pulse Repetition Rate	1640 PPS
Pulse Duration	Variable in 5 steps from 1 to 5 microseconds.
Receiver-Superheterodyne	1 mc bandwidth, 30 mc IF frequency.
Receiver Noise Figure	Approximately 24 db.
Range Calibration	Electronic marks at 10,000 and 2,000 yard intervals.

ing height available aboard ship is fixed, the use of shorter wavelengths made it possible to keep the lowest ray more nearly horizontal where it could intercept a target's superstructure at greater distance.

The principal characteristics of the CXAS Radar as set up for operation at 700 megacycles are given in Table I.

This equipment gave useful results on surface targets at ranges of 10 miles or more (depending on the size of the target) and the range accuracy of about ±200 yards was then considered very usable in surface target fire control. The target azimuth could also be determined to a precision of one or two degrees by rapidly swinging the antenna back and forth and observing the point which gave a maximum echo signal. This angular information was hardly good enough for fire control use. The equipment was also of some use against low flying aircraft as a means of getting better range data for fire control. Minor equipment difficulties were not entirely solved; in particular the doorknob triodes in the transmitter had a very short life under the high voltage pulse operating conditions. They had, of course, been designed originally for CW communication use and strenuous development effort to make them more suitable for the intermittent high power radar use had not been very successful.

The Mark 1 Radar

In spite of the obvious unsolved development problems the Navy immediately ordered 10 equipments, similar to the CXAS, for use in the Fleet. These were first called the FA Radio Ranging Equipment but the designation was later changed to Radar Mark 1. Several changes were made to better adapt the equipment for installation aboard ship, the principal one being a servo driven antenna pedestal of the amplidyne type which was furnished by the General Electric Company. The servo system eliminated the antenna drive shaft problem while retaining control from a handwheel on the control desk. The desk was also modified to provide dials reading both relative and true azimuth bearing, the latter being obtained by interconnection with the ships gyro compass system.

The first Mark 1 Radar was shipped by the Western Electric Company in June 1941 and installation on the USS Wichita was completed at the Brooklyn Navy Yard early in July 1941. This was the first fire control radar in our Fleet and the first of many thousands of radars of all types which the Western Electric Company was destined to build for the Navy in the following four years.

The Mark 2 Radar

While the ten Mark 1 radars were being built, development work was proceeding at top speed on major improvements designed to increase performance, eliminate operating troubles, and to make this new device fit better into the existing fire control situation aboard ship. The older optical devices were neatly integrated into a system, many features of which were automatic. For example, the gyro stabilized telescopes and optical range finder were assembled into a compact rotating armored box called a *director*, located high on the ship. Target data from the director was sent automatically by *synchro* data transmitters to the computer below decks, which solved the fire control problem and likewise transmitted automatically the correct information to the guns. For the new radar target locating device to fit into the existing system it was necessary to make its angle finding function operate more in the manner of the telescopes. Not only was it desired to determine target angles more accurately but it was necessary to track target position continuously and smoothly. Finally, to take care of the anticipated need for rapidly changing back and forth during an engagement from optical to radar data it became apparent that the same operators should handle both jobs. Thus it was decided that the system should provide the existing operators with oscilloscopes to supplement their telescopes, and to arrange them so either could be used as desired. Further to coordinate the data it became obvious that the radar antenna should be connected with the optics in such a way that the two were always pointed in the same direction. This would make it possible to leave the existing data transmission system alone and would avoid any break in data when changing from optics to radar or vice versa. For example, if a visible target disappeared behind a fog bank the telescope operator would simply move his head to look at his oscilloscope and data would continue to flow smoothly to the computer and to the guns.

Thus the engineers of the Navy decided the new radar device could be fitted into the existing fire control system. Any other decision would likely have required modification of many parts of the system, and would have delayed the extensive use of fire control radar by a matter of years. The Bell Telephone Laboratories were accordingly asked to modify and improve the radar design to make possible the coordination of optics and radar as just discussed. The new radar was to be called Mark 2 and was to be similar to the Mark 1 but modified to provide continuous tracking in azimuth with an accuracy of ± 15 minutes of arc, and continuous tracking in range with an accuracy of ± 50 yards. Further, the operator's oscilloscopes and controls were to be put into small units that could be mounted alongside of the telescopes in the director, and the antenna was to mount on the director. These requirements demanded some important forward steps in radar development which will be described in some detail. Before Radar Mark 2 got into production a much higher powered transmitter was developed and with this change the equipment was re-named Radar Mark 3.

The Mark 3 Radar

The general arrangement of apparatus for this radar differed from the Mark 1 principally in the indicators, which were designed to mount in the already crowded gun director. These indicators are shown in Figs. 16, 17 and 19. Fig. 16 shows the range operator's oscilloscope, called the Control and Indicator, which was located near the optical range finder. Adjacent to this unit was mounted the range unit, shown in Fig. 17 by means of which the operator could select the target to be followed and continuously

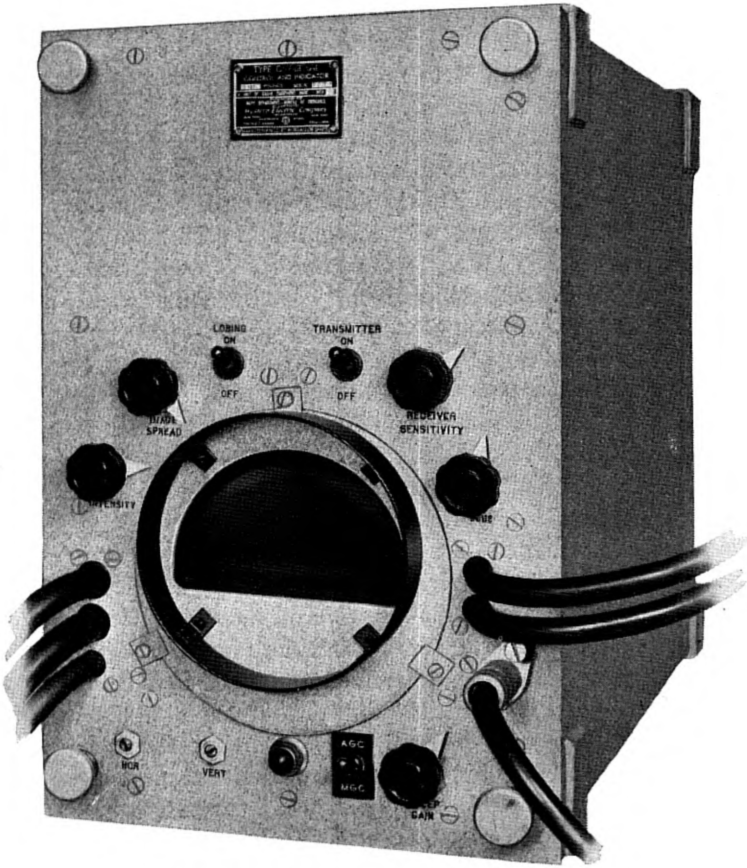


Fig. 16—Control & indicator—Radars Mark 2, 3 & 4

maintain accurate range readings. A typical installation of these two units is shown in Fig. 18. The third unit, shown in Fig. 19, is called a Train or Elevation Indicator and, in Radar Mark 3 (which was for surface fire only) this indicator was mounted adjacent to the Train (azimuth) Operator's telescope.

In addition to the Train Indicator, the azimuth operator was provided

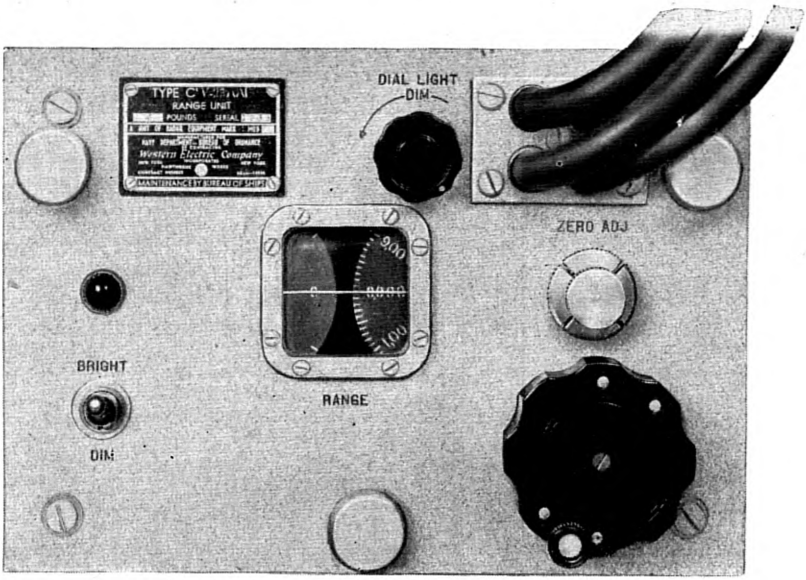


Fig. 17—Range unit—Radars Mark 2, 3 & 4

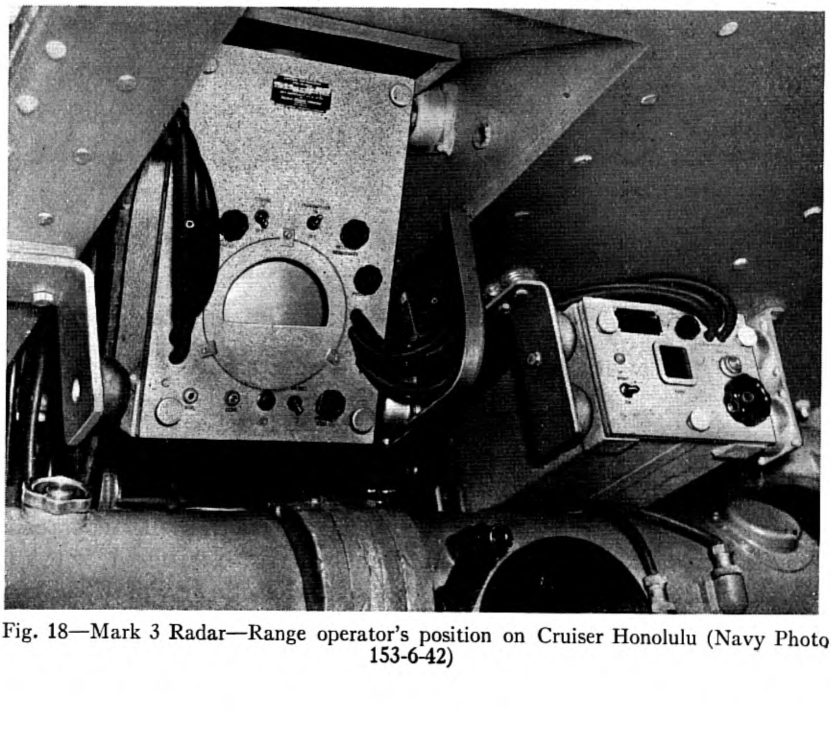


Fig. 18—Mark 3 Radar—Range operator's position on Cruiser Honolulu (Navy Photo 153-6-42)

with a Train Meter of the zero center type which indicated the direction of deviation from true target position. One of these meters of early design can be seen in Fig. 38. Two meters of later design are shown in Fig. 39 mounted immediately below optical telescopes. The pulse generator, receiver, transmitter, rectifiers, etc., were located below decks in the Trans-

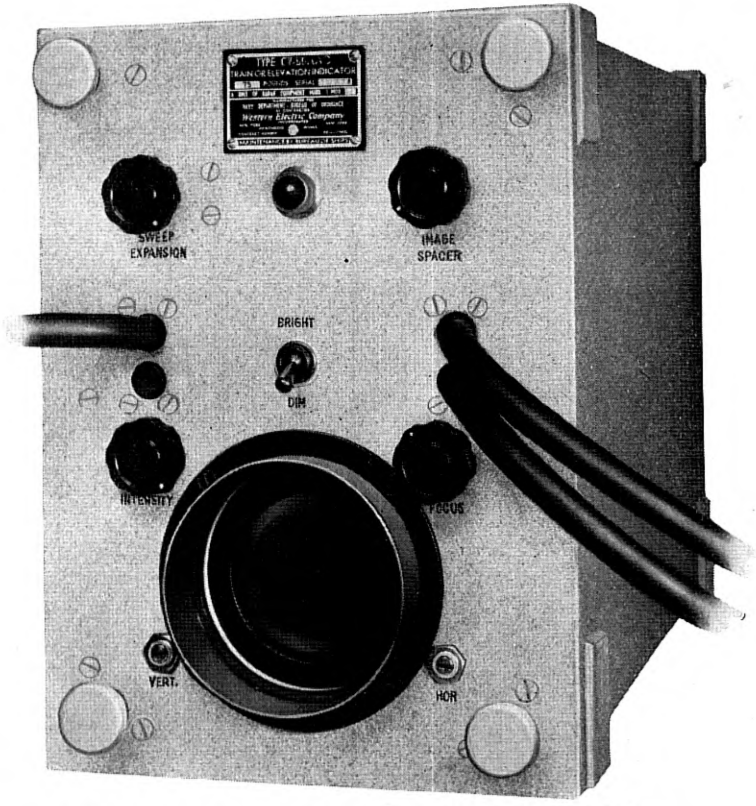


Fig. 19—Train or elevation indicator—Radars Mark 2, 3 & 4

mitter-Receiver, or Main Unit which was very similar in appearance to the Main Unit of Radar Mark 1 shown in Fig. 9.

Two types of antennas were provided for this radar: a 6 ft. by 6 ft. parabolic array similar to the Mark 1 antenna, and a 3 ft. by 12 ft. parabolic array. Either one or the other of these antennas was mounted on top of the gun director and rotated with it in azimuth. Both were provided with azimuth lobe switching to be described later. Because of the relatively narrow elevation beam of the 6 ft. by 6 ft. array, this antenna required gyro stabilization in elevation to take care of pitch and roll of the ship. Such stabilization was not required with the broad elevation beam obtained with the 3 ft. by 12 ft. antenna; and in addition, this wider antenna provided more accurate tracking due to the narrower antenna beam in azimuth. Installations of these antennas aboard ship are shown in Figs. 20 and 21 and 22, 23 and 24.

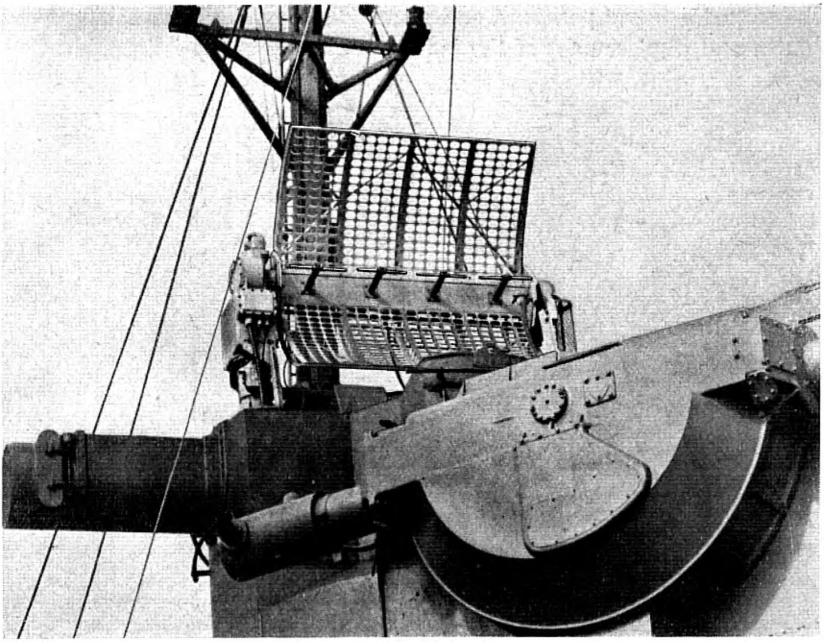


Fig. 20—Radar Mark 3 antenna (6′ x 6′) on Cruiser Honolulu (Navy Photo 144-6-42)

Antenna Lobe Switching

The problem of measuring angles accurately with a relatively broad radio beam has been faced many times in the radio direction finding art. The most successful attack has made use of the fact that while the nose of a radio antenna beam is blunt, the sides of the beam are relatively steep; i.e., while the rate of change of signal amplitude with angle is very low near the nose of the beam it becomes substantial down on the side of the beam. A very well known application of this principle is the airway radio range wherein two very broad overlapping beams define a narrow path by utilizing the points where the two overlap with equal intensity. A somewhat similar scheme in which the antenna beam is switched rapidly between two positions has been applied in radar, and in an early form was first used in this country by the Signal Corps in the work described by General Colton, to which reference has been made.

The use of two antenna beam (or lobe) positions to obtain more accurate radar angle d[illegible] referred to as *lobe switching* and the operating principle is illustrated in Fig. 25. The antenna beam is shown in two positions: position 1 being directed to the right, and position 2 to the left of the mechanical axis of the antenna. The antenna beam is caused to switch rapidly between these two positions, and simultaneous with this switching a small horizontal displacement of the indicator Class A sweep is introduced. In

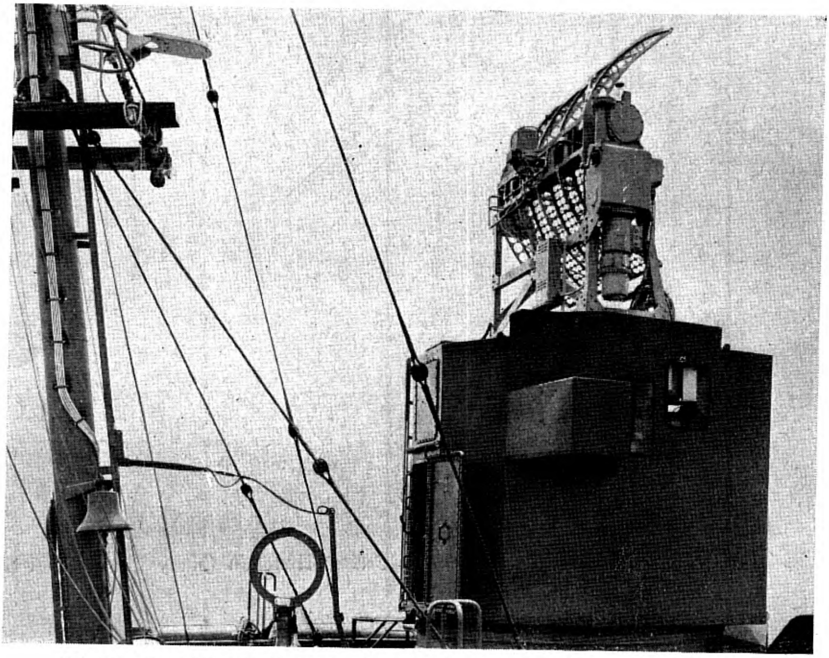


Fig. 21—Radar Mark 3 antenna on Destroyer Porter (Navy Photo 2711-42)

this manner the signals received in the two beam positions may be viewed separately. The speed of switching is made sufficiently high to minimize flicker and the effect of fading signals. It will be noted from this diagram that the signal strength received from target A is the same for both beam positions thereby producing equal "pip" heights on the indicator screen. However, for target B the signal amplitude is greater in position 1 than in position 2 and the "pip" amplitudes on the indicator differ correspondingly. If the operator wishes to track target B it is only necessary for him to rotate the antenna until the two "pips" are of equal amplitude. Smooth

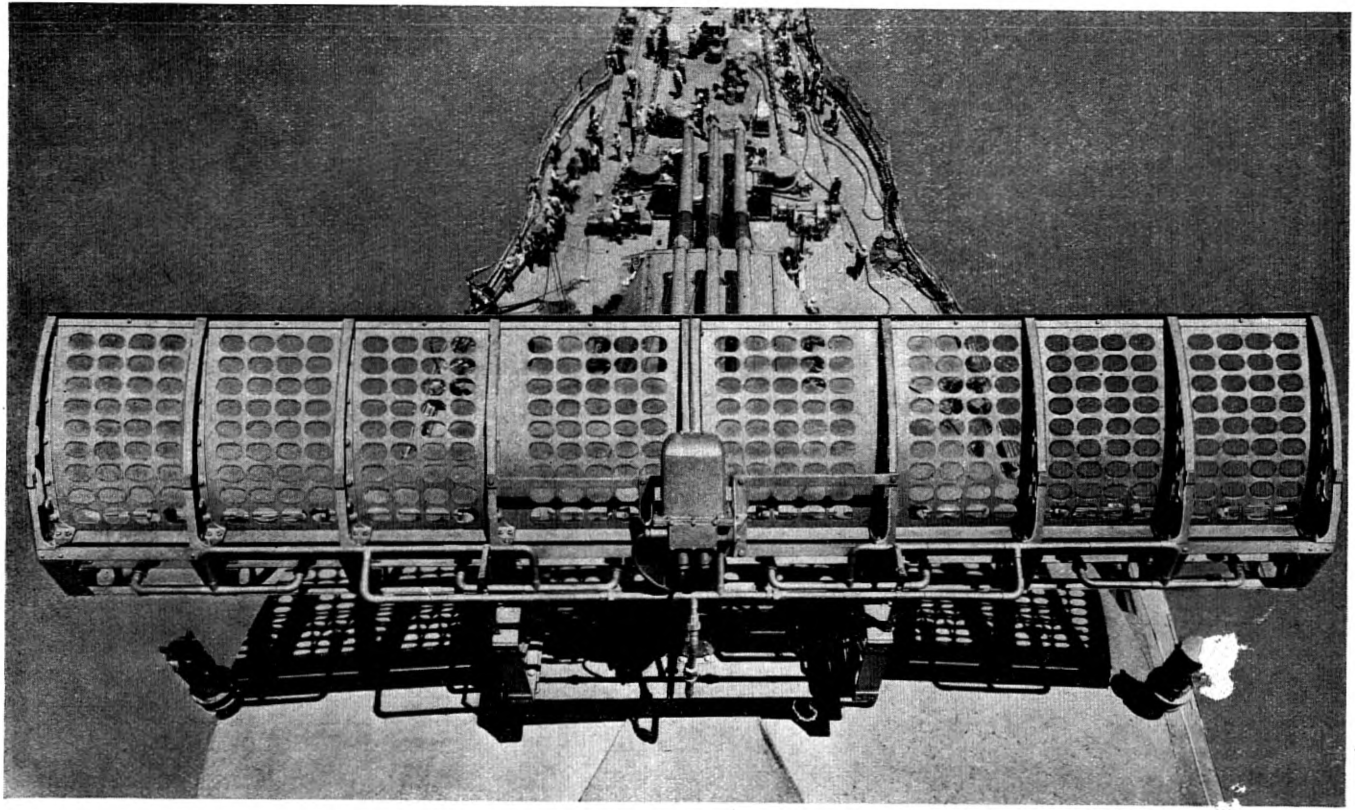


Fig. 22—Radar Mark 3 antenna (3′ x 12′) on Battleship Pennsylvania (Navy Photo 4273-42)

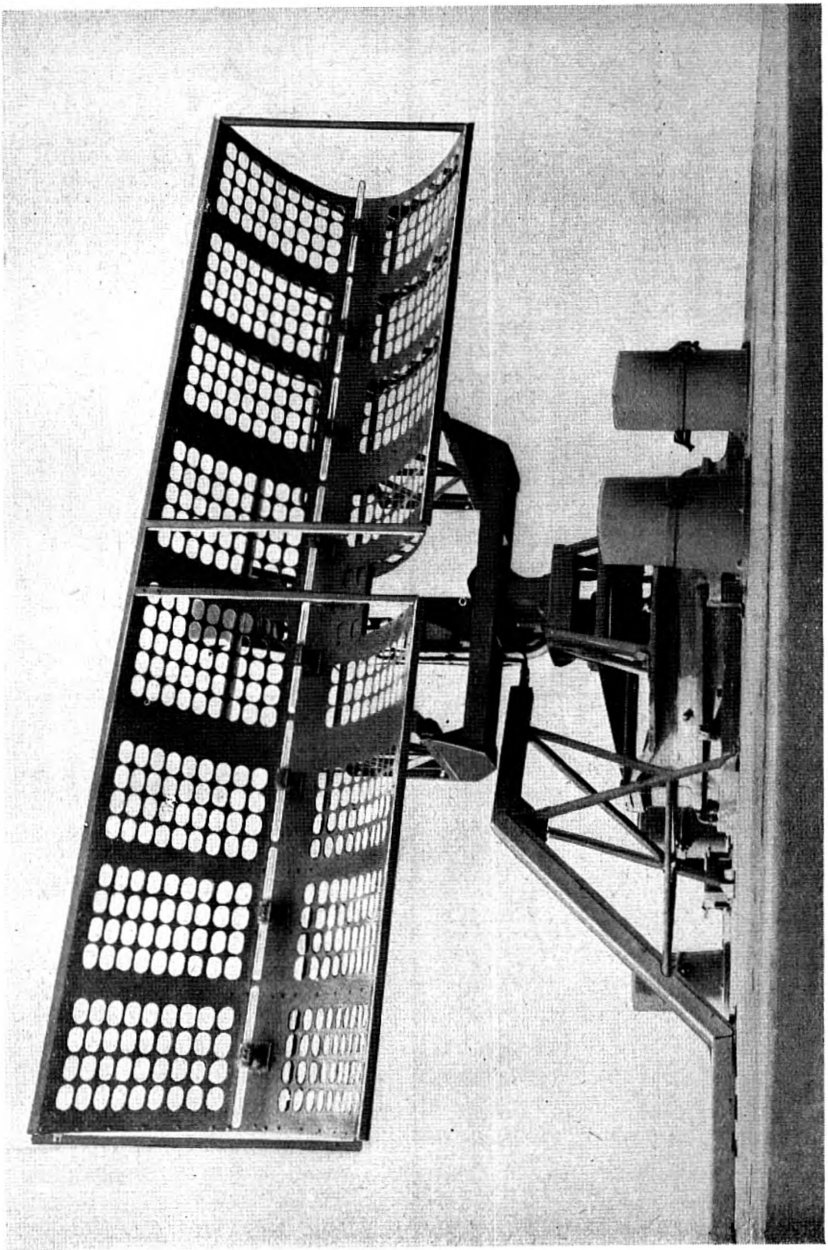


Fig. 23—Radar Mark 3 antenna (3′ x 12′) on Battleship New Jersey. (Navy Photo 181812)

flow of azimuth data will be obtained if the operator continuously maintains equal amplitude of the two "pips".

In the Signal Corps equipment to which reference has been made, separate antennas were used for transmission and reception with lobe switching

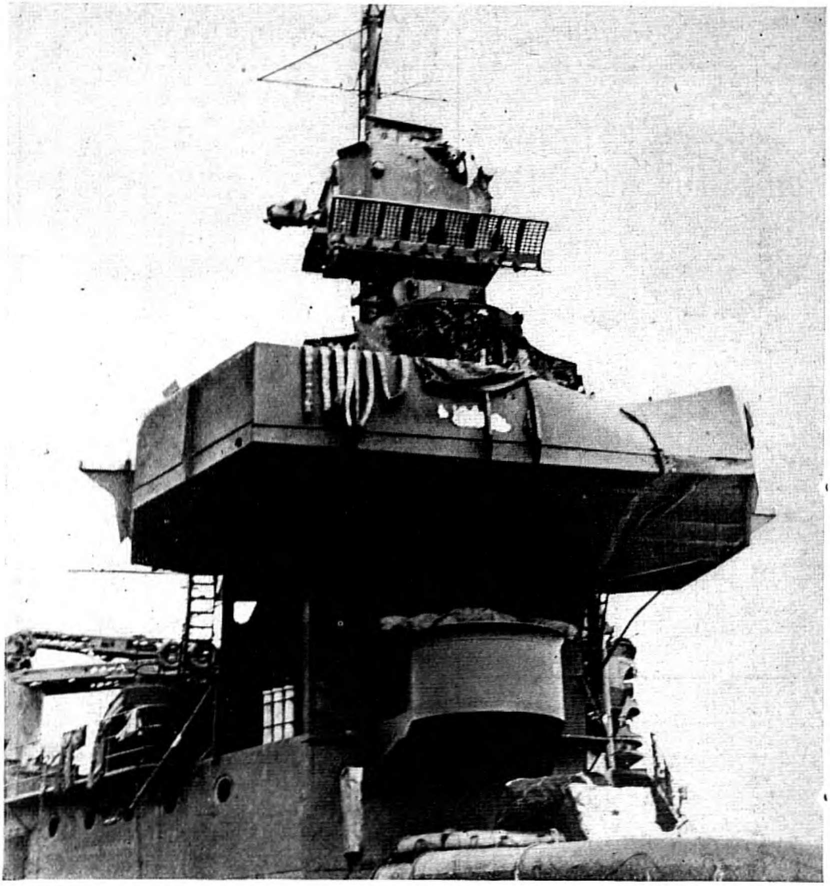


Fig. 24—Radar Mark 3 antenna (3′ x 12′) on Cruiser San Francisco after Pacific battle (Navy Photo 34133)

applied only to the receiving antenna. Space limitations aboard ship made it mandatory to accomplish all functions using a single antenna. This required the development of a lobe switching device capable of withstanding the high peak power during the transmitted pulse; a problem which had not been faced in the Signal Corps equipment. It was further desired to provide a weatherproof lobe switching device, free from radio

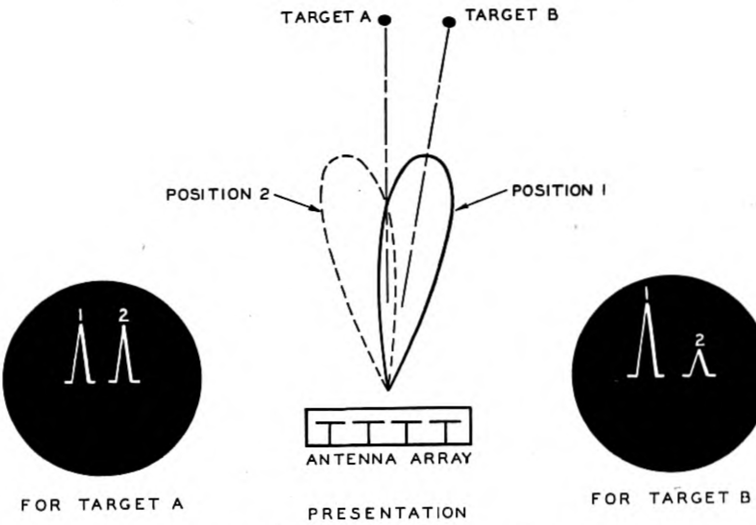


Fig. 25—Principle of lobe switching

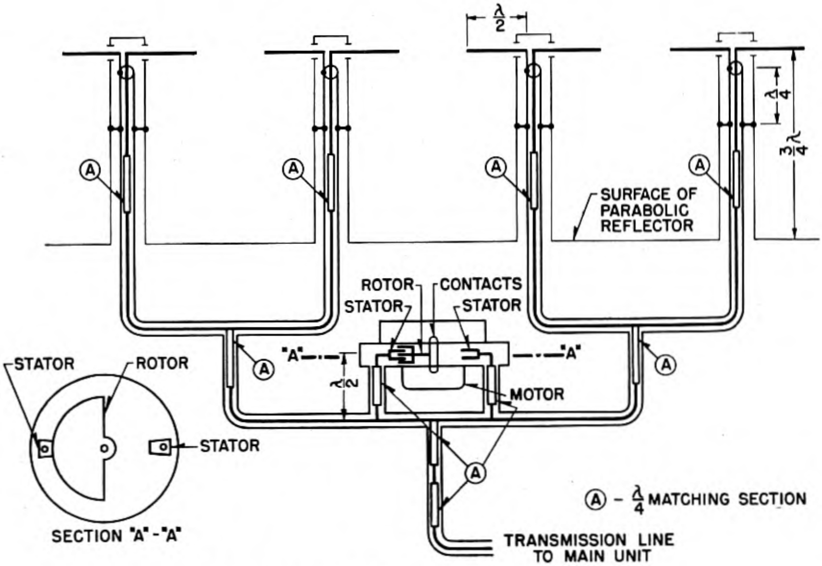


Fig. 26—Mark 2 & 3—Antenna schematic

frequency adjustments, in order to simplify operation and maintenance. The manner in which these objectives were met is described below.

To obtain lobe switching of the antenna beam, use was made of the fact that the beam position depends upon the relative phase of the excitation applied to the radiating elements of the array. If all elements are excited in phase, as in Radar Mark 1, the beam will be normal to the line of the array, while gradually increasing phase difference across the array will result in displacement of the beam. For small angles of beam shift, entirely satisfactory results may be obtained by shifting the phase of excitation applied to one-half of the array with respect to the other, and this expedient results in a much simpler phase shifting mechanism than would be required to obtain uniform phase change. This system was used in Radar Mark 3 and its application is illustrated schematically in Fig. 26. It will be seen that this array is identical to that used for Radar Mark 1 except for the central section of transmission line in which a lobe switching unit has been added. In this unit the phase of excitation to one-half of the array is retarded with respect to the other half by connecting a capacitive reactance alternately across one feed line or the other to obtain the two beam positions. Switching is accomplished by the use of a motor driven rotary capacitor shown in Section A-A. The rotor is a semicircular aluminum casting which is maintained at substantially ground potential by very close spacing to the grounded metal housing. The two stators are small metal plates which interleave with the rotor during approximately one-half revolution and are connected through half-wavelength coaxial lines to the antenna transmission lines. The purpose of the half-wavelength stub lines is to avoid physical limitations which would otherwise be encountered in connecting the rotary capacitor to the lines. Allowance is made in these stubs for end-loading caused by stray capacitance of the stator plates and supporting insulators. It will be seen that during nearly one-half revolution of the rotor one of the stators is engaged to shift the antenna beam in one direction while during the other half revolution the other stator is engaged to produce the other lobe position. The switching occurs during the small interval in which both stators are engaged by the rotor. Signals received during this interval are blanked out in the indicator. The rotor of the lobe switcher is driven at about 30 RPS by an induction motor mounted within a weatherproof housing. The motor shaft also carries cam operated contacts to produce image spacing on the indicators, control signals for the Train Meter, and blanking during the lobe switch interval. The entire unit is gas tight and is filled with dry gas through the transmission line.

The value of the lobe switching capacitor and its position along the feed line must satisfy two conditions: first, the phase shift must be such that the antenna beam will be displaced by the desired amount; and second, the impedance at the feed point must be such that equal division of power will be obtained in the two halves of the array. In the first Radar Mark 3 antenna (6 ft. by 6 ft. parabolic array) a beam displacement of about 3.0

degrees was chosen as a suitable compromise between target angle sensitivity (steepness of beam) and reduction of signal amplitude "on target". This displacement required a phase shift of approximately 53 degrees between the two halves of the array. From transmission line theory it can be shown that this phase difference will be obtained with a capacitive reactance equal to the characteristic impedance of the feed line when connected at a point 0.176 wavelength from the feed point. It can also be shown that this condition satisfies the requirement for equal power division to the two halves of the array. A capacitor of the required value (about 3 micromicrofarads) can readily be built to withstand the peak transmitted power by proper condenser plate separation. A frequency variation of about 40 megacycles can be tolerated without materially affecting the antenna performance.

TABLE II.—*Antenna Characteristics*

	Radar Mark 3		Radar Mark 4
Dimensions	3′ x 12′	6′ x 6′	6′ x 7′
Apperture in Wavelengths			
Azimuth	8.5	4.25	4.25
Elevation	2.1	4.25	4.95
Beam Width in Degrees (between half power points in one way pattern)			
Azimuth	6	12	12
Elevation	30	14	12
Antenna Gain in db	22.0	22.0	22.5
Beam Shift in Degrees			
Azimuth	±1.5°	±3.0°	±3.0°
Elevation	—	—	±3.0°

A lobe switching unit similar to that described above was also applied to the 3 ft. by 12 ft. antenna. Pertinent information regarding beam widths and lobing angles for both antennas (together with information on the antenna for Radar Mark 4 to be described later) is given in Table II.

The effective beam widths as used in these radars were somewhat narrower than the values given above due to the square law characteristic of the second detector in the receiver, and the deflection sensitivity was such that the specified tracking accuracy of ±15 minutes of arc could readily be achieved. The "on target" position or axis of the antenna (lobe crossover) was carefully aligned with the optical telescopes at the time of installation so that either optics or radar angles could be used. The symmetrical design of the antenna made this alignment substantially independent of small changes in operating frequency.

To minimize target confusion the signals presented on the Train or Elevation Indicator (azimuth operator's oscilloscope) consisted only of those received from the target being tracked by the range operator, all others being blanked out in the indicator circuits.

Accurate Range Measurement

The second major problem which required solution to adapt radar to the fire control problem was the provision of means for accurate and continuous range tracking. It was obvious that what was required was some sort of electronic range mark on the indicator sweeps, the position of which could be varied by a rotary device whose motion could be used to transmit range information to a remote point over a synchro system. The range mark could then be aligned with the target "pip" on the oscilloscope. For accurate data transmission it was necessary to obtain a linear relationship between angular rotation of the range handwheel and corresponding range to the marker on the radar indicator screen.

One method which was first employed by the Signal Corps made use of the fact that the transmitted pulses were generated at a periodic rate from a sine wave oscillator of fixed frequency; the pulse being produced at a fixed point in each cycle. By transmitting this same sine wave through a linear phase shifter a new pulse could be generated whose position in time, relative to the transmitted pulse, could be varied by rotation of the phase shifter. In the Signal Corps equipment a special goniometer was used to produce the phase shift and the accuracy obtained was considered adequate for the intended purpose. However, non-linearity of the phase shifting device, though small, was much greater than could be tolerated in the Navy fire control system. A study indicated that large scale manufacture of special phase shifters, hand adjusted to meet the stringent accuracy requirements was out of the question. It was therefore decided that a two speed system be used, in which the phase shifter errors would be divided by the gear ratio to the high-speed unit in much the same way that accurate synchro information is transmitted by a "coarse" and a "fine" synchro. The manner in which this was worked out by Bell Telephone Laboratories and applied to Radars Mark 3 and 4 is described below.

The method of range measurement can perhaps best be understood by first examining the method of presentation used on the cathode ray tube indicator for the range operator. This presentation is shown in Fig. 27 in which it will be noted that a Class A sweep is used to display the transmitted pulse and received echoes. This horizontal sweep, however, differs from the simple sweep of earlier radars in several respects. First, the central portion of the sweep is expanded to permit more accurate viewing of signals appearing within this region; second, a downward deflection called the range "notch" is produced in the approximate center of the expanded section; and third, the circuits are so arranged that the notch remains centered as the range unit phase shifters are rotated thus causing all of the signals (rather than the notch) to move across the screen. Range measurement is made by rotating the range unit handcrank to place the desired signal in the center of the range notch on the indicator. This type of presentation has several advantages. It permits the full 100,000-yard range to be viewed at all times so that new targets may be immediately detected, and permits accurate viewing of the desired target in the expanded

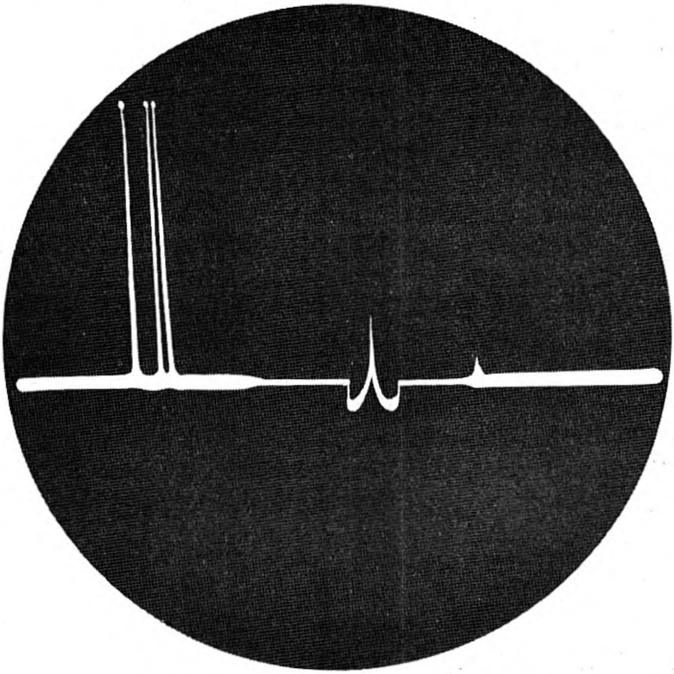


Fig. 27—Mark 3 & 4—Range presentation

center of the sweep where best focus is obtained. For smooth range tracking it is only necessary for the operator to rotate the range unit hand crank to keep the desired signal centered in the range notch.

A block diagram of the range measuring system, together with the circuits used to obtain the cathode ray indicator presentation described above, is shown in Fig. 28. A base or reference oscillator generates a sine wave of 1.639 kc, one cycle of which corresponds to a radar range of 100,000 yards. This wave, after amplification, is applied to a non-linear coil pulse generator[3] which generates short pulses (one positive and one negative pulse

[3] "Magnetic Generation of a group of Harmonics," E. Petersen, J. M. Manley, L. R. Wrathall—August 1937, *B. S. T. J.*, October 1937.

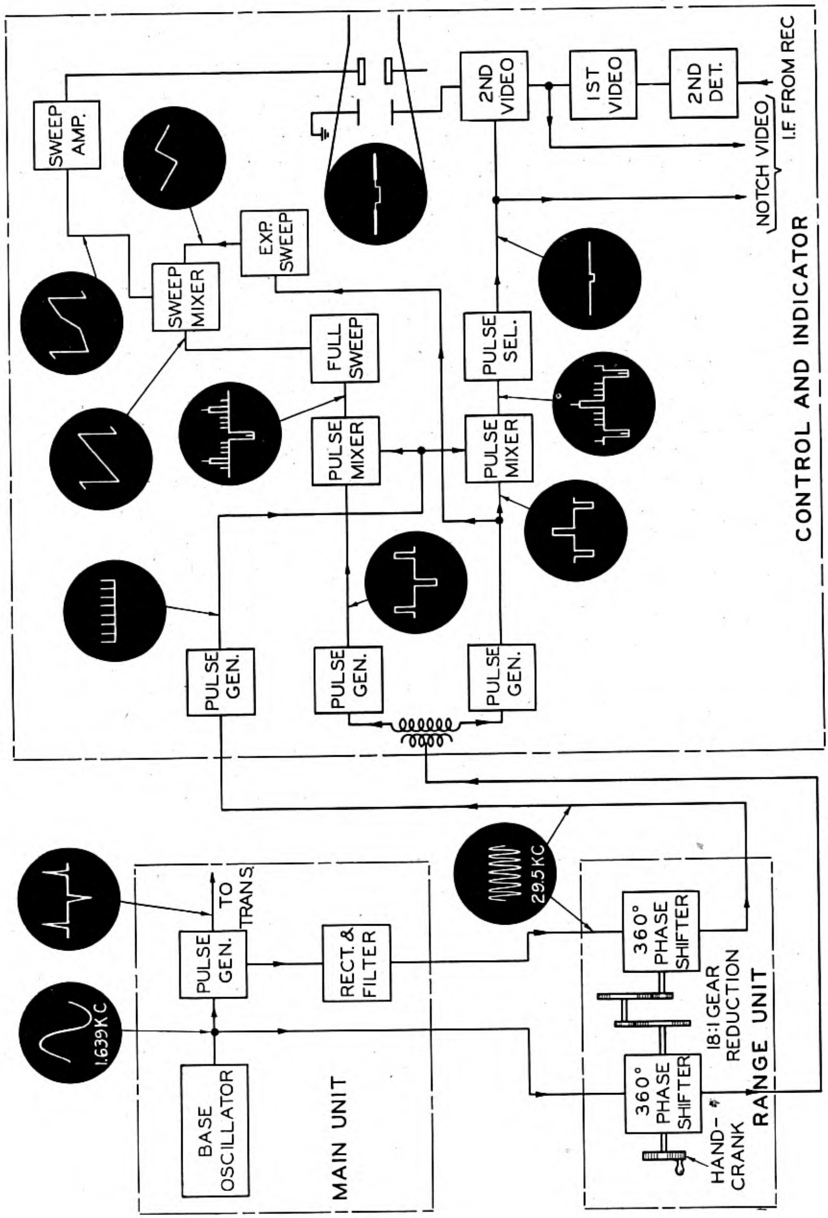


Fig. 28—Mark 3 & 4—Range measuring system

per cycle); the positive pulses being used for keying the transmitter. These pulses are rich in odd harmonics of the base oscillator frequency. By rectifying these pulses to reverse the negative pulses, even harmonics of the base frequency are obtained and the 18th harmonic (29.5 kc) is selected by means of a filter. This harmonic frequency and the original base frequency are applied to two phase shifters whose shafts are geared together in the ratio of 18 to 1. Since one revolution of the one speed phase shifter corresponds to 100,000 yards, one revolution of the 18-speed unit corresponds to only 5550 yards with the result that range errors caused by non-linearity of this phase shifter are reduced by a factor of 18. The phase shifters employed are similar to those designed by Bell Telephone Laboratories for use in a phase measuring bridge[4] and are linear to within ± 1.5 degrees or about 0.4 per cent. The possible range error introduced by imperfections in the 18-speed phase shifter was therefore only 23 yards, well within the design requirements. It remains to be shown how this accurate range information was applied to the indicator.

