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NOTES ON VISITS TO WESTINGHOUSE RESEARCH LABORATORIES, GENERAL ELECTRIC RESEARCH LABORATORIES, AND THE RADIATION LABORATORY

- July 21st to August 3rd, 1943 -

-- F. H. Sanders --

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August 1943

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July 21st to August 3rd, 1943 - F. H. Sanders

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CHAPTER I

VISIT TO WESTINGHOUSE RESEARCH LABORATORY, East Pittsburgh, Pennsylvania, July 21st and 22nd, 1943

The Westinghouse Company has not been working in radar very long and their production schedule on radar sets is relatively small. They have, however, a small but very active research group working on microwave tubes and components under Dr. E. U. Condon. I might remark that my reception by the Westinghouse group was probably the most cordial I have received at any of the industrial laboratories. The following sections cover the components seen and discussed at the laboratory.

I. CRYSTALS (S. J. Angello)

Westinghouse are working hard to produce, by controlled methods, an equivalent of the British hand-picked "green spot" crystals, and appear to be having moderately good success. To date they have not gone into quantity production, which explains why our orders have been returned. A representative of the Bloomfield tube factory is now at East Pittsburgh studying the technique, and production is expected to begin this Fall. For the present we can obtain a limited number of crystals (twenty or so), for test purposes direct from the laboratory pilot shop by reference on our order to Dr. Condon.

All crystals are tested, at three centimetres, for noise temperature and conversion loss. Average values of these quantities are:

Noise Temperature	Conversion Loss	Noise Figure
1.3 db.	8.8 db.	14.2 db at 3 cm.
1.9 db.	6.2 db.	12.3 db at 10 cm.

Both sets of values are M.I.T.'s and the reason for the higher 10 cm. noise temperature is that no filter was used in the S-band test to reduce the McNally-Pierce tube noise. They are however, useful for comparison with M.I.T. and Western Ontario figures under similar conditions. The noise figure of the I.F. amplifier used in these measurements is about 4 db. For system use, Westinghouse place their amplifier noise figure at 5 db.

The following outline of the Westinghouse technique may be of interest, as it is much more exacting than that of Sylvania, B.T.H. etc.

(a) Silicon Crystal Treatment

The silicon used is 99.99% impurity free, supplied by Dupont. It is received in finely-divided form and is mixed with 0.6% pure aluminum. The mixture is heated slowly for one-half hour in a 20 kc induction

furnace to outgas it. A quartz crucible surrounded by graphite shield is used as a container, the graphite being required for heating purposes, as the silicon has very low conductivity. The mixture is next brought up to melting point over a ten-minute period, super-heated for one minute, the quick-frozen by fans. The quick-freezing is to prevent the aluminum from separating out.

The solid silicon is cut in wafers about 3 mm. x 3 mm. x 0.6 mm. thick, using a bronze wheel impregnated with 600-mesh diamond powder. Westinghouse claim that the nickel plating is much superior to copper for soldering. The wafers are soldered to a rod about 1 mm. diameter (not threaded) after which the edges of the wafer are ground off to the size of the rod. The nickel is ground off the surface of the silicon with #600 silicon carbide, and the surface then etched in two steps:

(i) A drop of mixed nitric and hydrofluoric acids is placed on the crystal and washed off almost immediately. This leaves the silicon with a bluish finish.

(ii) The crystal is etched in a bath of 24% hydrofluoric acid and water at a potential of 7 volts a-c for 20 seconds. It is washed thoroughly and assembled as soon as possible after etching to avoid further oxidation.

(b) Whisker Construction

The whisker is made of 0.005" tungsten tinned at one end with a gold-silver-platinum alloy. It is soft-soldered into the pin, and trimmed to a definite length. It is next sharpened to a 72° conical point on a #600 resin-bonded wheel and crimped in a jig to the usual —∿— form. The point is given a final quick etch in a twice-normal sodium hydroxide bath at 3 volts d-c. The point is finally inspected under projection for splits or other defects. Too much final etching is bad and produces pits which can be seen when projected. Wedge points have been considered, but not tried yet.

(d) Assembly and Adjustment

The cap and pin are screwed into the ceramic with orange shellac and baked. This gives a very satisfactory bond. The cap in the Westinghouse crystal is made as shown below:

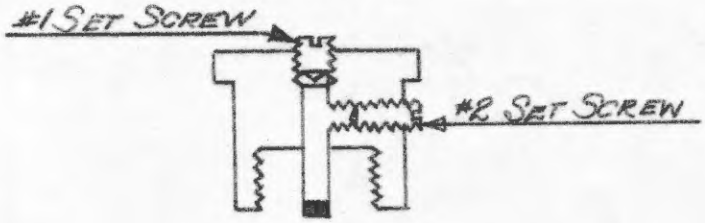

Figure 1

The rod holding the crystal is an easy fit in the hole through the cap. As #1 set-screw is advanced, the crystal approaches the whisker without rotating. This avoids any "wiping" action when the tungsten contacts the silicon. Westinghouse consider this very important. The crystal is adjusted with the 60-cycle characteristic displayed on a cathode ray tube, and set for a 45-ohm slope. One strong tap, followed by a lighter tap is given the unit. Too much tapping is bad, but some tapping, as above, appears to be necessary, as an untapped crystal will invariably have higher noise than a tapped one. The unit is vacuum-impregnated with Opal Wax and the filling hole sealed over with a non-hydrocarbon-soluble cement.

(d) Testing

All crystals are tested for noise temperature and conversion loss at 3 cm. in equipment of the Roberts (M.I.T.) type. I made the following notes on high and low figures from a report by Roberts:

	Noise Temperature	Conversion Loss	Noise Figure	
S-Band	4.2	8.8	14	HIGH
	1.1	4.7	10	LOW
X-Band	2.1	11.2	16	HIGH
	1.3	7.4	12	LOW

(See - Westinghouse Research Report - SR-176
entitled "WESTINGHOUSE CRYSTAL PILOT SHOP"
by S. J. Angello)

As regards matching to the amplifier input, Westinghouse adjust the input current to present 300 ohms (30 mc.) to the crystal.

