The Satellite Traveling-Wave Tube

By M. G. BODMER, J. P. LAICO, E. G. OLSEN
and A. T. ROSS

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The traveling-wave tube amplifier described provides a minimum output power of 3.5 watts at 4.0 to 4.2 gc. Design aspects that lead to lifetimes in excess of 10 years and to tube efficiencies between 35 to 40 per cent are discussed. The tube is focused by an improved version of the single-reversal magnetic circuit. Performance data pertinent to this particular satellite operation are shown. Highlights from the final production run and the subsequent life test serve to illustrate the care with which this TWT has been built.

I. INTRODUCTION

The output power amplifier in the Telstar spacecraft microwave repeater operates near 4 gc; the amplifier is required to accept a fractional milliwatt signal distributed over approximately 100 megacycles bandwidth and amplify it some 4000 times to provide an output of several watts. In the satellite, this power amplifier is the major power utilizing device, and its efficiency is controlling in the design of the satellite and of the system. Of the possible microwave devices which might be considered, the traveling-wave tube is outstandingly well suited to the application. The broad bandwidth and high gain is such that only a single tube is necessary. The efficiency is as high as or higher than that of competitive devices, and a considerable history exists to suggest that very long life and high reliability can be achieved.

This paper describes the development of the M4041 traveling-wave tube for this application. The design methods for traveling-wave tubes for radio relay applications are well known and can be found in such texts as Ref. 1; therefore, discussion will be limited to those aspects which are peculiar to this application. Since reliability is the most important aspect in the Telstar experiment, considerable attention will be paid to this aspect of the design. The development of the tube was carried on in five phases. Initially, there was a design phase in which close interaction with the systems area produced a final amplifier specification which was compatible with other parts of the system. This was followed by a qualification period, during which development models of the tube were subjected to extensive electrical and mechanical tests at levels in excess of the environment anticipated in the application. Next, a group of tubes was fabricated under the best available clean-room conditions, which included extensive engineering checks on the details of the fabrication. These tubes were tested and placed on aging racks at the established nominal operating conditions. Finally, from this group of tubes, those showing the most uniform and stable characteristics were selected and married to their final power supplies for incorporation into actual satellites. Each of these phases will be discussed in the text.

In considering the design and qualification phases of the development, it must be remembered that this amplifier is a relatively complex package, and it is therefore not possible to fabricate a sufficient number of models to permit extensive use of statistical methods and stress aging. It was therefore necessary to place great emphasis on design integrity: that is, upon the use of techniques which had been established as reliable in previous devices. While nearly every one of the electron tubes which have been developed by the Laboratories has contributed in some way to our knowledge, three developments are peculiarly related to the Telstar spacecraft application. The earliest of these was the development of the 175HQ, the pentode used in the present submarine cable repeaters. During this development, a large number of controlled laboratory experiments were carried out, some extending to 100,000 hours of real-time testing. These tests have given us a great deal of information concerning the effect of impurities and processing on cathode life. It was during the development of this tube that many of the techniques of building super-clean tubes for applications requiring high reliability were developed. In particular, the concepts of aging and selection to avoid manufacturing freaks appeared. There are currently 1608 such tubes in underwater applications, and these have accumulated over 60,000,000 tube hours of operation without failure. The second development which is of specific interest is that of the M1789 traveling-wave tube. This is a 5-watt amplifier developed for a 6-gc transcontinental radio relay. This tube is currently in production, and field experience has given us a great deal of information concerning failure mechanisms in traveling-wave amplifiers. Towards the end of the development, a group of final design tubes were fabricated, under what were then considered clean conditions; and from these, 12 tubes were selected on the basis of cathode activity for a life experiment. After some six years of operation, 11 of these tubes are still operating satisfactorily. (The twelfth tube was accidentally lost during a modification of the laboratory building.) This experiment suggests that our selection techniques can be successfully applied to a traveling-wave amplifier. These tube developments show that it is possible to develop tubes with extremely long life and with high reliability. The third development relates to the rigors of the launch environment. The M1958 traveling-wave amplifier is a 9-gc tube developed for a missile guidance system. In this system, the tube is mounted in the missile-borne equipment and must not only survive, but also operate satisfactorily, during the shock and vibration of the launch. In more than 100 launches, no failures of this device have been observed. In the design of the M4041 traveling-wave tube, the techniques developed for these previous devices have been employed wherever possible. Where the specialized application required new design approaches, these have been extensively qualified during this development.