The output of the 18-speed phase shifter in the range unit is connected to the Control and Indicator where the phase shifted sine wave is used to generate short, rectangular pulses of about 600 yards duration. One pulse is produced for each cycle of the 29.5 kc wave so that 18 of them occur during the 100,000-yard sweep interval. It is desired that only one of these pulses appear as a range notch on the indicator screen and this pulse is selected from the others by a pedestal pulse generated from the output of the one speed phase shifter. It will be noted that as the phase shifters are rotated by means of the range unit hand crank, the desired pulse from the 18-speed phase shifter will remain substantially centered on the one-speed pedestal pulse. After further shaping, the selected pulse is mixed with the received signals in the second video amplifier and is then applied to the vertical plates of the cathode ray indicator to form the "range notch". The range notch is also transmitted to the Train Indicator and Train Meter where it is used to prevent any signal from affecting those instruments except the one being tracked by the range operator.

Since it is desired to have the range notch appear in the center of the 100,000-yard sweep on the indicator, the sweep trigger pulse must occur 50,000 yards in advance of the notch. This trigger is obtained by selection of another pulse from the accurate phase shifter, this time using a one-speed pedestal produced by an input of reversed phase. The pulse thus selected is used as a trigger for starting a saw-tooth sweep wave with a duration corresponding to 100,000 yards radar range. Expansion of the center portion of this sweep is obtained by adding to this wave a second

[4] L. A. Meacham, U. S. Patent 2004613.

saw-tooth wave having maximum rate of change in the center of the sweep; the latter being derived from the range notch selection pedestal. The combined sweep is then applied to the horizontal plates of the cathode ray tube. The return trace is blanked by applying to the control grid of the cathode ray tube a voltage obtained by differentiating the sweep waveform.

Transmitter

As mentioned earlier the transmitter oscillator tube problem was one of the major obstacles in the march of radar development to higher frequencies. Intense development effort on many possible types of tubes was underway in several laboratories in this country and abroad during 1939

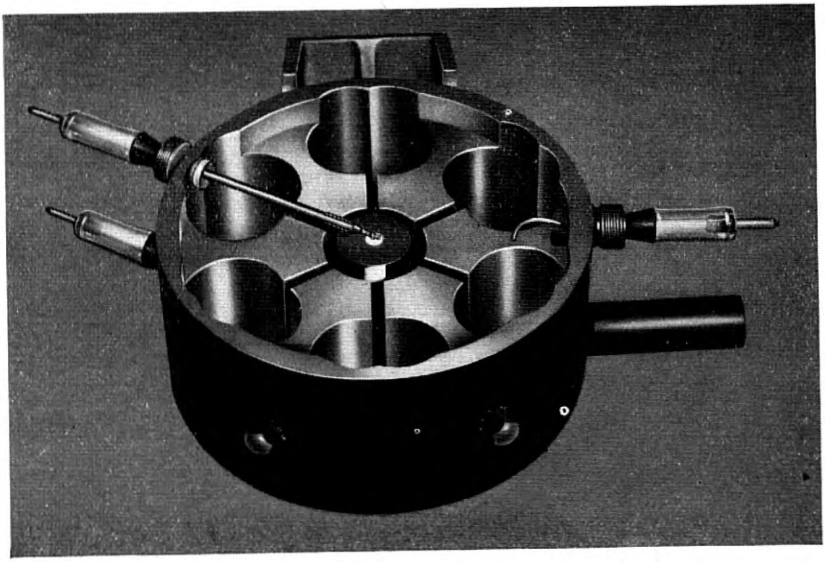


Fig. 29—W. E. 700-type magnetron—one side removed

and 1940. The first significant improvement came in England where work with multicavity magnetrons showed that this device was probably the answer to radar's need for a highly intermittent duty oscillator suitable for high power in the microwave region. A sample of this device was brought to this country by the Government and was tested in Bell Telephone Laboratories in October 1940. It produced pulses of several kilowatts at a frequency in the neighborhood of 3000 mc. A tremendous development of this device got under way immediately[5] and the multicavity magnetron

[5] "The Magnetron as a Generator of Centimeter Waves," J. B. Fisk, H. G. Hagstrum, and P. L. Hartman, *B. S. T. J.*, January, 1946.

became the key piece in the enormous development of radar equipment for still higher frequencies during the war. However, at the beginning of 1941 there were still many unsolved problems in 3000 mc radar other than that of the transmitter tube. On the other hand, the systems problems had been quite satisfactorily solved in the 700-mc region. The decision was therefore immediately made to extrapolate the British design down to

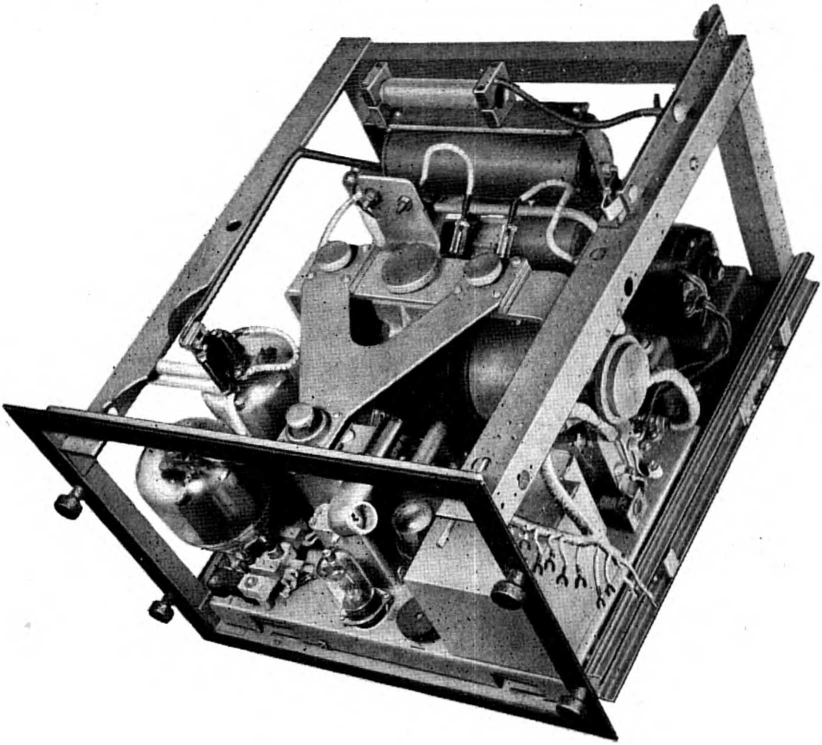


Fig. 30—Mark 3 & 4—transmitter

700 mc in order to obtain a higher powered and more satisfactory oscillator for the existing systems. This was done at top speed and a picture of the resulting tube is shown in Fig. 29. This was the first type of multi-cavity magnetron to go into production in this country. Concurrent with the design of the new magnetron the vacuum tube department of the Laboratories developed an improved tetrode modulator tube which was many times as efficient for radar pulse service as the triodes formerly used. This tube was designated W.E. 701-A.

A new transmitter using the magnetron and two of the new modulator tubes was rushed through development and produced in time to go with the first accurate fire control radars. This transmitter provided a peak power output of about 40 kw with a pulse duration of 2 microseconds. It resulted in a material increase in reliable range, with satisfactory tube life. The new transmitter, shown in Fig. 30, was made mechanically interchangeable with the old and was applied retroactively also to the Mark 1 Radars.

Duplexing

The use of the high-power transmitter required additional protection for the receiver during the transmitted pulse in order to prevent damage

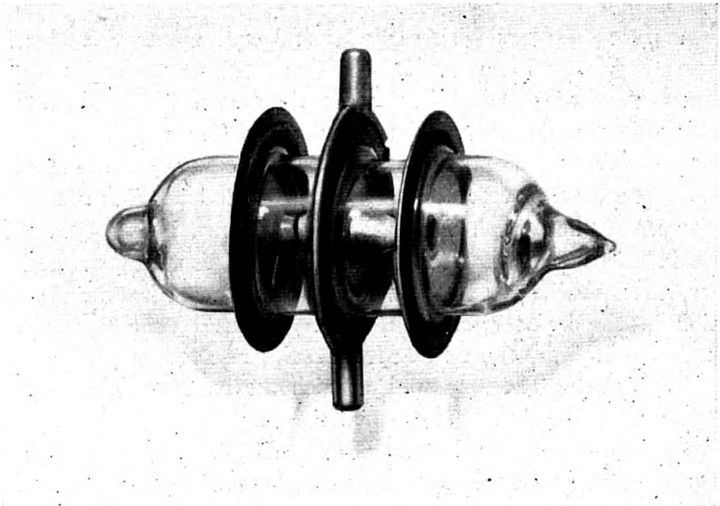


Fig. 31—W. E. 702—TR tube

and to permit the receiver to recover rapidly for reception of nearby echoes. The duplexing equipment was therefore modified to inclu de a gas switching tube in the receiving transmission line. This was a refinement of the method used earlier by the Naval Research Laboratory.

The switching tube (W.E. 702A) was developed specifically for this purpose and is shown in Fig. 31. It was the first of the "TR" tubes of this general form and consists of a hydrogen-water vapor filled glass chamber with three copper electrodes.[6] This tube was mounted in the center of a half-wavelength coaxial line short circuited at each end, the outer conductor being connected to the outer electrodes and the center conductor

[6] "The Gas Discharge Transmit-Receive Switch," A. L. Samuel, J. W. Clark, and W. W. Mumford, this issue of *B. S. T. J.*

to the middle electrode. Input and output connections were tapped on this half-wave line near the short circuited ends. During reception this assembly introduces negligible loss in the receiving line. However, during the transmitted pulse a small amount of the transmitted power ionizes the gas in the switching tube and effectively short-circuits the receiver line. This device, which in later forms came to be called a "T-R Box", is located near the receiver input and the length of line between it and the junction with the transmitter line can be adjusted to an odd multiple of quarter wavelengths to present the desired high impedance at that point during transmission.

Receiver

The receiver delivered with early Mark 3 equipments was identical to that used in Radar Mark 1. It was of the superheterodyne type employing one stage of RF amplification (doorknob tube), 316A oscillator tube, and doorknob first detector. The intermediate frequency amplifier had a bandwidth of about 1 megacycle at a midband frequency of about 30 megacycles. The second detector and video stages were located in the indicating equipment. A photograph of this receiver is shown in Fig. 11.

Since in microwave work the controlling noise is that produced in the receiver, it is desirable to reduce this noise to the theoretical limit of thermal agitation in the input circuit. However, in 1939 tube limitations and circuit design techniques at these frequencies resulted in performance far short of this goal. The amount by which the receiver noise exceeds the theoretical minimum has been termed the receiver "noise figure" and in this early receiver the noise figure was about 24 db. It was recognized that considerable improvement in maximum range could be obtained by reducing this receiver noise.

Shortly after first deliveries of Radar Mark 3 a new tube (GL-446 or "lighthouse" tube) was made available by the General Electric Company which showed promise of providing a substantial improvement in the receiver noise figure. An amplifier using this tube was accordingly designed by Bell Laboratories in which coaxial cavities were used for tuning elements. Two stages of amplification were used to replace the single "doorknob" tube stage previously employed. The new amplifier resulted in a reduction of the receiver noise figure to about 9 db and provided a marked improvement in maximum range capability of the radar. These amplifiers were manufactured and shipped to the Fleet for field installations on early equipments and were included in productions on equipments shipped subsequently to availability of the amplifiers. A photograph of the receiver with the two amplifiers installed is shown in Fig. 32.

Another field modification provided automatic gain control of the signal

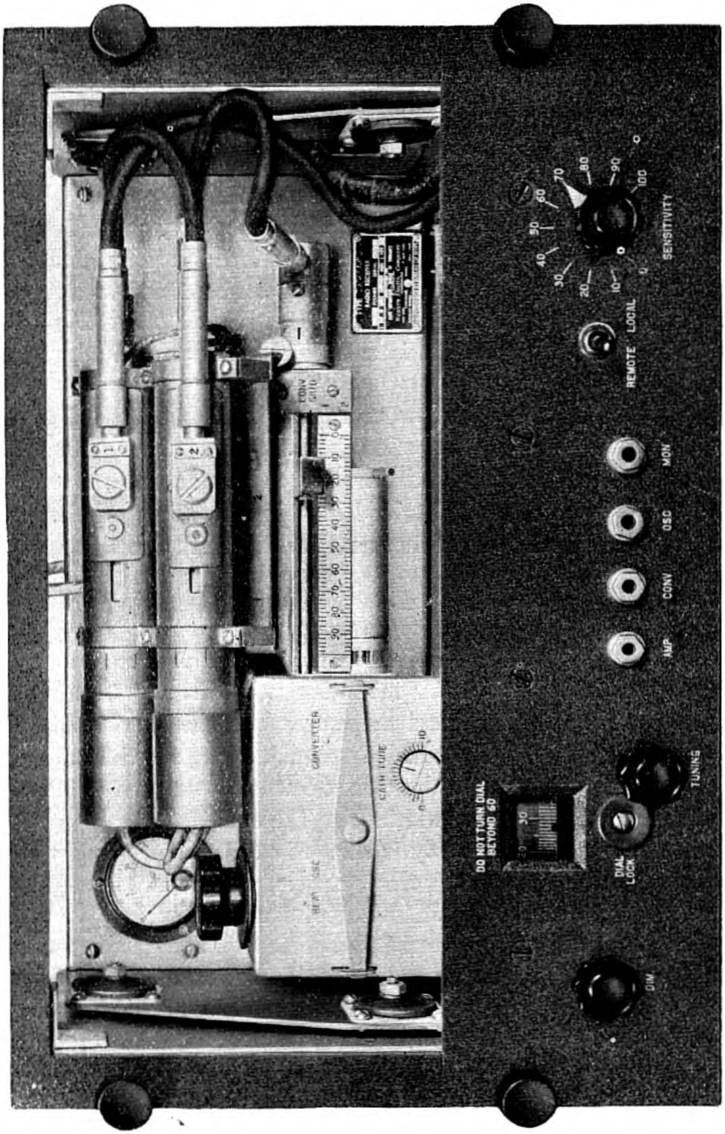


Fig. 32—Receiver—showing improved R. F. amplifier

selected by the range operator. This was supplied in the form of an external unit which controlled the gain of the receiver IF amplifier to reduce signal fluctuations produced by fading.

The first production Mark 3 Radars were delivered to the Navy in October 1941, and the first two installations were completed on the main battery directors of the U.S.S. Philadelphia at the Brooklyn Navy Yard that month.

Radar Mark IV

During the development work on Radar Mark 3 the Navy pointed out the need for a fire control radar for use with the 5-inch Naval guns against enemy aircraft. The Bell Telephone Laboratories was therefore requested to further modify the radar design to meet this need. The anti-aircraft equipment was first designated FD, later becoming known as Radar Mark 4.

For antiaircraft fire control a new coordinate had to be added to the target-locating system; namely, elevation angle. Again it was desired that the additional information be obtained from the single antenna with a precision equal to that already obtained in azimuth. This problem was approached in a manner similar to that used for the Mark 3 antenna and is described below.

Two Plane Lobe Switching

In considering two plane lobe switching methods it appeared that the desired result could be obtained by mounting two 3 ft. x 6 ft. parabolic arrays one above the other. This arrangement was tried and resulted in the array shown in Fig. 33. It provided two plane lobe switching with an antenna only slightly larger than the 6 ft. x 6 ft. antenna used before and had comparable gain and beam width (see Table II).

A schematic diagram of the array is shown in Fig. 34. Here it will be seen that there are two horizontal dipole arrays, each mounted along the focal line of a cylindrical parabola. The dipoles are in four groups and the interconnecting harness is criss-crossed and joined to the feed line at the center. Symmetrically placed around the feed point are four stub lines connected to the lobe switcher stators. Here again a semi-circular rotor is used for the lobing shifting capacitor. It will be observed that during each quarter turn of the rotor two stator plates are engaged, and the sequence is such that the beam shifts left, up, right, and down during one rotation. A separate Indicator was provided for the Pointer (elevation operator). To avoid signal confusion on the two Indicators it is necessary to show only left-right signals on the Trainer's oscilloscope and up-down signals on the Pointer's oscilloscope. This is accomplished by means of cam operated contacts in the lobe switcher which blank the indicators during the required intervals. Other contacts on this assembly provide left-right and up-down image spacing.

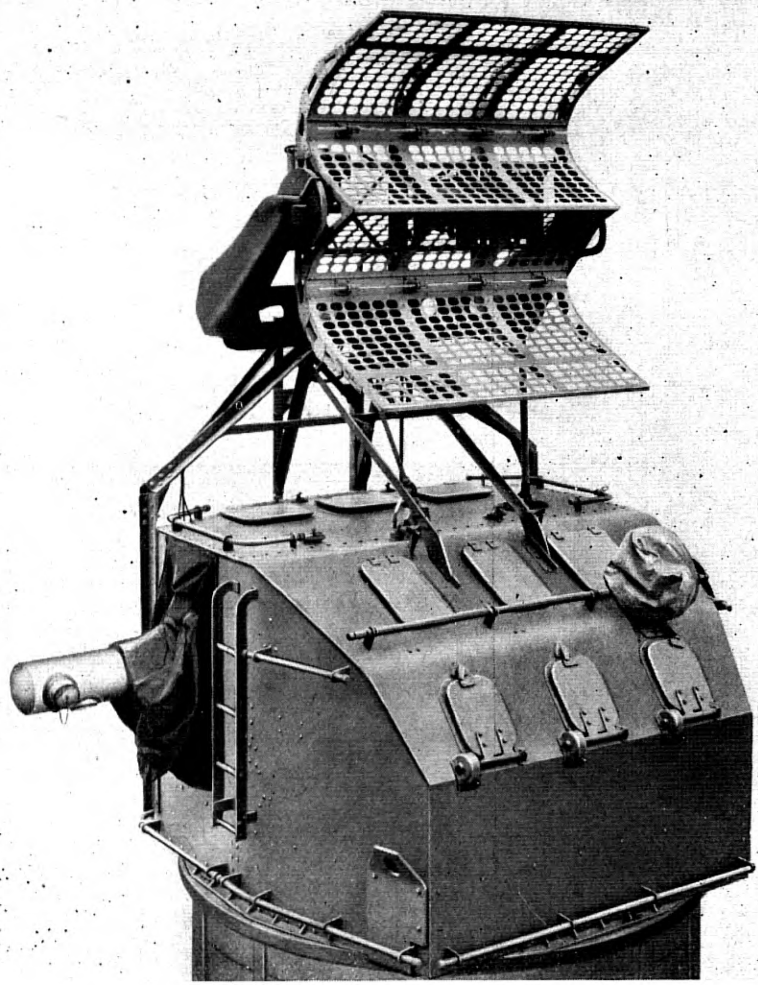


Fig. 33—Mark 4—antenna on gun director

Except for the new antenna and the additional Train or Elevation Indicator for the Pointer (elevation operator), this radar was identical to Radar Mark 3. The first demonstration of a development model of Radar Mark 4 was made at Atlantic Highlands, New Jersey, in September 1941 and this model was installed aboard the destroyer U.S.S. Roe the latter

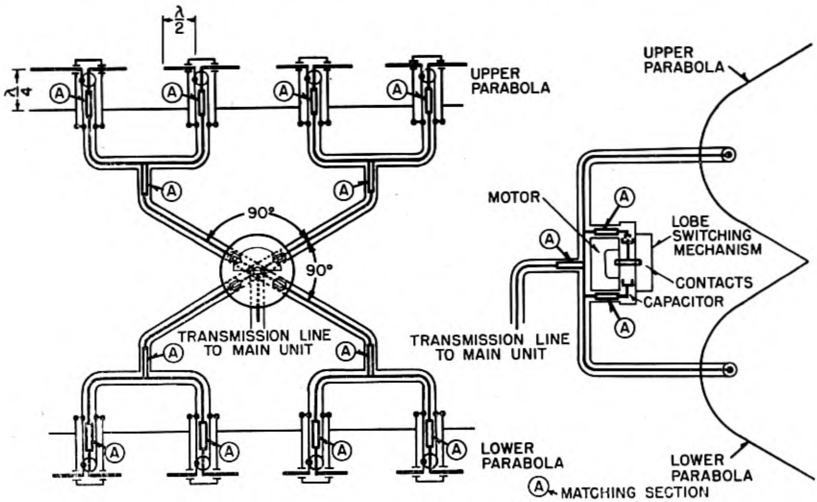


Fig. 34—Mark 4—Antenna schematic

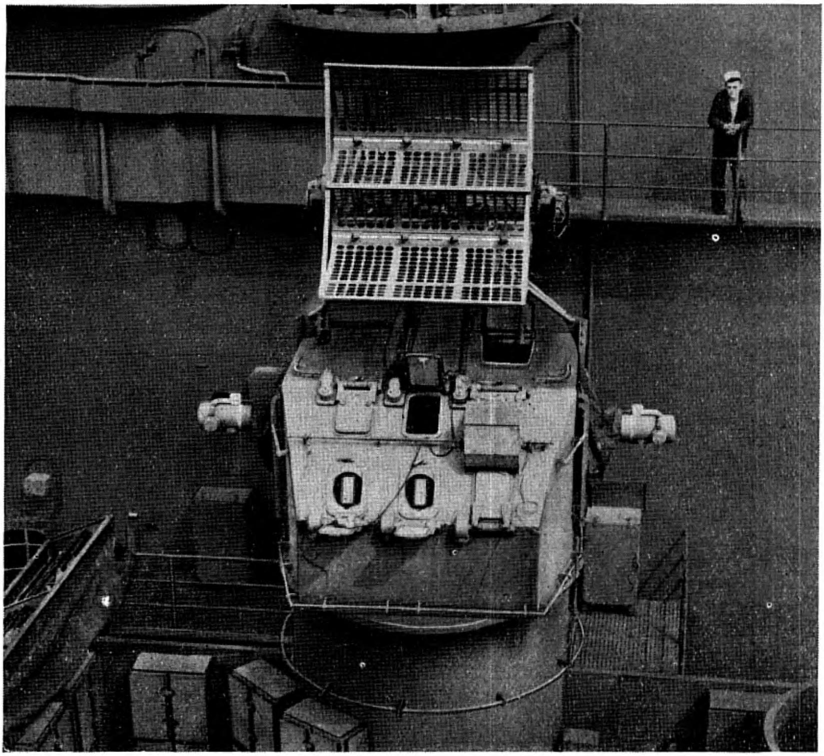


Fig. 35—Mark 4 antenna on Battleship Tennessee (Navy Photo 1908-43)

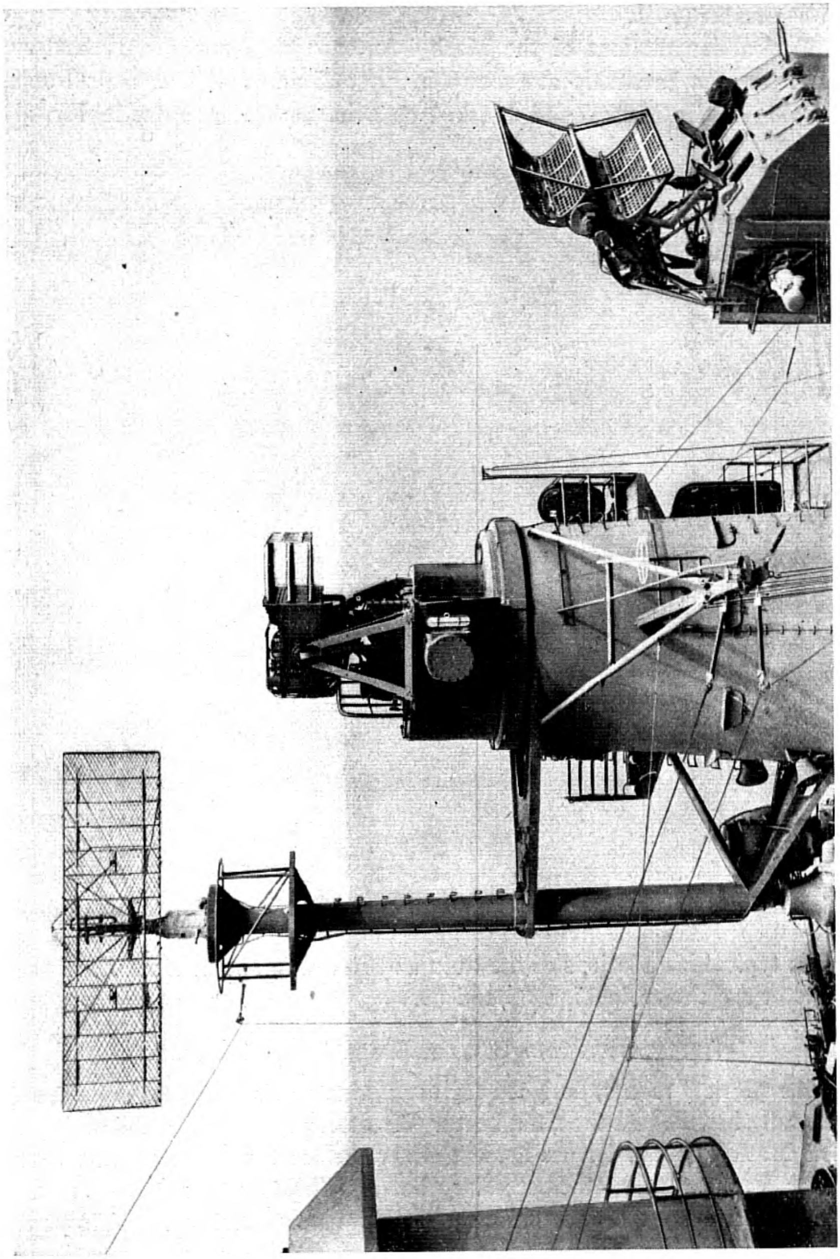


Fig. 36—Radar antennas on Battleship Tennessee (Navy Photo 1905-43)

part of that month. Initial production deliveries of these radars were made in December 1941.

Typical installations of the Mark 4 Antenna on the secondary battery directors of a battleship are shown in Figs. 35 and 36. The main frame installation for Mark 3 and Mark 4 on a battleship is shown in Fig. 37

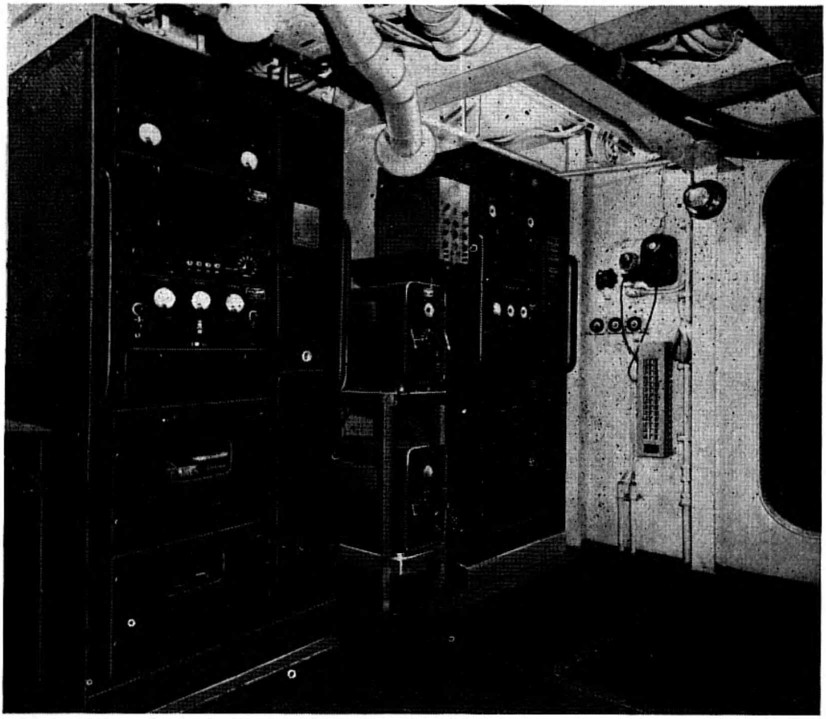


Fig. 37—Radars Mark 3 & 4—main units on Battleship New Jersey (Navy Photo 181809)

while typical installations of the train and elevation operator's units in the director are shown in Figs. 38 and 39.

Application and Use of Mark 3 and 4 Radars

The Mark 3 radars, designed for use against surface targets only, were generally installed on the main battery directors of battleships and cruisers. The Mark 4 radars for use against either surface targets or aircraft were generally installed on the secondary battery directors of battleships and cruisers, and on the one and only dual purpose director on destroyers. Thus a battleship usually had two Mark 3 and four Mark 4 equipments and a destroyer one Mark 4. Practically every ship in the fleet, of destroyer size or larger, was equipped with one or more of these equipments early in the war. A total of 139 Mark 3, and 670 Mark 4 radars were built, including those used ashore at schools. Although some of these equipments were replaced by more modern designs before the end of the war and some were lost in battle, there were still approximately 85 Mark 3 and 300 Mark 4

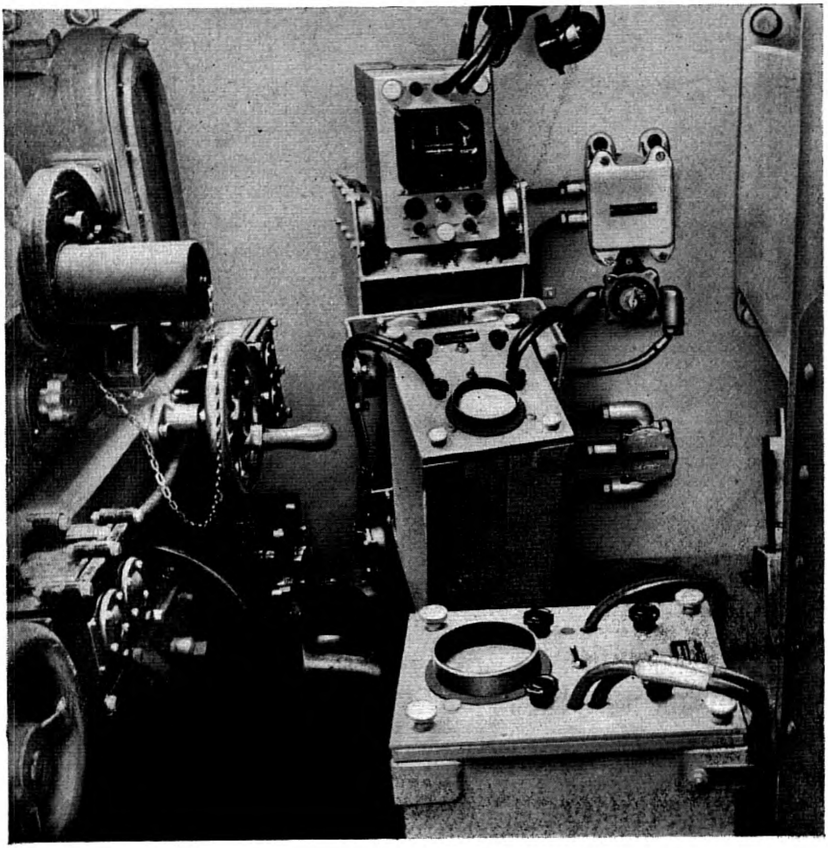


Fig. 38—Mark 4 Radar—trainer & pointer operators' positions on Aircraft Carrier Saratoga (Navy Photo 177347)

radars in service in the fleet on V-J day. The first four Mark 4's, Serial Nos. 1, 2, 3 and 5 installed on the battleship Washington were used until the middle of 1945, although newer designs had been going on all new vessels for more than a year.

These early equipments were the "guinea pigs" of fire control radar. They were the instruments with which our fleet learned to fight effectively at night and thereby gain a large advantage over the enemy whose radar was feeble and inaccurate. They played a part in every one of the early battles and most of the later ones in the Pacific. They controlled the cruiser Boise's guns in October 1942, when she blazed away at night at a vastly superior fleet in the Solomons and made the enemy pay 10 to 1 for the

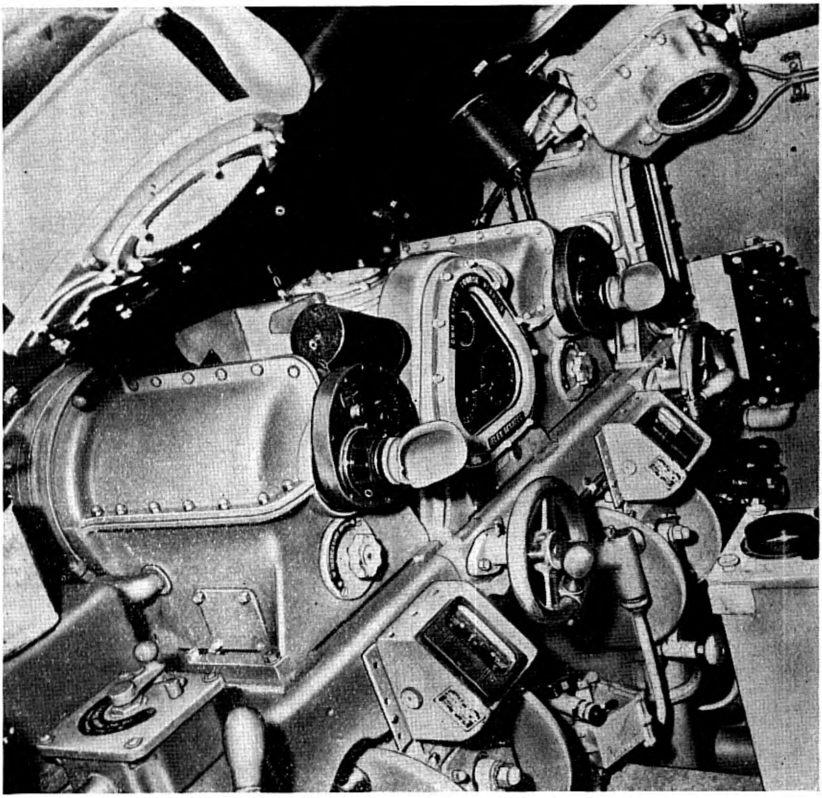


Fig. 39—Radar Mark 4—trainer & pointer operators' positions on Destroyer Barton (Navy Photo 181775)

damage they succeeded in doing. They were with the cruiser San Francisco on a night in November 1942, when a small U. S. force sank 27 enemy ships, almost completely destroying a large Japanese convoy bound for Guadalcanal when our hold there was at best precarious. The Mark 3 steered the big guns of the battleship South Dakota in the Solomons on the dark night of November 4, 1942, when she sank a major Japanese war vessel eight miles away with two salvos. Even in engagements in broad daylight when optics could be used for target angles these radars still played a vital part in furnishing accurate range which made 5″ gunfire against aircraft, for example, deadly at long range. Thus on October 16, 1942, when the South Dakota was attacked by planes she shot down an even 38 out of 38 attacking.

The rapid and widespread application of this rather complex electronic equipment was not accomplished without pain and confusion. It is beyond the scope of this paper to discuss the enormous problem of training in operation and maintenance that had to be solved, or of the tactical revolution in Naval warfare that fire-control radar produced. It is sufficient here to say that these and other problems were solved by heroic efforts of hundreds of officers and civilians in the Navy Department ashore and the thousands of officers and men of the fleet. Their problems were made more difficult by weaknesses in the equipment which were revealed by battle experience as the new science of radar got its baptism of fire. In every possible case the Laboratories attempted to remove the causes of recurring troubles by redesign and the furnishing of improvement kits of parts for installation in the fleet. The many lessons of experience learned from the Mark 3's and 4's were immediately applied in the design of the many more modern radars for the same and other types of service.

The authors of this paper wish to express their gratitude to the many Navy men with whom they have worked in connection with these equipments, and whose whole-hearted cooperation during difficult times made possible the successful development of these fire-control radars. They also wish to thank their colleagues in Bell Telephone Laboratories who worked as a team to make this important equipment possible, and the men of the Western Electric Company for their help on the many engineering problems which arose during production and use in the field. It is the hope of all who were concerned with this development that accurate radars, like other radars, will find peaceful use in a peaceful world, but it is also the determination of these engineers that as long as we need a Navy, we will try to provide it with radars as much superior to those of any possible enemy as they were in the recent war.

The Gas-Discharge Transmit-Receive Switch

By A. L. SAMUEL, J. W. CLARK and W. W. MUMFORD

THE gas-discharge transmit-receive switch has become an accepted part of every modern radar set. Indeed, without such a device, an efficient single-antenna micro-wave radar would be nearly impossible. Many of the early radar sets made in this country employed separate antennae for the transmitter and receiver. The advantages of single antenna operation are so apparent as hardly to require discussion. The saving in space or, if the same space is to be occupied, the increase in gain and directivity of a large single antenna is, of course, apparent. But even more important, perhaps, is the tremendous simplification in tracking offered by a single antenna, particularly where a very rapid complex scanning motion is desired.

The fact that the receiver needs to be operative only during periods between the transmitting pulses makes single antenna operation possible if four conditions are satisfied. These are: (1) the receiver must not absorb too large a fraction of the transmitter power during the transmitting period, (2) the receiver must not be permanently damaged by that portion of the transmitter power which it does absorb, (3) the receiver must recover its sensitivity after any possible overload during the transmitting pulse in a time interval shorter than the interval required by the reflected pulse to arrive back to the receiver from the nearest target, and (4) the transmitter must not absorb too large a fraction of the received power. At frequencies of the order of 700 megacycles and at low power levels these conditions are not impossible of attainment without recourse to any special switching mechanism other than that provided automatically by the usual circuit components. Conditions (1) and (2) can be met by designing the receiver in such a way that the change in input impedance as a result of overload will cause most of the available input power to the receiver to be reflected. Condition (3) requires careful attention to the time constants of all those receiver circuits which are subject to overload. Condition (4) fortunately is automatically satisfied by most transmitters, again as a result of the large mismatch reflections which occur at the connections to the transmitter's "tank" circuit when the transmitter is not operating. The United States Navy Mark 1 radar was operated on this basis.

The speed with which the transmit-receive switch must operate rules out all consideration of mechanical devices, at least for all but the longest range "early warning" equipment. For example, the go and return time to a target at 500 feet distance requires approximately one microsecond. Switching times must, therefore, be measured in microseconds. Since these short time intervals would at first sight seem to be too small to permit the use of gaseous discharge devices, some work was done on the use of specially designed vacuum diodes. It is possible to employ balancing circuits (sometimes called hybrid circuits) to achieve single antenna operation, but such circuits require critical balancing adjustments and they dissipate a large part of the available power in non-useful balancing loads. The need for a still different approach to the duplexing problem was clearly indicated.

Spark discharges either in air or in enclosed gaps bridged across parallel wire transmission lines were used in some of the early experimental long-wave radar sets. Dr. Robert M. Page of the Naval Research Laboratory was one of the pioneers in this work. These devices were only moderately satisfactory because of their erratic behavior and because of electrode wear. However, it was observed that the recovery time of such discharges was not as long as might be expected on the basis of a simple ionization and deionization explanation of their operation. This led to the investigation of the use of low-pressure gas discharges. These very early gas-discharge "switches" were actually much more in the nature of "lightning protectors", their principal function being to limit the power delivered to the receiver during the transmitting pulse in a gross sort of way, with considerable reliance on impedance changes at the receiver and on the rugged overload capabilities of the first tube in the receiver.

The trend toward shorter wavelengths and the desire for better protection led to the development of a partially evacuated gas-discharge tube located in a relatively high Q resonant cavity. In England, cavity type duplex tubes were made by inserting gas in a then current type (Sutton Tube) of local oscillator tube. These devices were called TR boxes (abbreviation for transmit-receive) by the English, a designation which has continued. It is a curious coincidence that some of the earliest cavity type duplex tubes made in this country at the Bell Telephone Laboratories were also constructed by inserting gas in an American type local oscillator tube (the 712A vacuum tube). This tube (later coded the 709A vacuum tube) was tested in an operative system which was subsequently demonstrated to the Army with such satisfactory results that the tube was adopted without change for several radar systems. The 709A vacuum tube and its associated cavity are shown in Fig. 1.

A similar structure, known as the 702A and shown in Fig. 2 (together with the 709A tube) was used for longer wavelengths. The need for these tubes was so very great that no time was allowed for their improvement before production was undertaken by the Western Electric Company.

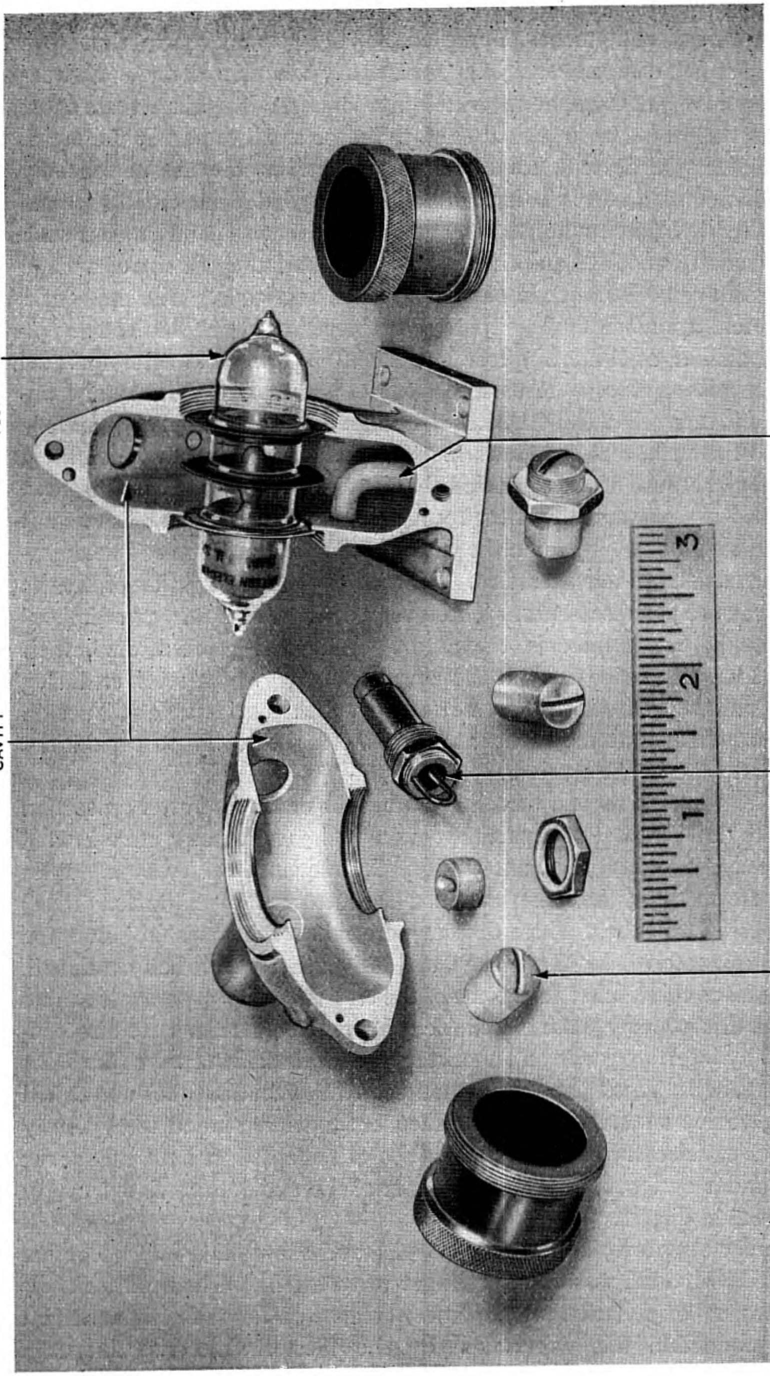


Fig. 1—The 709A vacuum tube and its associated cavity

The radar on the U.S.S. Boise in the battle off Savo Island on October 11–12, 1942 employed a 702A vacuum tube.