II. T/R SWITCHES - 3 CM. (S. Krassik)

Westinghouse appear to have inherited the development of a 3 cm. T/R switch from Sperry. The original Sperry T/R (of which N.R.C. had and used a number of samples) was operationally reasonably satisfactory, but was only produced in small, semi-hand-made lots by Sperry. Westinghouse were asked to mass-produce it, but decided that this was not practicable. They accordingly set out to develop something which could be mass-produced. In principle the Westinghouse T/R does not differ much from the Sperry unit, but its form is quite different. It starts out as a solid copper disc about 2" in diameter by 5/8" thick. A central hole about 1/2" diameter, with appropriate shoulders as shown in Figure 2, is bored out at right angles to the disc axis, and window recesses are cut on the axis. These are simple lathe operations.

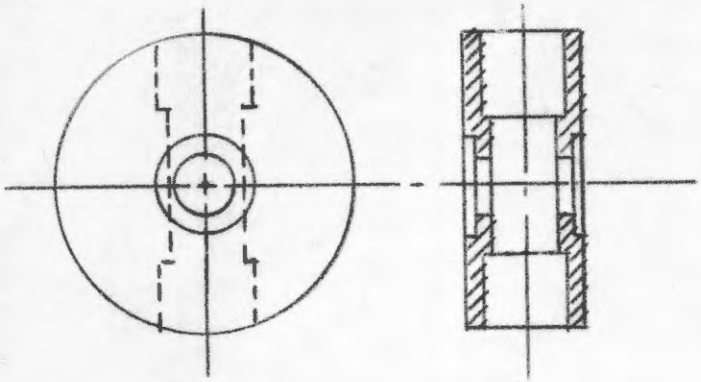

Figure 2

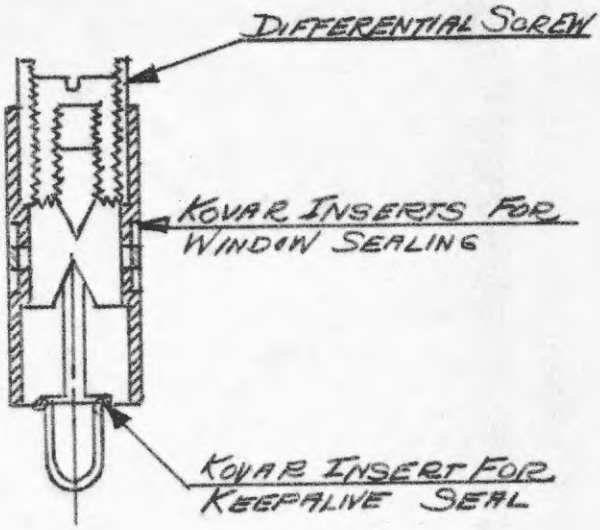

Figure 3

The fixed nose, which is hollow to allow for the keepalive wire, is turned separately and sweated into the cavity. A Kovar disc is set in for sealing of the glass keepalive support, as shown. The movable nose is made on a diaphragm and is also sweated into place in a hydrogen furnace. The differential screw assembly is removable and is locked in place by two Allen set-screws (not shown above). Glass windows are sealed into Kovar inserts and sweated into the window recesses. In the latest model a copper-plated steel gas reservoir is included, which has a volume 8 to 10 times that of the cavity. In the factory model this has been replaced by a glass reservoir which also serves as a keepalive support.

The filling is 15 mm. hydrogen with 10 mm. of water. The differential screw has threads of 36 and 40 t.p.i., which gives a movement of 0.0028" per turn. This corresponds to a tuning rate of 120 mc. per turn. The normal gap spacing for 3.20 cm. is about 0.008", though the actual metal-to-metal spacing is greater than this because of the keepalive hole in the fixed nose.

The designation on the older models which we have is WX-3199. The new models with resonator, screw-driver tuning, etc. will be 1B24. This model will have stops to limit the tuning range and prevent the differential screw being taken out. The WX-3199 is reported to be satisfactory and should have a life of several hundred hours. Due to its small volume the water pressure may drop and increase the recovery time, but this is not serious for our present applications.

When asked about leakage-power figures, Westinghouse stated that they no longer made them. It seems pretty definite now that the protective value of a T/R is so dependent on the "spike" value that average leakage-power measurements are meaningless. They are satisfied that the 1B24 will give adequate protection on ordinary low-burnout crystals up to 40 kw. transmitter power.

One point on which "policy" seems to have overridden technical performance is in the matter of a 3 cm. R/T. The Army-Navy policy at the moment appears to be to use the Western Electric 724 for an R/T in all future X-band systems, and the 1B24 for a T/R. The 724 is operationally satisfactory as an R/T, but the construction of the cavity for it is a bad production headache. Furthermore, the use of the awkward 724 R/T, instead of a simplified 1B24, appears technically unsound.

III. T/R SWITCHES - 1 CM.

The K-band T/R switch is essentially a scaled-down version of the 1B24. Its development was started after that of the 1B24, but actually a satisfactory working model was completed before the 3 cm. job. It fits between 1.25 cm. chokes in the same manner as the 3 cm. switch, and gives adequate protection up to at least 20 kw.

IV. T/R SWITCHES - 10 CM.

The Western Electric 721 T/R is considered satisfactory for all low- and medium-powered S-band systems. With careful control of coupling, standing waves, etc., it will give adequate protection to medium burnout crystals at powers up to 350 kw. Above this value, however, it is working on the thin edge, and any unusual surge or disturbance in the system may result in crystal burnout.

There seems little doubt that the burnout is due to the excessively high peak value of the "spike". Crystals will stand up satisfactorily to many times the maximum leakage power of the T/R if this power is applied in true pulse form, but in service fail apparently at much lower values. Measurements of the average power under the "spike" have shown this to be approximately equal to the average value of the square pulse. Since the width of the spike is now estimated to be of the order of 10^{-9} seconds, its peak value must be very high. The theoreticians have now resolved the "spike" into a "true spike" plus a "pseudo-flat" as in Figure 4.