II. SYSTEM REQUIREMENTS

Table I lists the final requirements placed upon the performance of the M4041 traveling-wave amplifier. The table lists not only specific maximum or minimum values for parameters, but also indicates other design constraints necessary to the application.

III. TUBE DESIGN PARAMETERS

Previous experience has established the practical range of a number of tube parameters. From this experience in using conventional traveling-wave tube analysis, a three-dimensional set of tube designs was computed using the following three parameter ranges:

$$\gamma a = 1.0\text{–}1.6$$

$$V_{\text{helix}} = 1000\text{–}2500 \text{ v}$$

$$I_0 = 5.0\text{–}20 \text{ ma.}$$

In these designs, a number of restrictions were imposed, based on past experience and on engineering judgment. These restrictions are listed in Table II and will be discussed in detail in subsequent sections. From this field of designs, a final set of parameters was chosen as the optimum, and this is summarized in Table III, where γ = radial propagation constant; a = helix radius; $K = 2\pi/\lambda_0$ and λ_0 = free-space wavelength; C = gain parameter from Pierce; and QC = space charge parameter from Pierce.

TABLE I — SYSTEM REQUIREMENTS FOR M4041 TWT

Life (average before failure)	In excess of 10 years
Operating frequency band Beacon at 4.08 gc Signal at 4.17 gc ± 25 mc	4.0–4.2 gc
Output power (saturated)	P_0 = 3.5 w minimum
Input drive available	P_{in} = 0 dbm maximum
Total dc power available	P_{dc} = 16 w

Weight of TWT
To be minimized along with its associated equipment — like the solar plant with its support structure, storage batteries, power supply, etc.

Hot matches at optimized V_{helix} and I_0
Input better than 18-db return loss in band (VSWR = 1.3)
Output better than 10-db return loss in band (VSWR = 1.9)
Output better than 5-db return loss over a 20% band (VSWR = 3.5)

Short circuit stability with V_{helix} reduced 75 volts from operating point*

Tube must operate with all voltages ±3% from set nominal value (because of long time drift in regulated 16-v supply)

Noise figure better than 30 db

AM to PM conversion less than 12°/db

Cooling of collector by conduction to housing and through waveguide to remainder of electronics canister

Completed package to withstand environmental conditions during launch, in orbit, and eclipse

Vibration — tube inoperative; 15-50-15 cps, 0.3-inch displacement 50-2000-50 cps at 20 g in all 3 directions at a sweep rate of one octave per minute

Thermal cycling ±15°F to 90°F to 15°F.

* The operating point for best efficiency was chosen at helix overvoltage (ΔV_{helix} ≈ 150 volts) where amplifier gain is considerably reduced from the low-level synchronous condition. Reducing the helix voltage from the operating point automatically increases the over-all gain and reduces short circuit stability.

TABLE II — DESIGN PARAMETERS FOR M4041 TWT

Cathode current density	<85 ma/cm²
Beam area convergence	<25
Beam perveance	<0.3 microperv
Voltages	<2000 volts
Magnetic flux density	<550 gauss
Saturated output power at output flange	>3.5 watts
Computed depressed efficiency (not including heater)	>35%
Intercept currents	<1%

TABLE III — SUMMARY OF M4041 DESIGN

Helix Dimensions

Mean diameter	90 mils
Wire diameter	10 mils
Turns per inch	49
Pitch	20.4 mils
Active length	5.75 inches

Voltages and Currents

	Voltage	Current
At 4.0 watts output cathode	0	17.4 ma
Beam forming electrode	0	0
Accelerator	1800	<0.1 ma
Helix (overvoltage)	1550	<0.15 ma
Collector	750	>17.15 ma
Heater power		1.4 watts (730°C true at cathode)

TWT Parameters at Midband (4.1 gc)

$\gamma a = 1.33$
$Ka = 0.098$
$C = 0.063$
$QC = 0.25$
N (number of λ's on helix) 26
Dielectric loading factor 0.86
Impedance reduction factor 0.4

Electron gun:

Gun type — converging Pierce gun
Cathode type — high purity nickel with 0.1% zirconium; base coating low-density double carbonate
Cathode current density 85 ma/cm² (I_k = 17.4 ma)
Cathode diameter 0.192 inch
Convergence half-angle 12° 45′
Cathode radius of curvature ($\bar{r}_c$) 0.435 inch
Anode radius of curvature ($\bar{r}_a$) 0.176 inch
$\bar{r}_c/\bar{r}_a = 2.48$.