Three developments soon led to the need for much improved TR boxes. One of these was the rapid progress which was being made in increasing the peak output power from the magnetron. The second was improvements in the silicon point contact rectifier, the so-called crystal detector, which increased its reliability and convenience and at the same time reduced its conversion loss and noise figure as compared with the vacuum tube converter. The third was the development of still higher frequency systems to

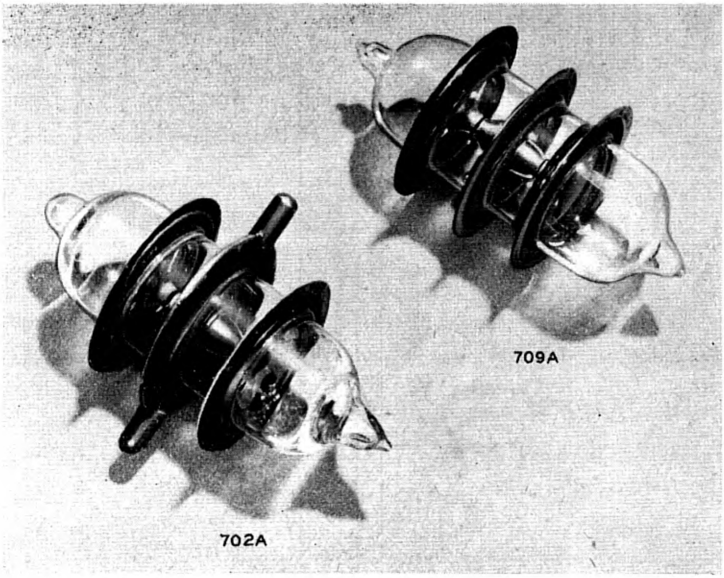


Fig. 2—The 702A and 709A vacuum tubes

achieve either greater antenna directivity or smaller size. Since satisfactory vacuum tube converters were not available for these frequencies, the silicon rectifier had to be used. Unfortunately the silicon rectifier, as then available, was subject to permanent damage if subjected to but very small amounts of power as compared with the magnetron power levels.

An active program of work was initiated at the Bell Telephone Laboratories to obtain designs of TR boxes offering adequate protection for contact rectifiers at any power levels then available or contemplated. Three tubes were developed, the 721A, 724B and 1B23 vacuum tubes shown in Fig. 3. These tubes are used at frequencies in the vicinity of 3000 megacycles, 10,000 megacycles, and 1000 megacycles respectively. They are all of the

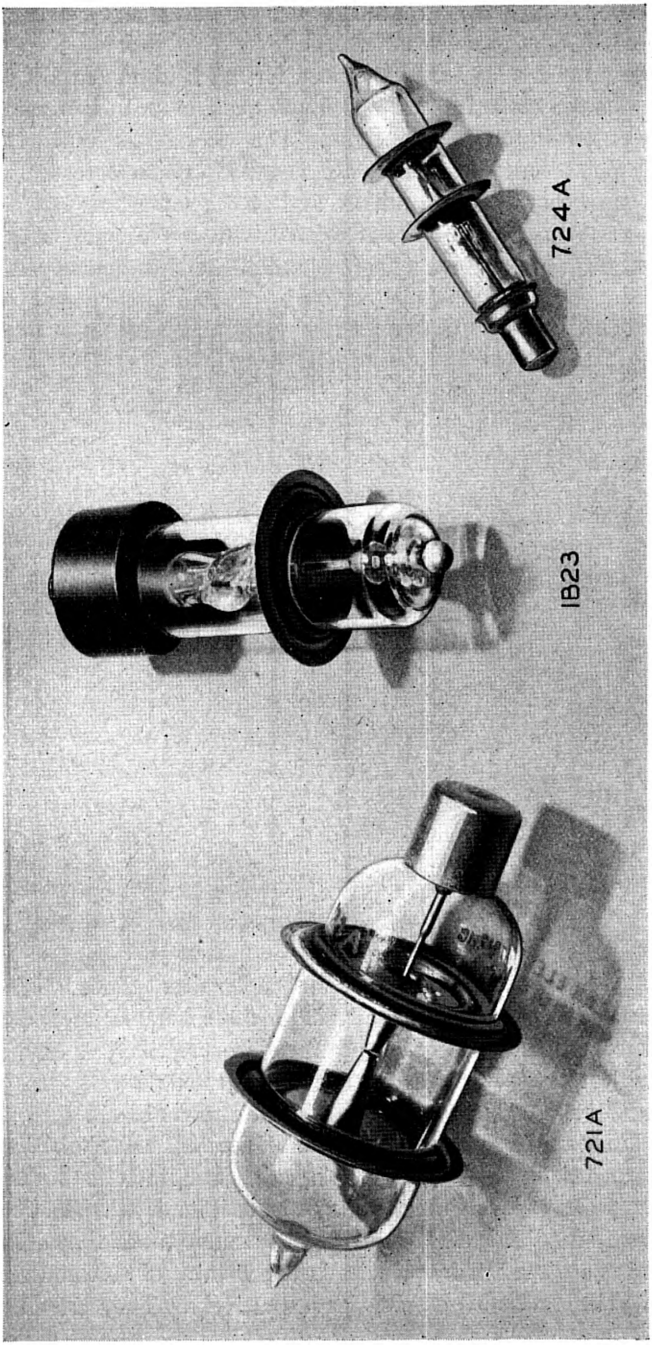


Fig. 3—The 721A, 724B and 1B23 vacuum tube

separate cavity type in which contact through the vacuum envelope is made by means of thin copper discs. More recently other designs of tubes have appeared in which the entire cavity is evacuated. Over 400,000 tubes of the three types discussed in this paper were manufactured in 1944 alone and substantially all of the American-made radars which saw active service employed one or more of these tubes.

The TR tubes used in American radars are, of course, no more essential than are the magnetrons, the beating oscillators, and the many other special parts which go to make up the modern radar. Nevertheless it is interesting to note that the 721A tube was an essential part of the radar equipment on almost every major ship in the United States Fleet, that the 724B tube was an essential part of the bombing equipment on nearly every bomber used against Japan, including the planes which carried the atomic bombs, and that the capture of Okinawa, to name a single case, would have been much more expensive in men's lives without equipment depending upon the 1B23 tube.

Method of Operation

The 709A tube as shown in Fig. 1 was operated in what has come to be known as a shunt branching circuit. Its operation can be explained in terms of Fig. 4. During transmission, energy flows from the transmitter along the coaxial line toward the antenna. Some of this energy enters the branch leading to the receiver where it encounters the TR box. This consists of a resonant cavity with a pair of spark gap electrodes arranged so that the maximum resonant voltage is built up across the gap. Since the voltage across the gap is then limited by the discharge voltage and the voltage applied to the receiver is still further reduced by an equivalent step-down ratio of the output coupling in the resonant cavity, the receiver input power is held to a small value. The power dissipated in the gas discharge, and therefore abstracted from the transmitted signal is kept small by the impedance mismatch. The discharge itself takes the form of a small pale blue glow between the electrodes. The effect of the discharge is to place a low impedance (predominantly resistive) across the maximum impedance point of the cavity. This results in the appearance of a still lower apparent impedance across the input to the cavity. If the length L_1 is an odd number of quarter wavelengths, the apparent impedance of the receiver branch at the branching point becomes very high in comparison with the impedance of the antenna and is therefore unable to abstract much power from the line.

At the end of the transmitting period, the conductance of the gas discharge falls rapidly to a very low value since the small received voltages will be insufficient to maintain the discharge. Signals arriving at the antenna can then be transmitted through the TR box to the receiver. However, in the circuit shown in Fig. 4, the receiver is still bridged by the transmitter. It is a fortunate fact that the internal impedance of many magnetrons (the most common type of transmitting tube) becomes very low when they are in the inoperative condition so that the tube is nearly the equivalent of a short circuit. By adjusting the length L_2, until this equivalent short circuit position is an odd number of quarter wavelengths from the junction point "B", the shunting impedance at "B" can be made very high so that only a small part of the received energy is lost. In the event that this change of impedance of the transmitter is not sufficient, a second TR switch commonly known as an ATR, may be introduced to perform this function as will be described later. During the receiving period, some loss will occur in the TR box resonant cavity as a result of the inherent resistive and dielectric losses. An additional loss will occur immediately after the transmitting period because of the loss producing particles (free electrons) which remain for a time in the discharge gap. The combined losses must be kept small so as not to impair the performance of the system.

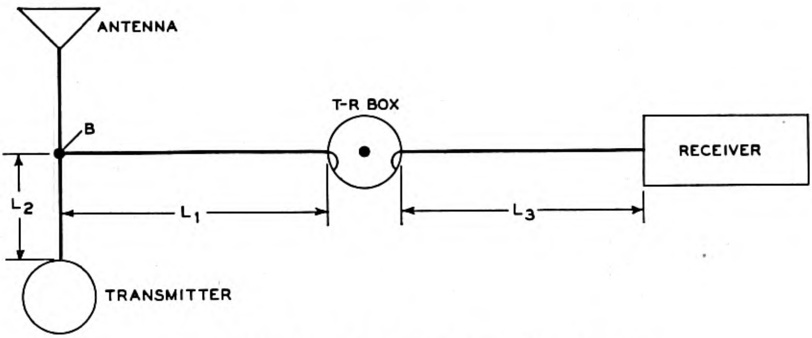


Fig. 4—The elements cf a shunt branching circuit

Most modern radars employ series branching circuits instead of the shunt branching circuit just described. A coaxial line example of such a system (from the SCR-545) employing the 721A tube is shown in Fig. 5. As shown in Fig. 6 the cavity is coupled to the coaxial line by means of a window which can be slid along on a slot in the outer conductor of the coaxial line leading from the transmitter to the antenna. Fig. 7 is an exploded view of the cavity. Such a cavity is in effect in series with the line as the currents existing in the outer conductor of the coaxial line are interrupted by the window. During the transmitting period the low impedance at this window limits the voltage across it to a small value and prevents serious loss of transmitter power.

Reception in the series branching circuit of Fig. 5 is achieved by adjusting

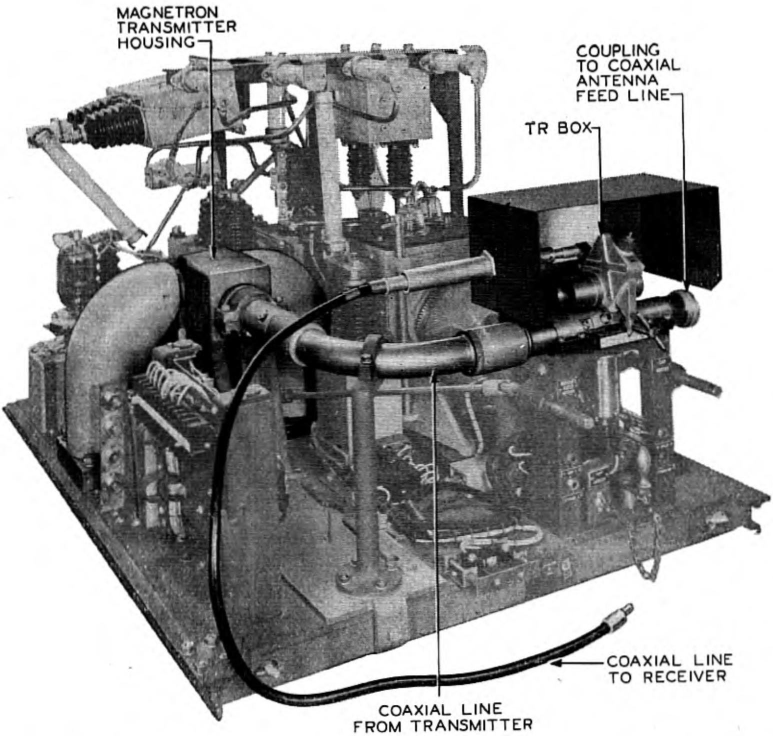


Fig. 5—The series branching circuit employing the 721A tube used in the SCR545

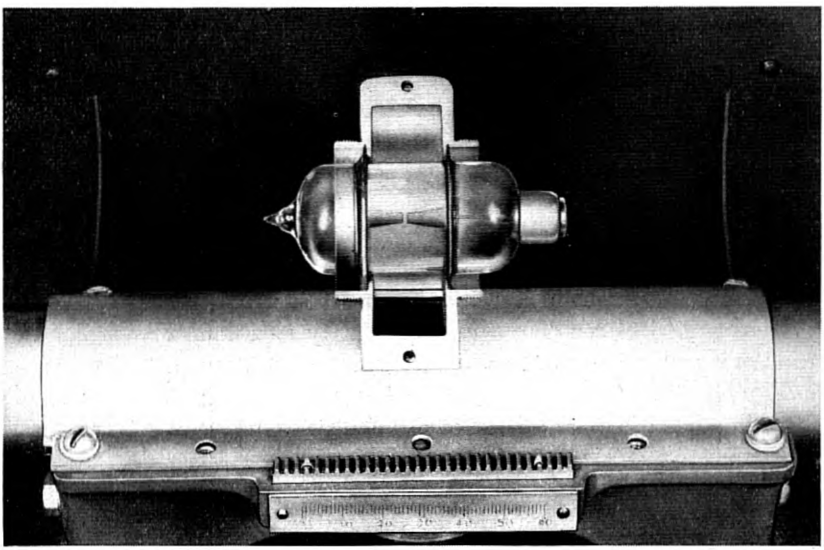


Fig. 6—Closeup view of the cavity shown in Fig. 5, partly disassembled to show coupling window

the position of the TR cavity along the slotted section of the line until the window is located the correct distance from the transmitting tube. This now corresponds to an even number of quarter wavelengths between the equivalent short-circuit plane and the junction, so that the maximum current is caused to enter the cavity. The output to the receiver is obtained from a small coupling loop in the TR cavity.

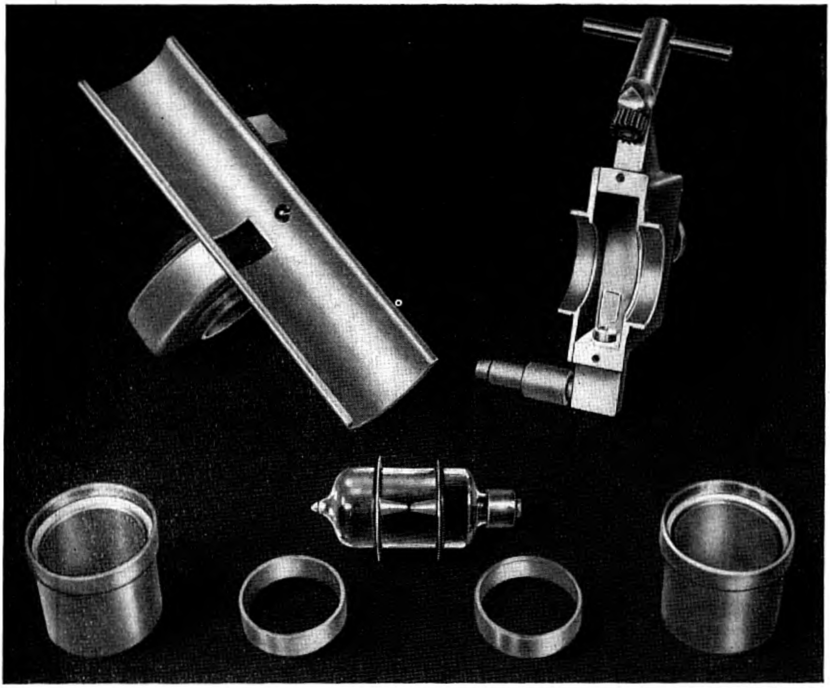


Fig. 7—Exploded view of the cavity of Fig. 6

A similar coaxial line series branching circuit using the 1B23 is shown in Fig. 8. The method of inserting the tube in the cavity is shown in Fig. 9 while Fig. 10 is an exploded view showing the details.

This method of coupling a resonant cavity to a transmission line by a window is not limited to the coaxial line case. A wave guide system is shown in Fig. 11. The distance between the TR cavity and the transmitting tube is again adjusted by sliding the cavity and its window along over a section of the rectangular wave guide containing a slot.

The ATR. In all of the systems so far described use is made of the impedance mismatch conditions at the magnetron or other transmitting tube terminals to prevent serious loss during the receiving period. If the magnetron "cold" impedance does not differ greatly from the surge impedance of the transmission line used, it may not be possible to avoid loss of reflected signal into the transmitter line. Also in some cases, an unreasonable amount of adjustment must be provided in the position of the TR cavity with respect to the transmitter to make up for large variations which may be encountered in transmitter "cold" impedance. Both difficulties

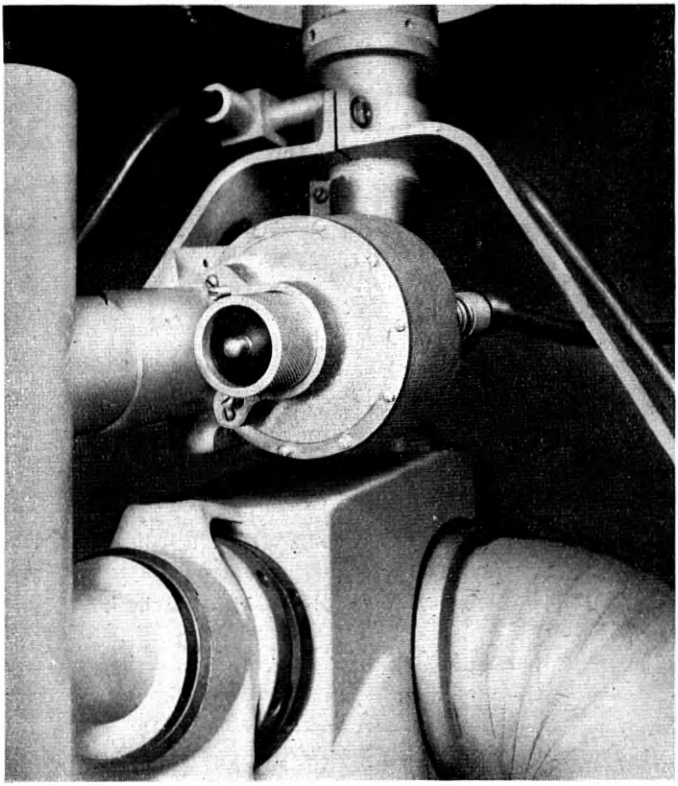


Fig. 8—Series branching circuit using the 1B23 vacuum tube

may be avoided by the use of a second gas discharge tube located between the transmitter and the TR and at an odd number of quarter wavelengths from the TR junction. This second tube is referred to as the anti-T-R tube (usually abbreviated to ATR), or sometimes as the RT tube. The use of an ATR tube was not found to be necessary in most of the systems which employed the 721A tube.

With the advent of still higher frequency systems, for which the 724B tube was designed, the "cold" impedance difficulties just mentioned made

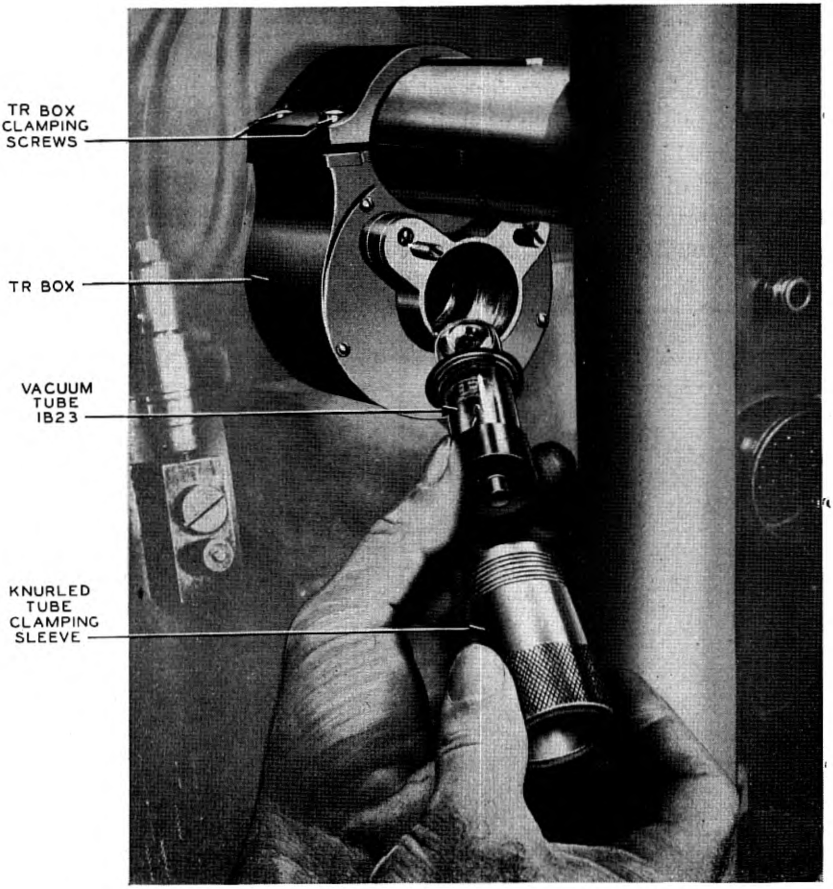


Fig. 9—Method of inserting the 1B23 into the circuit

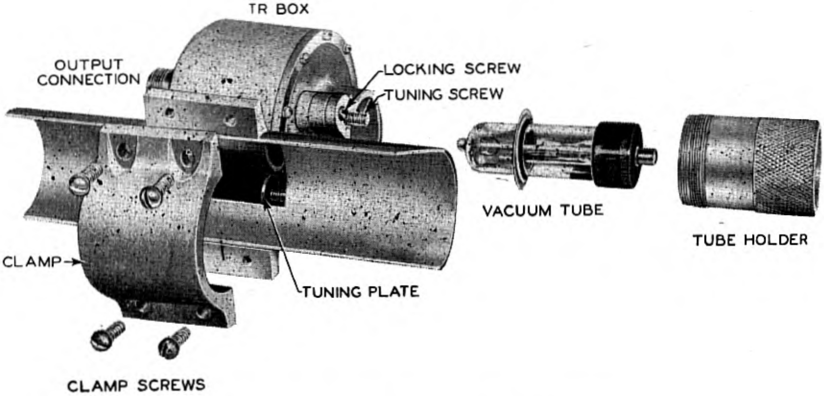


Fig. 10—Exploded view of the 1B23 cavity

it seem advisable to employ an ATR tube. The general arrangements of the circuit elements in one of these systems is shown in Fig. 12. The main wave guide section is shown removed from the rest of the equipment

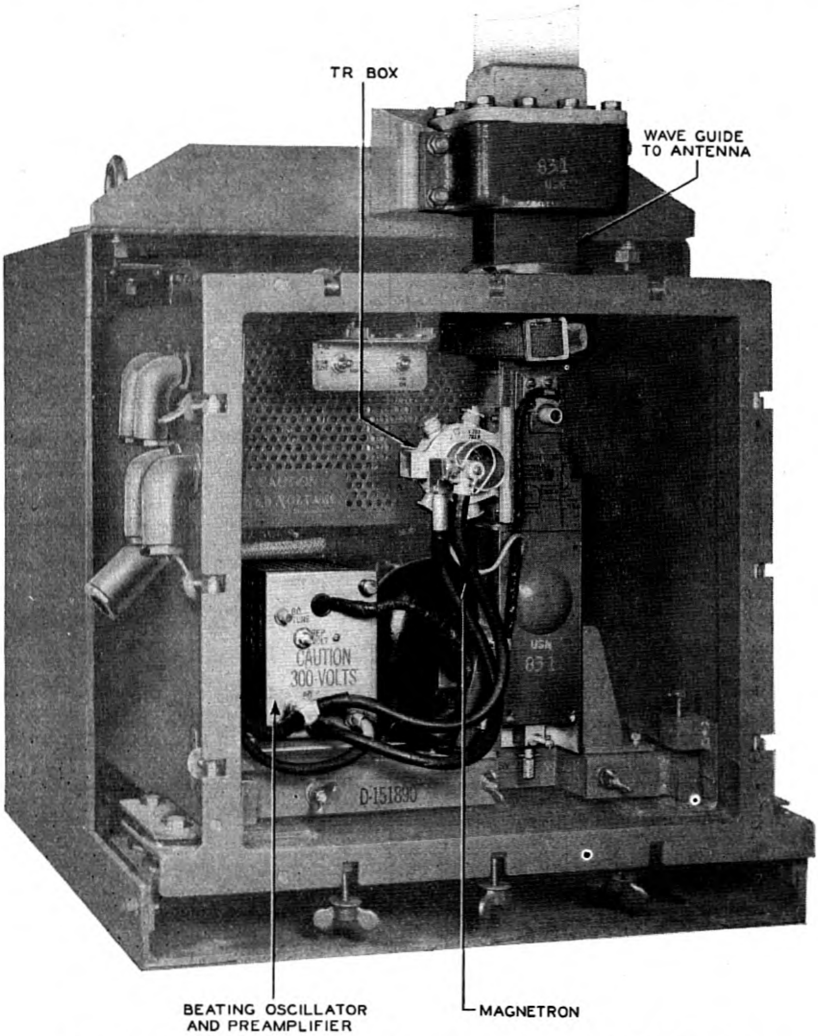


Fig. 11—The wave guide system of the SL radar employing the 721A tube

in Fig. 13 while Fig. 14 is an exploded view revealing the details of the cavity construction. The two cavities are, of course, coupled to the wave guide by means of windows. The wave guide branch leading to the receiver is in

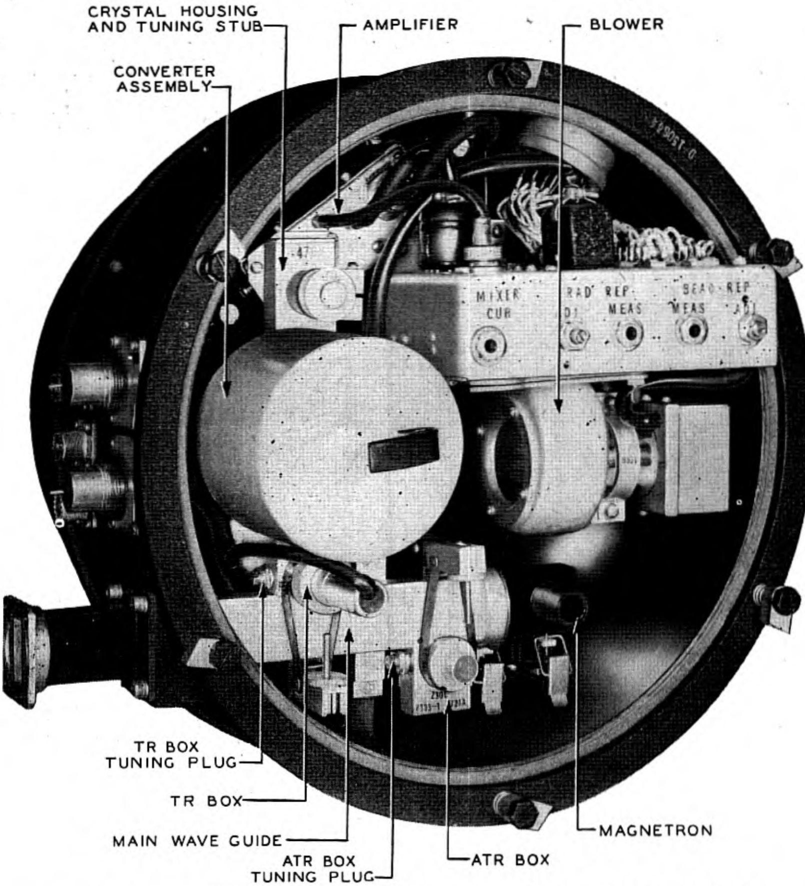


Fig. 12—A general view of a wave guide system employing a 724B tube in the TR box and a second 724B tube in the ATR

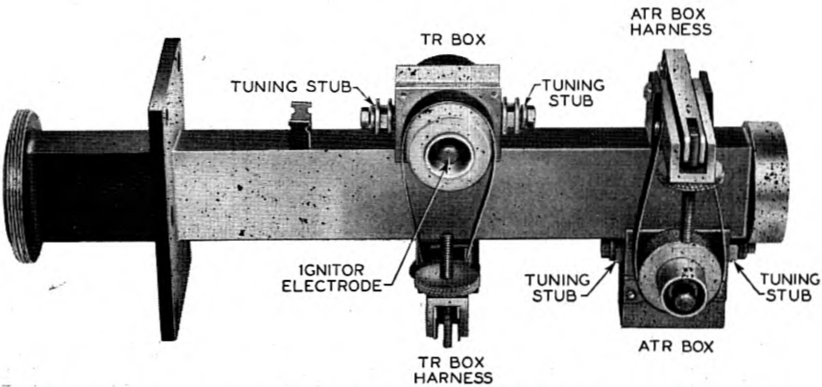


Fig. 13—The main wave guide of Fig. 12 removed from the rest of the equipment

turn coupled to the TR cavity by another window. The input and output windows of the TR cavity are adjusted in size to provide an impedance match to the line during the receiving period. The window to the ATR is, however, adjusted so that it presents a high impedance, that is much greater than the surge impedance, during the receiving period. This high impedance is effectively in series with the magnetron impedance. The resulting high impedance is located at an odd number of quarter wavelengths from the TR and so presents a very low impedance in series with the receiving branch.

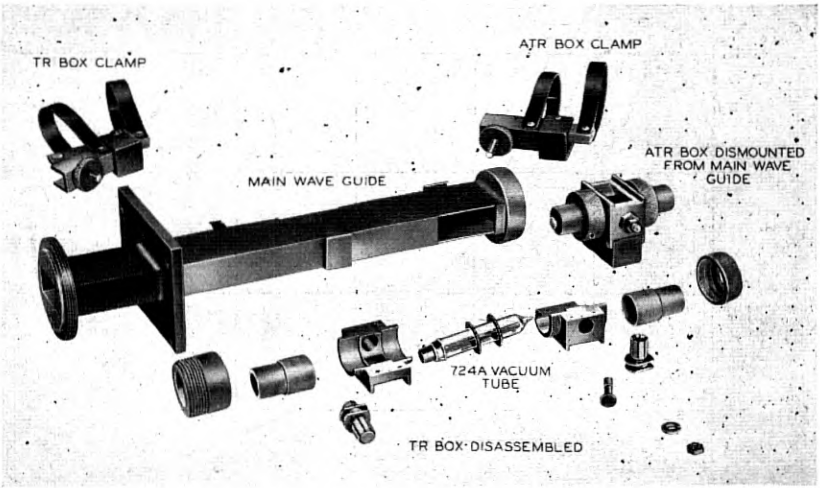


Fig. 14—An exploded view of Fig. 13

Both the TR box and the ATR box must be tuned to resonance at the magnetron frequency. Broad-band ATR boxes using very low Q circuits have been designed which require no adjustment over a 5% band. Such boxes, which obviously are very advantageous in tunable systems, do not use the copper-disc-seal tubes which form the principal subject matter of the present paper, and will not be discussed further.

TR Box Performance

The performance of a TR box can be described in terms of four parameters which are related to the four duplexing requirements mentioned earlier. These parameters are respectively: (1) the high level loss, which is the transmitting power loss in the TR tube; (2) the leakage power, which is the amount of transmitter power which reaches the receiver; (3) the recovery time, which measures the rate at which the TR box recovers its low level behavior after the termination of the transmitting period; and (4) the low-level loss, which describes the loss of the received signal including (a) the loss in the TR box itself and (b) the loss in the transmitting branch. These parameters are interrelated and conflicting. For example, the interdependence of the leakage power and the low-level loss may be computed on the basis of a somewhat idealized TR box as is done in Appendix A and the results presented in the form of the curves of Fig. 15. It is customary to design the cavities for matched input conditions ($\sigma = 1$), for obvious reasons, and for a low-level loss of one to two db. The relationship between the transmitting power dissipated in the TR tube and the low-level loss is shown

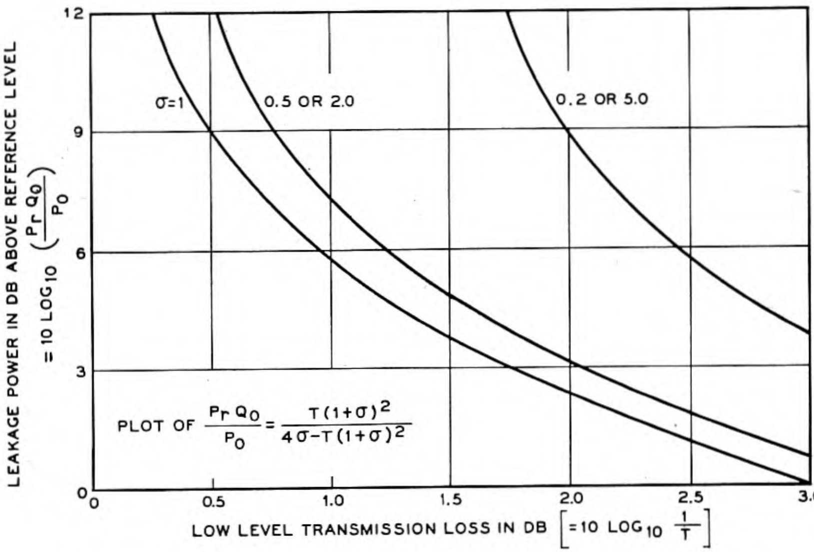


Fig. 15—The variation in leakage power with the low level loss adjustment

in Fig. 16. This curve may also be used to determine the effect of the low-level loss adjustment of a TR cavity on the recovery time characteristic since recovery time depends upon the gas discharge power rather than upon the transmitter power per se. In spite of this interdependence, it will be convenient to consider the different operating parameters separately in the sections to follow. The receiver protection aspect will be considered first.

Receiver Protection. The receiver protection problem is complicated by the fact that power reaches the receiver through the TR box by three different mechanisms. As shown in Fig. 17, the observed leakage power pattern is composed of three parts known respectively as the spike, the normal flat leakage and the direct coupling. The spike is the result of the transient condition existing at the beginning of each pulse. Normal leakage power can be thought of as due to the finite voltage drop across the gas discharge while the direct coupling is that component of the leakage power which would be present if the voltage drop across the discharge were zero.

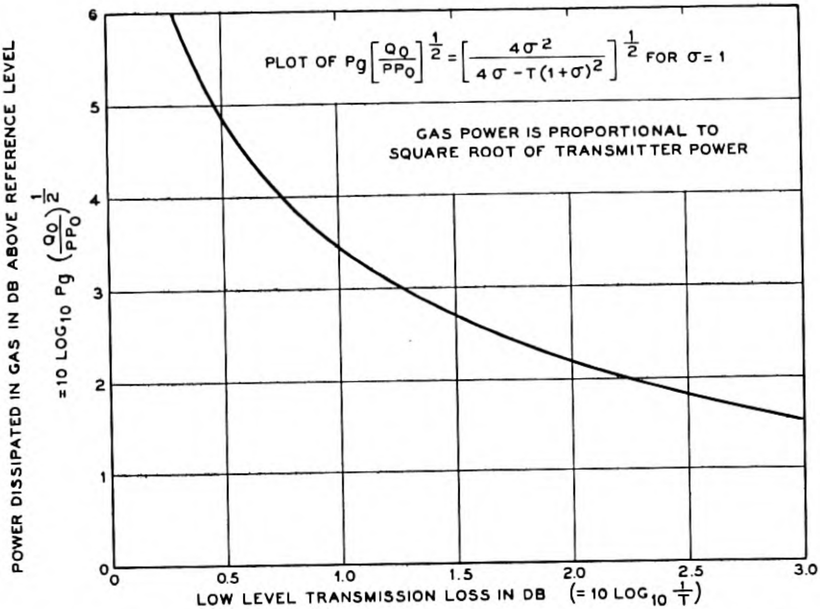


Fig. 16—The variation in gas discharge power with the low level loss adjustment

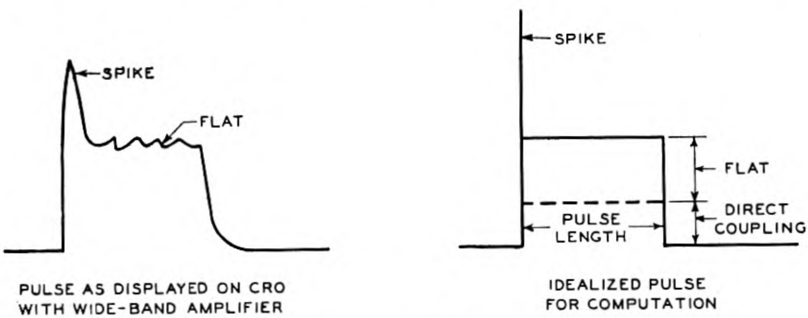


Fig. 17—The shape of the leakage power pulse

The Spike. Because of the rapid rate of rise and fall of the spike, the observable deflection on an oscilloscope is dependent upon the bandwidth of the video amplifier and upon the energy in the spike. Although an observation of the true shape of the spike has not yet been made, the duration is estimated to be of the order of 10^{-9} seconds, a time interval that is probably short compared with the thermal time constant of the contact on a converter crystal. However, it is possible to measure the energy content of the spike, and such measurements indicate that this energy is fairly independent of the length of the pulse and of the transmitted power level, although it is definitely dependent upon the steepness of the wave front of the transmitted pulse. The spike clearly represents energy transfer through the TR box during the period required to establish the discharge conditions which exist during the flat. The energy contained in the spike varies between a few hundredths of an erg to perhaps one erg per pulse, depending upon a variety of factors. By way of comparison, the conventional crystal rectifiers are proof tested in manufacture with a single spike of 0.3 erg to 5.0 ergs, depending upon the crystal type. It is generally believed that the spike is more damaging than the flat in most radar systems.

The energy in the spike is found to depend upon the repetition rate of the transmitting pulses, presumably because of residual ionization in the gas discharge gap. At low repetition rates (that is less than roughly 1,000 pulses per second), the spike energy may be materially decreased by a d-c glow discharge near the radio frequency gap. This discharge provides a continuous supply of ions and free electrons and so aids in establishing the desired condition in the r-f discharge path. A discharge is supplied in all the standard TR tubes. An auxiliary electrode called the "igniter" or "keep-alive" is used as the cathode, with the back or inside portion of one of the high frequency electrodes acting as the anode. A small amount of radioactive material is placed in the tube to insure that the igniter discharge starts on the application of the igniter voltage. Fig. 18 is a plot of the way in which the spike energy varies with the repetition rate both with and without an igniter discharge. Igniter oscillations sometimes occur as a result of the negative resistance characteristics of the igniter discharge. This causes a cyclic variation in the number of free electrons and ions with a resulting fluctuation in the spike energy. Inadequate protection may result from such oscillations. It is customary to mount a current limiting resistance very close to the igniter cap to minimize the effects of these undesirable oscillations. When such oscillations still occur they are usually evidence of an insufficiently high igniter voltage or of tube failure. The margin of safety in the igniter operation may be increased by increasing the discharge current but at the expense of greatly reduced tube life.

When a radar system is first turned on, the first pulse occurs without the benefit of residual ions in the discharge, and for the first few pulses the spike energy may easily reach dangerously high values. While the magnitude of this "turn on" effect is greatly reduced by the presence of the igniter discharge, it is customary to provide a "crystal gate" in the form of a shutter which isolates the crystal from the TR box until after stable transmitting conditions have been reached and until the TR tube discharge has been established. The need for this additional turn-on protection is somewhat greater with the 724B than it is with the 721A tube. Another important function of the "crystal gate" is to prevent the crystal in an idle radar from being damaged by energy from other radars operating nearby.

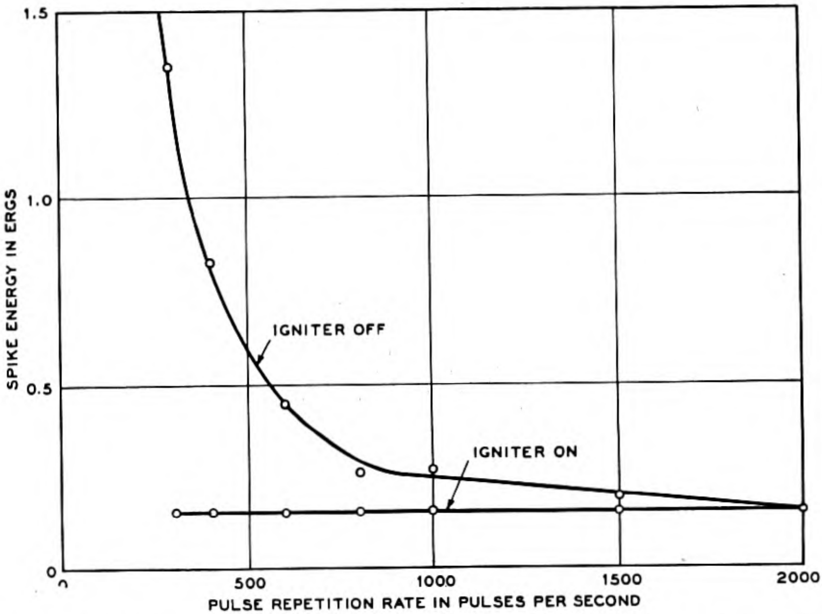


Fig. 18—The dependence of spike on the repetition rate for the 724B tube in a cavity adjusted for a 1.5 db low level loss and for a transmitter power level of 8 kw peak

The energy in the spike is a function of the effective size of the input and output coupling windows of the TR box. A convenient method of presenting this effect is to plot the spike energy as a function of the low-level transmission loss of the cavity which also depends upon the window sizes. Fig. 19 is such a plot for the 724B tube*. Comparing these experimental data with the computed flat power curve of Fig. 15, one notes that the spike energy varies at a more rapid rate than does the flat power. In both cases, the leakage decreases as the low-level loss increases and crystal protection can be purchased at the expense of receiver sensitivity.

* Based on data taken at the M.I.T. Radiation Laboratories by F. L. McMillan. Jr. and J. B. Wiesner.

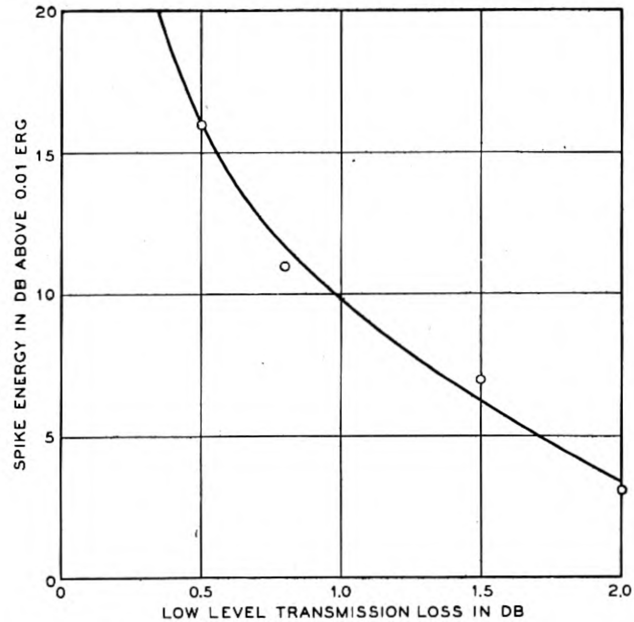


Fig. 19—The variation in spike energy with the low level loss adjustment ($\sigma = 1$) for the 724B. This experimental curve for the spike energy should be compared with the idealized flat power curves of Fig. 15

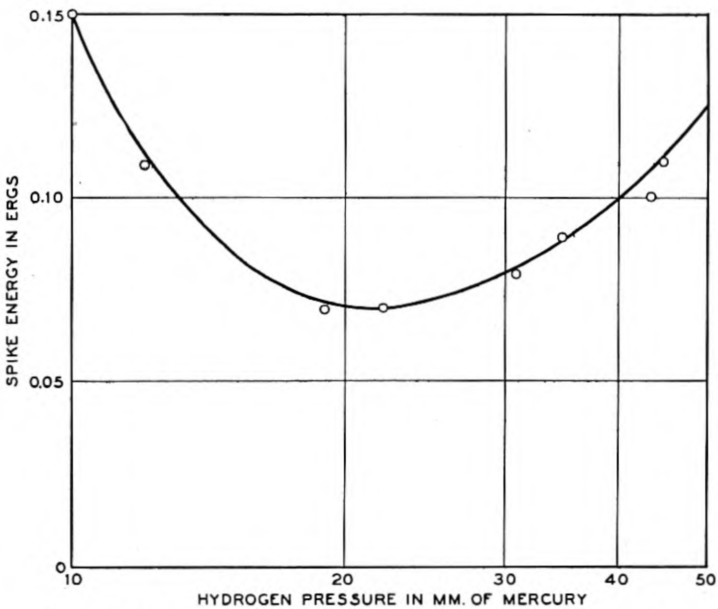


Fig. 20—The effect of gas pressure on the spike energy for the 724B

The way in which the spike energy varies with pressure of the gas in the TR tube is illustrated in Fig. 20. These data were obtained on the 724B tube structure. Other factors, yet to be discussed, prevent the use of the exact optimum pressure as determined on the basis of the spike energy only.