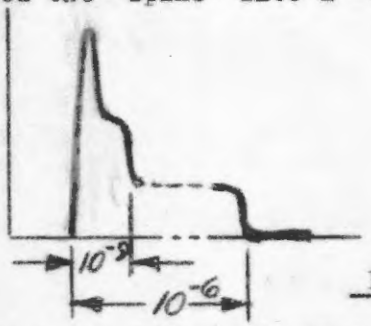

Figure 4

The height of the "pseudo-flat" is estimated to be 15-20 times that of the square pulse, while the height of the spike is apparently not even estimated.

From the above it would appear that elimination of the spike, rather than reduction of the average leakage power is what is required. Westinghouse are tackling this along the lines suggested by Nasmith and Miller; i.e. by deliberately firing the T/R some microseconds before the R.F. pulse arrives. They are constructing a 721 cavity in which the two noses

are insulated for low frequencies though still continuous to R.F. An arc will be struck across the noses, 5 to 10 microseconds before the main R.F. pulse, by a separate modulator triggered by the previous pulse of the magnetron modulator and appropriately delayed. They have completed the design of a cavity whose insertion loss is satisfactorily low, and hope to obtain results shortly. The present type of 10 cm. cavity which couples to the magnetron wave guide line via a window, and to the mixer via a loop, is not very satisfactory as losses etc. are hard to measure. Westinghouse propose to design a system whereby the cavity is coupled by window to both a wave guide power line and a wave guide receiver line. With such an arrangement it will be much easier to remove T/R's, measure losses, etc.

Some of the Westinghouse people are of the opinion that a T/R might be devised with two keepalive electrodes so arranged that the firing pulse could be applied across the gap between them and actually give a real arc in the space between the R.F. noses. They have tried remodelling 721's to do this, but have trouble because the 721 seals will not stand re-heating. They are interested in our new Type 29 universal filler and would like some samples.

V. MAGNETRONS - 10 CM.

Westinghouse are working on a high powered S-band magnetron to compete with the Western Electric Type 720. It is a 12-oscillator tube designed to give a megawatt or more output at 40% - 60% efficiencies. At a megawatt input, 25 kv, 40 amperes, 2450 gauss, the measured output is 570 kw. It is designed to work into a 1-5/8" 53-ohm concentric line. It is not yet in production form, but the N.R.C. should be able to obtain one or two model-shop samples within the next few months, under the designation "High Power S-Band Magnetron of VB-1 Series".

VI. MAGNETRONS - 3 CM.

Westinghouse have been working on a strapped 3 cm. magnetron with wave guide output. Their present model is fairly successful and gives around 50 kw with good stability. Its voltage requirements are, however, a bit high and they are now aiming at a 50 kw. tube which will operate at around 12 kv. They are completely departing from the concentric output of the Bell 725. A standard wave guide will be an integral part of the tube envelope, a sealed-in glass window of suitable aperture, serving as a transformer to match the tube to standard X-band guide.

VII. MISCELLANEOUS MEASURING EQUIPMENT

(a) Matched Bolometer

Westinghouse have a very nice matched 10 cm. bolometer unit. It consists of a Wollaston wire stretched across a standard S-band guide and matched for zero reflection. It was suggested that we could probably have one or two of these made up if desired.

(b) Spectrum Analyzer Type Y-3-B

Westinghouse have built up several spectrum analyzers of their own design. They are much like the M.I.T. model, but appear a bit more

compact. One nice feature is that the output of the sweeping oscillator is rectified and fed through a D.C. amplifier to the vertical plates of the display tube. This provides a very neat way of examining and adjusting a new Shepherd tube. They have offered to give us complete design data if desired.

(c) Attenuators, R.F.

Westinghouse have developed a very nice variable attenuator for precision measurements. It is a "flap" type, cut in the form of an Archimedes spiral. The attenuator is fed slowly into the guide by a planetary gear system with a vernier indicator. Accuracy of setting is 0.1 db. with a total attenuation of 18 db. per card, at 3 cm. To eliminate reflection by the variable attenuator, Westinghouse use buffer attenuators of about 10 db. before and after the variable unit. These are made of black or yellow Micarta in the form indicated below, and are baked and lacquered to eliminate moisture.

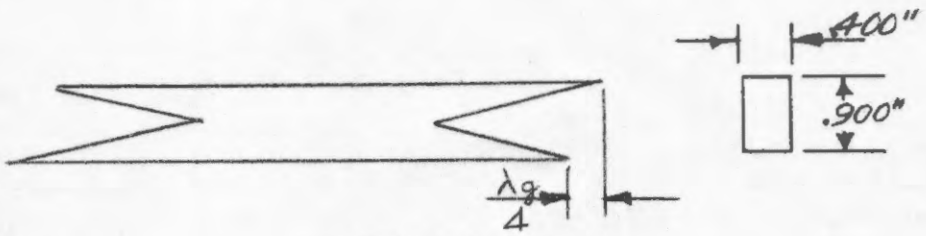

Figure 5

A "black end" giving a reflection of only 1.07:1 can be made as above in a length of about 12". Westinghouse claim that the above attenuators are very reliable.

(d) Directional Power-Measuring Units

Westinghouse have developed a variation of the "directional pick-up" mentioned in earlier reports on the Bell Telephone Laboratories and Sperry Gyroscope Company. In the Westinghouse model the detecting wave guide is coupled to the transmission-line guide by an off-centre slot cut in the wide face of the guide. The side of the slot coincides with the centre-line of the guide. The slots should be designed to be an integral number of $\lambda_g/2$ and odd integral number of $\lambda_o/4$.

CHAPTER II

VISIT TO GENERAL ELECTRIC RESEARCH LABORATORIES, Schenectady, New York, July 29th, 30th and 31st, 1943

The General Electric Company appear to have gone further than most other industrial concerns in the development of 10 cm. test equipment. They have a number of useful devices in product form and some of these appear to be fairly readily obtainable. They are still pursuing the development of a magnetron with built-in magnet. In addition, they are developing a number of tubes of the Lighthouse type and quite a line of gas thyratrons for modulator use. In the crystal field they are producing 10 cm. silicon crystals for use in their own sets (not for sale yet) and are developing the germanium crystal as a longer term project for 3 cm. use.