IV. DESIGN OF THE TRAVELING-WAVE TUBE

From the foregoing specification, it is apparent that the M4041 is, as might be expected from the reliability required in the application, a conservative design. On the other hand, if the goals in life and efficiency are met, the tube will represent the state-of-the-art in these parameters.

Fig. 1 shows a photograph of the completed traveling-wave tube amplifier. The functional parts — the TWT, the magnets with their respective pole-pieces, and the RF couplers — are displayed in their relative positions. The magnetic design used is a single-reversal circuit. It consists basically of two cylindrical magnets charged with the same polarity at the center plane and separated by a septum, the field reversal pole-piece. The tube is held in alignment with the magnets through

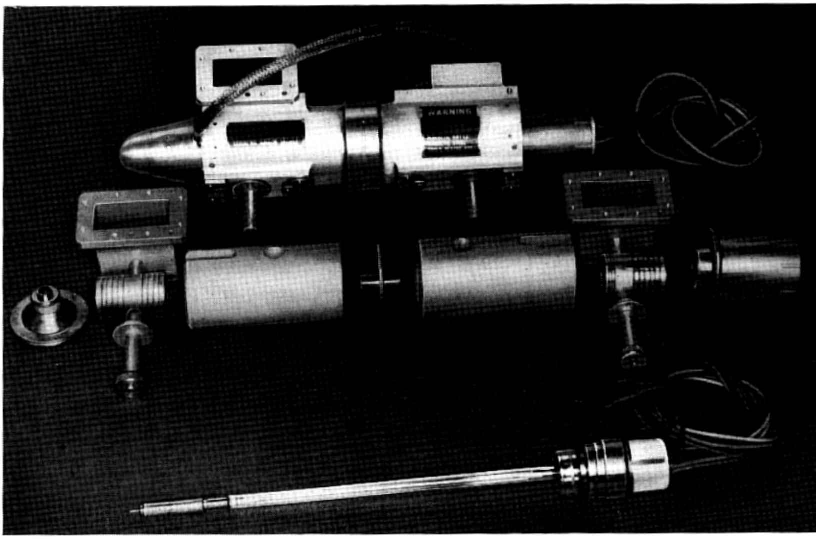

Fig. 1 — Packaged TWT amplifier with a layout of its major functional components.

reference surfaces in both gun and collector pole-pieces. RF connections to the TWT are established by externally tuned reentrant coaxial couplers which, in turn, are matched to the rectangular waveguide.

In this section, the tube is broken down into its individual parts of gun, helix, collector, envelope and focusing circuit, and each part with its major design parameters is discussed separately.

4.1 *The Gun*

The basic Pierce-type gun is characterized by three major parameters: perveance, convergence, and cathode current density. To maintain the concept of "proven integrity," these parameters were limited to the corresponding values of the 6-gc radio relay tube, our main source of life test data. The limiting values are 0.3 microperv for perveance and 25 for the area convergence. The choice of the cathode current density limit warrants a separate discussion which follows this paragraph.

Life tests on 12 M1789, 5-watt TWT's, developed for a 6-gc radio relay, had in 1960 exceeded without failure an individual accumulated life of 35,000 hours at a cathode current density of 210 ma/cm^2. Analyses of the life test data compiled over the past six years showed a slow, but steady, increase in accelerator and helix interception with constant cathode current in the majority of the 12 M1789 TWT's on life test, by a factor of as much as five. This has been interpreted as a small degradation of the beam profile within the gun, caused by small areas of lowered activity on the cathode. Their effect is an increase of the transverse velocities of the electrons, producing crossovers and consequently an increase of the final beam diameter. This type of beam degradation is aggravated by increasing the area convergence and perveance to higher values. Either increase results in a gun which is inherently less stable and more sensitive to aberration in the beam formation.