The Flat. The more or less flat portion of the leakage power is in reality the result of two different mechanisms of energy transfer, one of which is reasonably independent of the transmitter power level. It is this portion only with which we will now be concerned. This flat power is critically dependent on the chemical constitution and pressure of the gas within the TR tube. It can be thought of as being the power transmitted by the TR

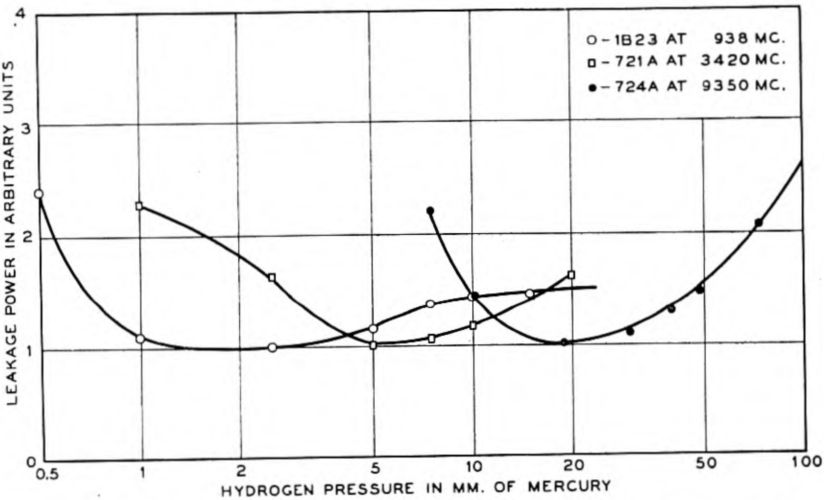


Fig. 21—Experimental curves showing the relationship between flat leakage power and gas pressure, taken with a c-w oscillator

box by virtue of the fact that the voltage drop across the gas discharge is not zero. The constancy of the flat power in spite of variations in the transmitter power level is presumably related to the similar phenomenon of a nearly constant voltage drop across a d-c gas discharge independent of the discharge current. Because of this constancy, the gas discharge parameter P_0, shown in Fig. 15, can be assumed to be a constant more-or-less independent of the transmitter power level. Reasonable values of P_0 for cavity design purposes are 20 volt-amperes for the 721A tube and 10 volt-amperes for the 724B tube. Corresponding values of the Q_0 parameters needed in interpreting Fig. 15 are 2500 for the 721A tube and 1500 for the 724B tube. Using these values the flat leakage power for a TR box using a 721A tube and having a low-level loss of 1 db would be 30 milliwatts. The corresponding flat leakage power for the 724B tube in a 1.5 db box would be 16 milliwatts. Actual measured values are usually somewhat less than these figures. As most crystals will withstand flat powers very much greater than this amount, the flat power is normally of much less importance than the spike in contributing to converter crystal failure.

Since the flat portion of the leakage power represents quasi-steady-state conditions, it is possible to simulate it for purposes of study by the use of a C.W. oscillator. Fig. 21 contains three experimental curves taken at

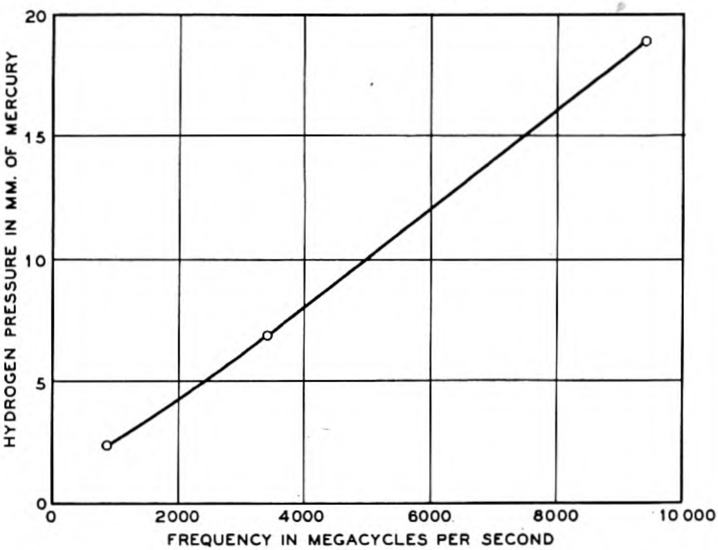


Fig. 22—The pressure for minimum leakage power as a function of frequency

three different frequencies showing the relationship between the flat leakage power and gas pressure. These curves were all taken with tubes filled with hydrogen only. Fig. 22 shows that the pressure for minimum flat leakage is proportional to the frequency. This simple law probably does not apply at frequencies much less than 1000 mc.

Water vapor is used in commercial TR tubes to improve the recovery time, as will be discussed later. The variation in flat leakage power with partial water vapor pressure as measured on a 721A type of tube containing both hydrogen and water is shown in Fig. 23. These data were taken in a radar system.

In this connection, it is of interest to note that the characteristics of the gas discharge in the TR box must of necessity be quite different from those that obtain at lower frequencies. Simple calculations indicate that the mean free path of an electron is in general of the same order as the distance between the electrodes but that very few electrons are able to reach the electrodes because of the very rapid reversals in the r-f field. Electrons therefore oscillate rapidly to and fro, losing energy to the neutral gas molecules and to positive ions through occasional collisions The positive ions do not contribute in any substantial way to the discharge current because of their large mass and correspondingly low velocity. The r-f voltage drop across the discharge is maintained at a relatively low value by the formation of more ions and free electrons by collisions between electrons and neutral

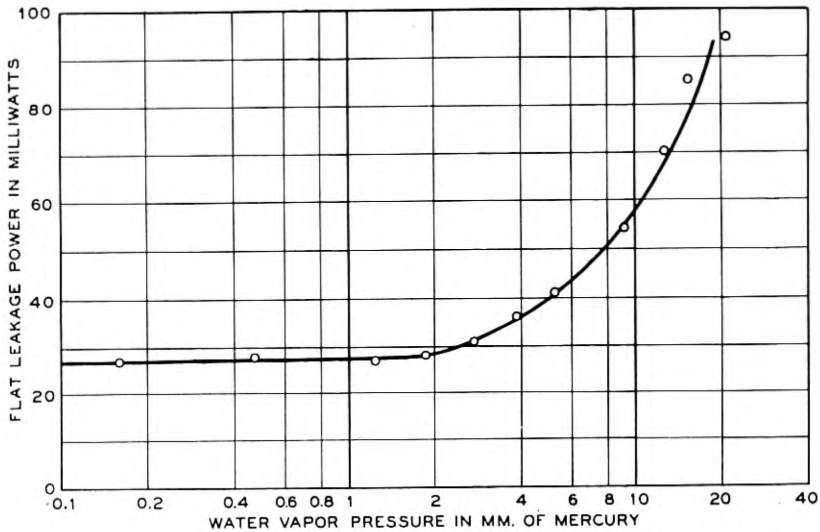


Fig. 23—The effect on leakage power of the addition of water vapor to 20 mm of hydrogen in the 721A type tube

molecules as soon as this voltage rises above some critical value. Measurements indicate that the voltage drop across the r-f gap is of the order of 80 to 100 volts for a typical TR tube. The variation in voltage drop with gap length may be inferred from the flat power measurements recorded in Fig. 24.

Direct Coupling. At very high transmitter power levels a third component of leakage power is observed which is directly proportional to the transmitter power. This component is usually called "direct coupling". It is due to the transmission of power through the cavity in modes which do not have voltage maxima at the gas discharge gap. It can therefore be observed even when the gap in the tube is short circuited. In fact measurements made under such short-circuited gap conditions yield results comparable to the values observed for actual tubes. The direct coupling component of the total flat power and the gas discharge limited component are found to be additive. Direct coupling power is logically measured in terms of db below the transmitter power level and for the usual TR box is of the order of 60 to 70 db. An abnormal form of direct coupling which may reach dangerous values can occur under certain improper operating conditions when the magnetron produces an appreciable amount of power at other than the normal operating frequency. Some of these spurious frequencies may be in the vicinity of the resonant frequencies for these "direct coupling"

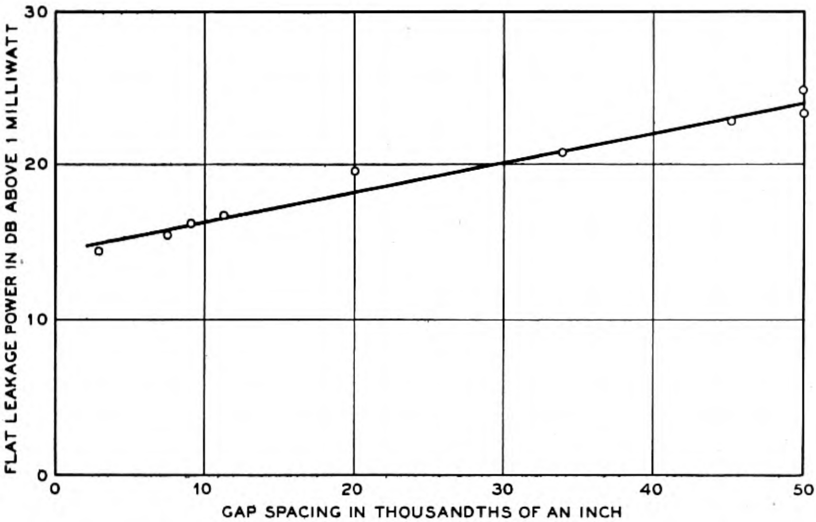


Fig. 24—The variation in flat leakage power with gap length, measured at 3000 megacycles

modes in the TR box and so be transmitted without much attenuation. Normally, direct coupling is of interest only in very high power systems.

Receiver Self-Protection. The fact was mentioned earlier that a receiver can provide itself with a certain amount of self-protection as a result of its change of impedance with level. This effect is still of use even in systems employing TR boxes. Unfortunately the apparent source impedance at the TR box output terminals is different for the different components of the leakage power so that the self-protection feature cannot be utilized for all components simultaneously. The matter is further complicated by the fact that the converter crystals themselves vary greatly in their impedance and in their variation of impedance with power level. The best designed converters as far as crystal protection is concerned are usually those which provide a certain amount of self-protection against the spike. It has been estimated that this self-protection seldom exceeds 2 db in practice.

Leakage Power Measurement. The c-w method of measuring the flat power has already been mentioned. Spike energy and direct coupling must, of course, be measured under normal high level operating conditions. Relative measurements of the spike can be made with an oscilloscope, acting ballistically, and the factors which affect the spikes can be studied in this manner. A correlation between the relative spike energies and the degree of crystal protection can be obtained by trial and from this correlation the operating conditions for adequate protection can be determined. Most of the early studies were made in this way. It is possible to deduce absolute values for spike energy, flat power, and direct coupling from measurements made when all three are present because of the different ways in which these parameters vary with the recurrence rate, pulse length and transmitter power. The method of doing this is outlined in appendix D.

A more precise method of measuring the spike energy involves the cancellation of the flat power by a signal of adjustable phase and amplitude obtained from the high-level transmission line. The average spike power is then measured directly and energy per spike computed. Most of the spike data quoted earlier were obtained in this fashion.

High-Level Loss. The power dissipated in the TR box as a result of the gas discharge is not ordinarily a large enough fraction of the total transmitter power to be of any concern. Using the P_0 values previously quoted, it is possible to compute the gas discharge power by the use of Fig. 16. At a line power of 100 kw and a low-level loss of 1 db the gas power in the 721A tube is 63 watts. The corresponding figure for a 1.5 db box using the 724B tube is 47 watts. For these cases the high-level loss is therefore less than 0.005 db. Low as this fraction is in db it still may be high enough to affect the life of the TR tube, as discussed in a later section. No trouble of this sort is ordinarily encountered with the 724B or 721A tubes. The chief cause of failure of the 1B23 is from loss of Q and this in turn is caused by the sputtering action of the high-frequency discharge.

Recovery Time. As mentioned earlier a TR box must recover its low-level properties at the end of the transmitting pulse in a very short period of time. The actual "recovery time" is in fact several orders of magnitude smaller than the deionization times of the usual gas discharge so that a quite different mechanism must be involved. While an exact theory of the recovery is beyond the scope of the present paper, a qualitative picture of the recovery process may be of interest.

During the transmitting period the free electrons provide almost all of the discharge current, and are replenished by electron-molecule collisions. At the end of the transmitting period these electrons may migrate from the discharge region, they may recombine with the positive ions, or they may be captured by molecules to form negative ions. Negative ion formation by attachment effectively removes an electron from the discharge because of the great increase in mass. It is an experimental fact that those gases which readily form such ions (of which water vapor is the most common) are the gases which exhibit good recovery in a TR box. This process is

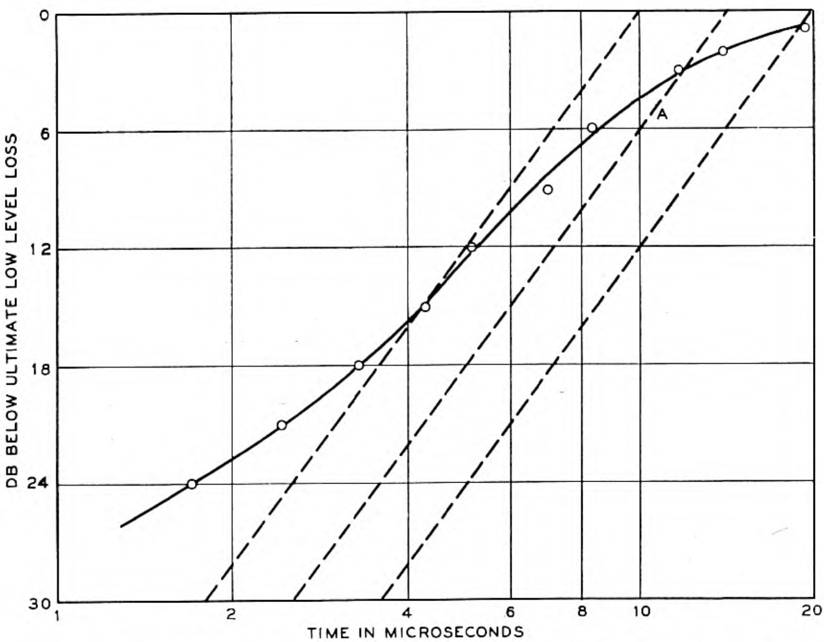


Fig. 25—A typical recovery time characteristic for the 721A tube in a TR cavity adjusted to 1.5 db low level loss with a transmitter power level of 100 kw peak

not deionization in the ordinary sense and it can take place at a surprisingly rapid rate.

Of course, immediately upon the termination of the transmitting pulse, the cloud of free electrons will cause an extremely high loss to any reflected signal but the loss will rapidly decrease to some limiting value set by the fixed losses in the TR cavity itself.

A typical recovery curve for the 721A tube is shown in Fig. 25. This curve has a particularly fortunate shape in that the variation in loss with distance, or more correctly with time, is at approximately the same rate as the variation in the reflected signal level with distance for a target of fixed size. The importance of this can be understood by considering the way in which the reflected signal intensity varies as an object of fixed size approaches a radar set from a great distance. Such an object as seen by a given radar set may be represented on Fig. 25 by a straight line having a slope of 12 db per factor of two in distance. Several such lines are shown. Considering line A it will be observed that this target can first be seen at a distance corresponding to 12 microseconds. Since this target line always remains below the TR recovery line for times shorter than that at the intersection point, an object once seen will remain in view continuously as it approaches

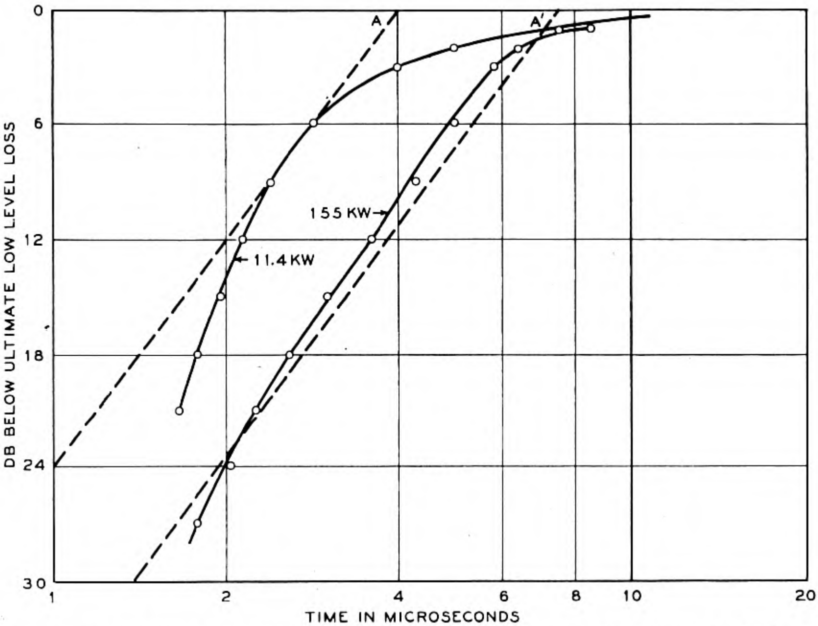


Fig. 26—The recovery time characteristic at two different transmitter power levels for the 724B tube in a 1.5 db TR box

the transmitter even in spite of the poor recovery characteristics of the TR box. A certain amount of sensitivity-time-control action is actually provided. The recovery time characteristic frequently does not necessarily set a lower limit on the effective range of a radar system although it always sets a limit on the smallest effective target size which can be observed.

The recovery time characteristic is critically related to the transmitter output power level as shown by the data for a 724B tube shown in Fig. 26. When the recovery time curves for two different power levels are compared, the target line which is just detectable at a power level of 11.4 kw is shown as the line marked A Contrasting with the 721A behavior this target would be visible only at one point and would then be lost from sight as it approached the transmitter. This same target is represented on the plot as line A′ for a transmitter output power of 155 kw, that is being displaced vertically by approximately 12 db to take account of the difference in transmitter power. At this higher power level the target would be visible at a much greater distance (corresponding to 7 microseconds elapsed time) and would remain in view until the target distance corresponded to 2.1 microseconds time. In this case an increase in power by 12 db resulted in an increase in range by a factor of 2.8. While this would indicate that an increase in range can be obtained by increasing the transmitter power, it should not be inferred that an increase in the near-range sensitivity will always result from an increase in power. At any specified range there appears to be a unique value of transmitter power output beyond which the loss in TR box recovery more than offsets any increase in range due to higher output powers. While accurate figures are not available for the 721A tube, there is some evidence that an output power of 100 kw is already too large for ranges corresponding to elapsed times of 10 microseconds or less. Under these conditions improved operation results from a decrease in the transmitter power level. Such an effect has never been observed by the writers with the 724B tube, probably because the transmitter powers available in its operating frequency range have usually been somewhat less than that available with the 721A tube.

It should be noted, at this point, that the recovery time does not depend upon the transmitter power only, but rather upon the gas discharge power which is a function of both the transmitter power and the low-level loss adjustment of the TR box as shown by Fig. 16. A very great improvement in near range sensitivity can usually be obtained by increasing the transmitter power level and at the same time increasing the low-level loss adjustment of the cavity to limit the gas power to a value for which the recovery time is satisfactory. This of course increases the ultimate low-level loss and so adversely affects the long-range sensitivity.

The dependence of the recovery time on the ambient temperature for the 721A tube is shown in Fig. 27. The 724B tube is much less temperature dependent. This variation in recovery time with temperature is caused by the reduction in water vapor pressure through condensation, as shown by the identity of the recovery curve for a standard 721A tube at $-186°$ C. with a special tube filled with hydrogen only.

With continued life the water vapor content of the tube decreases with the corresponding change in the recovery time characteristic. Fig. 28 shows the effect with the 721A tube. The dependence of the recovery time on the water vapor content in the 724B tube is shown in Fig. 29. Comparing this curve with Fig. 27, it will be observed that the loss of water vapor has much less effect on the recovery characteristics of the 724B tube than on the

721A tube. It should be noted, however, that the 724B tube frequently reaches the end of its useful life as a result of its failure to provide adequate receiver protection before serious loss of recovery occurs.

The ATR, if one is used, can also contribute to poor recovery as may be seen by referring to Fig. 30. These data are not necessarily representative since it is possible to adjust the length of line between the magnetron

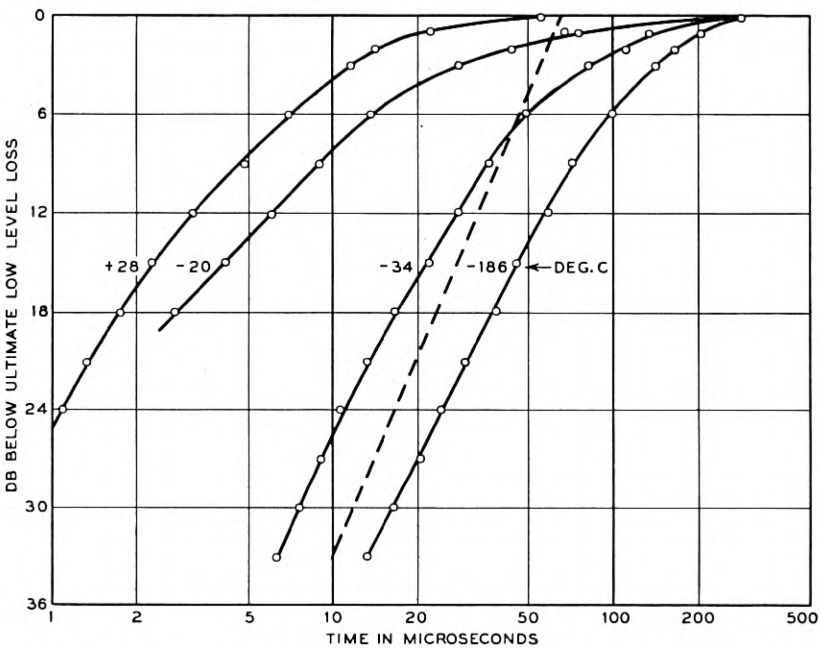


Fig. 27—The dependence of the recovery time on the ambient temperature for the 721A tube

and the ATR junction so as to minimize the effect. Nevertheless the effect is important and should not be overlooked.

Low-Level Loss. An analysis of the low-level loss must take into account two components of loss, the first resulting from power loss in the TR cavity itself and the second resulting from the fact that some power will always be absorbed by the transmitting branch of the system.

The relationships existing between the low-level loss adjustment of a TR box and its other performance characteristics have already been discussed. One aspect of the problem, not previously considered, has to do with the dependence of the performance on the Q of the cavity. This is clearly shown in Fig. 15 which has already been referred to in a different connection. From this aspect, at least, the higher the Q of the tube and its associated cavity the

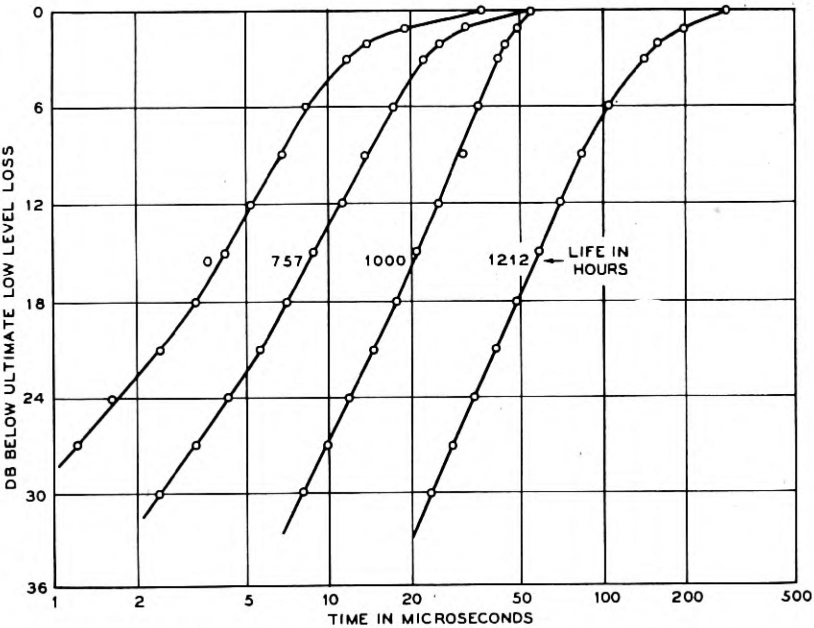


Fig. 28—The variation in recovery time with life for a typical 721A tube

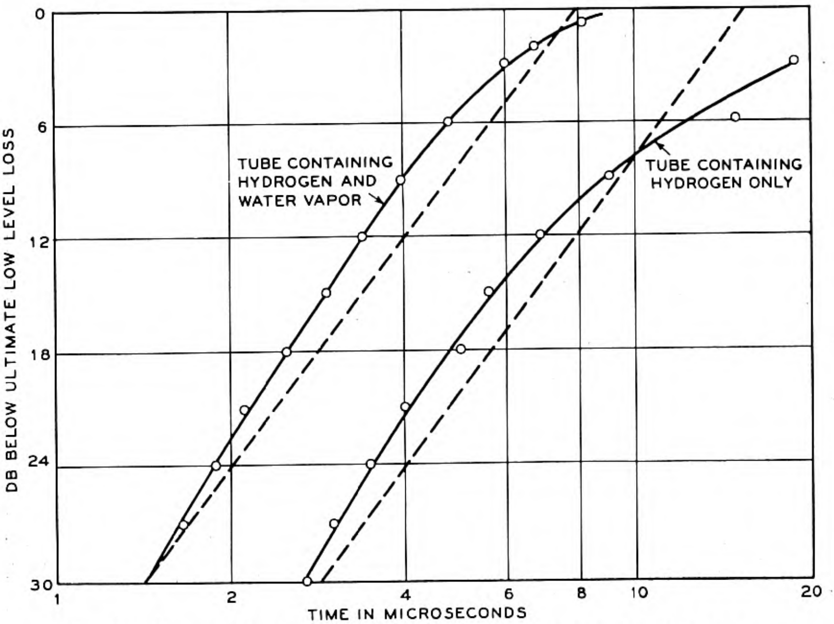


Fig. 29—The variation in recovery time with gas content for the 724B tube

better the over-all performance of the system.* Any basic improvement in Q can be reflected either in a lowering of the leakage power or in a reduction of the low-level loss, as may be desired.

Variations in the Q between tubes used in a given cavity of fixed design, are, however, seen as variations in the low-level loss only and have no

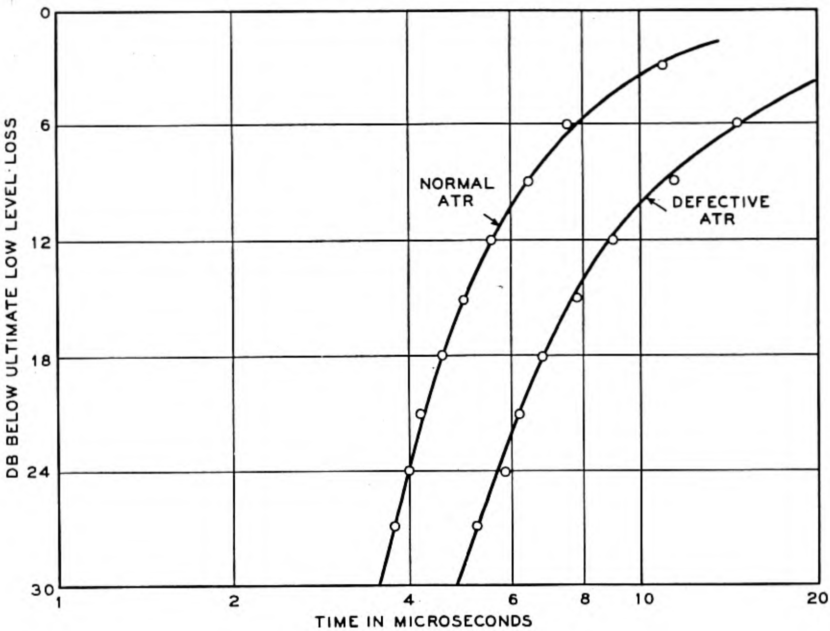


Fig. 30—The ATR recovery effect

noticeable effect on the leakage power. This may be understood by reference to the equations derived in appendix A. The performance of a somewhat idealized TR box may be expressed in terms of three design parameters δ_0, δ_1 and δ_2 which relate respectively to the properties of the cavity, its input coupling, and its output coupling; and in terms of a gas discharge parameter P_0. In terms of these new parameters the in-tune low-level tansmission of a TR box is given as a power ratio by

$$T = \frac{4\delta_1 \delta_2}{[\delta_0 + \delta_1 + \delta_2]^2}. \qquad (12)\dagger$$

* As explained later in this section, band width limitations set an upper limit to the permissible Q.

† Numbered equations in the text correspond with the numbers used in the appendices.

The input standing wave ratio on the input line is given by

$$\sigma = \frac{\delta_1}{\delta_0 + \delta_2}. \tag{13}$$

The leakage power is similarly given by

$$P_r = P_0\,\delta_2 \tag{14}$$

while the gas-discharge power in terms of these parameters and the power in the transmitting line (P) is given by

$$P_g \doteq (P\,P_0\,\delta_1)^{1/2} \tag{19}$$

The parameters δ_1 and δ_2 are properties of the input and output coupling as they are geometrically related to the cavity and are substantially independent of the Q of the cavity. The parameter δ_0 is, however, the reciprocal of the intrinsic or unloaded cavity Q. Equation 12 is seen to depend upon δ_0 but equations (14) and (19) do not. The effect of variations in Q is thus demonstrated.

The over-all performance is also affected by the relative values of δ_1 and δ_2. In view of the dependence of P_r on δ_2 directly and on δ_1 indirectly through the fact that P_0 is not entirely independent of P_g, it is advantageous to adjust the values of δ_1 and δ_2 so that the input standing wave ratio (σ of equation 13) is unity. Such a condition is also very desirable for system reasons as well. When this condition is met, equation (12) reduces to

$$T = \frac{\delta_2}{\delta_1}.$$

The curve marked $\sigma = 1$ of Fig. 15 and the curve of Fig. 16 were plotted on this basis. It should be noted that matched input requires that the input window be larger than the output window.

TR boxes are unfortunately not always operated in the in-tune condition, and they must also pass a band of frequencies as fixed by the narrowness of the transmitter pulse. For these reasons the Q must not be set at too high a value. The additional low-level loss which results from off-tune operation may be computed from equation 28 of appendix A.

Incidentally, it is an experimental fact that the leakage power and the gas-discharge power are not materially altered by small departures from the in-tune adjustment, presumably because of the very low effective Q of the gas discharge.

The ATR Low-Level Loss Component. The component of low-level loss which results from losses of power to the transmitting branch depends very greatly upon the "cold impedance" of the magnetron or other transmitting tube and upon the properties of an ATR box if one is used. As shown in appendix C the loss chargeable to the ATR and the associated transmitting arm can be expressed as a factor F given by

$$F = \frac{4}{(2 + G)^2 + B^2} \tag{33}$$

where G and B are respectively the conductance and susceptance of this branch in units of the surge admittance of the transmission line. Since

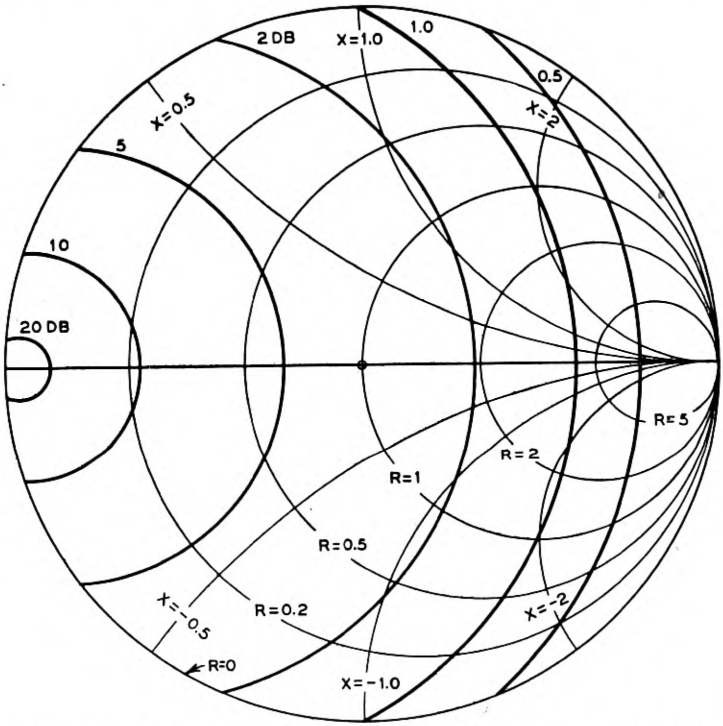


Fig. 31—Curves for constant ATR loss in db as a function of the impedance of the transmitting branch

curves for constant values of F appear on the reflection coefficient plane (Smith transmission line chart) as circles this presentation is very convenient. Fig. 31 is such a plot (impedance circles rather than admittance circles are shown).

If now an ATR is introduced having a resistive component of impedance the range of values of G and B is restricted so that a minimum value of F exists for any random value of the magnetron impedance. With variations in the magnetron cold impedance or in the effective length of line between the magnetron and the ATR junction the value of F will vary between this minimum value and some maximum value which may approach unity. For example if the ATR is adjusted to have the same gas-discharge power as that in a TR adjusted for a transmission of T, its low-level in-tune input impedance will be

$$Z = \frac{1}{1 - T}. \tag{38}$$

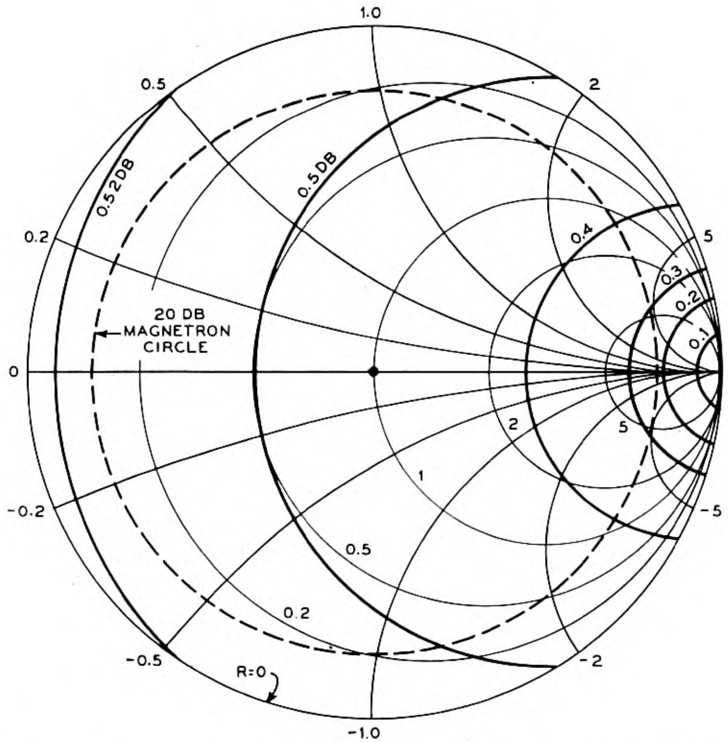


Fig. 32—The ATR low level loss as a function of the magnetron impedance with an ATR adjusted to an impedance of $8 + j0$

Actually since the gas-discharge power is usually not the limiting factor in the design it is possible to adjust the ATR to have an input impedance of 8 or 9 (in terms of the line characteristic impedance), corresponding to a TR low-level transmission of the order of 1/2 db ($T = 0.89$) and yielding an ATR loss of approximately 1/2 db.

Since the exact value of the impedance of the magnetron branch is not necessarily known it is convenient to show the dependence of the loss factor F for any given ATR on the magnetron impedance by a plot somewhat similar to Fig. 31 but transformed to the magnetron side of the ATR junction. This may be done by subtracting the ATR impedance from the values read off of Fig. 31 corresponding to desired values of F and replotting these on the reflection coefficient plane. As an example, the in-tune value of Z for one typical 724B ATR cavity is $8 + j0$. Points lying on the $R = 8$ circle on Fig. 31 will then lie on the magnetron $R = 0$ circle, the region inside being distorted and expanded to fill the entire positive R region on the reflection plane. The results are shown in Fig. 32. From this plot it is evident that the maximum possible low-level loss chargeable to the transmitting branch would be slightly more than 0.52 db and that this would occur only for a restricted range in the value of magnetron impedance. As a matter of practical interest the "cold impedance" of the usual magnetron is such as to give at most a 20-db standing wave. This restricts the possible range in impedance values to the area on Fig. 32 within the dotted circle, thus limiting the maximum loss to slightly less than 0.52 db, and imposing a minimum loss limit of 0.22 db.

This type of analysis may be extended to consider the ATR loss during the recovery period if desired although the problem becomes rather complicated as a result of the simultaneous variation in input impedance of both the TR and the ATR.

TR Box Design Considerations

The desired electrical properties for a TR box can of course be achieved in a variety of different physical structures. A construction technique which separates the gas-discharge tube from the rest of the TR box cavity offers many advantages. In the first place the cost of the entire device is kept low by reason of the fact that it is not necessary to transmit the tuning motion through the vacuum-tight tube enclosure. The replacement cost is also greatly reduced since the more complicated part of the TR box is a permanent part of the equipment. Then, the same tube structure can be used for a variety of different types of equipment operating in different wavelength bands and requiring different amounts of receiver protection by the use of different size cavities and different size coupling windows. This greatly simplifies the problem of maintaining replacement stocks. An additional factor, which was of importance during the early days of the war, is that the design of such a tube can be frozen at an early stage, before all the possible circuit aspects of the TR problem have been solved since changes in the external parts of the TR box can be made independent of the design of the replaceable tube element. The widespread use of the 721A and 724B vacuum tube is, in a sense, proof of the essential soundness of the arguments for the external cavity type of construction.

The chief difficulty to be overcome in the design of a separate cavity type of TR box has to do with the need for a low-loss contact between the internal portions of the tube and the external cavity. A copper-disc sealing technique, developed at the Bell Laboratories in connection with the construction of water cooled tubes* and later superseded by the now conventional Housekeeper seal, had previously been applied at ultra-high frequencies in the design of oscillators and amplifiers. This technique makes possible very satisfactory high-frequency connections by simply clamping the external portion of the disc between machined surfaces. The flexibility of the copper discs is sufficient to compensate for minor machining errors and for differential thermal expansions while the relative softness of the copper insures a continuous contact around the entire periphery. The goodness of contact provided by these contacts is evidenced by the fact that Q's of 4000 and greater are obtained at 3000 megacycles with discs of the 721A type. This technique was therefore adopted for the 721A tube and the 724B tube and for one electrode of the 1B23 tube. The second high-frequency electrode of the 1B23 was made in the form of a rod terminating in a ball for convenience in replacing tubes since the accompanying loss of Q can be tolerated in the frequency range where this tube is used.

In an external cavity type of TR box the over-all goodness of the design is largely determined by the design of the gas-discharge tube. It is the tube designer's responsibility to determine the optimum shape and size for the copper discs and for the glass tube envelope and to determine the optimum gas composition and pressure, with due consideration being given to such matters as mechanical ruggedness, manufactureability and freedom from undesirable ambient temperature, pressure and humidity effects.

With the copper-disc type of tube the system designer has at his disposal the ability to vary the design of the external cavity, and to arrive at any specific compromise between the various conflicting performance criteria which he feels to be the best for his particular application. For example, in systems employing vacuum tube converters it is customary to adjust the TR box for a low-level loss of 1 db or somewhat less since receiver protection is of minor interest while in systems employing crystal converters it is customary to fix the low-level loss at 1.5 db or sometimes as high as 2.0 db. Certain cavities, notably the one shown in Fig. 5, have to be designed to have an extended tuning range, in this case achieved by a piston tuner with, however, some loss in Q, while other cavities, the one shown in Fig. 11 being typical, do not require this same tuning range and a different tuning mechanism (in this case, tuning plugs) can be employed.

An extreme example, illustrating the advantages to the system designer

* W. Wilson, "A New Type of High-Power Tube," *B. S. T. J.*, vol. 1, p. 4, July 1922.

of the external cavity type of tube, is that of certain radar systems which were required to be capable of receiving signals on occasion at a frequency differing from their normal tuning. This was done by a solenoid-operated plunger which could be preset to alter the tuning of the cavity by the desired amount whenever the solenoid was energized.

The Tube Design

The 702A and 709A vacuum tubes, as previously mentioned, were put into service with little or no consideration of their real suitability. With these stop-gap designs in production the basic design problem was given serious consideration, with separate studies being made of the mechanical design considerations as they relate to the size and shape of the discs and glass of the tube, and of the gas filling.

The exact shape of the disc is determined first by the total tuning range which is to be required of the tube, and second by the necessity for maintaining the Q of the structure as high as possible. It has been shown that in a spherical resonator with coaxial cones the maximum Q occurs when the cone half-angle is nine degrees. The copper-disc tube can only roughly approximate the ideal spherical resonator; nevertheless it appears desirable to use cones of this angle. The disc spacings and diameters are so chosen that the tube resonates at the shortest wavelength at which it is to be used in a "square" cavity; i.e., one in which the inside diameter approximately equals the height. Such a cavity is about the closest practical approach to a sphere. The glass diameter is made as large as mechanical considerations permit so it is as far as possible removed from the region of high electric field intensity.

The experimental results of Fig. 24, previously noted, indicate that the leakage power of a TR box decreases as the gap spacing decreases; thus one is tempted to make the gap extremely small. Too small a gap is very troublesome, however, since such a gap has an unreasonably rapid variation of resonant frequency with gap separation, making the tuning extremely subject to change as a result of dimensional variations due to processing or to temperature changes. Accordingly one chooses a compromise gap separation. The electrode radius at the gap must be large enough to permit the radio frequency glow discharge to dissipate the required power without excessive spreading, and must be determined by experiment.

Rather than attempting to hold all of the mechanical variations in the tube (including glass thickness) to the necessary tolerances to insure the desired uniformity in tuning, the tubes are pretuned before exhaust by deforming the copper discs. The tubes are placed in a special cavity and the disc inside the envelope distorted by a tool until resonance is obtained at a specified frequency. It is quite easy to tune tubes in this way so that they are uniform to within $\pm$ 0.25%.

Unless the tube is properly designed, changes in ambient temperature may seriously affect its resonant frequency. The part of the disc which is inside the glass envelope may be considered as a diaphragm supported around its periphery by the glass which has a temperature coefficient of expansion negligibly small compared to that of the copper. An increase in temperature, which causes the copper to expand, will force the cone tip to move toward or away from the gap, depending on the initial slope of the nearly flat portion of the disc. The temperature coefficient of frequency may be either positive or negative, and will have extreme variations in magnitude from tube to tube if consideration is not given in disc design to avoid such difficulties.

A cavity made wholly of copper will have a fractional change in wavelength with temperature the same as the fractional change in length of copper (approximately fourteen parts in a million per degree centigrade). As the temperature increases, the frequency decreases. At a frequency of 1000 mc, the approximate temperature coefficient of frequency is $-.014$ megacycles per degree centigrade; at 3000 mc it is $-.042$ mc/°C; and at 10,000 mc it is $-.14$ mc/°C. Magnetrons normally have temperature coefficients of about these magnitudes. The ideal TR tube would have the same coefficient as the magnetron; practically speaking, any coefficient between zero and twice the value for copper is satisfactory.

It is practical to make a copper disc structure which has the required temperature coefficient. Fig. 33, which is a cross-section of a 721A tube, shows how temperature compensation within the tube is effected. The disc is slanted away from the center portion of the tube, so that as temperature rises the cone is carried away from the gap. At the same time the cone itself expands; the net effect is to increase the gap between the two cone tips. The angle of the slanted part of the disc must be such that the gap increases with temperature at the same rate that it would in an all-copper cavity. If this condition is fulfilled, the net result of the expansion of all the tube parts, and of the cavity itself, will be the same as if it were all made of copper. This result is achieved by an experimental series of successive approximations. A number of models are built until the angles are found which give the desired temperature coefficient of frequency.