I. CRYSTALS (Dr. North)

(a) Silicon Type

The General Electric Company have been producing silicon crystals for use in their own sets, along lines similar to those employed by Sylvania. These have been reasonably satisfactory, but the improved results obtained by Dr. Angello at Westinghouse have led them to study the Westinghouse technique. Previously they were using electro-metallurgical 99.8% pure silicon, and processing it in a quartz crucible in a vacuum furnace. Noise figures on these crystals were between those of the Western Electric and Sylvania crystals, while the burn-out figures were better than Western Electric, but slightly poorer than Sylvania. They are now procuring 99.99% silicon from Dupont and treating it with 1/2 of 1% aluminum, in a manner very similar to that used by Westinghouse. They were not prepared to quote actual figures yet, but stated that a definite improvement in both noise and burn-out value was apparent. It is improbable that General Electric will release crystals for general sale for some time yet.

(b) Germanium Type Crystals

General Electric have been experimenting with Ge crystals for some time. Sperry apparently were the first to try this material, and later, because of policy decisions, Sperry dropped out of the crystal field and General Electric took it over. Ge should give a better crystal than silicon because of the fact that the donors (charge carrying impurities) have a higher mobility in Ge than in silicon. The forward resistance of the conductor-to-semiconductor is given by the expression:

$$R_g = 1/2\ \sigma d$$

where: σ = conductivity
d = diameter of the contact

σ may be expressed as $n\ e\ v$,

where: n = number of carriers
e = their charge
v = mobility

The higher mobility of Ge should hence give a lower forward resistance.

To date Ge crystals, with antimony introduced as a donor, show the following characteristics:

(i) The d-c back-to-front ratio is very much greater than silicon, often running as high as 10^6.

(ii) The 60-cycle characteristic as observed on an oscillograph in the usual manner, is very abrupt, being an almost perfect right-angle.

(iii) The "knee" of the above characteristic is considerably displaced from the axis of zero voltage so that a permanent bias is required to get optimum rectification qualities.

(iv) A number of Ge crystals have been produced in which either the noise or the conversion loss is markedly improved over silicon. To date they have been unable to produce a crystal in which noise and conversion loss are reduced at the same time, but Dr. North is confident that in time he can produce Ge crystals which will give a 3 cm. over-all noise figure 3 db better than that of silicon.

(v) Stability and burn-out with Ge crystals are at present not as good as silicon, but again Dr. North expressed confidence that these points could be overcome.

The Ge crystal development is rated as a fairly long term project, but is being pursued steadily in the anticipation of improved three- and one-centimetre crystals. Dr. North has designed a 1 cm. crystal in a capsule which, if successful, will be a considerable improvement over the present type where the crystal is mounted across a 1-cm. guide and is not removable. General Electric consider that a reasonable amplifier noise figure is 4 - 5 db.

The U.S. Navy is attempting to bring all groups working on crystals into line on the matter of 3 cm. testing. Noise temperature is to be determined by comparison with a resistance, in the manner now employed by M.I.T. and the University of Western Ontario, etc. Conversion gain is to be measured by a simplified method originated by Roberts at M.I.T. Three-centimetre power from a modulated Shepherd tube is fed through a noise reducing filter into the crystal, used as a straight detector. The crystal is followed by an amplifier and indicating meter. The crystal is mounted in a standard pre-adjusted mixer of the M.I.T. type and the input to the amplifier is matched for 300 ohms. The output of the Sheppard tube is monitored by a crystal and is further checked from time to time against a bolometer. A certain minimum output from the crystal is specified, in order for the crystal to be acceptable. If either the conversion gain of the r-f impedance is off, the crystal will be rejected.

II. T/R SWITCHES - 10 CM. (Dr. Fiske)

General Electric are working on a new type of T)R which will not require tuning. It is essentially an extension of the M.I.T. "beetle" tube idea. The T/R consists of a resonant slit in a metal plate placed across a standard 3" x 1-1/2" wave guide. The unit is enclosed in a glass envelope as indicated in Figure 6, the seals being made with Fernico.

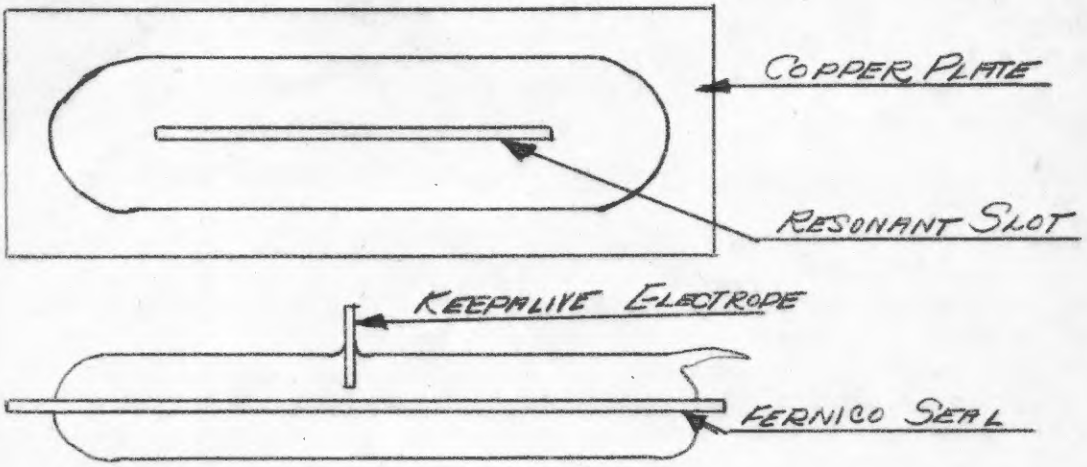

Figure 6

A keep-alive electrode is brought in quite near the centre of the slot, and the d-c glow discharge is said to cover the entire slot. The T/R has an effective loaded Q around 3, and the protection of a single tube is not great. It is planned to use three or more of these tubes in series, $\lambda/4$ apart, in a guide. The keep-alive will be fired by a pulse a few microsecond ahead of the r-f pulse. A set of three of the above tubes gave adequate protection for 50 kw. peaks, and had a frequency characteristic which did not drop below 80% transmission over a wavelength range of 9 mm. It is claimed that only spike energy gets through. The transmission loss is about 5% per unit at resonance. The aim is to produce a T/R system giving good protection at 200 kw. with a total bandwidth of 1 cm. in the 10 cm. region.