The cathode current density chosen has a first-order effect on the life capability of the TWT. From our past life tests on TWT's, we have observed that the average life is highly dependent on the actual cathode temperature; a decrease of 25°C will, in general, double the life of the cathode. Similar data have been obtained with microwave triodes, using a considerably larger universe for testing. The cathode temperature, in turn, is dependent on cathode current density and the work function of the coating. In Fig. 2, these relations are approximated by a line of constant slope; a lower work function moves the line to the right, a higher work function to the left. We cannot measure the work function in completed tubes, but we have a point which represents our tube art of several years ago. In our final life test, all M1789 TWT's had exceeded 35,000 hours in 1960. This point is plotted at the proper cathode current density in Fig. 2 and a line with the proper constant slope drawn through it. This curve was used as our design basis and is quite conservative, since not all tubes will fail at one time. For a ten-year life, the current density should be less than 85 ma/cm^2. Since that time, most of these same tubes have passed 50,000 hours (however, one envelope broke due to an interruption of the cooling air). The graph has been revised accordingly (1962). It must be pointed out that our area of experience is limited and that, in the interest of conservatism, the extrapolations indicated by the dashed part of the line should be used with caution at the present time.

In choosing the cathode base material for the M4041, a number of factors must be considered. Most important in this application are questions of rate of activation, sublimation and coating adherence. Of the 12 M1789 TWT's in the life test mentioned earlier, several exhibited internal arcing, usually between 5000 and 20,000 hours of operating life. This arcing is attributed to a build-up of a conducting film on the electrode insulators. The film is believed to be due in part to sublimation of the additive from the base nickel of the cathode. This problem is distinct from those encountered in gridded tubes like the submarine cable pentode, just as interface resistance does not influence the choice in this case. Several alloys were considered for the cathode base. The final choice was a pure nickel with a single 0.1 per cent Zr additive. It is produced

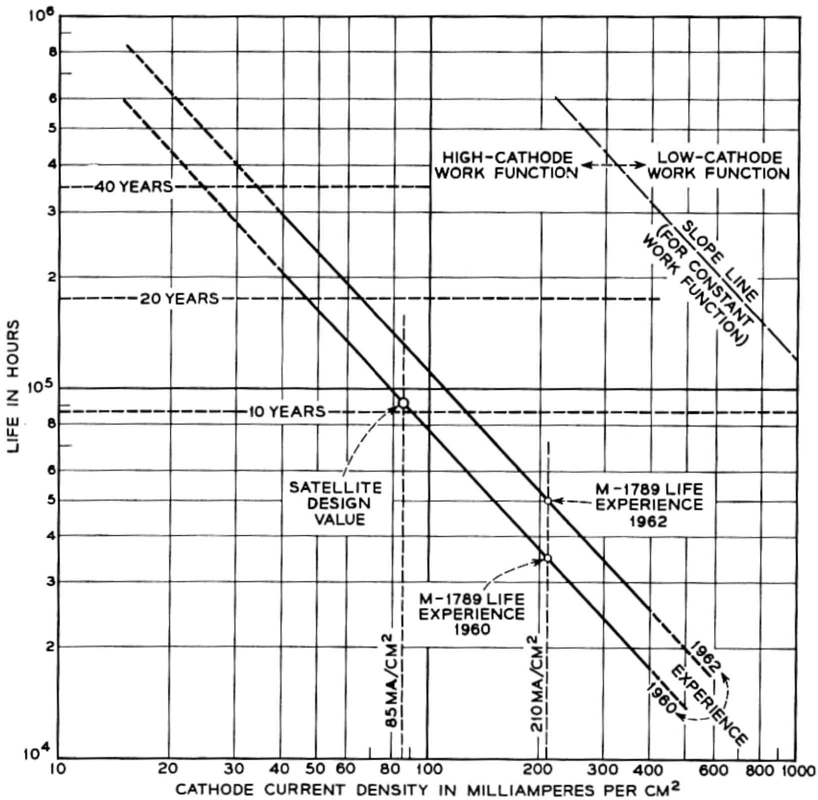

Fig. 2 — Average life expectancy vs cathode current density.