The gas content of the tube was the subject of considerable study. As stated in the section on Recovery Time, gases which readily form negative ions are invariably the most satisfactory from that viewpoint. Gases of low ionization voltage, such as the rare gases, give excellent protection but usually have extremely poor recovery. The choice of a TR gas must of necessity be a compromise between the two requirements. Some otherwise satisfactory gases are not useful because of other characteristics. HCl is an excellent TR gas, but is very corrosive. Freon, a common refrigerant, is excellent but is unstable. In general, no gas which contains a solid elementary constituent is a satisfactory TR gas. The most satisfactory gas found was water vapor. It is cheap, stable, and easy to handle. Water vapor alone is not safe to use at a low temperature, so a small amount of hydrogen is added to ensure adequate protection when the water vapor is frozen out.

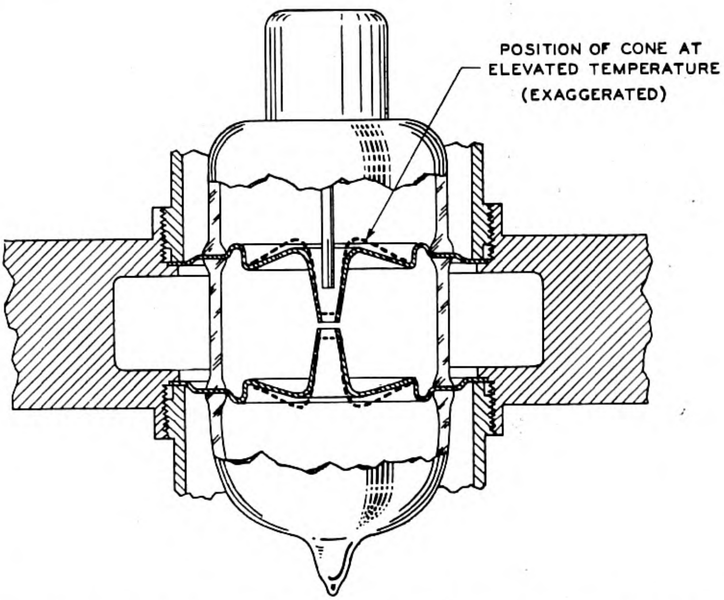


Fig. 33—Cross section of a 721A TR Tube, showing the special shape of the temperature compensated discs

The life of a TR box is in general determined by the gas volume. The radio-frequency discharge consumes no gas except at extremely high power levels; the igniter discharge accounts for the greater part of the loss of the gas initially placed in the tube. Reduction of the water vapor to hydrogen by formation of copper oxide on copper parts of the tube seems to be the principal process which goes on. This change results in no change in total pressure until the water vapor is exhausted; thereafter sputtering becomes more important and accounts for a fairly rapid hydrogen clean-up. The life of a TR tube is determined by the igniter current, which is maintained at a value as small as possible consistent with adequate spike protection, and by the volume of the tube.

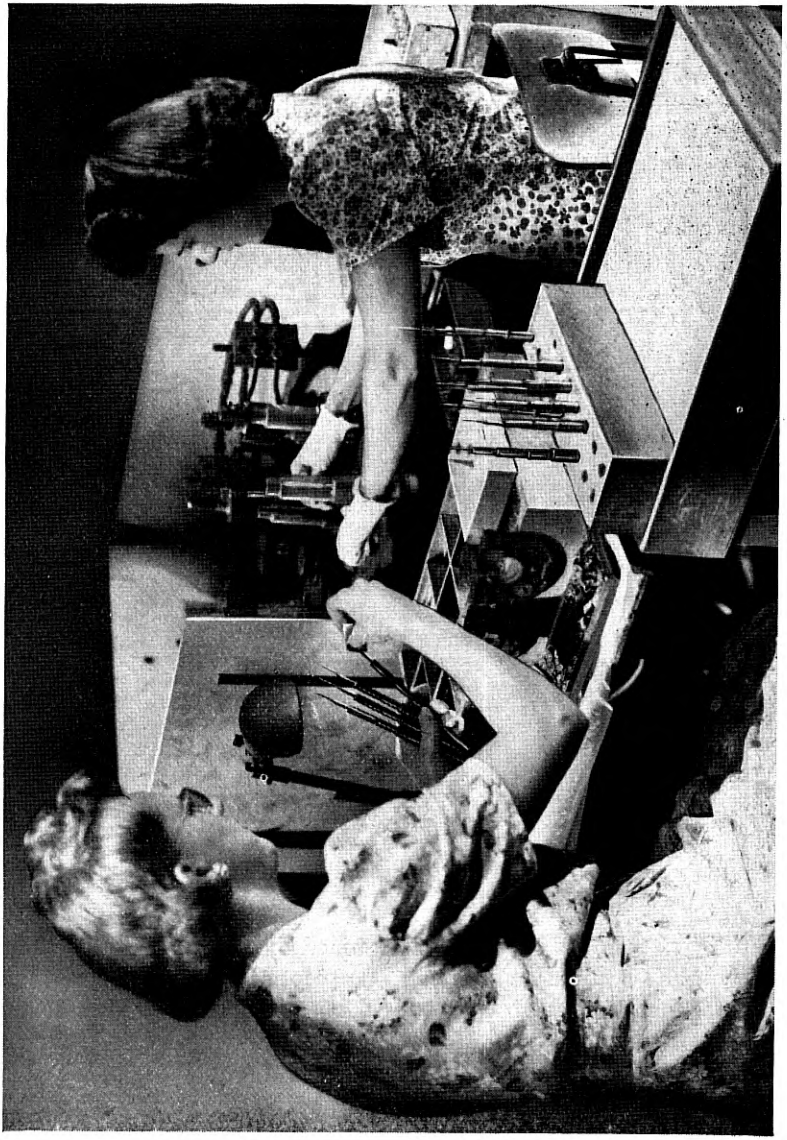


Fig. 34—Setup for making 724B copper-to-glass disc seal

The lack of water vapor in a tube which has been operated for some hundreds of hours may manifest itself by a failure in either protection or recovery time. The operating frequency determines which failure becomes important first; at long wavelength it is likely to be recovery, while at shorter wavelength the spike protection is likely to fail first.

The life of a TR tube operated without igniter is very much longer. This may be understood from the picture given above under "recovery," of the state of affairs existing in the radio-frequency discharge. Electrons do not completely traverse the gap, but oscillate about some mean position, while the positive ions hardly move at all. Thus there is little more interaction between the metal electrodes and the gas molecules with the R.F. discharge on than with it off. A few 721A's have been operated without igniter for as long as 5000 hours with no measurable change in either protection or recovery. This experiment was done at a transmitter power level of 250 kw. peak power. The best life that can be expected with the igniter operating at 100 microamperes is 500 hours, at which time the recovery time is badly deteriorated. In order to maximize the life of the tube, the initial gas filling consists of a minimum amount of hydrogen and as much water vapor as may be introduced without causing excessive leakage power (see Figs. 20 and 23).

Manufacturing and Testing

Some interesting problems occur in the manufacture of copper-disc seal TR tubes which are quite different from those encountered in the construction of more conventional tubes. The copper-disc seals are usually made by high-frequency induction heating. Close control of the spacing between discs must be maintained during the bulb-making operation in which the discs are fused to the glass parts of the tube. One way of accomplishing this is shown in Fig. 34, which depicts a machine setup for making the 724B TR tube. The parts are held by lavite forms which support and locate them during the bulb-making process. The seal is made possible by a correct choice of copper thickness. The copper disc is stressed due to forces set up by the different expansion coefficients of the glass and the copper, and if too thick will pull the seal apart. If too thin, the copper itself will tear. Nevertheless, a properly designed copper-disc seal is very strong; the copper-disc seal TR tubes will pass the JAN1-a* mechanical and thermal shock tests for glass tubes without any difficulty.

The electrical pretuning operation, referred to earlier, comes right in the middle of the manufacturing process. Before the igniter is sealed in, the bulb is placed in a special pretuning cavity. The setup includes an oscillator

* Joint Army-Navy Specification for electron tubes.

of appropriate frequency range, a wavemeter, and some device for indicating resonance. The part inside the glass of one of the copper discs is bent, by gentle tapping, until the resonant frequency of the bulb in the special cavity is within the required tolerance (which may be as small as 0.25%) of the pretuning frequency.

No heat treatment of any kind is used in the pumping of TR tubes. It is obviously unnecessary to subject the tubes to the usual baking, the principal purpose of which is to remove water vapor film from the tube parts. On

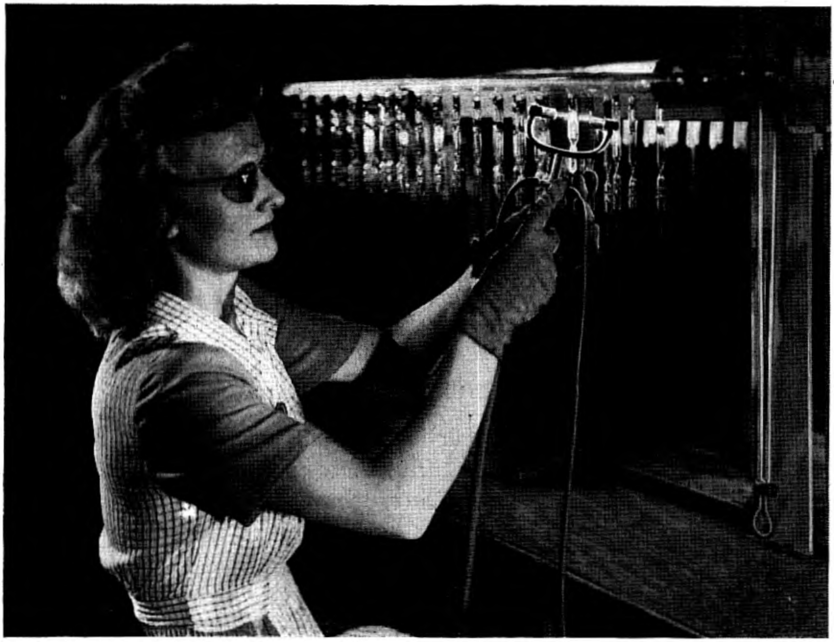


Fig. 35—Pump Station for the 724B Vacuum Tube

the contrary, it is difficult to control the water vapor pressure in tubes which have been baked as the parts absorb a surprising quantity of water. The tubes are filled to fairly high pressure, so a diffusion pump is not necessary. Fig. 35 shows a pump station used in production of the 724B.

The test procedure for TR tubes must verify that each individual tube will fulfill its fourfold function of protecting the crystal, of recovering rapidly, and of introducing neither excessive high-level loss nor excessive low-level loss. The tuning of each tube must be verified, and it must pass mechanical and dimensional tests. Fortunately a tube which is otherwise sound will never introduce excessive high-level loss, so no specific test is required.

The protection test may be made either with a c-w oscillator of sufficiently high level to ionize the TR tube gap, or with a magnetron in the equivalent of a radar microwave head. The high-level test bench used for the 724B is shown in Fig. 36. This bench uses a radar microwave head fitted to special plumbing. In either case, the leakage power is measured at a specified R.F. level. For production testing, an actual measurement of recovery time is not used. Instead a test which measures the quantity of

Fig. 36—High Level Test Bench for the 724B Vacuum Tube

water vapor in the tube in a relative way has been developed. This test involves touching some part of the tube envelope with a piece of carbon dioxide ice, so that most of the water vapor is frozen out forming a small spot of ice on the inside of the tube. Only the hydrogen remains, and the resulting change in either the leakage power or the igniter arc drop is indicative of the quantity of hydrogen and of water vapor in the tube. Careful correlation must be made between this simple dry-ice test and absolute recovery time measurements; experience has shown the dry-ice test to be reliable and in the hands of a skilled operator very informative.

Low-level loss and tuning are checked at such low level that the gas does not ionize in a cavity of restricted tuning range. Every tube must resonate within the range of the tuning adjustment, and the transmission loss through the test cavity must not be excessive.

Two additional tests are made at the time the d-c igniter characteristics are checked. One, igniter interaction, is important in the 721A, the 10 cm. TR tube. This tube has rather large openings in its cone tips, so that if the igniter electrode is sealed in too close to the cone tip, the glow discharge which surrounds it may extend out into the gap. Such a defective tube will show igniter interaction; the low-level loss through it will be more when the igniter arc is on than when it is off. Normal tubes do not show this effect.

The 724B 3 cm. TR tube has such a tiny opening in its cone tip that igniter interaction does not occur. The tube is more subject to igniter oscillations, perhaps because it is filled to a higher gas pressure. The consequences of these oscillations was explained in the section on The Spike. Igniter oscillations are usually due to an improper gas filling, and are detected by means of a cathode ray oscilloscope.

The above tests are made on each tube as it comes off the production line. Some additional tests are made on selected samples to insure that the quality is being maintained. Selected tubes are subjected to mechanical shock tests and to temperature variation tests to verify both their resistance to thermal changes and that their temperature coefficient of frequency is not excessive. Absolute recovery time, Q, and leakage power tests are made on these tubes, and some are set aside for life testing. By all these tests the important electrical properties of the tube are under constant scrutiny and the danger of shipping defective tubes is minimized. The importance of adequate testing can hardly be over-emphasized, as a defective TR tube may render a whole radar system inoperative.

Acknowledgements

Because of the very close liaison maintained during the war period between various industrial and governmental laboratories, the developments described in this paper were carried on with the constant advice and criticism of many individuals. It is not therefore possible to assign credit to specific individuals for any particular aspect of the work with any certainty. The authors would be remiss, however, were they not to call attention to the many contributions made at the M.I.T. Radiation Laboratory particularly by members of the group under the direction of Dr. J. R. Zacharias and later Dr. A. G. Hill. Colonel J. W. McRae assisted in the early formulation of the TR problem and Captain A. Eugene Anderson did much of the original development work on the 724B tube while at the Bell Laboratories and was later involved in the formulation of test methods and test limits in connection with his Signal Corps work. Mr. C. F. Crandell of the Southwestern

Bell Telephone Company, while at the Bell Laboratories, was responsible for the construction of test equipment and for most of the recovery time measurements reported in this paper. At various periods during the development work Messrs. A. B. Crawford, V. C. Rideout, G. M. Eberhardt and J. P. Schafer were closely associated with the measurement of the system performance of TR tubes. Mr. R. M. Purinton of the Bureau of Ships deserves much credit for his encouragement and assistance in the standardization program which led to the adoption of the 721A and 724B tube designs by all manufacturers. The Thermionics Branch of the Evans Signal Laboratory provided the bulk of the electrical standardization, calibration and engineering service associated with these tubes and assisted in the development of improved test methods. The magnificent production job done by the Western Electric Company and by other manufacturers, particularly by the Sylvania Electric Products Inc. in making these tubes available to the armed services also deserves mention. Perhaps the final mention should go to the many circuit design engineers both within the Bell Laboratories and elsewhere who handled the many difficult problems relating to the design and use of TR cavities in actual radar systems.

APPENDIX A

Analysis of the Idealized TR Box

Schelkunoff has shown* that the impedance of a resonant cavity can be represented in terms of its resonant frequencies as

$$Z = \sum_a \frac{Z_a}{j\left(\frac{\omega}{\omega_a} - \frac{\omega_a}{\omega}\right) + \frac{1}{Q_a}} \tag{1}$$

or in the vicinity of any single resonance as

$$Z = Z_1 + \frac{Z_n}{j\left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right) + \frac{1}{Q_n}}. \tag{2}$$

Under most conditions the Z_1 term is negligibly small. We are therefore justified in thinking of the generalized resonant cavity used as a TR switch as a shunt resonant circuit to which are coupled input and output circuits. For the moment we will consider (1) that these external circuits are resistive only, (2) that the Z_1 in equation (2) is zero; and (3) we will restrict the analysis to the in tune condition.

When the cavity is excited by energy supplied from the input circuit there exists in the cavity a certain amount of reactive power which will be

* S. A. Schelkunoff, "Representation of Impedance Functions in Terms of Resonant Frequencies," *Proc. I.R.E.*, vol. 32, pp. 83–90, February (1944).

designated by the symbol P_0. Of this power, a certain fraction δ_0 is dissipated as losses in the cavity itself where

$$\delta_0 = \frac{1}{Q_0}. \tag{3}$$

The symbol Q_0 with the subscript is further defined as the intrinsic Q, that is, the Q without external loading, to differentiate it from the more general Q_L which is the measured Q when the cavity is loaded down by external coupling. It should be noted that this definition of δ differs from the logarithmic decrement by a factor π.

When coupled to the external circuits the loaded δ is increased. On the assumption that the loading effects of the input and output irises are independent we can write

$$\delta_L = \delta_0 + \delta_1 + \delta_2 \tag{4}$$

where δ_L is the loaded δ, and δ_1 and δ_2 are respectively the input and output loadings. Physically the assumption underlying this expression is that the distribution of electromagnetic fields within the cavity is not seriously altered by the input and output coupling devices. This assumption should certainly be valid as long as the absolute values of the δ's are very small compared to unity. Since the δ's usually encountered are of the order of 10^{-3} or less, the assumption seems to be justified.

Equation (4) may be written

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \delta_1 + \delta_2 \tag{5}$$

The values of δ_1 and δ_2 evidently depend upon the ratio of the apparent series resistance which the external coupling introduces into the resonant cavity to the effective reactance of the cavity, that is,

$$\delta_1 = \frac{k_1^2 R_1}{X} \tag{6}$$

where k_1 is the transformation ratio of the input coupling device, R_1 is the resistance of the input circuit and X is the cavity reactance. Similarly

$$\delta_2 = \frac{k_2^2 R_2}{X}. \tag{7}$$

The values of the δ's may be equally well considered as the ratios of the coupled conductance to the shunt susceptance of the cavity considered as a shunt resonant circuit so that equations (6) and (7) become

$$\delta_1 = \frac{G_1}{k_1^2 B} \tag{8}$$

and

$$\delta_2 = \frac{G_2}{k_2^2 B} \tag{9}$$

when the R's and X are replaced by their reciprocals and transformed from a shunt to a series circuit.

The equivalent circuit is shown in Fig. 37, where for convenience everything is referred to the cavity and the sources for receiving and transmitting are represented by constant current generators, I and I_m respectively.

The Low-Level Transmission. We are now in a position to express the low-level transmission of the cavity. For this purpose we will assume that

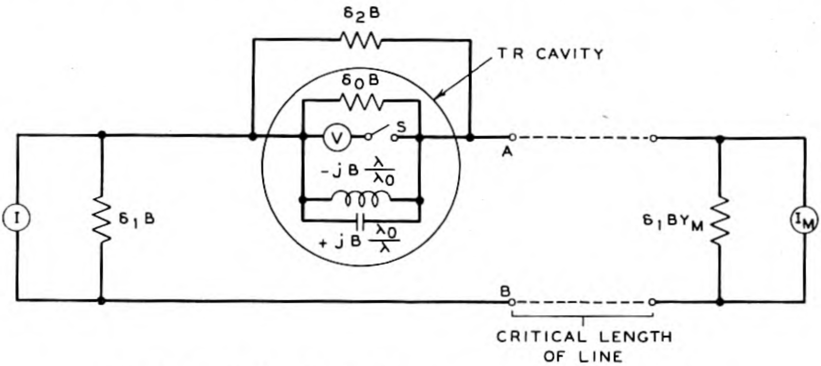


Fig. 37—Equivalent circuit of a system referred to the TR cavity

the admittance of the transmitting branch at plane AB is infinite. The available power is given by

$$P_{\text{avail}} = \frac{I^2}{4\delta_1 B}. \tag{10}$$

while the power actually going into the load is given by

$$P_{\text{out}} = \frac{I^2 \delta_2 B}{(\delta_0 + \delta_1 + \delta_2)^2 B^2} \tag{11}$$

the power transmission ratio defined as T is given by

$$T = \frac{4\delta_1 \delta_2}{(\delta_0 + \delta_1 + \delta_2)^2}. \tag{12}$$

One additional expression is desired. This is the ratio of cavity input resistance to the resistance of the input circuit. This is evidently the reciprocal of the conductance ratio and is given by

$$\sigma = \frac{\delta_1}{\delta_0 + \delta_2}. \tag{13}$$

The symbol σ is used to call attention to the fact that the in tune impedance ratio is numerically equal to the voltage standing wave ratio on the input line.

The low-level behavior of the cavity is thus defined by three equations.

$$\delta_L = \delta_0 + \delta_1 + \delta_2 \tag{4}$$

$$T = \frac{4\delta_1 \delta_2}{(\delta_0 + \delta_1 + \delta_2)^2} \tag{12}$$

$$\sigma = \frac{\delta_1}{\delta_0 + \delta_2}. \tag{13}$$

High-Level Operation. The high-level performance of the cavity containing a gas discharge can be expressed directly in terms of our original definitions. Fig. 37 still applies, the transmitter admittance changing to its operating value which is assumed to be $\delta_1 B$ at the plane AB. When the gas discharge becomes conducting, the switch S is closed, the value of the reactive power in the cavity (P_0) is set by the character of the discharge and the leakage power is given by

$$P_r = P_0\delta_2. \tag{14}$$

A constant value of P_0 is equivalent to a constant value of V in the figure. The power dissipated in the cavity walls, the gas discharge and in the output circuit must evidently be given by

$$P_1 = \frac{I_m V}{2} = (PP_0\delta_1)^{1/2} \tag{15}$$

if

$$V << I_m/\delta_1 B.$$

Of this power an amount called the excitation power

$$P_e = P_0\delta_0 \tag{16}$$

is lost in the cavity walls. The net loss of power in the gas discharge is given by

$$P_g = P_1 - P_r - P_e \tag{17}$$

or

$$P_g = (P\,P_0\delta_1)^{1/2} - P_0(\delta_0 + \delta_2). \tag{18}$$

Since the last term is usually very small compared to the first term, we may write

$$P_g \doteq (P\,P_0\delta_1)^{1/2}. \tag{19}$$

This equation was used for plotting Fig. 16, where δ_1 is replaced by its equivalent in terms of σ, Q_0 and T.

The Derived g Parameters. For some purposes it is convenient to eliminate δ_0 from the expressions for T and σ. This may be done by defining

$$g_1 = \frac{\delta_1}{\delta_0} \tag{20}$$

and

$$g_2 = \frac{\delta_2}{\delta_0}. \tag{21}$$

Introducing these new parameters the equations become

$$\frac{Q_0}{Q_L} = 1 + g_1 + g_2 \tag{22}$$

$$T = \frac{4g_1 g_2}{(1 + g_1 + g_2)^2} \tag{23}$$

$$\sigma = \frac{g_1}{1 + g_2} \tag{24}$$

$$P_r = P_e g_2 \tag{25}$$

$$P_g = (PP_e g_1)^{1/2} \tag{26}$$

The g parameters are particularly useful in defining the behavior of a tube and cavity combination when δ_0 is a fixed quantity while the effects of changes of δ_0 are more clearly shown when the δ parameters are used. The g parameters may be determined experimentally, using equations (21) and (22) without knowing the value of δ_0, that is of Q_0. On the other hand the g's are altered if a tube is replaced by one giving a different Q value while the δ's are intrinsic properties of the coupling mechanisms and remain fixed as long as the cavity and the tube tune at the same frequency and have the same effective reactance.

Tabulation of Related Equations. In the interest of completeness a number of the more important combinations of the basic equations are listed in Table 1. Some of these are of interest for measurement purposes while others apply particularly to actual system conditions.

Off-Resonance Analysis. The analysis can be extended to predict the transmission when the cavity is detuned from resonance by introducing the necessary susceptance term in equation (11) above and solving for T. This gives for the absolute value (neglecting phase)

$$T = \frac{4\delta_1 \delta_2}{[\delta_0 + \delta_1 + \delta_2]^2 + \left[\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}\right]^2} \tag{27}$$

TABLE 1.—*Relations between Cavity Parameters*

	Quantity	Symbol	General Expressions: In terms of δ's & Q_0	General Expressions: In terms of σ, T, & Q_0	Special Cases: TR case $\sigma = 1$	Special Cases: ATR case $T = 0$
Low level parameters	Input standing wave ratio	σ	$\frac{\delta_1}{\delta_0 + \delta_2}$	σ	1	$\frac{Q_0}{Q_L} - 1$
	Low Level Transmission	T	$\frac{4\delta_1 \delta_2}{(\delta_0 + \delta_1 + \delta_2)^2}$	$\frac{4\sigma}{(1+\sigma)^2}\left[1 - (1+\sigma)\frac{Q_L}{Q_0}\right]$	$1 - 2\frac{Q_L}{Q_0}$	0
	Q ratio	$\frac{Q_0}{Q_L}$	$(\delta_0 + \delta_1 + \delta_2)Q_0$	$\frac{4\sigma(1+\sigma)}{4\sigma - (1+\sigma)^2 T}$	$\frac{2}{1-T}$	$1 + \sigma$
	Input δ	δ_1	δ_1	$\frac{4\sigma^2}{[4\sigma - (1+\sigma)^2 T]Q_0}$	$\frac{1}{(1-T)Q_0}$	$\frac{\sigma}{Q_0}$
	Output δ	δ_2	δ_2	$\frac{(1+\sigma)^2 T}{[4\sigma - (1+\sigma)^2 T]Q_0}$	$\frac{T}{(1-T)Q_0}$	0
High level parameters	Leakage power	P_r	$P_0 \delta_2$	$\frac{P_0(1+\sigma)^2 T}{Q_0[4\sigma - (1+\sigma)^2 T]}$	$\frac{P_0 T}{Q_0(1-T)}$	0
	Gas discharge power	P_g	$[PP_0 \delta_1]^{\frac{1}{2}} - P_0(\delta_0 + \delta_2)$	$\frac{2\sigma}{1+\sigma}\left[\frac{PP_r}{T}\right]^{\frac{1}{2}} - \frac{4P_r \sigma}{T(1+\sigma)^2}$	$\left[\frac{PP_0}{(1-T)Q_0}\right]^{\frac{1}{2}} - \frac{P_0}{(1-T)Q_0}$	$\left[\frac{PP_0 \sigma}{Q_0}\right]^{\frac{1}{2}} - \frac{P_0}{Q_0}$

where ω_0 and ω are respectively the resonant angular frequency and the operating angular frequency.

This may be rewritten as

$$T = \frac{T_0}{1 + Q_L^2 \left[\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right]^2} \tag{28}$$

where T_0 is the in tune transmission and Q_L is the loaded Q, if one assumes that the δ's and Q_L remain unchanged for small departures from the resonant wavelength.

The input impedance of the cavity in terms of the input line impedance is then

$$Z = \frac{\delta_1}{j \left[\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right] + \delta_0 + \delta_2}. \tag{29}$$

The effect of other resonant modes which have been neglected in this analysis may be included by the addition of a term (σ_1) in equation (29) giving

$$Z = \sigma_1 + \frac{\delta_1}{j \left[\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right] + \delta_0 + \delta_2}. \tag{30}$$

Equation (30) and equation (2) are identical except for terminology.

APPENDIX B

Experimental Determination of "g" Parameters of Windows

The derived g-parameters which express the electrical size of a window between a resonant cavity and a surge impedance line were defined in Equations 20 and 21 of Appendix A. Numerical values of these parameters may be of some interest, together with their relation to physical dimensions of the windows. The 721A test cavity was used for an experimental determination of the relation between window width and "g." This cavity is $2\frac{1}{16}$ inches inside diameter, and is coupled by means of windows to two $\frac{9}{16}$ diameter coaxial lines. The width of the windows may be adjusted by rotating the coaxial lines so as partially to close the openings. The insertion loss through the cavity was measured at 3100 mc. by means of a superheterodyne receiver which included a calibrated attenuator in its intermediate frequency section. The windows were carefully maintained geometrically equal. In this case,

$$g = \frac{T^{1/2}}{2(1 - T^{1/2})}$$

which follows immediately from equation 23 of Appendix A on the assumption that $g_1 = g_2$. Fig. 38 shows the results; g proves to be proportional to the fifth power of the window width, over a very large range of values of g. A knowledge of this relationship permits one, with the aid of equations 23, 24, 25, 26, and 27 of Appendix A to calculate the window size

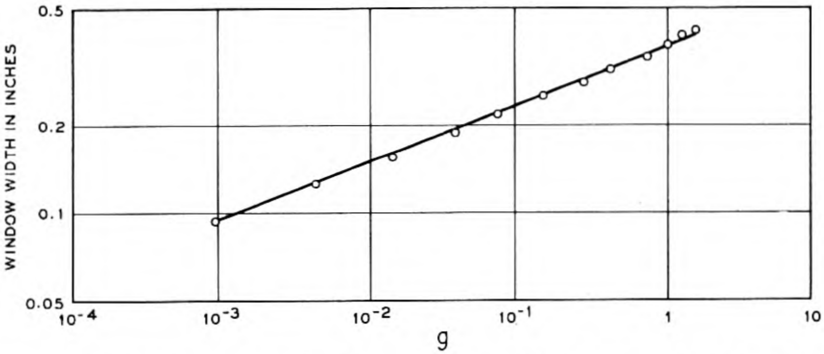


Fig. 38—The relationship between window conductance (g) and window width for the 721A test cavity

necessary to give any desired conditions of match, insertion loss, and leakage power.

APPENDIX C

The ATR Box

The value of the input impedance of the ATR is given by equation 29 with δ_2 equal to zero so that

$$Z = \frac{\delta_1}{j\left[\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}\right] + \delta_0} \tag{31}$$

which reduces to

$$Z = \frac{\delta_1}{\delta_0} \tag{32}$$

for the in tune case. This impedance is in series with the magnetron branch and hence restricts the possible range in values for the impedance at plane AB. Defining as F the fraction of the available power which is not absorbed by the ATR, then from Fig. 39 with the admittance of the receiver branch assumed to be $\delta_1 B$,

$$F = \frac{4}{(2 + G)^2 + B^2}, \tag{33}$$

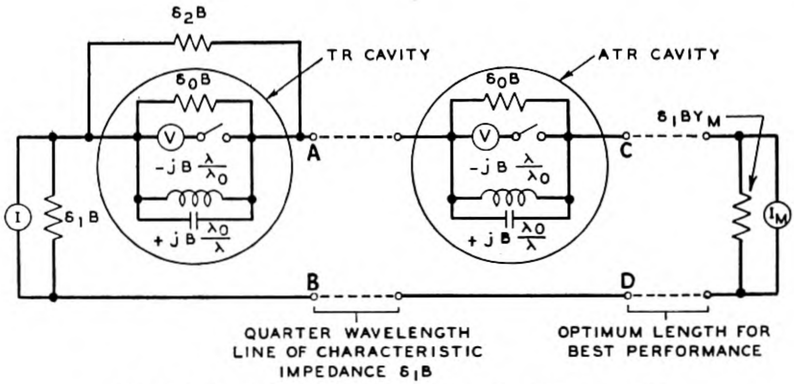


Fig. 39—Equivalent circuit of a system including an ATR

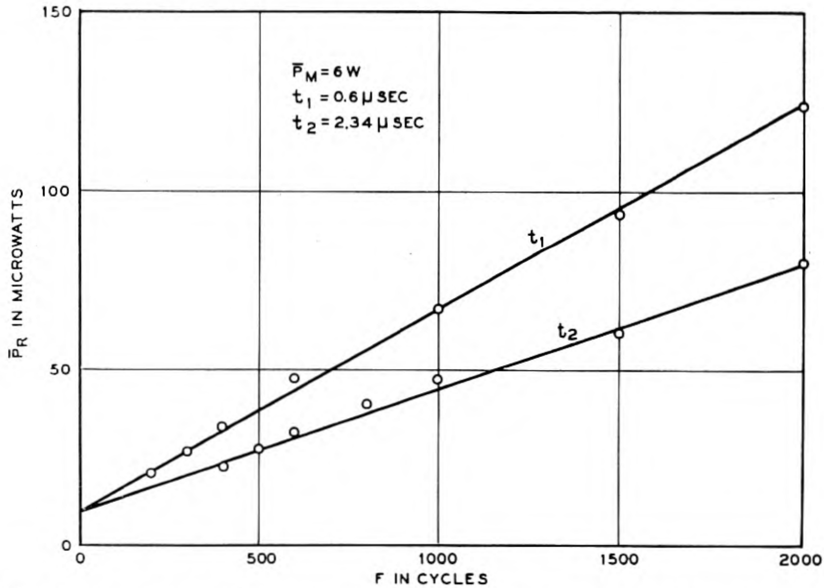


Fig. 40—Average leakage power as a function of repetition rate for two different values of pulse duration for 724B tube

where

$$G - jB = \frac{1}{(Z_m + Z)} \tag{34}$$

and Z_m is the impedance of the transmitter referred to the cavity and measured at the plane CD. The worst condition will occur when $Z_m = 0$. Under these conditions but assuming that the ATR is in tune

$$F = \frac{4}{(2 + G)^2}, \tag{35}$$

But now G is the reciprocal of the Z of equation (32) so that

$$F = \frac{4\delta_1^2}{[2\delta_1 + \delta_0]^2}. \tag{36}$$

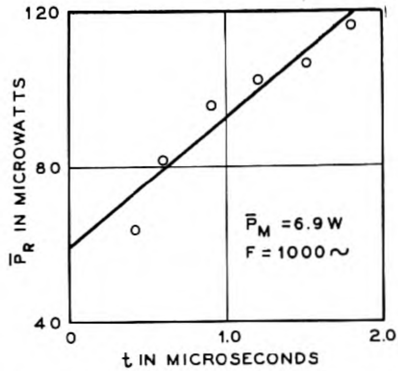


Fig. 41—Average leakage power as a function of pulse duration for the 724B tube

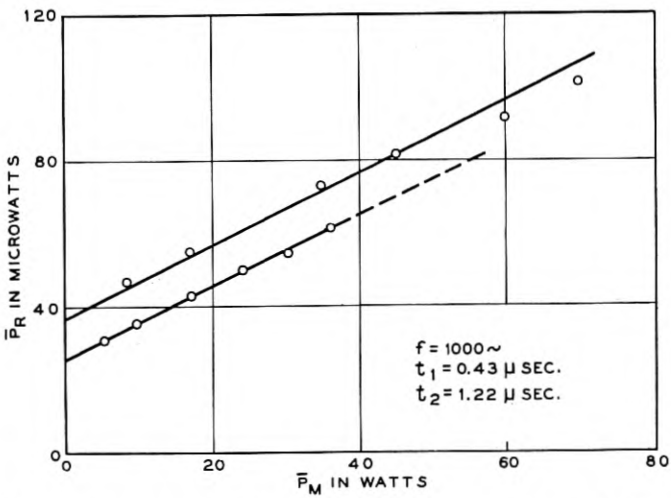


Fig. 42—Average leakage power as a function of average magnetron power for two different values of pulse duration for the 724B tube

This equation is analogous to equation (12) of Appendix A. At high levels the gas discharge power will be given by equation (19) as for the TR

$$P_g = [P\, P_0\, \delta_1]^{1/2} \tag{19}$$

If the ATR and the TR are designed to have the same value of P_g then the values of δ_1 and δ_0 must be the same so that a relationship will exist between F and T given by

$$F = \frac{4}{(3 - T)^2} \tag{37}$$

The input impedance Z to an ATR adjusted to the same gas discharge power of a TR with a transmission of T is given by

$$Z = \frac{1}{1 - T}. \tag{38}$$

APPENDIX D

The Analysis of Leakage Power Data

The section on receiver protection described the three components of leakage power which were referred to as spike, flat, and direct coupling. One may write down at once the following simple expression for leakage power:

$$\overline{P}_R = E_s f + P_F f t + \overline{P}_M T_D \tag{39}$$

where $\overline{P}_R$ is average leakage power
E_s is energy in a single spike
f is pulse repetition frequency
P_F is flat power
t is pulse duration
$\overline{P}_M$ is average magnetron power (averaged over the recurrence period) and
T_D is direct coupling insertion loss.

Experimental curves verifying the linear relationships indicated by this simple equation are shown in Figs. 40, 41, and 42. It is a straightforward operation to deduce numerical values for the three TR box leakage parameters from the slopes and intercepts of these curves.

Equation (39) was written on the assumption that gas-limited flat power and direct coupling power add linearly. If instead we assume that a phase angle θ exists between the two currents, we find:

$$\overline{P}_R = E_s f + P_F f t + T_D \overline{P}_M + 2\sqrt{\overline{P}_F f t T_D \overline{P}_M} \cos\theta \tag{40}$$

This of course is identical with equation (39) except for the cos θ term. If cos θ is not zero, we no longer expect a linear variation of $\overline{P}_R$ with f, t, or $\overline{P}_M$; the experimental curves demonstrate quite clearly that cos θ must vanish, hence θ must equal 90°.

A Wood Soil Contact Culture Technique for Laboratory Study of Wood-Destroying Fungi, Wood Decay and Wood Preservation

By JOHN LEUTRITZ, JR.

Limitations imposed by other biological test methods have largely been overcome by using autoclaved top soil for the substrate and pure cultures of the decay organisms. The use of soil was the direct result of observations on the rapid decay of wood in contact with soil in laboratory termite colonies.

Development of a wood-soil contact culture technique as a result of these observations furnished an excellent laboratory tool for further research on the biological factors promoting and the preservative compounds proposed for preventing decay. Research on the factors promoting decay showed not only that the average top soil furnishes nutrients and nutrilites in the quantity and proportion highly favorable to many decay organisms but also an effective means of regulating the water content of wood or cellulose during the decay period.

Comparisons between laboratory and field results showed the amount of decay obtained by the wood soil contact technique to be more rapid and uniform than decay in the field. The severity of the exposure in the laboratory ensures immediate eliminations of compounds unworthy of further more expensive field studies and evaluates compounds in the same order of effectiveness.

Comparisons and evaluation of wood and cellulose preservatives plus artificial weathering cycles followed by exposure to the method will provide valuable information on initial toxicity and permanence thereby affording a sound basis for the engineering selection of preservatives for a variety of purposes.

LABORATORY tests for evaluating fungicides are often used as a means of predicting field results and for investigating the action of cellulose and wood-destroying fungi. Of the several laboratory procedures hitherto devised for these purposes, however, none has been entirely adequate. This has led to incorrect interpretation of laboratory assays of fungicidal compounds, with attendant misapplication of preservatives. The confusion and misunderstanding concerning the use of preservatives have been further increased by the misapplication of the laboratory procedures themselves. A brief review and explanation of some procedures and their application will clarify these statements.

Minute quantities of toxic agents and growth-promoting substances which are not readily detected by known chemical analyses may be determined by bio assay methods, the value of which depends upon a prior determination of the reaction of one or more organisms to known quantities of these substances. Another bio assay is the so-called "acceptance test" for fungicides, by which the fungus resistant qualities of materials impregnated with fungicides may be determined. Since fungus resistant qualities are the primary concern in such a test, the identity and quantity of the preservative are of only incidental interest. However, the identity, fungus-proof qualities and quantity of fungicidal compounds are important when laboratory procedures are devised for comparing effectiveness in the development of different preservatives. In addition, the chemical and physical properties of the different preservatives must be considered for the determination of their subsequent behavior when exposed to a variety of environmental conditions. Bio assays may thus be used for quantitative, qualitative, comparative, or predictive purposes.

In order to survey existing tests, it may be helpful to classify them. There are three groups of rather ill-defined laboratory methods based on the nutrient and physical properties of the substrate. The first group is comprised of those methods in which an agar or similar base is used. Various nutrients or nutrilites* may be added to this base[1], and prior to inoculation with one or more fungi the preservative may also be added. This group includes the standard petri dish test described by Richards[2], 1923, which has had extensive use in the field of wood preservation. The carbohydrate source in the standard petri dish method was malt sugar. Later, in response to the requests by industry, Richards attempted to substitute wood flour as the nutrient. However, the radial fungus growth used as the criterion of toxicity was very sparse and thin and the substitution of wood flour for sugar was discarded. It is of interest to record here that Richards also summarized the previous work on toximetric tests of wood preservatives.

The second group includes those methods in which the preservative is added directly to a cellulose material before exposure to organisms. The preserved material may be the only source of nutrient for the fungi, or a piece of similar untreated material may be provided. Such a method is described in a paper by Waterman, Leutritz and Hill[3], 1938. No agar is used, and the untreated wood is supported over water by mechanical means. When agar is used to support the preserved material and to supply water, nutrients, nutrilites or combinations of each of these may be added to the agar. This may be done in several ways, among which are the kolle flask method for wood preservatives described by Falck[4], 1927, the standard method of the American Society for Testing Materials for testing fabrics[5], 1942, and the present Signal Corps test of fungicidal coatings[6], 1943. Of these, the first two methods are used chiefly as "acceptance" tests by determining the fungus-proof qualities of fungicidally treated wood and fabrics. They are also used in development work for comparison and for predicting the field behavior of preservatives when supplemented by artificial weathering cycles. The Signal Corps test is used as an acceptance test of fungicidal coatings which are sprayed on electical equipment. Since the criterion is the inhibition of fungus growth at some distance from a paper impreg-

* Nutrients here include the sugars and compounds used by the fungi for food purposes, and nutrilites will be referred to in this paper as those compounds necessary to fungus nutrition, such as vitamins, growth substances and minerals, Williams, R. J., 1928. (See Bibliography at end of this paper.)

nated with the fungicidal coating it is fundamentally a quantitative measure of the amount of fungicide which diffuses into the agar from the impregnated paper specimen.

A third group of test procedures employs soil or soil suspension in conjunction with the preservative materials. Here the soil furnishes an active microbial culture and supplementary nutrients and nutrilites. The soil suspension method has been described by Furry, and Zametkin[7], 1943, and the soil burial method by the American Society for Testing Materials.

The techniques included in the first group are time saving, permit of replication, and are readily duplicated by other investigators. However, the results in the agar-fungicide system do not apply to a cellulose-fungicide system and are therefore a source of confusion resulting from their misinterpretation when so used. Agar-fungicide systems as originally described by Richards are quantitative tests and have been used principally for comparative toxicity studies. From such comparative studies attempts to predict the behavior of a preservative in subsequent field tests have been generally unsuccessful. Examples of the discrepancies between the results from field and petri dish tests will be discussed later in this paper.

In general, the second group of methods takes a longer time, and replication leaves much to be desired. Since the preserved material is the same for laboratory and field tests, better agreement between field and laboratory results should be obtained with the kolle flask-wood block method and the A.S.T.M. fabric methods. However, the Signal Corps method for testing fungicidal coatings used on electrical equipment is not a a true test of the coating material per se.

The third group of methods introduces a large number of variables through the use of soil. Previously, replication of results and concomitant duplication by other investigators had been lacking, due to microbial activity, physical properties, nutrient properties, and moisture variations of the soil. However, during experimental work with termites, the author[8] made certain observations on the various factors involved in the decay process. These led to an intensive study of the problem resulting in the development of a test method for wood preservatives which overcomes many of the limitations of earlier methods. The soil burial method is a severe test of fungicide treated material, and, with the modification to be discussed in this paper, it is anticipated that the variables which cause non-uniformity of results can be eliminated. The method is also evaluated by comparison between the results obtained in the laboratory and those obtained from parallel field tests.

Rapid decay of wood in contact with soil was observed during an attempt to establish experimental termite colonies in the laboratory (Leutritz[8], 1939). Instead of becoming infested by the termites, nearly all the blocks decayed more rapidly and more completely than in any previous laboratory test. Preliminary experiments were devised to ascertain the factors responsible for the accelerated decay and to establish optimum conditions for growth of fungi in laboratory tests of wood preservatives. As a result of this exploratory work a laboratory technique was devised which permitted study of these factors and which offered a convenient means of evaluating toxicity and preservative properties of chemical compounds. Further investigation was made on the effect of nutrients and nutrilites in the soil, temperature, and the moisture content of the wood. Parallel with this laboratory investigation, a study was made of the fungus attack on wood under climatic conditions very favorable for decay at Gulfport, Mississippi.

Initial Experiments and Results

As a preliminary step, the moisture content of the soil from the termite colonies was determined by oven-drying 100-gram samples. This was found to average 22% of the oven-dry weight of the soil. Tests with several soils showed that approximately the same moisture content could be obtained by merely adding to dry soil just enough water to make the mixture cohere when squeezed in the hand.

A one-hundred-gram sample of moist soil was placed in each of 24 large-mouthed, eight-ounce, screw-capped bottles (12 cm. high and 6 cm. in diameter). A weighed oven-dry block of southern pine sapwood, 2 x 2 x 2 cm., was pushed to a depth of about 2 cm. into the soil in each bottle. The caps were put on, and the preparations were sterilized for 30 minutes at 15 pounds' pressure in an autoclave. After cooling, the block in each of twelve of the bottles was inoculated with a pure culture of one of seven common wood-destorying fungi—*Lentinus lepideus*, *Fomes roseus*, *Poria microspora*,* *Polyporus vaporarius*, *Coniophora cerebella*, *Poria incrassata*, and *Lenzites trabea*. Twelve bottles, not inoculated, were used for moisture determinations.