III. MAGNETRONS - 10 CM. (Dr. Bailey)

Messrs. Happe and Webb reported about a year ago that General Electric were developing a very nice magnetron incorporating its own magnet. An attempt was made at the time to obtain samples, but the order was rejected by the War Production Board. General Electric are still working on this tube and have improved it considerably. They hope to be making it in small quantities in the near future for the G-band, under the designation ZP-505G. It is designed for operation at 11-13 kv., 15 amperes, with an efficiency range from 25 to 45%. It will work satisfactorily on 2000 cycles, 1 microsecond pulses and is mechanically interchangeable with the M.I.T. "2J" series of magnetrons. (A slight reservation must be made as regards the space required on the end away from the filament leads, as this end is slightly longer than the standard magnetron). The over-all weight of the tube is 3-1/2 pounds, and the G wavelength model should be obtainable by

N.R.C., if wanted, within the next few months. Ultimately three models will be made: ZP-505A, corresponding to 2J45; ZP-505S, corresponding to 2J46; and ZP-505G, corresponding to 2J47.

IV. LIGHTHOUSE TUBES (Dr. Bailey)

The lighthouse tube situation appears to be clearing up in the U.S. According to General Electric, a great deal of difficulty arose because military and naval authorities laid down the specifications on the basis of performance of early non-production samples. After many production difficulties, tubes are now being produced which satisfy the specifications:

(a) GL-446A and GL-446B

The GL-446A is the standard Lighthouse receiving tube now made with a slightly longer base in order to conform with the technique of RCA, who are also producing it. All 446A tubes are satisfactory for decimetre wave amplifier use. Certain of the tubes are hand-picked by testing them in a standard re-entrant oscillator cavity. If they give 50 milliwatts output at 8.9 cm. with 6-1/4 watts input, they are marked GL-446B and set aside for use in the 10-15 cm. region. Actually most 446A's oscillate satisfactorily in the 10 cm. region, but require more than 6-1/4 watts input.

(b) GL-464A and RMA-2C44

The GL-464A is the transmitting Lighthouse tube. It differs from the 446 only in that it has a larger plate cap and is run at 7 volts on the heater in order that it may be pulsed. All 464's are tested in the Naval SB radar set. They must give 0.5 kw. peak output at a plate voltage of 3.2 kv., and not show arcing between grid and cathode. Tubes which fail on this test are designeted RMA-2C44. These 2C44's are used in an Army equipment as a 200 mc. amplifier, but have no special advantage over the 446A.

The General Electric Company thinks very highly of the Lighthouse type tube and they advance various arguments for its use as a microwave oscillator and detector. For signal generators the 446 is very good as it is highly stable and can be tuned smoothly over quite a range. They consider that it is "head and shoulders" above any V.M. tube for signal generator use. As a frequency convertor they admit that the over-all noise figure attainable is 20 db. According to them this is only 4 db below the value usually obtained in crystal receivers. (The usual noise figure quoted for a crystal receiver at 10 cm. is 12-14 db). General Electric point out however, that in many cases crystal receivers operate at noise figures nearer 16 db because of T/R losses, partial burnout, etc.

(c) ZP-522

This is a tube of the Lighthouse type but considerably larger than the 446 and 464. It is intended to give about 70 watts c.w. in the 600-1000 mc. region, at 25% efficiency. It is not usable at microwave frequencies, and is not yet in production.

V. OSCILLATORS - 1 CM. (Dr. Lafferty)

General Electric have been working on a 1-cm. local oscillator in competition with the M.I.T. Neher tube. According to several different authorities, the General Electric version, designated as ZP-577, has a rather better output than the Neher tube. It operates at 1500 volts on the resonator and will give from 15 to 50 milliwatts output at 1.25 cm. The electronic tuning available at present is only about 50 mc. which is insufficient to cover the frequency spread of the K-band magnetrons. General Electric are making one model which will have several hundred megacycles of thermal tuning, and another for laboratory use which will have only mechanical tuning. A great deal of trouble has been experienced with the mechanically-tuned model, because of the expansion of the mechanical controls, which change over a much greater frequency range than does the resonator itself. The latest model will have invar members in it.

VI. GAS THYRATRONS (P. W. Crapuchettes)

(a) ZG-530

This is a hydrogen thyratron capable of giving a power output of one megawatt. It has a directly heated cathode requiring 16 amperes at 5 volts. Peak voltage and current ranges are 15 kv and 180 amperes. The tube has given over 200 hours life at 2,000 cycles recurrence.

(b) ZG-515

This is a lower powered hydrogen thyratron rated to give 5 kv. and 60 amperes pulses at 2,000 cycles. Cathode is directly heated, requiring 9 amperes at 2-1/2 volts. Driving power required is 150 volts at 10 ma. Lives around 300 hours have been obtained, and it is hoped that the tube will be available in production form within the next six months.

(c) ZG-547

This is a low powered hydrogen thyratron rated for 2-1/2 kv. 30 amperes at recurrence frequencies up to 4,000 cycles. It requires 75 volts at 5 milliamperes to drive it. Life is not yet good and further work is required.

(d) ZG-529

This is a hydrogen thyratron with directly heated cathode, rated for 10 kv. at 125 amperes. Still in development stage.

(e) ZG-569

This is almost identical with the ZG-530 except for its indirectly heated cathode. Still in development stage.