in this Laboratory[2] under conditions in which impurities, particularly carbon, are held to less than 0.005 per cent. The Zr additive as a reducing agent has the advantage of producing little or no sublimation. In addition, the production of donors is not limited by the diffusion of the reducing agent, but by the chemical reaction rate of the coating. The thickness of the alloy was chosen as 0.040 inch, which should give at 730°C a 100 per cent depletion of the coating with an 89 per cent depletion of the Zr after 19 years,[3] as shown in Fig. 3. This represents a safety margin of nine years over the expected tube life, a needed guarantee, since a tube will fail long before complete exhaustion of the cathode coating. As the coating becomes thin, the emission becomes nonuniform and the beam transmission is impaired. This results in excessive heating of the helix and subsequent further deactivation of the cathode through

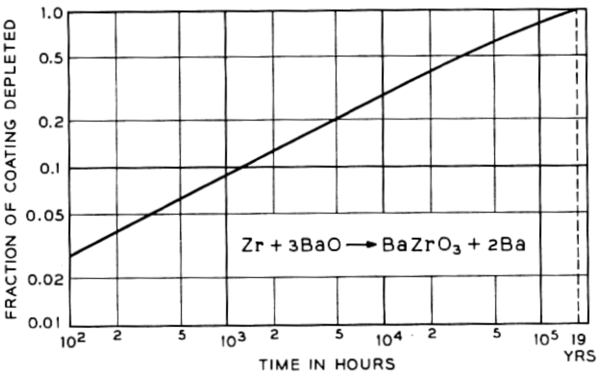

Fig. 3 — Calculated depletion of oxide coating on 0.1 per cent Zr-nickel base. Calculations are based on the following numbers, corresponding to values for M4041 tube:

thickness of nickel base	0.040 inch
thickness of coating	0.0015 inch
density of coating	1.1 gm/cm³
cathode temperature	730°C, true.

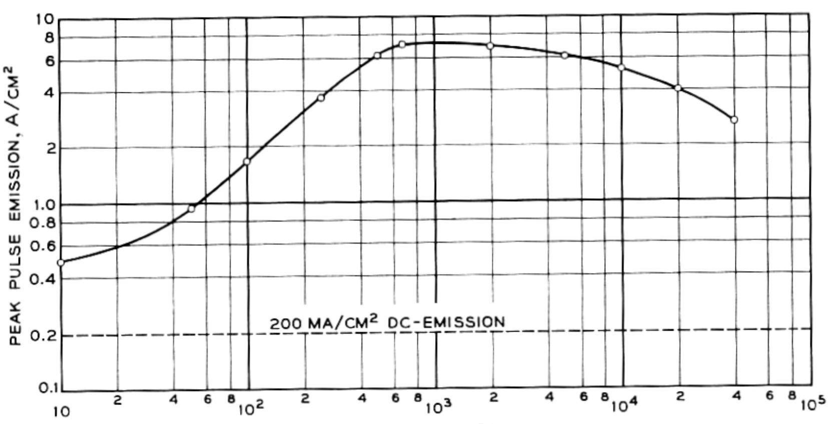

Fig. 4 — Life tests of control diodes with 0.1 per cent Zr-nickel base. Normal operating condition 200 ma/cm² dc, cathode temperature 740°C true. Activity measured by superimposing pulse directly over dc.

the released gases. It is predicted that uniform emission will be maintained at least to the design figure of ten years. This estimate is supported by tests with diodes constructed with this alloy, which have been operating close to six years without noticeable decreases in emission. Fig. 4 gives the average peak pulse emission versus elapsed time which has been obtained in diode testers with this alloy in recent tests.[2] Beyond choosing a low sublimation rate base nickel, a maximum voltage limit of 2000 volts per electrode was imposed and all possible leakage paths were lengthened and shielded. These steps were taken because some of the leakage may be due to the deposition of barium from the coating.

The emitter is physically in the form of a button, machined precisely to shape. The surface on which the cathode coating is to be applied is liquid-honed with calcium oxide powder to provide a roughened area to facilitate adherence. Calcium oxide is used because it is chemically compatible with the cathode coating materials, should any particles be embedded. A combined coating of barium and strontium carbonates is machine sprayed on the roughened surface. The density of the coating is held to 1.10 ± 0.1 gm/cm^3, equivalent to a thickness of 1.5 ± 0.10 mils.