The bottles were then placed in an incubator maintained at 26°–28°C. At the end of each month three of the bottles inoculated with each fungus were taken from the incubator. Each block was removed from the soil and weighed immediately; it was then allowed to dry in an oven at 105°–110°C. to a constant weight. The average percentage loss in dry weight due to decay was calculated. The results, recorded in Fig. 1, show that the very rapid decay of wooden blocks in contact with the soil is not the result of any one particularly active fungus. Each of the seven species produced exceedingly rapid decay under the conditions of the soil assay.

* This fungus was designated BTL U-10 until recently identified as *Poria microspora* by Miss Mildred K. Nobles, Dept. of Agriculture, Ottawa, Canada, 1943. (See Bibliography at end of paper.)

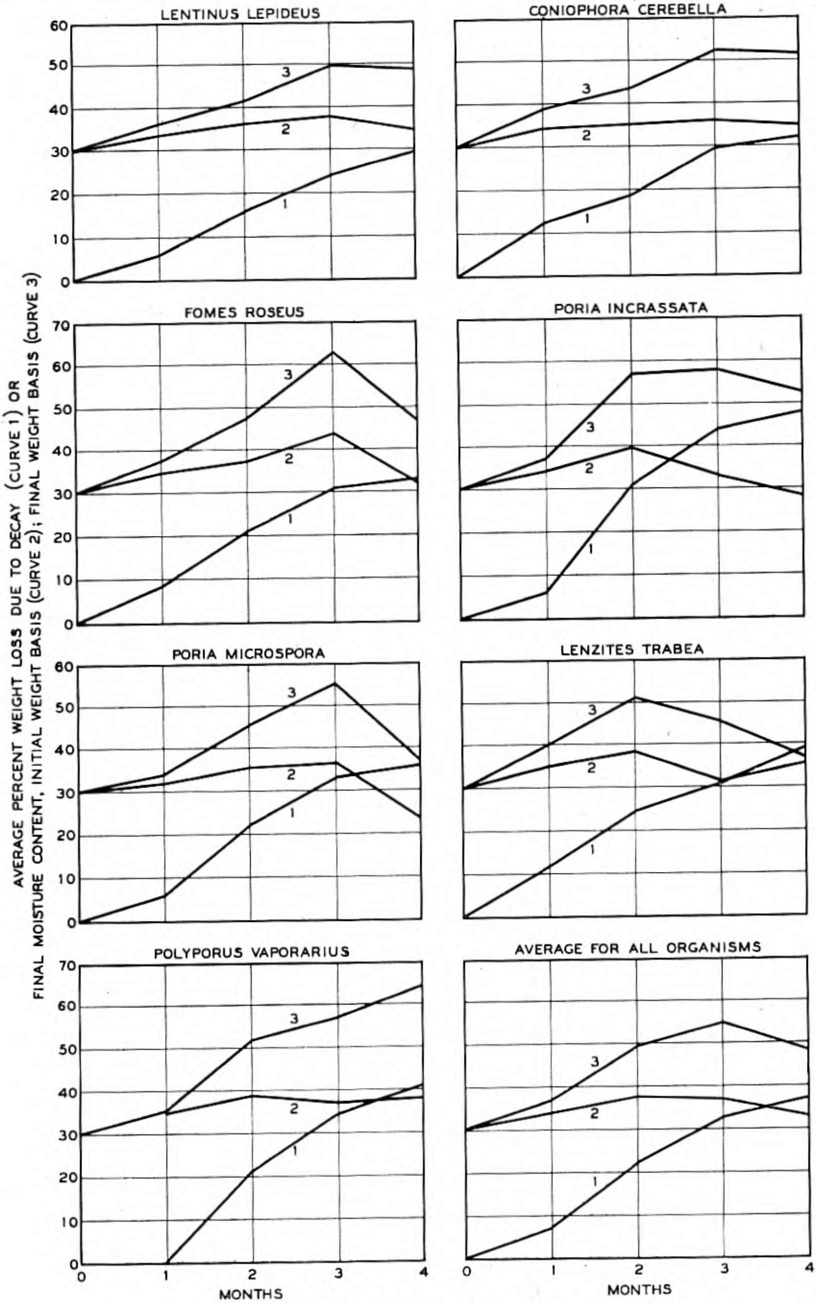


Fig. 1—Wood soil contact technique

For comparison, a similar test was made according to the method described by Waterman, Leutritz, and Hill[8], 1938, in which the test blocks are placed on inoculated sapwood slabs supported over water in capped wide-mouthed bottles. Comparison of the average percent weight loss due to decay for all organisms by both methods, Fig. 2, shows that the water-wood method is far less effective in producing decay than the soil method.

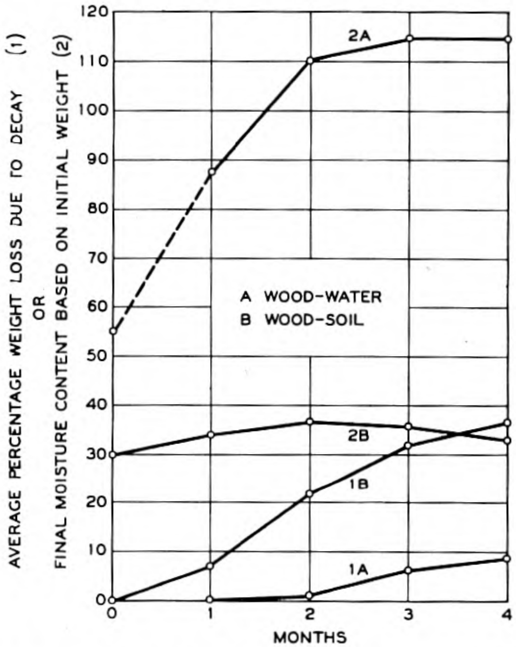


Fig. 2—Comparison of average weight loss and final moisture content by wood-water and wood-soil techniques

An additional experiment was conducted with several strains of two of the fungi previously used, *Coniophora cerebella* and *Lentinus lepideus*. The *Coniophora cerebella* strains were as follows:

Baarn, from Dr. Johanna Westerdyjk, Holland

Liese, from Dr. Liese, Germany

Idaweiche, from Dr. Idaweiche, Germany

Madison, from Forest Products Laboratory, Madison, Wisconsin, isolated from oak, November 13, 1919

BTL, also from Forest Products Laboratory, Madison, Wisconsin, 1930

The *Lentinus lepideus* strains were from the following sources:

No. 534, from Forest Products Laboratory, Madison (No. 534)

BTL U-1, U-13, U-14, and U-32, from creosoted pine telephone poles which had failed in service

Gulfport, from a test post in Gulfport, Mississippi, used for our assay work

The results of the assay with these strains of *Coniophora cerebella* and *Lentinus lepideus* showed the average weight loss in percent due to decay to be 32.0 and 27.3 percent respectively which was as great as that in the previous soil tests with the single representative of these species. A greater amount of decay was obtained with one strain of Coniophora cerebella due to a slight change in technique, i.e., the fungus was first established on small slabs of southern pine sapwood, and then sterile oven-dry blocks were dropped on the vigorously growing fungus. The large amount of decay (60%) which resulted led to the adoption of this modification in all subsequent tests.

The foregoing tests may be regarded as supporting the use of the criteria previously employed in the selection of fungi for laboratory tests—namely, their occurrence as saprophytes of wood, their isolation from service materials for example, pine telephone poles or tests posts, and their demonstrated ability to bring about decay of wood in the laboratory.

As a result of these preliminary experiments, the use of soil as the medium in testing procedure was adopted.

Soil Contact Technique

On the basis of the foregoing experiments and in view of the rapidity of the decay occurring on test blocks in the soil-contact test, the following method is described as a means of evaluating the effectiveness of preservatives or toxic materials which are recommended for the protection of wood or other cellulosic materials. The method may also be used to study environmental factors which affect decay or it may be adapted to the study of fungi other than the wood-destroying fungi of the Basidiomycetes.

Ordinary top soil, such as a florist would use for potted plants, is satisfactory for the test. While experience has shown that top soil from a number of different sources may be used without materially affecting the results, standardization would be desirable. Therefore the term "soil" will be defined as a sandy loam type which contains 4–6 percent of organic matter and a pH originally between 5–7. The soil is passed through a coarse-mesh screen to remove rubble, stones and other debris; this is most easily accomplished when the soil is dry. The screened soil is moistened with just enough water to effect cohesion into a soft ball when squeezed in the hand, and a check may then be made by determining the moisture content of the soil. When prepared in this manner the moisture content of the soil should be 20–25% on an oven-dry weight basis. In an alternative procedure, the moisture content of the dry soil is ascertained and then sufficient water is added to give a moisture content of 20–25%.

Bottles, 12 cm. high and 6 cm. in diameter, are half filled (60–100 grams) with the moistened soil. Two pieces of southern pine sapwood "feeder strips" (3.5 x 2.0 x 0.3 cm.) are placed on the soil in each bottle, Fig. 3. The bottles are closed tightly with screw caps and then autoclaved for 30 minutes at 15 pounds' pressure. When the bottles have cooled, a small inoculum (a few millimeters square) cut from a pure culture of a suitable wood-destroying fungus is placed on the sapwood substrate. Each bottle contains a single dominant fungus culture. It is best to use at least four to eight selected species of fungi for an assay. The bottles are again capped and placed in an incubator, or a controlled temperature room, held at 26°–28°C., for at least one month. Any contaminated or weak cultures are

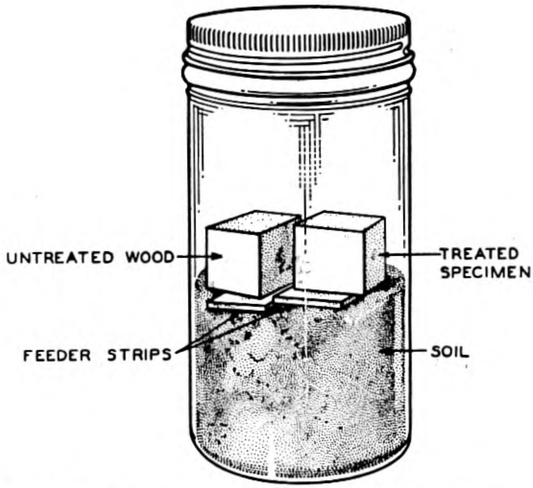


Fig. 3—Schematic diagram of wood soil contact method

discarded. This completes the preparation of the pure fungus cultures, Fig. 4, and they are now ready to receive the test blocks.

To each bottle containing a culture established on sapwood substrate are added an untreated control block and a block treated with a preservative according to the following method:

The required number of $\frac{3}{4}''$ cubes of sapwood blocks are placed in a humidity chamber at 30°C. and 76% relative humidity until the blocks have reached a constant weight. Then the necessary number of weighed blocks, weighted to ensure immersion, are placed in a container of convenient size under a bell jar fitted with a separatory funnel. After evacuation of the bell jar to a pressure not greater than 2 cm. as measured by a mercury manometer, the vacuum is held for 5 minutes. The stopcock in the pump line is then closed, and sufficient solution is admitted from the separatory funnel

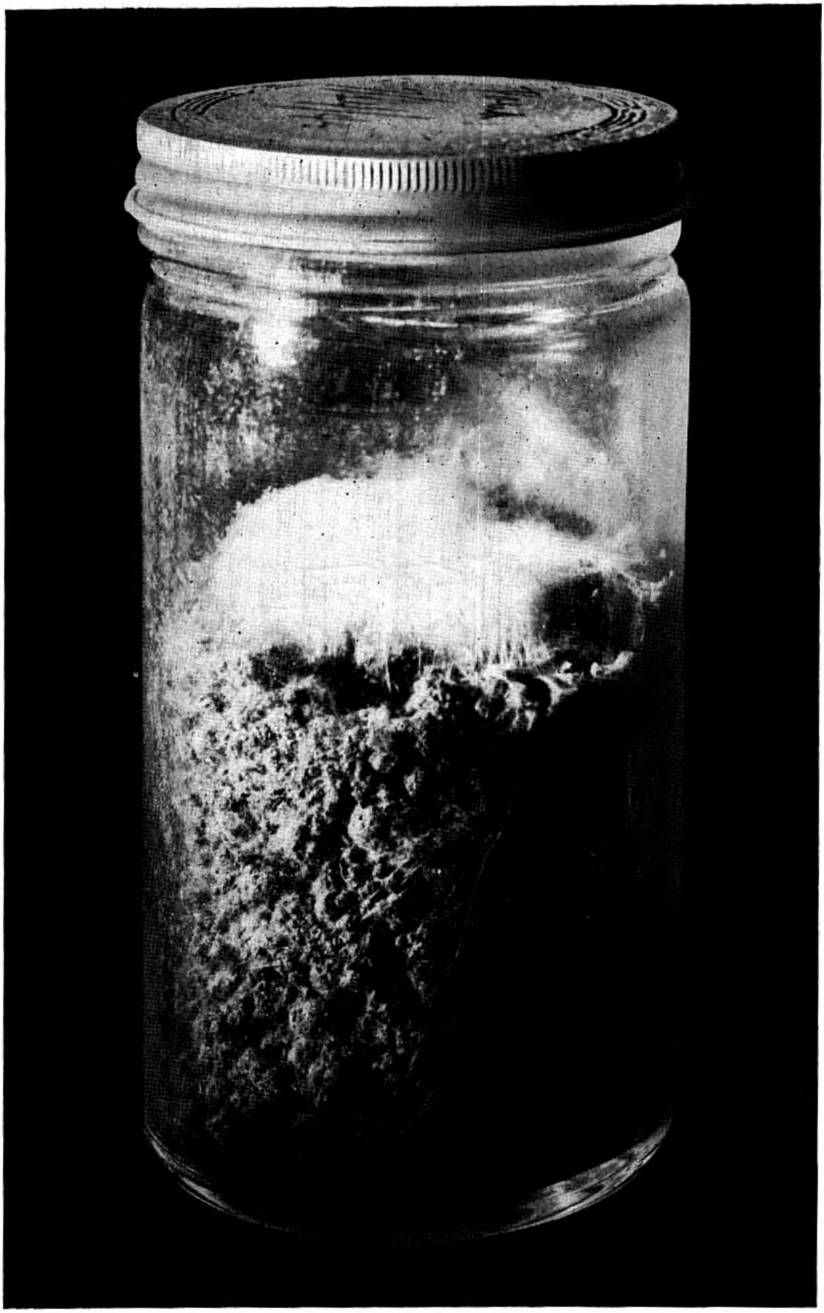


Fig. 4—Pure fungus culture of Poria incrassata

to submerge the blocks completely when the air is admitted. After remaining in the solution for 5 minutes, the blocks are wiped superficially and and weighed. This treated weight is used for calculation of the theoretical retention according to the following formula:

$$R = \frac{GC\,(62.4)}{100\ V}$$

in which R^* = pounds of preservative per cubic foot of wood, G = gain in weight in grams, C= grams of the preservative in 100 grams of solution, and V = volume of the test piece in cubic centimeters. When the solvent has evaporated from the blocks, they are placed on racks, returned to the humidity chamber and brought to constant weight. The difference between the humidity weights before and after treatment serves as the basis for calculating the actual retention, and the final equilibrium weight is used also as the initial weight of the treated block before exposure to the fungus.

The cross-section side of the blocks is placed in contact with the vigorously growing mycelia of the sapwood culture which in turn is in contact with the soil. For each concentration of preservative, three treated blocks and three untreated control blocks are exposed to each species of fungus. The bottles are recapped and place in an incubator or constant temperature room at 26°–28° C. with a relative humidity of 85–95%.

Exposure of the blocks to the fungus for from twelve to twenty-four weeks gives satisfactory results. If a sufficient number of treated specimens is exposed to the same organism, one or two specimens may be removed at the end of twelve weeks; and if considerable decay has taken place, the test may be concluded. At the end of the exposure period the blocks are brushed free of mycelia and immediately weighed to determine their moisture content. The blocks are then allowed to stand in the room until dry, after which they are again transferred to the humid chamber (temperature 30°C., relative humidity 76%) for two-three days until a constant weight is attained.

In the toxicity work reported in this paper an untreated reference block was added to each test bottle. If a large number of assays are contemplated, the number of weighings may be reduced by eliminating the untreated blocks except for occasional reference purposes. The reduction in the number of reference blocks may be accomplished by establishing a decay norm for each test organism. This norm would be based on data similar to that used in Fig. 1 except that the procedure would be the same as that described for treated blocks. Comparison of the percentage weight loss due to decay

* To express the retention metrically $R \times 16.018 = \frac{\text{Kilograms}}{\text{Cubic meter}}$.

of the norm with the percentage weight loss due to decay of the test block may be used as a measure of the effectiveness of the preservative or toxic material. An index of the value of a preservative treatment may be obtained from the following computation:

$$\frac{\%\text{ loss of norm} - \%\text{ loss of treated block}}{\%\text{ loss of norm}} \times 100$$

Values of the index would range from 100, representing complete protection against decay, to 0, representing no protection whatever.

In most cases, especially when no volatile preservative is present, the untreated reference block disintegrates completely within twelve to sixteen weeks. An inspection rating based on strength may be used to supplement weight loss due to decay. The rating is made on the basis of appearance and strength: 10 denotes a sound condition, 9 superficial decay, 8 superficial decay in spots or streaks, 7 general surface decay, 6 considerable decay but not enough to allow specimen to be broken easily, 5 advanced decay, and 4, 3, 2, and 1 different stages of advanced decay, determined primarily by the ease with which the specimen is broken; 0 denotes complete disintegration. Ratings of 5 and below are considered failures. Similar ratings have been used for sticks in field work. This method of rating was used in the field trials of preservatives which appear later in this paper. Although the system is an arbitrary one, considerable correlation has been shown between these dissection ratings and the weight loss in percentage. With a series of field sticks or blocks treated with the same low amount of a preservative, ratings based on strength for the series are found to be very closely correlated with weight losses, even when the ratings are made by different workers.

The Influence of Moisture on Decay

The first experimental factor studied was the moisture content of the wood preceding and during the time that decay took place. Statements in the literature concerning the optimum moisture content for the decay of wood have placed the figure variously from fiber saturation, 27–30% to 60% (Schorger, 1926)[10] and 150% (Benton & Ehrlich, 1940)[11] of the wood substance based on the oven-dry weight.

Figure 1 gives data on the moisture content of blocks exposed to the seven species of fungi for periods of one, two, three, and four months. Uninoculated control blocks, removed at the end of each of these periods, were found to be at fiber saturation, indicating 100% relative humidity in the bottles and little or no migration of liquid water.

During the progress of decay there is a rapid decrease in the weight of the wood substance. But the amount of water present in each block does not decrease and at all stages of decay corresponds to about 35% of the original dry weight of the block. Since the amount of water does not decrease as the amount of wood substance decreases, there is an increase in the percentage of water expressed in terms of dry weight as shown by curves labeled 3 in Fig. 1. Such an increase in the amount of water relative to the remaining wood substance would tend to limit decay if the optimum moisture content for initiating decay is considered to be at or near fiber saturation.

If the absolute amount of water in the blocks does not change during the progress of decay, then the final amount of moisture divided by the initial weight of the blocks should give a percentage figure fairly close to the initial fiber saturation of approximately 30%. The curves labeled 2 in Fig. 1 showing the moisture content based on the initial weight indicate that this is the case. For example, Fig. 1 shows that the average for all organisms is 4% greater than 30% after one month, 7% greater after two, 6.3 after three, and only 2.1 greater after four months. Between the third and fourth months the soil showed signs of drying out and examination of all of the moisture curves, Fig. 1, indicates a loss of water through the bottle caps, which accounts partially for the discrepancy. The 5–10% increase in water over the original fiber saturation may be due to slight condensation on the blocks or to the respiratory activity of the fungi in breaking down carbohydrates into CO_2 and water.

The average amount of decay (curve 1) and the final moisture content referred to the initial weight (curve 2) for all the organisms obtained by the wood-water (A) and wood-soil (B) assays are compared in Fig. 2. The water content of the blocks in the water test varied from 55–165% based on the oven-dry weight of wood and the decay was much less in amount and uniformity than that obtained by the wood-soil technique with the same organisms. From the results for individual blocks, the limiting water content at which no decay took place was determined as 78% for *Poria incrassata*, 84% for *Coniophora cerebella*, and 66% for *Polyporus vaporarius*. In a few instances, despite the full cell saturated conditions, decay did take place. Examination of these blocks indicated that most of the decay was confined to the surfaces of the blocks. This indicates that lack of oxygen was the limiting factor.

When wood was supported on glass rods over agar (kolle flash technique) full cell saturation of the blocks often occurs due to capillarity of the glass, condensation of water, accidental contact between wood and agar, and conduction by the fungus filaments. That the water content of the wood in the kolle flask technique is also too high is indicated by the "optimum" moisture content of 150% and the relatively small weight losses due to decay, less than 10%, cited in the experiments of Benton and Ehrlich.[11] The amount of decay was again shown to be affected by the water content of the wood. If decay is to be used as a criterion of toxic effectiveness, the importance of eliminating variations in the water content of the block can be fully realized. The wood soil technique offers an excellent means of controlling moisture for studies of wood decay.

Sand, cotton, sawdust, wood flour, and soils with varying moisture contents were also used as supporting substrates, but in no case was the amount of decay as great as that with the same technique using soil of 20–25% moisture described above. When soils with water contents of 5%, 10%, 20–25% and 30% were compared, the moisture contents of blocks in contact with them were 12.8%, 23.9%, 27–30% and 73.9%, respectively. Decay of the blocks was adversely affected by lack of moisture in the first two cases and by full cell saturation of the wood in the last instance. However, if moisture were the only controlling factor the amount of decay of wood in contact with sand should be comparable to that in soil, but this was not the case.

The Influence of Soil Nutrient or Nutrilites

Nitrogen in the form of asparagine has been shown by Schmitz and Kaufert[12] (1936) to cause an increase in the amount of decay of *Pinus resinosa* by *Lenzites trabea*. Since wood contains only about 0.1% to 0.3% of nitrogen, any additional nitrogen received from the soil should promote decay. It might be expected that the soil supplies nitrogenous and other nutrients, nutrilites, vitamins, etc., that accelerate decay. Evidence for this was obtained by comparing the decay of blocks in contact with (1) top soil, (2) top soil that had been leached for several days with hot water, and (3) three artificial soils composed of washed sand and fuller's earth. In this experiment *Poria incrassata* was used as the inoculum for a test period of 12 weeks. The moisture content of the uninoculated control blocks was 27–30 percent and of the substrate for each series 22 percent; the temperature and time were constant. The average weight loss for the blocks in contact with top soil was 54%, with water extracted top soil 45.4% and the three mixtures of sand-fuller's earth 24.7%.

It is apparent from these data that the top soil promotes decay to a far greater extent than the sand-fuller's earth mixtures and slightly more than the water extracted top soil, despite the same moisture (fiber saturation) content of the blocks. The actual rate of decay of blocks in contact with the top soil was more than double that of the other mixtures. Therefore, the conclusion may be drawn that nutrients or nutrilites are present in the top soil which stimulate growth of the fungus and promote decay.

Since the water-extracted soil proved not so favorable for decay as the original top soil, some of the growth-promoting substances must have been soluble in water. The greater decay of wood in contact with the extracted top soil than of that on the mixtures of sand and fuller's earth indicates that the nutrients present in the soil were not all removed by the water extraction. Further information was obtained by adding soil extract and other nutrient solutions to the sand-fuller's earth mixtures. The following materials were used:

4500 grams of washed beach sand
900 grams of fuller's earth
300 ml. of soil extract
60 ml. of malt extract (2% water solution)
50 leached blocks
vitamins B_1, B_6 and biotin (free acid)
stock mineral solution of the following composition:
1.5 grams per liter of KH_2PO_4
1.0 gram per liter of $MgSO_4 7H_2O$
plus the following elements in parts per million:
0.02 Cu, 0.01 Mn, 0.005 B, 0.10 Fe, 0.01 Mo, 0.09 Zn
pure cultures of the fungus *Poria incrassata*
42 eight-ounce bottles, screw capped (12 cm. high by 6 cm. diameter)
maltose

Procedure:

The sand and fuller's earth in the proportions mentioned above were mixed in a porcelain jar on a ball mill for six hours. The blocks were leached for two years with weekly changes of distilled water, using 50 ml. of distilled water for each block. Before the test, the blocks were oven-dried to constant weight at 105°C. and a volume measurement was made by mercury displacement method. The volume at fiber saturation was calculated from the oven-dry volume according to the formula: Volume at fiber saturation = Oven-dry volume + 0.25 × oven-dry weight.

One hundred grams of the soil moistened with 20 ml. of the appropriate nutrient solution (Table 1) was placed in an eight-ounce bottle for each block. The weighed block was pushed into the soil with a cross-section of the block facing upward until the top of the block was level with the soil.

The bottles were capped and autoclaved for 20 minutes at 20 pounds' pressure. After sterilization and cooling, an inoculum from a pure culture of the fungus *Poria incrassata* was placed on the top of each block. The bottles were then placed in a controlled temperature room (26°–28°C., relative humidity 90–95%) for 16 weeks.

At the end of this time the blocks, brushed free of soil and mycelia, were weighed immediately, and the volume was measured. Finally, the blocks were again oven-dried to constant weight and the volume was measured again.

The average volume at fiber saturation of the 42 blocks calculated from the initial volume when oven-dry was found to be 7.24 cc., and the final average volume when removed from the test was 7.26 cc. No shrinkage took place until the blocks were oven-dried, and then the distortion became permanent. This constancy of the volume during the decay period indicates the mechanism by which the water is held practically constant during the decay period. Any loss of water would result in a shrinkage from which there would be no recovery.

Table 1 gives a list of the solutions used to moisten the artificial soil and the average weight loss for 3 blocks in percentage for each variation. Several

TABLE 1

EFFECT ON THE DECAY OF WOOD IN CONTACT WITH SAND AND FULLER'S EARTH MIXTURES MOISTENED WITH VARIOUS NUTRIENTS AND NUTRILITES

Organism *Poria Incrassata.* Time 12 Weeks

Solution Used to Moisten Artificial Soil	Average Weight Loss in Per Cent Due to Decay
Top Soil (Control)	67.0
M.S.* + 0.2% Ammonium Nitrate + 1% Maltose + Vitamins B_1, B_6 and Biotin†	62.7
2% Malt Extract	59.3
M.S. + 2% Ammonium Nitrate + Vitamins	51.3
M.S. + 2% Ammonium Nitrate	47.9
M.S. + Various Combinations of Vitamins‡	29.1
Distilled Water	28.4
M.S. + Vitamins + 1% Maltose	11.6
M.S. + 1% Maltose	12.9

* M.S. = mineral solution containing the following minerals:

Potassium Dihydrogen Phosphate	1.5 grams per liter
Magnesium Sulfate	1.0 gram per liter
Copper	0.02 parts per million
Manganese	0.01 parts per million
Boron	0.005 parts per million
Iron	0.10 parts per million
Molybdenum	0.10 parts per million
Zinc	0.09 parts per million

† The vitamins used and the concentrations per liter were as follows:

B_1	0.1 milligrams per liter
B_6	0.1 milligrams per liter
Biotin	0.02 milligrams per liter

‡ The vitamins were added singly and in the following combinations:

B_1 + B_6 + Biotin—Concentration of each vitamin as listed above.
B_1 + B_6
B_1 + Biotin
B_6 + Biotin

conclusions may be drawn. It is evident that the soil greatly accelerates decay, and that the soil extract contains a large portion of the nutrients and nutrilites which accelerate decay. Malt extract, which contains proteins and sugars, and the mineral solution fortified with ammonium nitrate also stimulate decay. The effect of nitrogen in increasing decay confirms the experiments made by Schmitz and Kaufert,[12] 1936. When nitrogen is lacking and a simple sugar is present, the fungus consumes the simpler sugar instead of the more complex carbohydrate cellulose. This preference is not evident if sufficient nitrogen is present since both carbohydrates are destroyed. There is a slight indication that the vitamin mixtures promote decay but the effect as measured by the weight loss is not very pronounced. The basic mineral solution which was used in this experiment promoted only slightly more decay than the distilled water. While the results are not included in the table, it may be stated that leaching of the blocks had no apparent effect on decay when compared with unleached blocks.

Influence of Temperature on Decay

Most of the early work in the Bell Telephone Laboratories was conducted by the petri dish method at temperatures in the range 26°–28°C., following the recommendations of Richards, 1923. But certain fungi, including *Merulius lachrymans*, failed to grow at this temperature. When several inocula of *Merulius lachrymans* that had failed to grow at 26°–28°C. were transplanted to sterile blocks, according to the earlier sapwood-water technique, the loss in weight due to decay after six months averaged 34% at 21°C. and only 7% at 26°–28°C.

An experiment was planned to test the influence of a wide range of temperatures on the decay of wood in the soil contact assay method. Four kinds of fungi were established under sterile conditions on untreated wood slabs laid on moist garden soil. An abundant growth of the fungi was secured within one to two months. Cubes of sapwood were placed on the vigorously growing mycelia, both of which had been conditioned by exposure overnight to the various temperatures. Sterile soil, also conditioned to the temperatures, was used to cover the blocks. After 15 weeks' exposure, the results were as follows:

	Average Weight Loss in Per Cent				
	0°C.	21°C.	26–28°C.	30°C.	35°C.
Poria incrassata	0.0	35.6	58.2	34.7	0.7
Polyporus vaporarius	0.0	42.7	58.9	1.0	0.8
Poria microspora	0.0	53.3	59.0	42.4	2.4
BTL-U-11	0.0	27.1	62.7	60.5	1.3

The results indicate that the standard temperature, 26°–28°C., was optimum for the four fungi tested. No decay was produced by any of the fungi at 0°C. A temperature of 35°C. was too high for active decay; in the case of *Poria microspora*, for instance, only a single block was attacked. The series at 35°C. was repeated because the soil in some of the bottles seemed to have become rather dry, although the blocks contained 30% moisture. In the new series the humidity was maintained at 76% around the bottles to reduce loss of water, and three more organisms were used. The results of the previous temperature tests were confirmed and the weight losses due to decay by the three additional fungi, which are known to tolerate higher temperatures, were as follows:

Organism	Percentage Weight Loss Due to Decay
Lentinus lepideus	21.8
Lenzites sepiaria	21.3
Lenzites trabea (BTL U-40)	44.0

These results indicate that certain fungi are able to bring about decay of wood over a wider temperature range than others. It is clear that a complete statement cannot be made until the effects of various temperatures between 0°C. and 21°C. have been ascertained. In the light of results with *Lentinus lepideus*, *Lenzites sepiaria*, and *Lenzites trabea* showing considerable decay at 35°C., the upper limits of temperature should be determined for these fungi.

Humphrey and Siggers,[13] 1933, studied the effects of different temperatures on the growth of sixty-four fungi. Two different nutrient substrates were used, but the optimum temperature with these rarely differed by more than 2°C. The following summary shows a comparison of their results with those obtained in the above tests:

	Optimum, °C.		Upper Limit, °C.	
	H&S	BTL	H&S	BTL
Merulius lachrymans	20	21*	28	>28
Poria incrassata	24–30	26–28	34	34
Lentinus lepideus	28	28	36	>35
Lenzites trabea	28–36	28–35	40	>35
Lenzites sepiaria	28–36	28		>35

* Bottle method used; no test has been made yet with soil.

Two of the fungi, *Merulius lachrymans* and *Lentinus lepideus*, brought about decay at limits higher than those reported for cessation of growth by Humphrey and Siggers. *Poria incrassata* had the same limiting temperature in both tests. The temperatures for maximum growth and maximum decay check rather well in both tests.

Field Studies

The rapid decay obtained in the foregoing laboratory experiments based on the soil technique was further evaluated by investigating the rapidity of decay in the field.

Selection of Wood:

For both laboratory and field assays care is exercised in selecting the wood. Boards of southern pine sapwood of the shortleaf type, which includes *Pinus echinata*, and *Pinus taeda*, are obtained from local lumber dealers and are cut into sticks $\frac{3}{4}$ x $\frac{3}{4}$ x 32 inches. Since the square sticks facilitate calculation of volume and retention of toxics or preservatives, they have superseded the round saplings cited by Waterman and Williams,[14] 1934. The sticks are selected on the basis of uniformity of growth, density and ratio of springwood to summerwood. The presence of any heartwood,

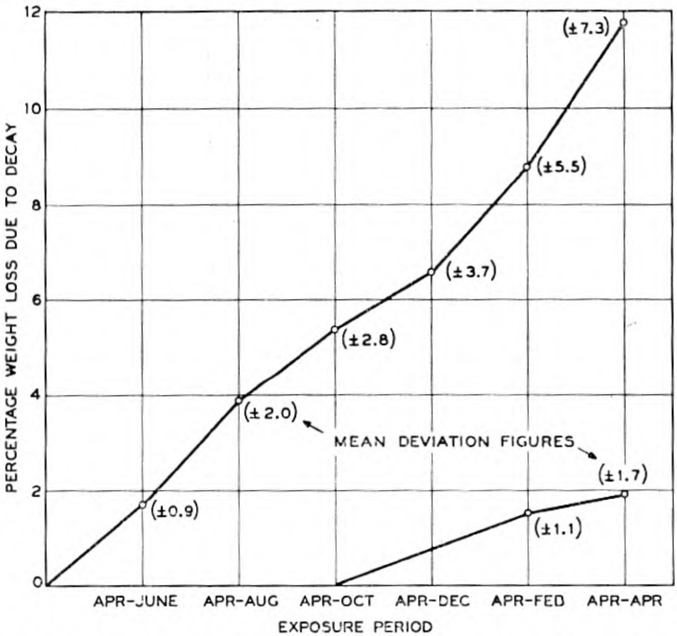


Fig. 5—Field test of untreated sapwood squares exposed at Gulfport, Mississippi, 1941-42

sap stain or other indication of incipient invasion by fungi is cause for rejection. After classification into piles according to arbitrarily chosen weight increments, twenty to twenty-five 32″ sticks, for each concentration of preservative used in field studies are selected by taking the appropriate number of specimens from each pile to give a representative distribution based on density. Since the specimens are subsequently cut in half each individual treatment is represented by 40–50 specimens. Sticks in the median range of density are generally used for laboratory studies after they have been cut into $\frac{3}{4}$″ cubes (8 cc. volume).

An experiment with untreated sticks was carried out at Gulfport, Mississippi, where the climatic conditions are very favorable for decay and also for termite attack. Six hundred 8-inch lengths were dried in the oven in the laboratory at 105°–110°C. and then weighed. The specimens were then shipped to Gulfport, Mississippi, and distributed throughout the test plot in April. Each eight-inch specimen was buried in the soil until the end of the specimen was even with the level of the soil. At the end of each two-month period subsequent to exposure about 80 specimens were removed, brushed free of dirt and mycelia, oven-dried, and reweighed. In order to study decay during the winter months, 150 additional pieces were planted in October; seventy-five of these were removed after four months and the rest after six months exposure.

From Fig. 5 it is evident that in the field test the loss in weight due to decay was far less than that obtained in the soil test in the laboratory. The maximum amount of decay in the field after two months was as high as 10% in only two out of the 81 samples exposed; after four months it was 19%, after six months 30%, after eight months 20%, after 10 months 30%, and after 12 months 50%. While the maximum percentage loss applies only to one specimen in each case, in general the average percentage losses noted in the figure were far below these figures. Therefore, decay in the field does not approach in uniformity and rapidity that occurring under controlled conditions in the laboratory.

Experiment at Chester, New Jersey, Using Various Nutrients:

Another field experiment was devised in which an attempt was made to increase the rate of decay by using nutrient materials and salts which would change the pH of the soil. Sixteen-inch untreated sticks were selected for uniformity within a very narrow density range and exposed in each of six specially prepared plots in northern New Jersey. The ground was first plowed, then harrowed and raked free of stones so that the soil in all plots was nearly uniform before treatment. Then fifty sticks were buried to a depth of 7 inches in each plot in rows of five, with two feet between each row and one foot between the sticks in each row. The plots were treated as follows:

Plot No.	Treatment
1	Control
2	Barnyard manure
3	5 pounds lime
4	5 pounds commercial fertilizer (5–10–5)
5	5 pounds aluminum sulfate
6	Nutrient solution*

* Containing the following minerals dissolved in ten gallons of water, then sprinkled over the entire plot:

		grams
A)	$Ca(NO_3)_2 \cdot 4H_2O$	297.0
	$MgSO_4 \cdot 7H_2O$	118.8
	KH_2PO_4	83.6
B)	$ZnSO_4$	0.176
	$MnSO_4 \cdot 7H_2O$	0.572
	Boric Acid	0.704
	$Al_2(SO_4)_3$	0.176
C)	$FeSO_4$	5.0

Note: The salts in A, B, and C were dissolved separately and then the three parts mixed.

The sticks were removed and examined at intervals of three, twelve, and fifteen months. The percentage failure, as determined by the ease with which the specimen could be broken, is shown in the following:

	Percentage Failure		
	3 mo.	12 mo.	15 mo.
Control	2	8	72
Manure	10	12	96
Lime	2	10	80
Fertilizer	4	8	94
Aluminum sulfate	16	36	100
Nutrient solution	4	12	100

At the end of 12 months the greatest number of failures due to decay was observed in the plot treated with the acid salt (aluminum sulfate). Colorimetric determinations of the pH of the soil showed it to be between 5.8 to 6.0 for the soil treated with the acid salt and about 6.6 to 6.8 for the control plot. This experiment needs to be repeated for confirmation of results, but the present indications are that the acid soil was much more favorable for decay than the soil in the control plot. Limed and fertilized soils gave results comparable to those of the control plot, with an indication that the fertilizer increased the decay. The complete disintegration of the sticks in the acid treated soil was particularly noticeable, whereas the sticks in the soil treated with manure were intact, though easily broken. The plot treated with the nutrient solution showed the same rate of decay as the manure plot at the end of the twelve-month period. Ten pounds of aluminum sulfate were then added to the nutrient plot, and three months later all the sticks were completely disintegrated. The rapid disintegration of the sticks in the plot treated with the acid salt points to the importance of further work on the effect of the pH on the rate of decay.

Comparison of Soil Technique With Other Toxicity Assays

In the selection of a method for testing relative toxicity of chemicals to microorganisms, the rapidity of test, the standardization of the medium, the choice of test organisms, the ease of manipulation, the replication of results, and the duplication by other investigators have been the paramount objectives.

A hypothetical test which would meet these requirements could be performed with distilled water to which could be added increasing concentrations of the chemical to be tested. A known amount of fungus mycelium or spores could be shaken with the toxic solution and left for several different time intervals. The fungus filaments or spores could then be removed to a nutrient agar, and the viability of the fungal filaments or percentage of spores germinating could be readily determined. Comparative toxicity of a large number of compounds could be quickly and easily ascertained. The results, however, would be applicable only to a distilled water-poison system, and the concentration of most toxic materials necessary to inhibit growth would be very low.

The addition of nutrients would necessitate larger amounts of the toxic materials (Van den Berge,[15] 1935). Therefore the mineral solutions—nutrient agar, soil extract agar, soil or wood substrate would in general necessitate an increase in toxic material, the amount of increase depending upon which substrate best meets the nutritional requirements of any particular fungus. Some toxicity values would also be affected by chemical or certain physical changes resulting from interaction between the toxic material and the substrate.

In the petri dish method, the fungi selected for studies of wood destruction grow well on the nutrient substrate containing 1.5% malt extract and 2% agar. Although such a mixture has been recommended as a standard substrate,[2] it should be pointed out that the malt syrup is somewhat variable in composition and constituents and that even the agar varies in the amounts of various growth substances present, Robbins and Ma,[16] 1941. The interpretation of results obtained by the assay of a fungicide when dispersed in an agar system should be restricted to that specific system and not applied to a wood-fungicide system.

When wood preservation studies are carried out, reliance cannot be placed on the results of petri dish tests. The use of wood permits the testing of a large variety of the more common preservatives and fungus-proofing agents, many of which may react with the wood or are precipitated in the wood upon loss of solvent. Organic preservatives which are relatively insoluble in water are not readily tested by petri dish assay.

Comparison of the wood-soil contact method with the wood-water method when untreated wood blocks are used is shown in Fig. 2. The greater uniformity in the amount and rapidity of decay and the better control of moisture showed the soil technique to be superior. It is obvious that if the amount of decay is variable and adversely affected by other factors, the effect of the preservative or fungicide will be obscured. When the sapwood-water method[3] was published, comparison between it and the kolle flask method showed that the wood-water method had certain advantages.

Comparing the method of soil contact with that of soil burial, the principal point of difference is that a pure culture is used in the soil contact method and a mixed culture is used in the soil burial method. Common to both are the moisture-regulating and nutrient properties of the soil. Since the microbial activity of unsterile soil is diverse, depending on the type and source of soil, uniform results from soil burial could not be expected. When wood specimens were exposed individually in bottles of non-sterile soil in the laboratory, the amount of decay after 12 weeks' exposure was less than 10% for all specimens. The results were similar to those obtained by the exposure of untreated wood out-of-doors at Gulfport, Mississippi, for the two-month period (Fig. 5). Since decay-producing organisms were shown to be present, the other organisms in the soil must have interfered with the growth of the wood-destroying fungi. The antagonism between the wood-destroying fungus *Lentinus lepideus* and a contamination is shown in Fig. 6.

The soil-contact technique instead of the soil burial method has been used extensively to test cotton fabric, thread, paper, jute, fibers, and a variety of other materials. The organisms have been varied according to their occurrence on the particular substrate in nature. The fungi *Chaetomium globosum*, *Aspergillus niger*, *Stachybotrys atra*, *Stysanus media*, and *Metarrhizium* have been established with excellent results on a substrate of cloth when testing fabric. The loss in tensile strength of an unprotected cotton thread which had an initial absolute pull of 30 pounds was 90–100% after two weeks' exposure to *Chaetomium globosum*. Treated threads or other cellulosic materials may be tested as satisfactorily as treated wood.

Examination of numerous reports from soil burial studies of treated textiles indicates that organisms which tolerate certain types of chemicals become dominant in the test beds. As a result, a preservative which shows great promise initially may suddently fail when the test is repeated. If a pure culture technique were used, a better evaluation of the preservative would be possible.

Similarly the controversies which have arisen over the ability of certain fungi to destroy cellulose could be resolved by using the suitable cellulose soil technique. At least there is very good evidence that many of the environmental variations affecting decay are at or near the optimum.

Toxicity Tests

In the toxicity tests which follow, petri dish results are given for several compounds, soil contact test results are given for compounds not readily assayed by the petri dish method, and the field test results are included for comparison with the results of the soil contact test method.

Fig. 6—Antagonism which has persisted for over one year between the wood-destroying fungus, Lentinus lepideus (outer portion) and contaminating fungus (inner portion) in a soil culture.

During the initial stages of this research on the evaluation of toxic properties of various compounds for wood preservation, the petri dish method was used for assay studies in the laboratory and the modified sapling method of Waterman and Williams[14] (1934) was used for the field tests at Gulfport, Mississippi. Table 2 shows the results obtained with the petri dish method on the toxicity of four common inorganic salts and a creosote to several of the usual test fungi.

TABLE 2

TOXICITY EXPRESSED IN PER CENT TOXIC AGENT PRESENT IN NUTRIENT AGAR AS DETERMINED BY PETRI DISH ASSAY

Compound	Fungi	Inhibition Point	Killing Point
Arsenic Trioxide	Madison #517	0.04	0.064
	Poria incrassata	0.10	0.10
	Lentinus lepideus	0.30	0.30
	Fomes roseus	0.30	0.30
	Poria microspora	0.30	0.30
	Polyporus vaporarius	0.49	0.49
Zinc Chloride	*Poria incrassata*	0.16	0.16
	Madison #517	0.15	0.23
	Lentinus lepideus	0.16	0.40
	Fomes roseus	0.64	0.64
	Poria microspora	1.40	1.90
	Polyporus vaporarius	1.40	1.90
Mercuric Chloride	Madison #517	0.0012	0.0012
	Lentinus lepideus	0.002	0.002
	Polyporus vaporarius	0.002	0.002
	Poria incrassata	0.005	0.005
	Poria microspora	0.01	0.01
	Fomes roseus	0.01	0.01
Copper Sulfate	*Lentinus lepideus*	0.06	0.16
	Madison #517	0.10	0.16
	Lenzites sepiaria	0.30	0.30
	Fomes roseus	0.24	0.36
	Poria incrassata	0.50	0.50
	Polyporus vaporarius	1.00	1.00
	Poria microspora	1.0	1.00
Creosote	*Poria incrassata*	0.012	0.096
	Polyporus vaporarius	0.024	0.12
	Lenzites sepiaria	0.96	1.00
	Poria microspora	0.20	1.40
	Lentinus lepideus	0.96	1.60

Resistance of the fungi to the four salts is variable, but it will be noted that *Lentinus lepideus*, which is most sensitive to copper sulfate, tolerates the highest concentration of creosote. *Poria incrassata*, which is fairly tolerant of copper salts by petri dish test, is the most sensitive to zinc chloride and creosote. *Poria microspora* tolerates relatively greater concentrations of all the compounds than any of the fungi tested.