(f) ZG-568

This is identical with the ZG-515, except for its indirectly heated cathode. Still in development form.

(g) ZG-567

This is identical with the ZG-547, except for its indirectly heated cathode. Still in development form.

VII. OTHER TYPES OF THYRATRON

(a) ZG-473

This is a megawatt mercury thyratron rated for 15 kv., 150 amperes at a maximum of 1,000 cycles recurrence.

(b) Hall Thyratron

This is a 3-megawatt tube rated for 25 kv, 300 amperes at 500 cycles. The vapour source is an amalgam of mercury and cadmium.

VIII. DELAY LINES (J.P.Blewett)

General Electric have been working on delay lines of the continuous (non-lumped) type for use in the video region. The first models of this type of line consisted of two coils of Formex wire wound on a dielectric core. The Formex is a good insulator and the lines worked satisfactorily. One difficulty however, was that the delayed pulse was raised in voltage. To eliminate this the outer coil was replaced by ordinary flexible-line braid. In addition, to improve the insulation, a layer of insulating plastic tape was provided between the inner coil and the outer braid. These lines give a delay of approximately one microsecond per foot and will operate up to about 5 mc. They are good for 400 volts and have a characteristic impedance of 1100 ohms. The attenuation is 1.3 db. per microsecond of length. Machines have been set up for production of these lines and they are being turned out in considerable quantities to fill a heavy U.S. demand. It is hoped that two more machines will be added shortly; in which case the supply should be fairly adequate. A short length of this line was brought back as a sample, and is now being examined. General Electric have not done anything on high voltage continuous lines for pulse-forming use, but are considering doing this. With the facilities at their disposal they should be able to produce high voltage lines quite readily. They were interested in the work of our modulator group on pulse forming lines, and I think would welcome an exchange of information.

This work is covered by a report by Blewett, Langmuir, Nelson and Rubel, entitled: "DELAY LINES", dated May 31st, 1943.

IX. TEST EQUIPMENT

General Electric have developed a number of useful pieces of test gear. The names and designations of these are listed at the close of this chapter. More detailed information is available in the Microwave Section's files. A few of the items appear of special interest, and are mentioned below:

(a) Wide Band Oscilloscope (Type CRO-9-W, Cat. #4980173)

This is a very wide band oscillograph designed originally for use in testing television equipment. The amplifiers, etc. are suitable for radar use. It has sufficient special features that a description is being

published in the I.R.E. for August 1943. Price: $2975.00.

(b) Servo-Sweep Generator (Type YE-2, Cat. #6922610)

This unit was designed for the Wide Band Oscilloscope (above). Price $225.00.

(c) Square Wave Generator (Type SG-13, Cat. #8062490)

This is a square wave generator operating from 5 cycles to 125 kilocycles. The output is variable from 0-75 volts; output impedance 20 ohms/volt. Requires synchronous voltage of 7 volts or less. Price: $330.00.

(d) Precision Wavemeter (Type WM-1-T, Cat. #8248800G1)

This is a precision cavity type wavemeter working from 8-12 cm. It has a direct-reading scale giving an accuracy of one part in 1,000. It is complete with bolometer type detector and indicating meter. It is an extremely nice unit, though rater expensive. This bolometer type model can be used on pulses. Price: $150.00.

(e) Precision Wavemeter (Type WM-1-C, Cat #8248800G2)

This is identical with the above except that it has a crystal detector and is about 50 times as sensitive. It cannot be used on short pulses. Price: $150.00.

(f) Searching Wavemeter (Type WM-2, Cat. #8240019)

This wavemeter operates over the range 5-30 cm. Its accuracy is considerably less than the WM-1 type, but it will swing over the full frequency range at the turn of a knob, and would be extremely useful for spotting unknown wavelengths. Like the WM-1 type, it has detector and indicating meter included, but is not direct reading. Price: $195.00.

(g) Searching Wavemeter (Type WM-3, Cat. #8248805)

This is a wide range wavemeter operating from 2-8 cm. It again is complete with detector and indicating meter. Price: $185.00.

(h) Thermocouple Ammeter (Type PM-3, no catalogue number)

This is a rather nice r-f ammeter operating up to 200 mc. It is made in the following ranges: 0.1, 0.5, 3.0, 5.0, 8.0 amperes. Impedance is approximately linear with frequency, 3 ohms at 100 mc. Price on quotation.

(i) R-F Capacitometer (Type PM-6, Cat. #8014484)

This is a capacity bridge operating at 150 kc. Its range is 0-1100 μμF and 0-1100 μH. Price: $750.00.

(j) Visual Alignment Signal Generator (Type VA-1, Cat. #5106313)

This is a sweep signal generator for use in the i-f region,--1/2 to 160 mc. The sweep can be varied from 0-550 kc. Price: $550.00.

(k) Radar Test Set (no type or catalogue number)

This is a test set for field use, designed to do much what the Western Electric LZ set does. It will measure magnetron output power, transmitter frequency, pulse shape, T/R recovery time, receiver sensitivity, receiver fidelity, and produce an artificial echo. It is a great deal more compact than the LZ set and promises to be a very fine piece of test equipment. Probably not available for 8-12 months. (Price probably about $4,000.00)

(l) 5 Kw. Modulator (no type or catalogue number)

This is a small hard-tube modulator designed to give 1 μsec, 1000-cycle pulses. It uses an 829A in the output stage and is designed to work into loads of 3,000 ohms or 750 ohms. It is 9" x 9" x 7", and weight 20 pounds, complete with power supply.

Attachment to PRB-112, Chap. II.

GENERAL ELECTRIC COMPANY
ELECTRONIC INSTRUMENTS FOR LABORATORY USE
ELECTRONICS DEPARTMENT - SCHENECTADY, N. Y.

TYPE	CATALOGUE No.		APPROX. WEIGHT	TOTAL NET PRICE
CRO-9-W	4980173	9" wide-band oscilloscope	700 lb.	$2975.
YE-2	6922610	Servo-Sweep Generator (Auxiliary Unit for Type CRO-9-W Oscilloscope)	15 lb	225.
SG-13	8062490	Square Wave Generator	45 lb	330.
SG-19	6992298	Microwave Convertor	10 lb	275.
WM-1-T	8248800G1	Precision Wavemeter	6 lb	150.
WM-1-C	8248800G2	Precision Wavemeter	6 lb	150.
WM-2	8240019	Searching Wavemeter	8 lb	195.
WM-3	8248805	Searching Wavemeter	8 lb	185.
WM-9-T	6992285G1	Precision Wavemeter	6 lb	150.
PS-1	6977033	Standard Regulated Power Supply	75 lb	275.
PS-2	6992267	Small Regulated Power Supply	35 lb	175.
PS-4	5106802	Dual Regulated Power Supply	140 lb	825.
TT-3	- -	Cathode Ray Tube Tester (for development)	-	Available on request
TT-4	-	Cathode Ray Tube Tester (for production)	-	Available on request
RA-3	7351035	Modulator Unit	-	Available on request
RA-4	6866928	High Voltage Rectifier	-	Available on request
PM-1	8240092	Microwave Power Bridge	30 lb	775.
PM-2	8014467	Standing Wave Indicator and impedance analyzer	25 lb	1725.
PM-3	-	Low Impedance Thermocouple Ammeter	1 lb	Available on request.
PM-6	8014484	R-F Capacitometer	55lb.	750.
SN-1	6933939	Signal-to-Noise Ratio Measuring Instrument	400 lb	3975.
VA-1	5106313	Visual Alignment Signal Generator	65 lb	550.
YE-1	-	Recording Field Strength Meter	-	Available on request

CHAPTER III

VISIT TO THE RADIATION LABORATORY, M.I.T., August 2nd and 3rd, 1943

I. CRYSTALS

I asked M.I.T. about the performance of crystals made by the various commercial concerns in order to get an overall picture. On sensitivity it would appear that for 10 cm. use Westinghouse crystals run highest, Sylvania next, and Western Electric lowest. Average noise figures for these various types, assuming a 4 db. amplifier, are Westinghouse 12 db, Sylvania 13 db, Western Electric 14.7 db. Burn-out tests on normal crystals (not high burn-out types) indicate that Sylvania are best. An insufficient number of Westinghouse crystals has been yet produced for conclusive tests of burn-out to be available, but they appear very comparable with Sylvania. The standard Western Electric crystals are poorer than Sylvania on burn-out. The Western Electric high burn-out type are quite good on burn-out characteristics; however they usually start with a higher noise figure than the average Sylvania crystals so that their over-all performance is effectively no better.

The M.I.T. technique of comparing crystals for burn-out is to apply a known level of r-f power to the crystals and to measure the noise figure at certain intervals. Crystals are rated according to the number surviving a specific burn-out treatment with a given noise figure. As an example, Sylvania crystals may start with a noise figure around 13 db. and after a given treatment, fall to 15 db. A Western Electric crystals of the high burn-out type will probably start at 15 db. and maintain this sensitivity throughout the burn-out treatment. Thus, while the Sylvania crystal has actually deteriorated in the burn-out treatment, its over-all performance is as good as the Western Electric crystal.

At 3 cm. the Westinghouse crystals are definitely better than any other type, except possibly the hand-picked British "green spot" crystals. Incidentally there is very little correlation between 10 cm. performance and 3 cm.

II. T/R SWITCHES - 3 CM.

M.I.T. have been having a great deal of trouble with the 724 T/R switch. This trouble showed up first in the early models of the ASD set when they were placed on trial in the field. In many cases it was found that operators were running with crystals 3 - 6 db. down in sensitivity without being aware of it. Since it is now clear that spike energy is what causes burn-out, M.I.T. are measuring spike energy instead of average leakage power. This is accomplished by measuring the total leakage power through a T/R with the square wave portion balanced out by means of an artificial signal equal in amplitude and 180° out of phase with the power passing the T/R. Spike energy is expressed in ergs. The Western Electric-built 724's are performing better than the Sylvania type. They usually show a spike energy of .2-.3 ergs; whereas the Sylvania model runs about .4-.6 ergs. This difference seems to be due to the fact that Western Electric are using a higher pressure gas filling than Sylvania. Sylvania are

now using 10 mm. H_2 and 7 mm. H_2O. The new filling will be either $10H_2 - 20H_2O$ or $15H_2 - 15H_2O$.

M.I.T. have recently released a report (No. 53-24) which includes a great deal of information on T/R leakage and spike energy. I believe this report has been received, but the following salient points may be of interest:

(1) Spike energy is virtually independent of input power.

(2) Spike energy goes up rapidly as recurrence frequency is decreased. This indicates that there are quite a few residual ions from the r-f breakdown, and that a good supply of ions in the gap space is necessary to reduce spike energy.

(3) The higher the keepalive current, the better the protection, though this must be kept to something of the order of 100 ma. average; otherwise tube life will be seriously impaired.

(4) Considerable improvement in protection was obtained by coating the r-f cones with glass, thereby forming an "ion trap". This is not a satisfactory procedure for production tubes, however.

(5) Passing a heavy pulse of d-c through the keepalive before the r-f pulse arrives is definitely helpful, but hard to accomplish in service.

(6) Protection increases up to a certain point with gas pressure, a total pressure around 30 mm. appearing to be optimum.

The Westinghouse 1B24 promises to be very satisfactory. Sylvania are tooling up to make this tube. They will probably use a gas mixture of 15 mm. H_2 and 15 mm. H_2O. In this model the keepalive will have a glass sleeve which forces the keepalive arc to occur only at the tip of the electrode. The present Westinghouse tube, without glass-covered keepalive should be run at 100-120 μa. The new Sylvania models should operate satisfactorily at 50 μa.