The four salts assayed can be easily dissolved in an agar medium in concentrations high enough to be toxic, but uniform dispersal of insoluble salts in the agar is not so easily accomplished. Many salts may be made soluble by dissolving them in dilute ammonia or acetic acid solutions. For example, copper arsenate or zinc meta-arsenite are soluble in ammonia or acetic acid, and by evaporation of the volatile portions of the solvent the salts are precipitated. When precipitation of the salts from ammoniacal or acetic acid solution is carried out in treatments of wood, subsequent evaporation of ammonia or acetic acid from the wood is rather rapid. In agar solutions, uniform precipitation of the salts through evaporation of the ammonia and acetic acid is not easily attained.

TABLE 3

TWENTY FOUR WEEK SOIL ASSAY OF WOOD PRESERVATIVE COMPOUNDS NOT READILY ASSAYABLE BY PETRI DISH METHODS

Mixture #1	Average Weight Loss in Per Cent			
	1.60 lbs/cu.ft.	0.80 lbs/cu.ft.	0.41 lbs/cu.ft.	Untreated*
Poria incrassata	0.0	10.1	10.1	61.8
Polyporus vaporarius	0.0	0.7	0.6	34.1
B.T.L. U-11	0.0	1.8	6.4	56.3
Mixture #2	2.79 lbs/cu.ft.	1.40 lbs/cu.ft.	0.68 lbs/cu.ft.	
Poria incrassata	40.9	31.9	38.8	52.0
Polyporus vaporarius	45.9	30.6		48.6
B.T.L. U-11	21.3	57.0	31.8	48.5
Mixture #3	0.35 lbs/cu.ft.	0.15 lbs/cu.ft.		
Poria incrassata	46.7	22.9		52.4
Polyporus vaporarius	0.0	6.1		63.8
B.T.L. U-11	0.0	5.9		56.4
Mixture #4	0.72 lbs/cu.ft.	0.36 lbs/cu.ft.		
Poria incrassata	1.0	13.8		50.7
Polyporus vaporarius	0.0			55.4
B.T.L. U-11	1.0	14.5		53.6

* Average per cent weight loss of untreated blocks in the same bottles with the treated blocks.

Agar cannot readily be used for assays of two other types of compounds used as wood preservatives. The first type depends on chemical reactions with and also within the wood. Specific examples of this type are the series of compounds fixed in the wood by the reduction of chromium salts which was first studied by Kamesam,[17] 1934. It is now the generally accepted view that the reduction of the chromium is brought about by various sugars in the wood. Subsequent research led to the use of Ascu (Kamesam) or Greensalt K and to the later development of Greensalt "O" by the Bell Telephone Laboratories in the United States and the Bolidens' salts in Sweden. These inorganic salt mixtures were developed in the search for preservatives which would be fixed in the wood and thus resist leaching when exposed to the action of ground waters.

The second type is comprised of organic compounds or mixtures of organic compounds, such as creosote, which has had an excellent service record as a preservative. Also included in this type of compounds (which are insoluble in water and have a relatively low vapor pressure) are certain chlorinated phenols and cresols. Because of the low water solubility or immiscibility with agar solutions, the uniform dispersal of the toxic agents in the agar system, which is essential to reproducibility of results, is almost impossible. Uniform injection of these materials into wood, however, presents no particular problem.

Assays of four representative mixtures not readily assayable in the petri dish are included in the results of Table 3. The composition of the treating solutions of the mixtures 1, 2, 3, and 4 is given below:

Mixture 1	Zinc oxide	46.6%
	Chromic acid	3.8%
	Arsenic acid	49.6% dissolved in a 10% ammonia solution
Mixture 2	Copper phenolate	4%
	Zinc phenolates	1%
Mixture 3	Sodium fluoride	25%
	Disodium hydrogen arsenate	25%
	Sodium chromate	37.5%
	Dinitrophenol	12.5%
Mixture 4	Zinc oxide	22.5%
	Arsenic oxide	35.5%
	Sodium carbonate	1.0%
	Acetic acid	41.0%

In the assays shown in Table 3 the maximum retention of the mixture by the wood is that recommended for the treatment of wood that is not to be used in contact with the ground. To make the test as severe as possible, organisms were selected which were known from petri dish, kolle flask, and wood-water assays to have a high tolerance for various inorganic salts.

Examination of the data in Table 3 shows that the compounds produced in the wood by mixture 4 afford almost complete protection to the wood which was treated with 0.72 pound of the salt per cubic foot. The vigorous attack on the untreated blocks is evidence of the severity of the test. Similarly, the comparable treatment of the wood with 0.8 pound of mixture 1 per cubic foot was very effective in protecting the wood against fungus attack. If the amount of mixture 1 in the wood is doubled, almost perfect protection against decay may be obtained. Wood treated with 0.35 pound of mixture 3 per cubic foot is protected against *Polyporus vaporarius* and BTL U-11 but not against *Poria incrassata*. The latter fungus completely disintegrates both the treated and the untreated wood. Despite the fact that the wood treated with mixture 2 represented the highest concentration of any preservative used (2.8 pounds per cubic foot), complete disintegration of the wood results from the action of the three fungi just mentioned.

Compounds of the Greensalt type were also assayed by means of the soil-contact method. The solution commonly used for treatment of wood with Greensalt K contains three chemicals in the following proportions:

Potassium dichromate	$K_2Cr_2O_7$	55%
Copper sulfate	$CuSO_4 \cdot 5H_2O$	33%
Arsenic acid	$As_2O_5 \cdot 2H_2O$	11%

After treatment of the wood with this solution, reduction of the chromium by the sugars in the wood together with evaporation of water precipitates in the wood fibers several complex insoluble salts, among which presumably

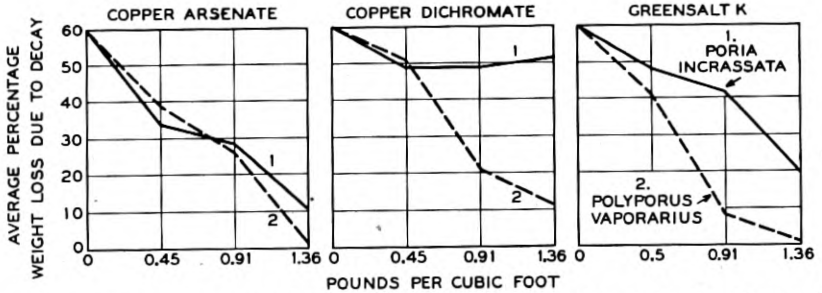


Fig. 7—Comparison by wood-soil assay of components with the whole salt of Greensalt K. Organisms Poria incrassata and Polyporous vaporarius. 24 weeks' time.

are copper arsenate and copper dichromate. Results of soil-contact assay of wood treated separately with solutions of these two components and with the whole Greensalt K complex are given in Fig. 7. Before exposure to the fungi, the wood specimens were leached by a diffusion method described by Waterman, Leutritz and Hill[3], 1938. No untreated control blocks were included in the bottles with this test, which was conducted for 24 weeks. The copper arsenate component of the Greensalt K complex is shown to be much more effective as a preservative than the copper dichromate component but not as effective as the whole K salt complex. Figure 8 shows the setup for the wood-soil assay of 0.75 lbs/cu. ft. of Greensalt K from a recent series of cooperative experiments conducted by the Forest Products Laboratory, Madison, Wisconsin. Figure 9 is a comparison of the Greensalt K treated and untreated reference blocks in the same bottles after exposure to the following fungi:

Blocks	Fungi
A	*Lenzites trabea* #617 F.P.L.
B	*Poria incrassata* #563 F.P.L.
D	*Lentinus lepideus* #534 F.P.L.
E	*Poria microspora* #106 F.P.L.
F	*Poria luteofibrata* (Baxter)

The distortion and shrinkage of the blocks can be used as a visual confirmation of the weight loss due to decay.

The more recently developed Greensalt O is similar to the K salt. The treating solution of this salt mixture is composed of copper oxide, hydroxide or carbonate, chromic acid anhydride, and arsenic acid in percentages based on the chemical equivalents of the copper, chromate and arsenic salts in the K salt solution. The toxicity from the wood-soil assay of Greensalt O is given in Table 4 for fourteen fungi and for three concentrations of the preservative. The effectiveness of the Greensalt O treatment of wood is apparent from examination of the toxicity index. The weight losses due to decay of the untreated reference blocks indicated in general that conditions for decay were again very severe, but the reference blocks exposed to the fungus *Lentinus lepideus* were protected by their proximity to the treated specimens. As previously pointed out, the fungus *Lentinus lepideus* does not tolerate even slight concentrations of copper, which is a major component of the Greensalt complex.

The fungus *Poria incrassata* was again shown to be the least affected by the toxicity of the preservative. The toxicity index for the blocks treated with the highest concentration of the preservative was 94% after 16 weeks' exposure to this organism. In view of the excellent field record for the equivalent K salt preservatives ratings 90 to 100% by the toxicity index would be satisfactory. Additional data will undoubtedly determine the limits of the toxicity index.

At the end of the 24-week period, the fungi BTL U-11, *Lenzites trabea*, *Trametes serialis*, *Polyporus vaporarius*, and one strain of *Coniophora cerebella* caused slight decay of one or more blocks treated with the maximum concentration of preservative, the fungi *Lenzites trabea*, *Coniophora cerebella*, and *Trametes serialis* were still capable of causing only slight losses. Exposure of the blocks treated with the low contentration of preservative to *Polyporus vaporarius* and BTL U-11 resulted in an increase in the amount of decay.

Since the resultant salts of the Greensalt O reaction should be similar to those produced by Greensalt K, field trials of these materials would be expected to give comparable results. Extended field tests of wood treated with one pound of Greensalt K per cubic foot have been in progress for ten years without a single failure having occurred in more than 40 specimens. Specimens treated with Greensalt O have been tested in the field for only

Fig. 8—Wood-soil assay of 0.75 lbs/cu. ft. of Greensalt K (courtesy of Forest Products Laboratory, Madison, Wisconsin). Reading left to right the samples are:

Blocks	*Fungi*
A	*Lenzites trabea* #617 F.P.L.
B	*Poria incrassata* #563 F.P.L.
D	*Lentinus lepideus* #534 F.P.L.
E	*Poria microspora* #106 F.P.L.
F	*Poria luteofibrata* (Baxter)

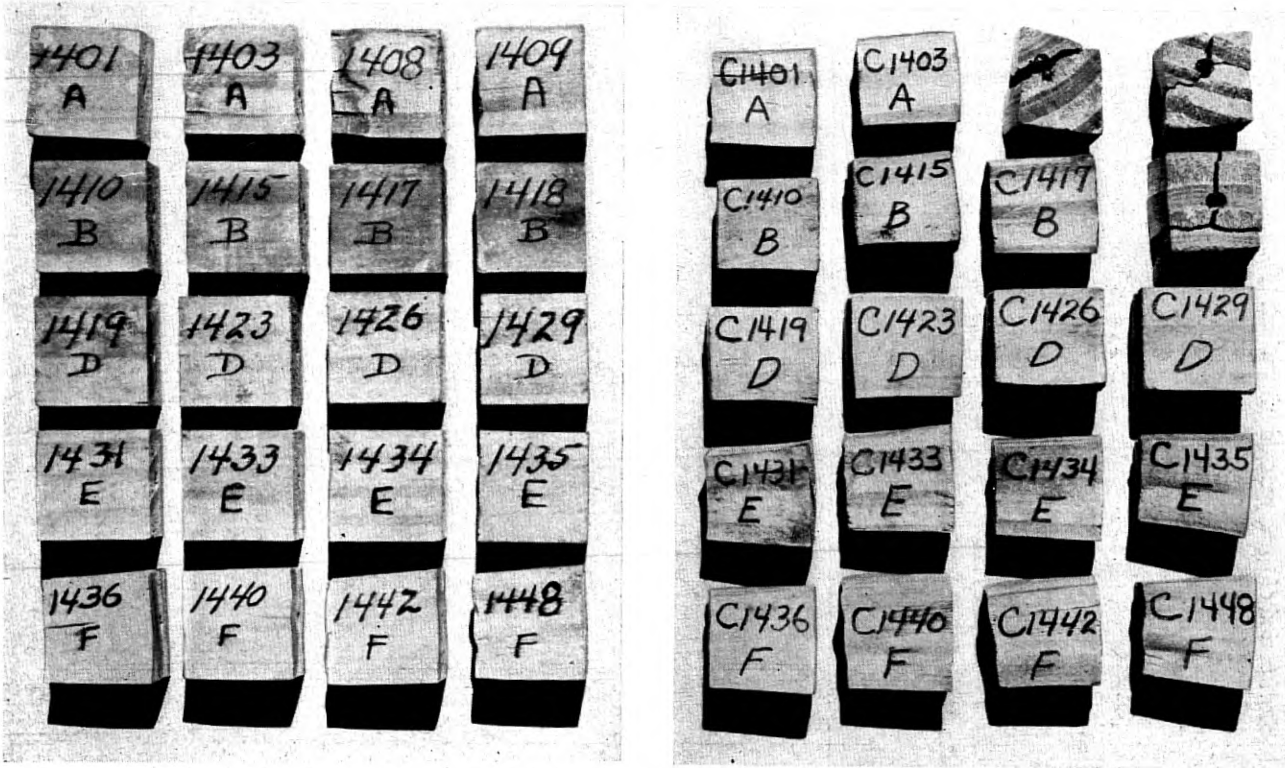


Fig. 9—A comparison of the Greensalt K treated and untreated reference blocks after exposure to fungi. (Treated on the left—untreated on the right side of picture.)

Blocks	*Fungi*
A—	*Lenzites trabea* #617 F.P.L.
B—	*Poria incrassata* #563 F.P.L.
D—	*Lentinus lepideus* #534 F.P.L.
E—	*Poria microspora* #106 F.P.L.
F—	*Poria luteofibrata* (Baxter)

the relatively short period of three years, during which time all the specimens have remained sound.

Results of other field trials for a three-year period with the same mixtures 1, 2, 3, and 4, listed previously, copper arsenate, Greensalt O, and a creosote are given in Fig. 10. Twenty-five untreated controls showed 84% failure, 4% sound, and 12% badly infected in one year. All had failed at the end of the second year. Twenty specimens were used for each retention of the individual preservatives, with the exception of the creosote. The reason for fewer creosote specimens within the correct retention is that the empty-cell treatments of wood with creosote give a wider range of retention than the full-cell treatments of the wood with water solutions of the salts.

TABLE 4

TWENTY FOUR WEEK—WOOD SOIL ASSAY OF GREENSALT "0" USING 13 SPECIES OF WOOD DESTROYING FUNGI

	Toxicity Index*		
	1.17 lbs/cu.ft.	0.96 lbs/cu.ft.	0.476 lbs/cu.ft.
Poria incrassata (16 wks)	94	68	25
B.T.L. U-11	98	88	62
Polyporus vaporarius	98	93	55
Lenzites trabea	98	96	94
Coniophora cerebella	98	98	98
Trametes serialis	98	98	98
B.T.L. U-4	100	98	98
Polyporus anceps	100	98	98
B.T.L. U-53	100	99	98
B.T.L. U-24	100	99	98
Lenzites sepiaria	100	100	98
Poria microspora	100	100	98
Fomes roseus	100	100	100
Lentinus lepideus	100	100	100

$$* \text{ Toxicity Index} = \frac{\%\text{ loss of norm} - \%\text{ loss of treated block}}{\%\text{ loss of norm}} \times 100.$$

In the three-year period of exposure only the treatments of wood with 1.3 pounds of copper arsenate and 7 pounds of creosote per cubic foot showed a perfect record. Copper arsenate had previously been shown to be a very effective component of the Greensalt complexes when tested by the soil-contact method. Mixture 2 was found to be the poorest by soil-contact assay and also in the field trials. Mixtures 4, 1, and 3 were rated in that order of decreasing effectiveness in the field test. In the soil-contact assays at comparable retention, 0.72 and 0.80 pound of salt per cubic foot of wood, respectively, mixture 4 was better than 1; and at 0.41 and 0.35 pound of salt per cubic foot of wood, respectively, compound 1 was slightly better than 3, especially against *Poria incrassata*.

Results from field and laboratory tests show good agreement in the evaluation of the compounds. The advantage of the laboratory method in the matter of time is a decided one, but the field trial is valuable for testing the permanence of the preservative. For example, mixture 4 was found in the laboratory test to be a very effective preservative, but the initial preservative properties were dissipated by exposure to the weather, since 50% of the

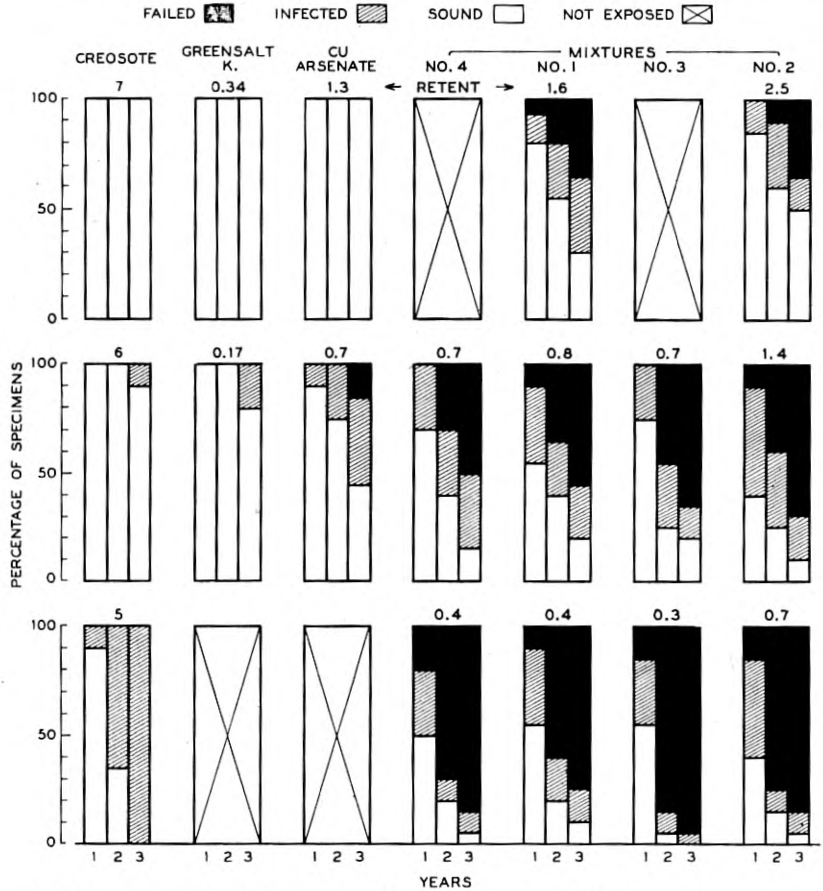


Fig. 10—Results of field exposures on the four mixtures of Table 3 and other compounds creosote, Greensalt K, copper arsenate (retent in pounds per cubic foot).

specimens had to be removed because of failure within three years. When a compound is a poor preservative, as in the case of mixture 2, both laboratory and field trials serve to eliminate it from further consideration. By the soil-contact method every specimen treated with mixture 2 was badly attacked by all the organisms used, whereas at a comparable retention only 35% of the specimens in the field trials had failed after three years' exposure.

Since these results indicate that the soil-contact provides optimum conditions for decay, the laboratory method serves as a means of quickly eliminating inferior preservatives and minimizing the number for field studies.

Summary

The soil-contact method described in this paper has been shown to be a valuable laboratory tool for the study of fungus destruction of cellulose and wood and for the determination of the value of wood and cellulose preservatives.

Top soil containing 20 to 25% moisture on a dry-weight basis, when used as a supporting substrate for decaying wood, proved to be an excellent means controlling the moisture content of wood during the decay process. Investigation showed that the optimum moisture content for initiating the decay of wood was fiber saturation. It also was found that during decay the initial water content of the wood remained constant, through maintenance of a constant volume of the wood structure despite loss of wood substance.

Experiments with various combinations of nutrients and nutrilites added to artificial soil showed the importance of these materials in decay studies. The need for nitrogen in the destruction of cellulose by fungi was confirmed. Lack of wood decay in the presence of a sugar when there is also a deficiency of nitrogen presents an interesting problem the explanation of which may throw considerable light on discrepancies in many test procedures. Comparison of results with nutrient artificial soils and an average top soil indicates the possibility of employing a standard artificial soil in the contact test method.

The optimum temperature for most wood-destroying fungi tested was found to be 26°–28°C. Decay occurred over a wider range of temperature in soil-contact tests than in petri dish tests.

It was found that decay was much more uniform and more rapid in the soil-contact method than in other laboratory methods or in field trials. There is a large, single, vigorous inoculum in the soil-contact laboratory method, while in the field antagonism between wood-destroying organisms and the other flora and fauna of the soil frequently checks the decay process.

Toxicity studies based on petri dish assays showed that the amount of a compound tolerated by several fungi varies considerably. Petri dish assays of toxic materials are often misleading. Generally, higher retentions of the preservatives are needed to prevent decay than are indicated by petri dish assay. Occasionally, a material which performs poorly in the petri dish test will, however, act as a satisfactory preservative of cellulosic derivatives in both soil-contact and field tests.

Field trials of preservatives, though in general less rapid, confirm the results of the soil-contact method and in addition determine the degree of

permanence of the preservative. However, heating, leaching and other simulated weathering cycles may be used in conjunction with the soil-contact method to determine the stability of a preservative to evaporation, to the solvent action of ground water, and to chemical deterioration by ultraviolet light. Futher comparisons between soil-contact assay and field test of a wood preservative such as Greensalt confirms the fact that conditions for decay are more nearly optimum in the former and result in an unusually severe test of the preservatives.

The soil-contact method is an excellent laboratory tool easily adapted to fundamental studies of the decay process and to evaluation of preservatives. The method has shown considerable promise in evaluating preservatives for a wide variety of materials, including leather, cotton, felt, paper and jute. Since the factors influencing decay are very near optimum in the soil-contact method, any preservative that prevents decay in this laboratory test and is permanently retained will be effective under any climatic conditions.

Acknowledgment

I wish to express my appreciation to Dr. S. F. Trelease of Columbia University for his help and guidance in the preparation of the manuscript and to Dr. R. H. Colley and other members of the Bell Telephone Laboratories Staff for their advice and counsel throughout the work.

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X-Ray Studies of Surface Layers of Crystals

By ELIZABETH J. ARMSTRONG

1. Introduction

WHEN a crystalline substance is sawed, ground, lapped or polished, the crystal structure adjacent to the worked surface is distorted and ruptured. Since the selective diffraction of X-rays by a crystal is a result of the orderly arrangement of the planes of atoms of the crystal, disturbance of this arrangement is detectable by X-ray diffraction.

Research on aging of quartz oscillator plates seems to indicate that changes which are accelerated by high humidity take place in this disturbed material resulting in changes in the frequeny and activity[1] of the crystal plate. A knowledge of the nature and extent of this disturbed layer is essential to an understanding of the changes that are taking place in it and may contribute to the improvement of the quality of crystal plates, apart from the problem of aging.

The purpose of this paper is to present a review of X-ray techniques that have been or may be useful tools for the examination of the nature of the surface layers of crystals. Each technique is also discussed from the standpoint of the kind of evidence which it seem best suited to bring to light. Familiarity with the general principles of X-ray diffraction as outlined in this Journal, volume xxii, number 3, pages 293 and 297, is assumed.

It has long been known that the nature of the surface preparation of a crystalline substance affects the intensity of the reflected X-rays. As early as 1913, about a year after the first X-ray diffraction experiments with crystals, de Broglié and Lindemann[2] noticed that the spots in Laue photographs of certain crystals were inhomogeneous and suggested the interpretation that the darker parts of the spots might result from disturbed material. A. H. Compton[3], using a double crystal spectrometer in 1917, found that the reflection from a ground surface of a calcite crystal was three times that from a cleavage face.

[1] One plate is said to have greater activity than another similar plate if its amplitude of oscillation is greater when the two are tested under identical conditions. The activity of a plate is reduced by friction with its mountings or with particles on its surface, either of quartz or of a foreign material.

[2] de Broglié, M. and Lindemann, F.-A., "*Sur les Phénomènes Optiques Présentés par les Rayons de Röntgen Rencontrant des Milieux Cristallins, Comptes Rendus,* 156 (1913), pp. 1461–1463.

[3] Compton, A. H., "*The Reflection Coefficient of Monochromatic X-Rays from Rock Salt and Calcite,*" *Phys. Rev.*, 10 (1917), pp. 95–96.

The explanation of the higher intensity of reflection from the disturbed surface lies in the fact that the rays of the incident X-ray beam, collimated by a pair of slits, are not perfectly parallel, but diverge, meeting the crystal plate at various angles, whose range, depending on the geometry of the slits, is usually about 15 to 25 minutes of arc. If the surface regiln of the crystal plate is undisturbed only a very small part of the incident beam will meet the crystal at the Bragg angle for X-ray reflection. If, however, some of the quartz has been disturbed it will have a variety of orientations with respect to the main crystal structure and the various disturbed bits of quartz will be at the Bragg angle for the various divergent rays of the incident X-ray beam. In this way more of the incident beam is reflected by a disturbed crystal surface than by an undisturbed crystal surface. The disturbed material measured by this technique differs in orientation from that of the main plate by not more than a few minutes so that even this disturbed material uses only a small sector of the divergent incident beam. Surface particles misoriented by larger angles are not numerous enough to reflect X-rays into the ionization chamber with measurable intensity.

An alternative interpretation of the higher intensity of reflection from the disturbed material should be mentioned although it has little practical significance. Consideration of the Bragg equation, $n\lambda = 2d \sin\theta$, will show that a range of d values would make it possible for a range of θ values to satisfy the equation. If, therefore, there were some variability in the spacing, d, between the atomic planes from which the X-rays were being reflected, reflection would take place over a corresponding range of angles of incidence.[4] Such variability in d spacing would be a result of lattice distortion. It would generally be accompanied by misorientation and therefore its consideration as a phenomenon distinct from misorientation becomes rather academic. The disturbance will therefore be spoken of as misorientation although it probably also involves small changes in d spacing.

Measurable lattice distortion can be produced by other means than surface working. The reflection-intensity of an etched plate is increased three or four times if the plate is strained by bending during the reflection of the X-ray beam. When the pressure on the plate is released the reflection-intensity resumes its former value. The distortion produced by unequal pressures on the plate results in the heterogeneity of orientation which makes possible the use of a larger part of the incident beam, resulting in higher reflection-intensity. When lapped plates are similarly deformed the increase in reflection-intensity is less since some heterogeneity of orientation already exists. As would be expected, the effect of the deformation is progressively less with

[4] Consideration of the known compressibility and tensile strength of quartz indicates that the maximum change in d spacing which could be obtained would be of the order of 0.1%. For small values of θ the change in θ for this d change would also be 0.1%, increasing, with larger θ values to about 0.2% at $\theta = 70°$.

increasing grain size of the abrasive with which the surface of the plate was lapped.

2.1 The Single Crystal Spectrometer

The single crystal spectrometer is used for X-ray measurement of the orientation of quartz oscillator plates. In this instrument slit-collimated X-rays are reflected from a crystal into an ionization chamber and the relative intensity of the reflected X-rays is read from a meter showing the

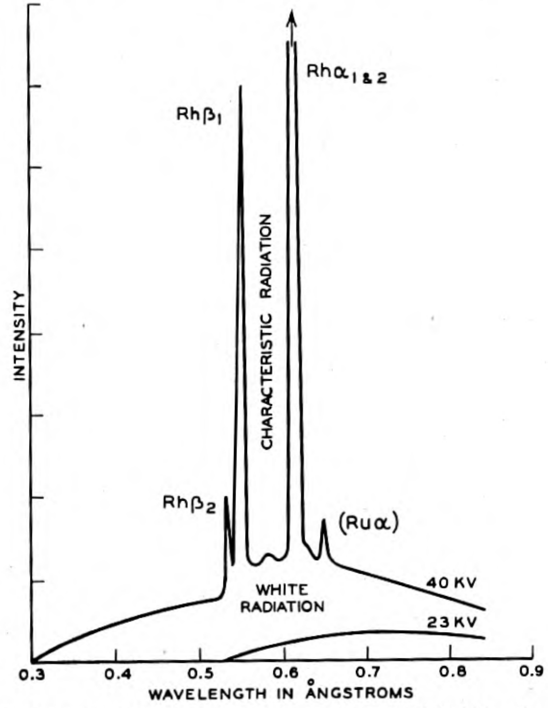


Fig. 1.—X-Ray spectra from a rhodium target at 23 and 40 kilovolts. Ruthenium impurity present. (Adapted from *Siegbahn, Spectroscopy of X-Rays*).

amplified current resulting from the ionization of the gas in the chamber by the X-rays. Since the reflected white radiation is too weak to cause a measurable amount of ionization, only the reflected characteristic radiation is measured by the ionization chamber. For most purposes a copper-target tube is used and the β radiation (comparable to Rh_β of Fig. 1) is eliminated by a selective filter so that only the α radiation is used, the X-rays thus being essentially "monochromatic".

Three different techniques for examining surface layers of crystals with the single crystal spectrometer will be described. Two of these employ photographic films or plates in addition to the ionization chamber for measuring the reflected rays.

2.2 Reflection-Intensity Measurements on the Single Crystal Spectrometer with the Ionization Chamber (Fig. 2)

Working with the single-crystal spectrometer, Bragg, James and Bosanquet[5] found the reflection-intensity from a ground face of rock salt two to four times that from a cleavage face. Dickinson and Goodhue[6] found the reflection-intensity from ground faces of sodium chlorate and sodium

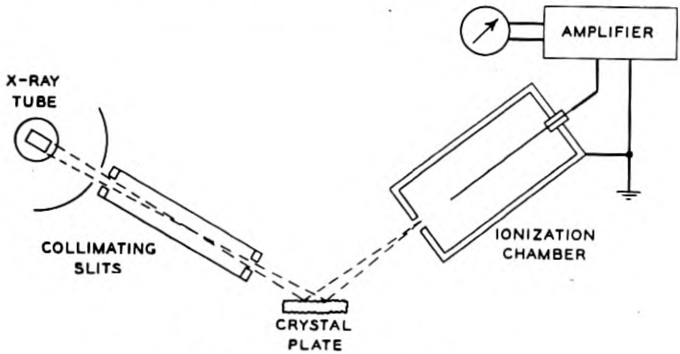


Fig. 2.—Single crystal spectrometer

bromate twice that from the natural face. Sakisaka[7] found the reflection-intensity from a quartz plate lapped with #30 carborundum $2\frac{1}{4}$ times that from a plate lapped with very fine emery, which, in turn, was twice that from an etched plate. Recent measurements by the writer have shown that the reflection-intensity of an etched surface increases with progressive lapping and that of a ground surface decreases with progressive etching as shown in Fig. 3. In these figures the reflection-intensity is given in terms of the ratio of the intensity from the test plate to that from a standard plate of the same cut, etched 20 minutes following fine lapping. The initial rate of increase of intensity-ratio with lapping or decrease with etching is very high.

This technique would be most useful in sample-testing groups of plates to check whether they had been inadequately etched or whether any lapping at all had occurred after etching. (In either case the plate would be subject to

[5] Bragg, W. L.; James, R. W. and Bosanquet, C. H.; "The Intensity of Reflexion of X-Rays by Rock Salt," Part I. *Phil. Mag.* 41 (1921) pp. 309–337; Part II, *Phil. Mag.* 42 (1921) pp. 1–17.

[6] Dickinson, R. G. and Goodhue, E. A.; "The Crystal Structure of Sodium Chlorate and Sodium Bromate," *Jour. Amer. Chem. Soc.* 43 (1921) pp. 2045–2055.

[7] Sakisaka, Y.; "The Effects of the Surface Conditions on the Intensity of Reflexion of X-Rays by Quartz," *Japanese Jour. Phys.* 4 (1927) pp. 171–181.

aging.) Although a plate lapped with 180 carborundum can be easily distinguished from one lapped with 303½ emery by a comparison of intensity ratios, plates lapped with nearly similar abrasives cannot be distinguished with certainty, except on a statistical basis.

That the disturbed material measured by this technique differs in orientation from that of the main plate by less than a few minutes is shown by the fact that the range of incident angles over which ionization-detectable X-ray reflection takes place from a lapped crystal plate is the same within the

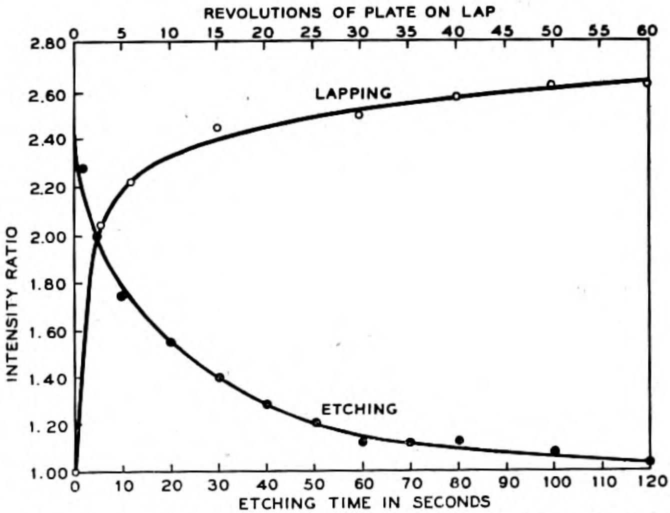


Fig. 3.—Effect on reflection-intensity produced by lapping on etched plate with 303½ emery and soap solution and by etching the lapped plate with 48% hydrofluoric acid at 25°C.

limits of error of measurement as that for reflection from an etched crystal plate.

2.3 Photographic Measurement of Angular Misorientation with the Single Crystal Spectrometer

A technique which does indicate quartz misoriented by more than a few minutes has been devised by Dr. C. J. Davisson. Although the X-rays reflected from this material are too weak to produce a measurable current in the ionization chamber, they will darken a photographic plate or film if adequate exposure time is allowed. The principles of this technique are illustrated in Fig. 4 and some of the resulting photographs are shown in Figs. 5 and 6.

The plate to be measured is placed at the Bragg angle to the incident X-rays as determined by preliminary measurement of the maximum ionization current produced in the ionization chamber which is at twice the Bragg angle to the incident beam. A film in a paper envelope is then placed before the ionization chamber in a holder which permits a small portion of it to be exposed at a time. A brief (5 or 10-second) exposure is then made with the crystal plate in this "zero position",[8] (see Figs. 4 and 5), recording the strong characteristic radiation reflected from the main crystal plate. At the same

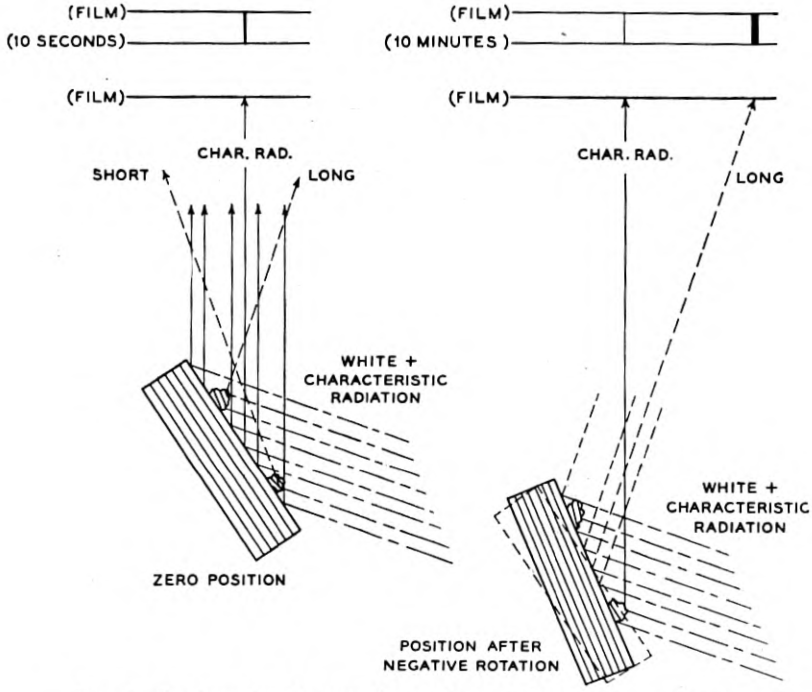


Fig. 4.—Spectrometer photography of misoriented crystalline material

time the weak white radiation is being reflected from the disturbed material, but this radiation is relatively so weak and the disturbed material of such

[8] To check the correctness of the "zero" setting, a "rocking" exposure is taken, during which the plate is rocked through the Bragg angle. The upper half of the beam should be shielded for the "zero" exposure and the lower half for the "rocking" exposure so that the film need not be moved between the two exposures. In the "rocking" exposure the beam is reflected during only a fraction of the exposure time and because the exposure is so brief only the reflection of the strongest part of the incident beam (the part that is going to produce the reflections in later exposures) is recorded. In the "zero" exposure the crystal plate may have been set so as to reflect the divergent, weaker rays of the beam which may differ in direction from the strong part of the beam by as much as 15 minutes. The terms "stronger" and "weaker" do not refer here to characteristic and white radiation, but to parts of the beam that have more or fewer X-rays due to the geometry of the collimating system with relation to the target.

relatively small volume that the reflection does not noticeably darken the photographic film in five seconds. Successive ten-minute exposures are then taken with the crystal plate turned at successively greater angles from the zero position. At any given angle the disturbed quartz that has thus been brought into the proper position to reflect the characteristic radiation does so, producing a center line on the film whose intensity is roughly proportional to

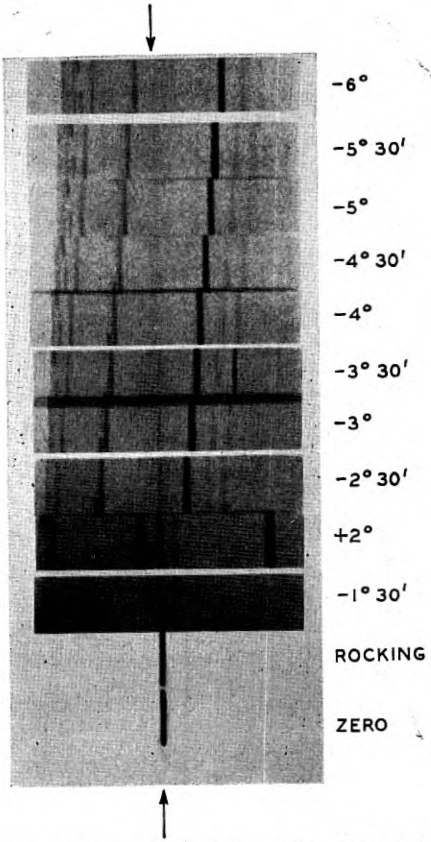


Fig. 5.—Spectrometer photograph of BT quartz plate lapped with 303½ emery

the volume of quartz misoriented to this angle. Various wave-lengths of the white radiation will satisfy the Bragg equations for various atomic planes of the main plate at each angular position and will be reflected to other positions on the film. Although the incident white radiation is relatively weak the reflected beams are strong enough to darken the film in ten minutes because rays reflected from the main plate are reflected by a much greater volume of quartz than are rays reflected from the disturbed layer. The strongest of these "white" reflections from the main plate is that from the set of atomic planes most nearly parallel to the surface of the plate, the planes that reflected the characteristic radiation in the zero position.

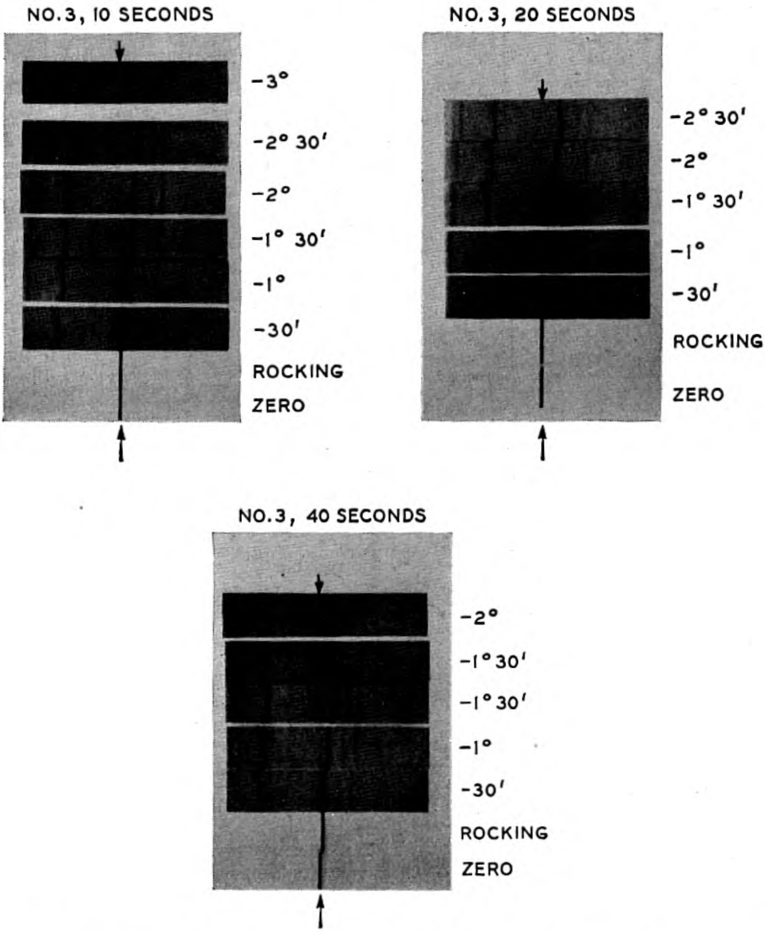


Fig. 6.—Spectrometer photographs showing effect of etching a 303½ emery-lapped BT quartz plate with 48% hydrofluoric acid

In Fig. 5, the central line (indicated by the arrow) resulting from the characteristic radiation reflecting from the disturbed quartz, is distinctly present through the 4° exposure but not in higher-angle exposures, indicating that in the 303½ emery-lapped surface from which the X-rays were reflected there was not enough quartz misaligned by more than 4° to reflect a beam that would visibly affect a photographic film during a ten-minute exposure. The dark line that moves to the right as the negative angular rotation increases results from the reflection of progressively longer wave-lengths from the quartz of the main plate. The three series of exposures in Fig. 6 show the progressive removal of the disturbed quartz by etching with 48% hydrofluoric acid. After ten seconds' etching the line from the disturbed material does not show distinctly beyond the 1° 30′ position; after 20 seconds' etching it is distinct only through the 1° 00′ position and after 40 seconds it can only be seen distinctly at the 30′ position. If the film had been exposed for a longer time at each position the line from the disturbed material at each angle would have persisted with longer etching. With the arbitrarily

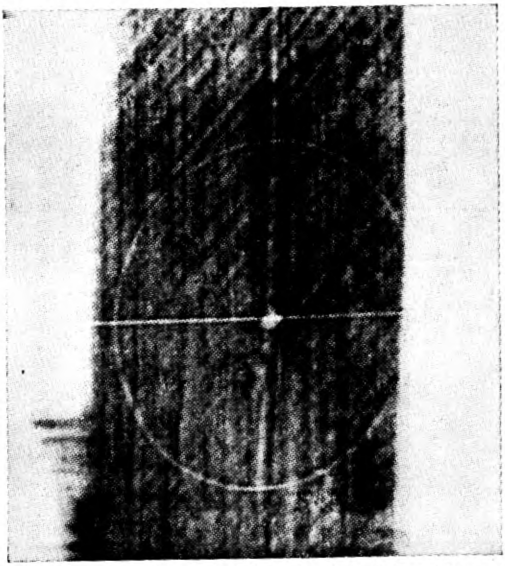


Fig. 7.—Photograph produced by reflection of a broad X-ray beam from the (100) cleavage face of a rock salt crystal (Berg)

chosen ten-minute exposures a line from material misoriented by 45′ disappears after about 25 seconds' etching with 48% hydrofluoric acid, but the disappearance of the 30′ line occurs only after 70 seconds' etching, which removes an amount of quartz equivalent in weight to a layer about four-tenths of a micron thick on each surface.