III. T/R SWITCHES - 10 CM.

The 721 T/R appears to be reasonably satisfactory for all medium power systems (less than 300 kw.). With higher powers however, trouble is being experienced. Even though spike energy is independent of input power, the sum of spike energy plus high square wave energy will cause burn-out at 400 kw. and up. In an attempt to reduce this, M.I.T. have been "pre-pulsing" the keepalive in their MEW system, which has a 700 kw. transmitter. This is done by taking about 800 volts off the primary of the main pulse transformer and applying this to the keepalive on top of a steady 400-volt d-c voltage as shown in Figure 7.

It is extremely doubtful if this keep-alive pulse arrives before the main r-f pulse, but it apparently does help the situation. Previously some

721's gave adequate protection at 700 kw., whereas others failed. With the pre-pulsed keepalive, all 721's seem to give adequate protection. M.I.T. have considered the Westinghouse scheme of firing the keepalive, or the actual r-f gap, some microseconds ahead of the main pulse. The difficulty however, is that their spark modulator has a jitter of around 40 microseconds so that it is impossible to fire the keepalive from the previous pulse.

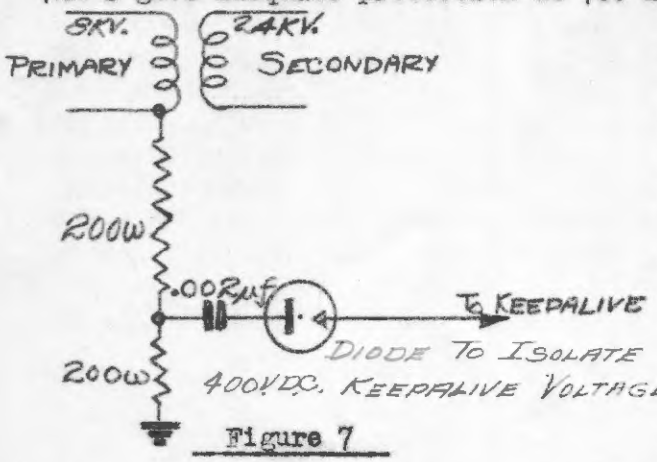

Figure 7

M.I.T. are developing a new T/R switch suggested by Dr. Cork. The Cork T/R is so arranged that when it fires, there is actually a sheath of ions right across the coupling window. Measurements have shown practically zero square wave leakage power, though the spike is of course still present.

IV. MAGNETRONS - 10 CM.

The ordinary 2J type of magnetron will apparently operate satisfactorily up to 700 kw. output and is being used under these conditions in the MEW. For a higher output than this they will probably use the Western Electric 720, or something equivalent.

Dr. K. R. More has been working on the "starting time" of magnetrons. A great deal of difficulty has been experienced in eliminating delays in transmission lines, etc. but he is now set up to study magnetron pulses with resolving power around 1/100th microsecond. A sweep speed of 5 inches per microsecond is used, and to avoid the construction of an impossibly wide-band video, rectified r-f power is taken directly from a diode of the Lighthouse tube type. The current through the magnetron is observed by the use of a special non-inductive resistor built by Western Electric. These are unfortunately almost unobtainable at present, and M.I.T. are having a hard time getting two which they badly need. With the above equipment, Dr. More has made very fine records of magnetron pulses. The current pulse lags the voltage by about .015 microsecond, as shown in the figure below:

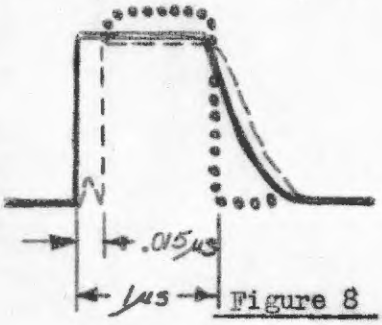

Figure 8

Voltage ———

Current - - - - - -

R.F. .....

At the start, the current pulse rises slowly due to charging of the magnetron capacity. At the end of the charging period, the current drops momentarily, then rises abruptly to full value. The r-f pulse itself follows

the straight portion of the current pulse very beautifully. R-F pulses .05 microsecond long have been obtained with the voltage pulse only slightly longer. One interesting observation was that spark modulators may give considerable trouble when the leading edge of the pulse rises too abruptly. Since the magnetron current cannot follow immediately, the pulser is working into a much higher impedance than that for which it was designed; and accordingly over-shoots considerably. This may result in spark-over inside the magnetron or an oscillation of the pulser. The trouble is easily corrected by adding a little capacity to the pulse lead, to slow up the leading edge slightly.

V. MAGNETRONS - 1 CM.

I asked Dr. Purcell about the magnet required for the Columbia K-band magnetron. The standard Cinaudagraph magnet designed for the 2J21 is usable, with suitable pole pieces, but is a little low on field strength. Cinaudagraph are now making a special magnet for the 725, and this apparently is very satisfactory for the K-band tubes. Present power output is between 10 and 20 kw.

VI. SCANNING ANTENNAE

(a) Foster Antenna

The Foster conical-drum type scanning antenna is still under construction. A great deal of difficulty has been encountered in fabricating it, but it is now nearing completion. The stator of this unit had finally to be made by copper plating on a dummy form. The construction of the teeth or fingers, which serve to switch the r-f power, is nearing completion. In the present system these teeth are .043" wide, with a clearance of 7 mils on each side. The machining of these teeth for a 36-inch antenna presents quite a problem.

(b) Alvarez Antenna

In the Alvarez model, phase changing is effected by moving in and out one side of the wave guide. A six-foot model has been made up for K-band use and has worked very satisfactorily. It is however, extremely difficult to fabricate. Dr. Purcell believes that the Foster type, while hard to make in a single unit, will be much easier than the Alvarez type when turned out on a production basis.

VII. OSCILLATORS - 1 CM.

The Neher and General Electric K-band oscillators work satisfactorily on all except two points:

(i) The voltage is still rather high for system use, and it would be desirable to reduce this from 2,000 volts to something under 1,000 volts.

(ii) The electronic tuning is only about $\pm$ 40-50 mc. so that for A.F.C. use hot wire tuning appears essential, since the magnetron spread is of the order of $\pm$ 240 mc. Power output is now 15-50 milliwatts.