With this technique we are measuring the more grossly misoriented surface material, material that is probably not continuous with the quartz of the main plate. This is evident from the fact that a piece of quartz would have to have a length-thickness ratio of 26 to 1 to take a 3° deflection without breaking and the microscopic evidence does not indicate the presence of any such long, thin pieces of quartz attached to the plate.

Although about a half-minute's etching with 48% hydrofluoric acid removes all quartz misoriented by more than 45′, quartz misoriented by a smaller angle than this is not entirely removed by more than an hour's etching, as indicated by photographs taken with X-rays passing through the plate, a technique to be described later in this paper. The ionization chamber and amplifier are not sensitive enough to register the reflection from the small amount of this material left after two minutes' etching.

The disappearance of the more widely misoriented material in the earlier stages of etching may mean either that this material is preferentially removed or that there is uniform removal of all the misoriented material with the consequent disappearance of that which is smallest in amount. Geiger-Müller counter measurements of the intensity-distribution of the reflections from the misaligned material at various angles at the various stages of etching would indicate which of the two alternatives is true. These measurements are being made by Davisson and Haworth, but are not yet complete.

2.4 Photography of the Disturbed Surface with a Broad X-Ray Beam

A second photographic method with the single-crystal spectrometer, used by Berg in 1931[9], Gogoberidze in 1940[10], and others involves the reflection of a broad monochromatic beam from an appreciable area of the crystal surface (placed at the Bragg Angle, θ) onto a photographic plate or film placed parallel to the crystal face. The different reflection-intensities from the variously disturbed parts of the surface of the crystal plate darken the film differently, giving a map-like picture of the distribution of different degrees of disturbance over the surface of the plate. One picture produced in this way by Berg is reproduced in Fig. 7. The thin white cross and circle are reference marks scratched on the surface of the rock-salt crystal, the lines being parallel to the cube edges. The two sets of sub-parallel streaks are the traces of dodecahedral {101} planes and "show that the crystal structure in these places differed from the ideal lattice". They are interpreted as slip planes (störebenen) in the crystal. C. S. Barrett[11] has recently refined this technique and broadened its application to the study of a wide variety of metallurgical problems.

The application of this technique to the study of quartz surfaces might provide useful information on disturbance distribution which is not furnished by the other techniques.

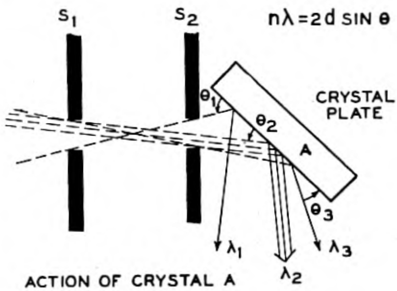
[9] Berg, Wolfgang, "Über eine röntenographische Methode zur Untersuchung von Gitterstörungen an Kristallen," *Naturwissenschaften* 19 (1931), pp. 391–396.

[10] Gogoberidze, D. B., "Investigation of Surface Structure of Crystals by Means of Reflection of a Monochromatic X-Ray Beam, *Jour. Exptl. Physics, U.S.S.R.* 10 (1940) p. 96 (in Russian).

[11] C. S. Barrett; "A New Microscopy and Its Potentialities," *Metals Technology*, April, 1945.

3.1 The Double Crystal Spectrometer

In the double crystal spectrometer (Fig. 8), X-rays reflected from a crystal plate are again reflected from a second crystal plate into the ionization chamber. Their intensity is indicated by a meter showing the amplified ionization current, as in the case of the single crystal spectrometer. The divergent white rays from the collimating slits are reflected from crystal plate A as shown in Fig. 8: those of longer wave-length at higher angles and those of shorter wave-length at lower angles in accordance with Bragg's law. If



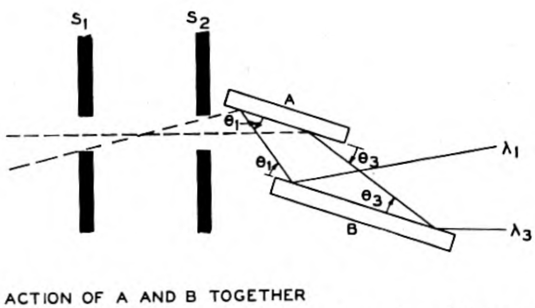


Fig. 8.—Double crystal spectrometer, parallel position. S_1 and S_2 are collimating slits

crystal plates A and B are placed so that similar sets of atomic planes in the two plates are parallel, the same rays that were reflected from plate A will also reflect from plate B as shown in Fig. 9 since each ray will meet this plate at the particular angle, θ, which will satisfy Bragg's law for that wave-length for the atomic planes in question.

If plate B is rotated a few seconds away from this position, however, and if the crystal is perfect, the conditions for reflection are destroyed for all rays so that no X-rays enter the ionization chamber. However, a plate with a surface layer of misoriented crystal material will still reflect when thus rotated because the misoriented particles will be brought into the reflecting position as the main plate is turned away from it. The farther the main plate is turned from the reflecting position, the weaker will be the reflected radiation because less quartz will be misoriented to this angle. In this respect the double crystal spectrometer technique is similar to C. J. Davisson's photographic technique, but is measuring much smaller angular rotation and higher reflection-intensity. A curve of the variation of reflection-intensity with angular rotation of the B crystal plate for two differently finished crystal plates measured by Davis and Stempel[12] is shown in Fig. 9

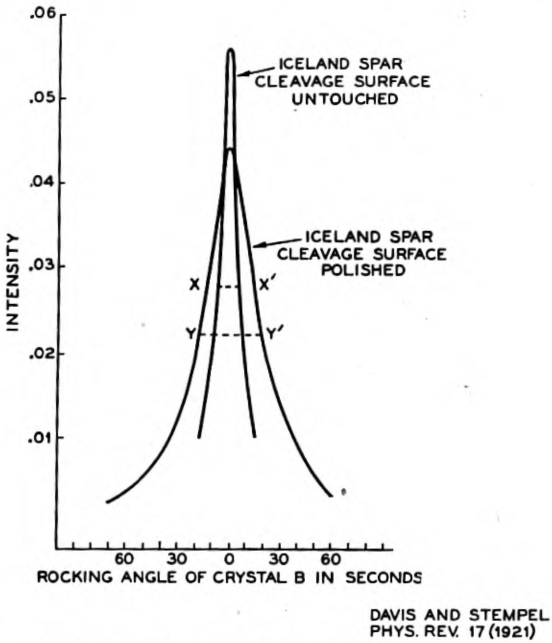


Fig. 9.—Double crystal spectrometer rocking curves

The higher reflection-intensity at the "zero angle" and the very rapid decrease of intensity as the plate is turned away from this position show that the untouched surface is less disturbed. The lower reflection-intensity at the "zero angle" and the less rapid decrease of intensity as the plate is turned away from this position show the polished surface to be more disturbed. The width of such "rocking" curves at half-maximum (as x–x′ and Y-Y′ in Fig. 9) has often been taken as a measure of perfection of the reflec-

[12] Davis, B. and Stempel, W. M., "An Experimental Study of the Reflection of X-Rays from Calcite," *Phys. Rev.* 17 (1921) pp. 608–623.

ting crystal. Bozorth and Haworth[13] made such measurements for variously prepared surfaces of quartz and found that the rocking-curve width at half-maximum was least for etched plates, the smallest width measured being 1.7 seconds. The greatest rocking-curve width measured was 88 seconds for which both crystal plates (A and B, Fig. 8) were lapped with 100-mesh carborundum. Bozorth and Haworth also showed that the rocking-curve width decreased very rapidly in the initial stages of etching

With this technique we are measuring the angular frequency distribution of the disturbed material that was detected with the intensity-ratio measure-measurements with the single crystal spectrometer. Thus, with the rocking curve, we show the intensity for each angle of incidence separately, but with the single crystal spectrometer we measure the intensity for a relatively wide range of angles of incidence at one measurement, which is the integrated intensity under the double crystal spectrometer rocking curve.

None of this small-angle disturbance is detectable by the Davisson photographic technique because at small angles the reflected rays are too close to those from the main plate and become confused with them on the film. Conversely, none of the material detected by the Davisson photographic technique is detectable by this technique because the intensity of the reflected rays from large-angle disturbance is not great enough to produce a measurable current in the ionization chamber.

Together, these various measurements indicate a relatively large amount of quartz misoriented by less than a minute and a smaller amount of quartz misoriented by larger angles up to three or four degrees.

The use of a photographic film in place of the ionization chamber in the double crystal spectrometer would presumably permit the precise measurement of the smaller amount of material misoriented by more than that now measured with this instrument, as in the Davisson technique with the single crystal spectrometer. This has not, to the writer's knowledge, been done.

4.1 The Transmission Laue Camera

In the transmission Laue camera (see Fig. 10) a beam comprising a large range of wave-lengths is passed through a stationary plate. Various sets of atomic planes in the crystal, each with a different interplanar spacing, d, making a variety of angles, θ, with the incident beam, reflect whatever wave-lengths of radiation in the incident beam satisfy the Bragg equation, $n\lambda = 2d \sin \theta$, and the reflected beams are recorded photographically. Figure 11 shows films resulting from one-hour exposures. As in the case of the single-crystal spectrometer, the slit-collimated beam comprises non-parallel rays,

[13] Bozorth, R. M. and Haworth, F. E., "The Perfection of Quartz and Other Crystals and Its Relation to Surface Treatment," *Phys. Rev.* 45 (1934) p. 821–826; *Bell Telephone System Technical Publications Monograph* B-801.

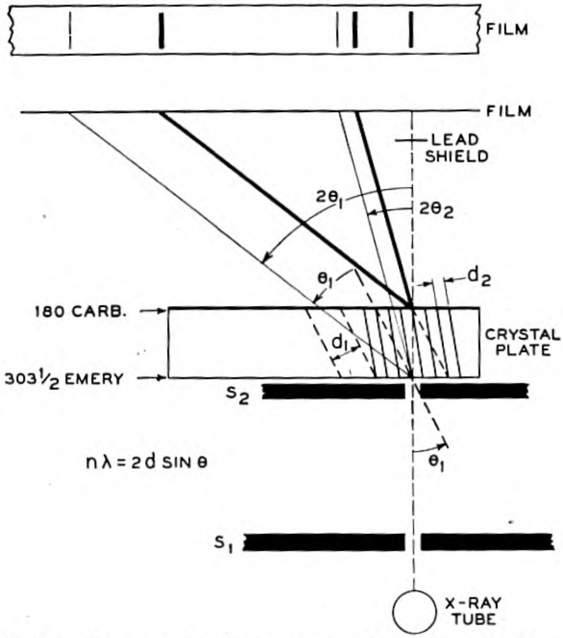


Fig. 10.—Section of transmission Laue camera. S_1 and S_2 are collimating slits

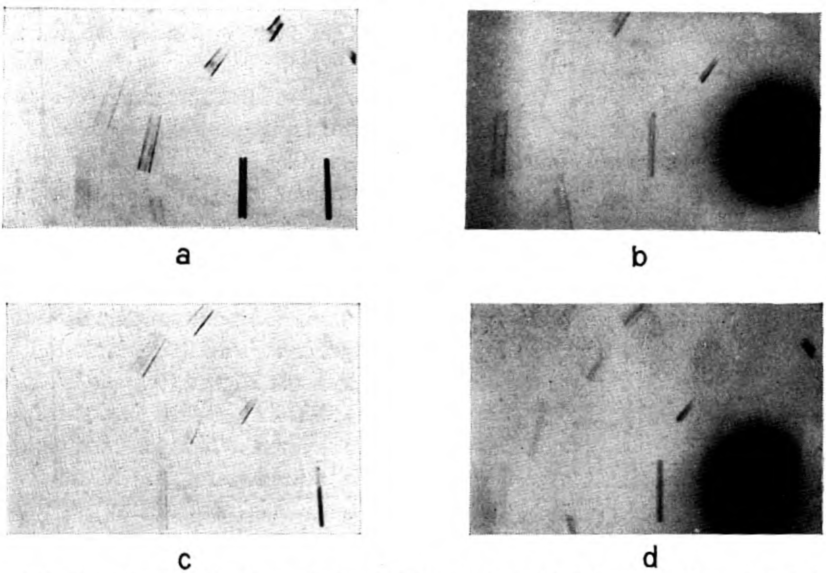


Fig. 11.—Transmission Laue photographs of a 4 mm.-thick BT quartz plate. (a) Face nearer film lapped with 180 carborundum. Other face lapped with 303½ emery. (b) Same as a, after 47 hours' etching. (c) Same as a, but through a different part of the plate. Plate rotated 180° in its own plane. (d) Same as c, after 20 minutes' etching.

but in this case exposures are long enough to record the "white" radiation reflected from both the small-angle disturbed and undisturbed material. If reflections from material misoriented by more than a few minutes were recorded on the film the lines from the reflected X-rays would be broader than they are.

In the undisturbed material there is one wave length from a ray traveling in a given direction that will satisfy the Bragg equation for a given set of atomic planes. Most of these "usable" X-rays are reflected by the first thin layer of undisturbed crystal they meet and therefore very little reflection of X-rays of this wave-length from this ray takes place from deeper layers of the undisturbed crystalline material. This removal of the reflectable X-rays by the first thin layer of undisturbed crystal is known as "primary extinction".

In the disturbed surface layer, on the other hand, regions of dissimilar orientation are superposed. In this case a ray traveling in a given direction will have X-rays of one wave-length subtracted from it by the first crystalline material of a particular orientation it meets in accordance with the Bragg equation; then, beneath this, crystalline material at a different orientation will subtract from it X-rays of a different wave-length and so on so that from each ray a broader range of wave-lengths is diffracted by the disturbed material than by the undisturbed, resulting in a stronger reflected beam from the disturbed material. Since the lapped surfaces of the crystal plate give a stronger reflected beam than the undisturbed interior of the plate, the reflection of the slit collimated beam from each set of atomic planes appears on the film as a pair of lines. The density of these lines is related to the disturbance and their width is related to the depth of the disturbed surface layer, as shown diagrammatically in Fig. 10. The four photographs in Fig. 11 were taken in this way, all through the same BT quartz plate. Figure 11a shows the reflections from the various atomic planes of the 4 mm.-thick BT-cut quartz plate, lapped on one side with coarse abrasive (180 carborundum) and on the other with fine abrasive (#303½ emery). As shown in Fig. 10, the coarsely lapped surface was toward the photographic film and therefore the line closer to the line from the direct beam (the single line in the lower right corner) is the stronger of the two. Figure 11b was taken in the same way after the plate had been etched in 48% hydrofluoric acid for 47 hours. The acid was renewed every few hours. The presence of disturbed material near the two surfaces is still discernible. Micrometer measurements after etching indicated that the thickness of the plate had been reduced by 0.14 mm.

Such a measurement is from the peaks of the rugged etched surface on one side of the plate to the peaks on the other side: over most of the plate the etching had proceeded to a greater depth than the .07 mm. indicated by the micrometer measurements. Since the disturbance is still discernible it appears that its depth in this plate was greater than .07 mm.

With the discovery that the disturbed material may be more than 70 microns thick, it becomes apparent that great care must be taken to remove the disturbance produced by all previous lapping and sawing prior to measurement of disturbance produced by a particular lapping technique. This may require more than 48 hours' etching with 48% hydrofluoric acid which will produce a rugged surface. An alternative procedure is to use a natural crystal which has never been cut or worked. Since the natural faces of some crystals do show disturbance, preliminary tests should be made with the various techniques for detecting the presence of any disturbed material. A transmission Laue photograph of a small quartz crystal from Herkimer County, N. Y., taken by C. J. Davisson, showed no disturbed material. If a natural face of such a crystal were lapped under carefully controlled conditions and the resulting disturbance measured by the various techniques, a reliable picture of the disturbance produced by that lapping procedure would be obtained.

In many of these photographs some darkening occurs between the two lines that mark the outer surfaces of the plate. In most cases it appears as well-defined streaks, as in 11c, but may be irregular, as in 11a. Such streaks appear to be due to disturbed zones within the quartz plate whose disturbance is related to the growth history of the crystal. Where they adjoin the disturbed surface layer they may be responsible for erroneous measurements of the misorientation and depth of the surface layer.

Photograph 11c was taken prior to any etching, like 11a, but through a different part of the plate and shows different internal imperfections. Photograph 11d was taken through the same part of the plate after only 20 minutes' etching and shows very little surface disturbance. To get a picture of the distribution of the surface disturbance and internal imperfections of a plate a series of exposures should be taken with the plate translated a short distance relative to the beam between each exposure.

Measurements of the depth of the disturbed layer have given widely different results with different techniques. The Laue photographs just described indicate the depth to be more than .07 mm. or 70 microns in some cases, even with a 303½ emery finish.[14] This is in accord with the 0.1 mm. depth assigned by Y. Sakisaka on the basis of two sets of measurements made by him with two widely different techniques.[15] This value is also in

[14] Since adequate precautions for the removal of all previous disturbance were not taken, this value may be erroneous.

[15] Sakisaka, Y., "The Effects of the Surface Conditions on the Intensity of Reflexion of X-rays by Quartz, *Japanese Journal of Physics* 4 (1927) p. 171–181.

Sakisaka, Y., "Reflexion of Monochromatic X-rays from Some Crystals," *Proc. Phys.-Math. Soc. of Japan*, Ser. III, v. 12 (1930), p. 189–202.

accord with the measurements on the double crystal spectrometer made by Bozorth and Haworth who show that after 20 hours' etching with 48% hydrofluoric acid at 30° C. the rocking-curve width of a plate originally lapped with 100-mesh carborundum was still measurably greater than that of a plate originally lapped with 600-mesh carborundum.[13]

The measurements that have given half a micron for the depth of the disturbed layer have been made with techniques incapable of showing part of the disturbed material. The reflection-intensity measurements made with

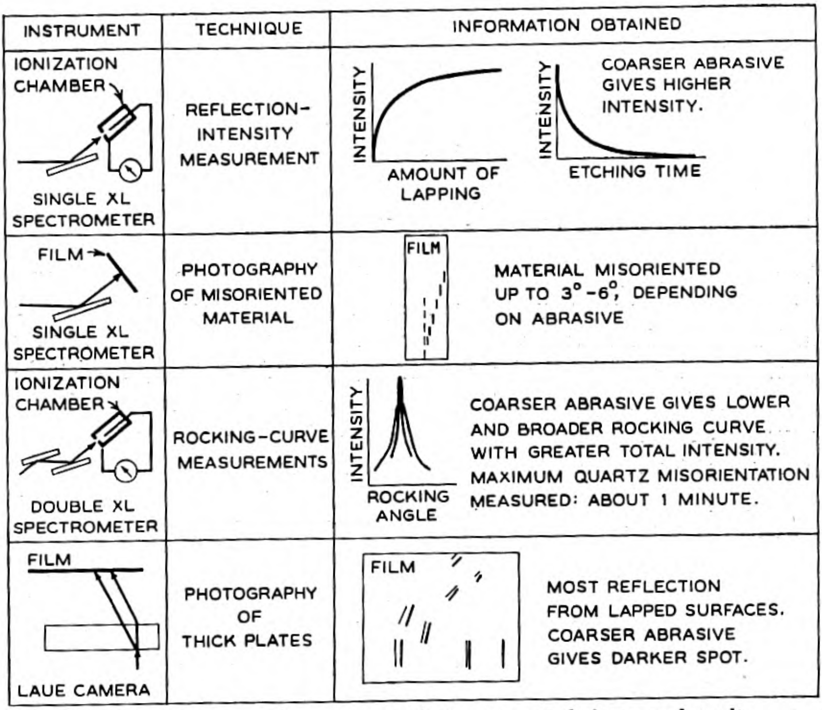


Fig. 12.—Diagrammatic summary of instruments, techniques, and results

the single crystal spectrometer can only show the material present in large enough amount to cause measurable ionization in the ionization chamber. The Davisson photographs with the single crystal spectrometer cannot show material misaligned by less than 15 minutes. Any photographic technique which is capable of measuring material misoriented by a few seconds has shown a disturbed layer much thicker than half a micron at any worked surface of quartz crystal.

Figure 12 is a diagrammatic summary of the various techniques that have been described. Table 1 summarizes the present knowledge concerning the

TABLE I

SUMMARY OF INFORMATION CONCERNING THE NATURE OF THE DISTURBED SURFACE MATERIAL OF QUARTZ PLATES

Description of the disturbed material	Method of detection
Randomly oriented powder on the surface, removable by scrubbing	Electron diffraction photography only
Material misoriented from approximately 45′ to approximately 4½°, removable by about 30 seconds' etching with 48% hydrofluoric acid. Not removable by scrubbing. About ½ micron thick.	Photography with the single crystal spectrometer
Material misoriented from 0° to 45′, in some cases requiring more than 47 hours' etching with 48% hydrofluoric acid for removal. Not removable by scrubbing. May be 50–100 microns thick.	Reflection intensity measurements with the single crystal spectrometer. Rocking-curve width measurements with the double-crystal spectrometer. Laue photography of thick crystal plates.

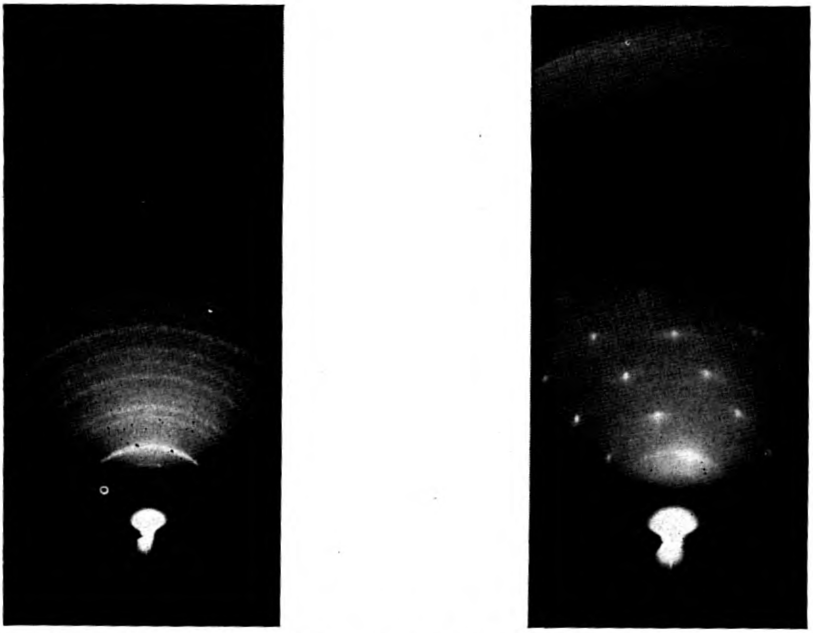


Fig. 13.—Electron diffraction photographs of a BT quartz plate taken with a 50 kv. electron beam (C. J. Davisson)

disturbed layer of worked surfaces of quartz, indicating the technique through which the information was obtained in each case. In order that this table shall be complete the electron diffraction work of C. J. Davisson must be included although it does not properly belong in a paper on X-ray techniques. Dr. Davisson took an electron diffraction photograph of a quartz plate that had been lapped with 303½ emery, water rinsed, and air dried. The plate was then scrubbed vigorously with soap and water and toothbrush and a second photograph was taken. The two photographs are reproduced in Fig. 13. The first shows a series of continuous rings indicating the presence of a large number of small particles of quartz with random orientation. In the second photograph, these rings have disappeared and there remain only arc-segments associated with spots. The spots are the "reflections" from undisturbed quartz. The arcs represent quartz rotated through a small range of angles from this position, the misoriented material indicated by the Davisson photographs with the single crystal spectrometer. These electron diffraction photographs show that a lapped plate has randomly oriented quartz on its surface which may be removed by scrubbing and quartz with limited misorientation which is not removed by scrubbing. No X-ray technique has shown the existence of the randomly oriented material.

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NOTE

Some Novel Expressions for the Propagation Constant of a Uniform Line

By J. L. CLARKE

IN a modern communication system the leakance is generally quite small and can be neglected in making propagation computations. Hence the case is taken of a circuit having resistance, inductance and capacitance.

Let R, L and C be the resistance, inductance and capacitance per mile of the circuit.

Now the formulae which have been developed for the real and imaginary parts of P, the propagation constant, are:

$$P = \alpha + j\beta$$

where

$$\alpha = \sqrt{\tfrac{1}{2}\omega C\{\sqrt{R^2 + \omega^2 L^2} - \omega L\}} \tag{1}$$

$$\beta = \sqrt{\tfrac{1}{2}\omega C\{\sqrt{R^2 + \omega^2 L^2} + \omega L\}} \tag{2}$$

Inspection of these formulae does not reveal any obvious reason for the particular structure of the expressions; however, they may be changed so as to present themselves in a different form.

P can be written:

$$P = \beta(\alpha/\beta + j) \tag{3}$$

Now

$$\frac{\alpha}{\beta} = \sqrt{\frac{\sqrt{R^2 + \omega^2 L^2} - \omega L}{\sqrt{R^2 + \omega^2 L^2} + \omega L}} = \tan\theta \tag{4}$$

where θ is the absolute value of the angle of the characteristic impedance.

Hence

$$P = \beta(\tan\theta + j) \tag{5}$$

The expression in (4) for $\tan\theta$ may be written:

$$\tan\theta = \sqrt{1 - LCV^2} \tag{6}$$

where V = the phase velocity.

Now $LC = 1/V_0^2$

where V_0 = the transient velocity.

Hence

$$\tan\theta = \sqrt{1 - V^2/V_0^2} \tag{7}$$

and

$$P = \beta(\sqrt{1 - V^2/V_0^2} + j) \tag{8}$$

Now it can also be shown that for a progressive wave:

$$\sqrt{1 - \frac{V^2}{V_0^2}} = \sqrt{\frac{\frac{1}{2}CE^2 - \frac{1}{2}LI^2}{\frac{1}{2}CE^2 + \frac{1}{2}LI^2}} \tag{9}$$

So that the real part of the propagation constant is equal to the square root of the difference between the electrostatic energy per mile and the electromagnetic energy per mile divided by the sum of the energies (multiplied by β).

This gives the attenuation constant in terms of the most fundamental entity that we know, namely energy.

Also multiplying each side of equation (8) by x the geographical length of the line between the origin and the point under consideration:

$$Px = \beta(\sqrt{1 - V^2/V_0^2}\,x + jx) \tag{10}$$

Now βx is the number of radians (i.e. total phase shift along the length x) and using relativity conceptions,

$$x\sqrt{1 - \frac{V^2}{V_0^2}}$$

is the apparent length of the wave structure in the length x (the waves moving at velocity V) as observed from a fixed point with signals moving at velocity V_0.

Also $\beta x\sqrt{1 - V^2/V_0^2}$ is the number of radians in the apparent length $x\sqrt{1 - V^2/V_0^2}$

The characteristic impedance may be stated in terms of the phase velocity as follows:

$$Z_0 = \frac{1}{CV} - j\,\frac{RV}{2\omega} \tag{11}$$

NOTE

Decibel Tables

By K. S. JOHNSON

ABOUT twenty years ago, Bell System communication engineers felt the need for, and adopted, a new "Transmission Unit," initially abbreviated "TU" but some five years later given the name "Decibel," or db. This unit is now universally used throughout the communication world and is fundamentally a measure of the ratio of any two powers. Quantitatively, the number of decibels corresponding to the ratio of any two powers is 10 times the common logarithm of that ratio.* If the ratio of the first power to the second power is greater than unity, the first power is said to represent a transmission "gain" with respect to the second power, or the latter is said to represent a "loss" with respect to the first power.

Since currents flowing through, or voltages impressed across, the same or equal impedances will result in powers that are proportional to the squares of these currents or voltages, it is possible, under these specific conditions, to state that the number of decibels corresponding to the ratio of any two such currents or voltages is 20 times the common logarithm of the absolute magnitude of the ratio of these currents or voltages.

Another unit that is frequently employed in theoretical transmission problems is the "Neper." The use of this unit often results in the simplification of such problems and, hence, its relationship to the decibel and to exponential and hyperbolic functions is frequently of interest to communication engineers.

Although the relations between these various values are obviously not complicated ones, it has been found by experience that tables of numerical values are often very useful to communication engineers. As a result, rather extended tables (21 pages) have been computed under the direction of the writer and P. H. Richardson, in which the entering arguments are: (1) decibels, with the tabular values giving the corresponding current, voltage, or power ratios—and their reciprocals; (2) current or voltage ratios, with the tabular values being the corresponding decibels. Tables (16 pages) have also been computed in which the entering arguments are decibels and the corresponding tabular values are nepers (A), e^{A}, e^{-A}, sinh A, cosh A and tanh A. These latter tables are, among other things, useful in the design of attenuators or pads, etc.

Photo offset copies of any of the above tables may be obtained gratis from the Director of Publication of the Bell Telephone Laboratories, Inc., 463 West Street, New York 14, N. Y.

* See "Decibel—The Name for the Transmission Unit", by W. H. Martin, *Bell Sys. Tech. Jour.*, January 1929.

Abstracts of Technical Articles by Bell System Authors

Network Analysis and Feedback Amplifier Design.[1] H. W. Bode. The material for this book was originally prepared as a text for an informal course at Bell Telephone Laboratories. It is the outgrowth of a research directed at the problem of designing degenerative feedback amplifiers to provide substantial feedback without instability. The solution of the feedback problem is, however, dependent upon certain propositions in general network theory which are applicable also to other situations. With the addition of other logically related material, this has made the book primarily a text on general network theory.

Earlier texts on networks have been concerned primarily with transmission line and filter theory. The present book emphasizes the broad-band aspects of network theory. In other words, it is concerned with the problem of providing characteristics which vary smoothly, and in some prescribed manner over a broad frequency range. This aspect of network theory is stressed because it is the one which best fits the feedback problem. It also has applications, however, to the many broad-band problems which arise in television, frequency modulation, multi-channel carrier telephone and other modern communication systems.

The emphasis on broad-band problems has a number of consequences. For example, it gives special importance to networks including resistances as well as reactances, since it is frequently only by the use of controlled dissipation that network characteristics can be made to vary smoothly over broad ranges. The emphasis on broad-band applications also requires special attention to the effects of parasitic elements, and several sections of the book are devoted to the development of design methods for networks including prescribed parasites. A final consequence is the importance which is assumed by the limitations on the characteristics which can be obtained from physical networks. Over very narrow bands only very mild limitations exist, but as the band becomes broader the available characteristics become more and more restricted.

The other principal point of emphasis of the book is on the use of networks in association with vacuum tubes, rather than as purely passive structures. The primary theoretical development of the book is stated in terms of general active circuits. Otherwise the effort to extend network

[1] Published by D. Van Nostrand Company, Inc., New York, N. Y., 1945.

theory to vacuum tube circuits consists chiefly in giving special emphasis to network design problems ordinarily found as part of vacuum tube amplifier design. The design of an over-all feedback loop is, of course, an outstanding example. In addition, special attention is also given to the design of such individual network units as input and output circuits, interstage networks, and local feedback circuits, especially when they appear as constituents of a broad-band amplifier.

Judging Mica Quality Electrically.[2] K. G. Coutlee. A threatened mica shortage resulting from an unprecedented wartime demand for mica capacitors used in electronic communication equipment by the Armed Forces was forestalled by rigid conservation measures, use of alternate materials, and the use of electrically selected mica from types previously considered unsuitable for capacitor use. By employing two electrical tests, developed by Bell Telephone Laboratories, Inc. for the War Production Board, in combination with visual and physical requirements, mica was selected from plentiful stocks of lower visual quality types of mica, effectively increasing the supply of capacitor mica by 60 per cent. This method of electrically judging the quality of raw mica was given a thorough commercial trial and found both practicable and reliable.

A Simple Optical Method for the Synthesis and Evaluation of Television Images.[3] R. E. Graham and F. W. Reynolds. A combination of a 35-millimeter motion-picture projector and a line screen enables the projection of still or motion pictures closely similar in appearance to those produced by television. This similarity of appearance is checked theoreticallly by an analysis of the type previously reported by Mertz and Gray in a discussion of the theory of scanning. From the analysis it is shown that five parameters of the optical-simulation system may be varied to obtain the equivalent of variations in television factors such as number of scanning lines, size and configuration of scanning apertures, and width of frequency band.

Photographs of simulated television pictures projected by this method are presented. These pictures include subject matter of general interest as well as as selected subjects to illustrate the spurious detail components introduced by the television scanning process. These components produce moiré patterns, "steps" on diagonal lines, and impairment of vertical resolution. Simulation pictures projected by this method have been compared with those produced by a television system and the expected agreement observed.

Calculations are given of the diffraction effects in optical systems of this type and it is shown that the departure from geometrical theory is small in the arrangements described.

[2] *Elec. Engg., Trans. Sec.*, November 1945.
[3] *Proc. I. R. E.* and *Waves and Electrons*, January 1946 (pp. 18W–30W).

A Coil-Neutralized Vacuum-Tube Amplifier at Very High Frequencies.[4] R. J. KIRCHER. This paper describes a two-stage single-side coil-neutralized amplifier employing an experimental triode operating in the vicinity of 140 megacycles. Circuit features are described and typical operating conditions are indicated. Typical distortion characteristics at low-power levels are also included.

Fundamental Theory of Servomechanisms.[5] LEROY A. MACCOLL. The use of servomechanisms and related devices for automatic control and regulation is very old, dating back to the latter part of the eighteenth century. However, it is only recently, approximately since the beginning of the war, that it has been recognized that these devices are essentially feedback amplifiers in a mechanical, or partly mechanical, form. From the recognition of this fact it follows that the highly developed theory of electrical feedback amplifiers can be applied at once to servomechanisms and similar devices.

This book, which was originally intended to be a National Defense Research Committee report, is an introduction to the theory of linear servomechanisms, considered as a special application of the general theory of feedback amplifiers. The steady-state theory of the systems is taken as fundamental, and the various problems concerning the stability and performance of the systems are discussed in terms of it. In the several chapters a variety of types of linear servomechanisms are considered. A brief discussion of one simple non-linear servomechanism is given in the Appendix.

Corrosion Protection for Transcontinental Cable West of Salt Lake City, Utah.[6] T. J. MAITLAND. This paper discusses the problems involved in maintaining the effectiveness of the thermoplastic covering provided on buried toll cables for installation in areas where corrosion is anticipated. It also describes the method used to obtain the required supplemental electrical drainage for the Transcontinental Cables across the Great Salt Desert west of Salt Lake City where the low earth resistivity and high concentration of alkali salts preclude the use of rectifiers connected between cable sheath and a made ground generally employed for drainage purposes. Such installations would result in negative potentials between cable and earth of sufficient magnitude to create conditions conducive to cathodic corrosion of the lead sheath in the presence of an alkali salt electrolyte.

To provide electrical drainage without incurring these excessive negative potentials a method was developed utilizing the normal potential difference between zinc and lead as the source of drainage current. Twenty-four pound zinc bars of commercially available zinc, 99 per cent pure, were installed directly in the ground a short distance from the cables at 12-mile

[4] *Proc. I. R. E.*, December, 1945.
[5] Published by D. Van Nostrand Company, Inc., New York, N. Y., 1945.
[6] *Corrosion,* June 1945.

intervals, making connection between the zinc anodes and the cable sheaths by buried wire. The cable-to-earth potentials were appreciably affected throughout the entire 120 route miles across the Great Salt Desert by this procedure.

During the year these anodes have been in place, the cables have remained at a satisfactory negative potential to earth (.20 to .50 volt) with a small current being constantly drained to the zinc anodes. It is considered from the results to date that for similar areas the use of metallic anodes offers an economical and satisfactory means for protecting buried cables against corrosion.

Transmission Networks for Frequency Modulation and Television.[7] HAROLD S. OSBORNE. Looking forward to a great post war expansion in the arts of frequency modulation and television this paper discusses plans of the Bell System for providing transmission networks required for the interconnection of broadcast stations. A review of cable and open-wire carrier systems shows how developments for purely message telephone business have at the same time put the Bell System in a position of being able at the present time to meet such network transmission requirements for frequency modulation as the broadcasters may select as desirable. Coaxial developments are reviewed briefly, including the application of these developments to television transmission. Future developments, together with the coaxial construction plans now under way, are expected to provide by about 1950 a fairly comprehensive nationwide network of facilities capable of providing for such transmission requirements as may be desired by the television industry. The important features involved in the operation of such networks are discussed, indicating a requirement for a highly trained nationwide organization and much equipment—a requirement which the Telephone Companies can face with confidence because of their experience in handling nationwide communications.

Visible Patterns of Sound.[8] RALPH K. POTTER. New ways of translating sounds into pictures are described. These methods of sound portrayal are unique because what may be seen in the sound patterns is consistent with what is heard in the original sound. The pictures display the three basic dimensions of sound-pitch, loudness and time—in a form somewhat analogous to a musical score. Experimental training has shown that with practice one may learn to read such patterns of speech so that the development offers the ultimate possibility of aid to the severely deafened in learning to speak correctly and to use the telephone by seeing rather than hearing the voice of the distant speaker. The patterns will also be of considerable interest in the fields of speech science and music.

[7] *Elec. Engg.*, November 1945.
[8] *Science*, November 9, 1945; *Bell Tel. Sys. Monograph* B-1368.

General Formulas for "T"- and "Π"- Network Equivalents.[9] MYRIL B. REED. This paper presents the development of two sets of general formulas which determine a set of "T" or "Π" impedances equivalent to any linear, lumped-constant, four-terminal network.

Concerning Hallén's Integral Equation for Cylindrical Antennas.[10] S. A. SCHELKUNOFF. The main purpose of this paper is to explain the substantial quantitative discrepancy between Hallén's formula for the impedance of cylindrical antennas, and ours. Hallén's first approximation involves a tacit assumption that the antenna is short compared with the wavelength. Since the subsequent approximations depend on the first, they are degraded by this initial assumption.

The approximations involved in his integral equation itself are justified; and, if properly handled, the equation yields results in much better agreement with ours. The last section of the paper is devoted to infinitely long antennas. Such antennas can be treated by at least three very different methods and a comparison is instructive. In practice, the solution for this case is an approximation to a long antenna designed to carry progressive waves.

Principal and Complementary Waves in Antennas.[11] S. A. SCHELKUNOFF. In response to an increased interest in mathematical aspects of antenna theory, this paper presents details of analysis of cylindrical and other non-conical antennas as a supplement to a previous paper containing the outline of the method and the main results. In the course of the present discussion the theory of principal waves on cylindrical conductors is extended to include the case in which the diameter is not small compared with the wavelength.

Research Revolutionizes Materials.[12] J. R. TOWNSEND. A technological lesson to be drawn from defeated Germany is that whereas Germans had been noted for their fundamental contributions to science, they were unable to compete with the United Nations in the field of applied science and particularly in high-speed production methods. Their defeat was due more to the overwhelming number than to the individual superiority of the arms brought against then. The miracle of American production is based on a design related to obtaining the most from the process used, materials of uniform quality, and high-speed production methods using high-power automatic machinery. Germany's failure was due to standardizing too early and too inflexibly and this meant that they could not compete with the steady improvements in the art. The usual procedure is the development of methods of test followed by collection of data and the formulation of specific requirements controlling the useful quality of the material. Modern

[9] *Proc. I. R. E.*, December, 1945.
[10] *Proc. I. R. E.*, December, 1945.
[11] *Proc. I. R. E.*, January, 1946.
[12] *A.S.T.M. Bulletin*, December, 1945.

industry is based upon such specifications because materials must be so controlled since the action of the machine is unvarying. Modern statistical methods can be applied to provide the tolerances and allowances necessary to achieve a uniform product. The work of the American Society for Testing Materials broadly covers the field of research in materials, methods of test, and quality control. The benefits of this work extend to vast improvement in process methods, more uniform and higher-quality material and result in economic gains of extensive character. Three examples were cited illustrating extensive projects of great use to the war effort. These were the development of requirements for sheet brass, which was applied specifically to production of cartridge cases, high-quality die-casting specifications resulting in the production of many parts used in communication and aviation equipment, and the development of a method of test for inspecting mica by an electrical rather than a visual test. This last resulted in a large economic saving of this scarce material.

Infantry Combat Communications.[13] RALPH E. WILLEY. Communications within an infantry division during combat involve not only the efficient installation, operation and maintenance of all means of communication normally provided and adopted for specific functions but also the use of standard equipment in improvised methods adapated to the needs of the particular situation. The paper covers a brief description of the major items of signal equipment issued to an infantry division together with their normal use. In addition, there is discussed the solution to many field problems based on the combat experience of the writer in Belgium, Holland and Germany.

Interesting information is given on the signal supply problem and combat losses over a six-month period of combat. Improvised field radio-link installations and remote controls for the protection of operating personnel are discussed briefly. Photographs included with the paper show pictorially the majority of the items of equipment described.

[13] *Elec. Engg.*, January, 1946.

Contributors to this Issue

Elizabeth J. Armstrong, M.A. in Geology, Bryn Mawr College, 1934; Ph.D., 1939. Lecturer in Geology, Barnard College, 1938–41; Research Assistant, Columbia University 1941–42; National Research Council Fellow, 1942–43; Bell Telephone Laboratories, 1943–. Recently Miss Armstrong has been working on X-ray studies of crystal strain and imperfections, X-ray irradiation and twinning.

J. L. Clarke, B.Sc. in Electrical Engineering, University of London, 1909. Bell Telephone Company of Canada, 1910–; Transmission Engineer, 1924–.

John W. Clark, A.B., University of Montana, 1935; M.S., University of of Illinois, 1937; Ph.D., 1939. Dr. Clark joined the Technical Staff of the Bell Telephone Laboratories in 1939, where his principal interest has been in the development of vacuum tubes for use at ultra-high frequencies.

William H. C. Higgins, Purdue University, B.S. 1929; E.E. 1934. Development and Research Department, American Telephone and Telegraph Company, 1929–34; Bell Telephone Laboratories, 1934–. During his employment with the A. T. & T. Company Mr. Higgins was engaged in carrier telephone and program transmission studies. Since his tranfer to Bell Telephone Laboratories he had been concerned with radio and radar development.

Kenneth S. Johnson, A.B., Harvard University, 1907; Harvard Graduate School of Applied Science, 1907–09. Transmission and Protection Department, American Telephone and Telegraph Company, 1909–13; Engineering Department, Western Electric Company, 1913–25; Bell Telephone Laboratories, 1925–. Formerly as Transmission Research Engineer and now as Transmission Standards Engineer, Mr. Johnson has long been engaged in work closely connected with all types of transmission network problems. He is the author of the book "Transmission Circuits for Telephonic Communication."

John Leutritz, B.S. in Chemistry, Bowdoin College, 1929; A. M. in Botany, Columbia University, 1934; Ph.D., Columbia University, 1945. U. S. Navy, Medical Corps, 1921–25. Bell Telephone Laboratories, 1929–. Mr. Leutritz' interest has been along biological lines, primarily in respect to wood preservation. During the war period he was active in the protection of electrical equipments against moisture and fungi attack when used in the tropics.

William W. Mumford, B.A., Willamette University, 1930. Bell Telephone Laboratories, 1930–. Mr. Mumford has been engaged in work that is chiefly concerned with ultra-short-wave and microwave radio communication.

A. L. Samuel, A.B., College of Emporia (Kansas), 1923; S.B. and S.M. in Electrical Engineering, Massachusetts Institute of Technology, 1926. Additional graduate work at M. I. T. and at Columbia University. Instructor in Electrical Engineering, M. I. T., 1926–28. Mr. Samuel joined the Technical Staff of the Bell Telephone Laboratories in 1928, where he has been engaged in electronic research and development. Since 1931, his principal interest has been in the development of vacuum tubes for use at ultra-high frequencies.

William C. Tinus, B.S. in Electrical Engineering, Texas A. & M. College, 1928. Bell Telephone Laboratories, 1928–. For ten years Mr. Tinus was engaged in the development of radio communication apparatus, principally for mobile use. In 1938 he organized and directed the first radar development work in the Laboratories. As Radio Development Engineer he is now responsible for a number of radar and related electronic development projects for the Army and Navy.