Structurally, the gun is designed in two sections, as shown in Fig. 5. One section, which might be considered a chassis, consists of two molybdenum focusing electrodes — the beam-forming electrode and the accelerating electrode — plus the molybdenum cathode-support sleeve, all of which are concentrically aligned and supported from a cupped molybdenum base. Support for the focusing electrodes from the base is obtained by glazing to three Alsimag 475 (zircon body) ceramic tubes,

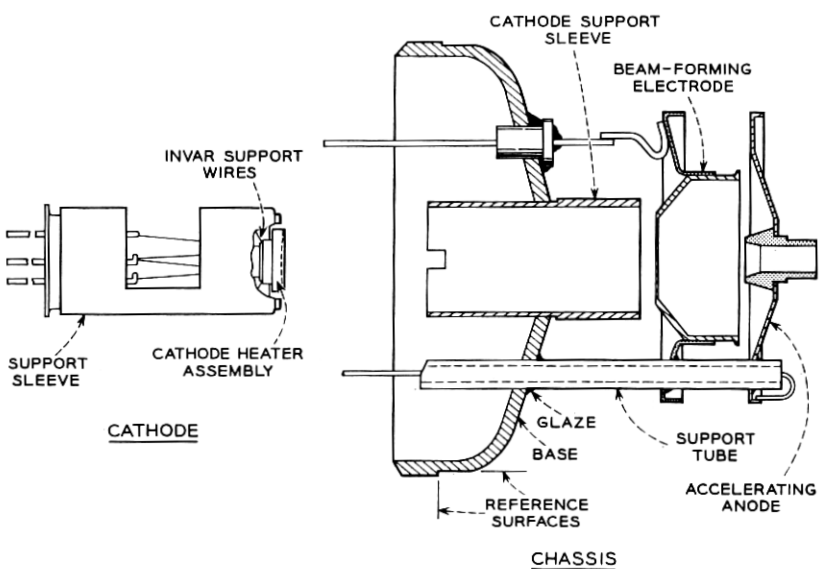

Fig. 5 — Gun assembly.

which also serve to insulate these electrodes. The cathode support sleeve is brazed concentric to the reference surface machined on the base. Tolerances in tenths of mils are readily held in concentricity, squareness and axial dimensions (see Fig. 5). These materials have compatible thermal expansions, are structurally stable, and are capable of withstanding thermal shock, rigorous cleaning, high-temperature outgassing, and vigorous vibrating.

The inner section consists of a cathode and heater mounted in a sleeve. The sleeve serves a double purpose. Its inside diameter encloses and supports the cathode heater assembly by means of fine Invar wires, while its outside diameter is machined to slide snugly, by selection, within the cathode support sleeve of the chassis.

The heater is one of the principal power consuming elements of the tube. It is therefore important to minimize this power, or else the over-all efficiency will be degraded. By virtue of the unique design,* in which the cathode is suspended by fine wires, and a minimized radiating area of the cathode body, a power of 1.4 watts is sufficient to heat the 0.192-inch diameter emitting surface of the cathode to an operating temperature of 730°C.

4.2 *The Helix*

The interaction efficiency of the TWT depends to a large degree on the helix itself, even if the beam parameters are optimized. In early prototypes, the depressed collector efficiency averaged around 27 to 30 per cent. In the final series of tubes, this value had climbed to 36–40 per cent. The only changes made were: the reduction of the cold loss, the increase of the dielectric loading factor and, finally, the optimization of the shape and length of the sprayed loss pattern. The cold loss of the 6-inch helix averaged 4.2 db; this value was reduced to 2.7 db with careful copper plating of the helix and subsequent sintering.

The original helix support was provided by three round F66 steatite rods. They were replaced by grooved rods of the same material, as illustrated in Fig. 6. Most of the dielectric material has been removed from the vicinity of the helix wire, where the RF fields are the strongest. The dielectric loading factor, which is computed from the low-current synchronous helix voltage, increased from 0.81 to 0.86. As a consequence, the helix turns-per-inch (TPI) was increased from 46 to 49 to maintain the same helix voltage.

The original loss section was about 2 inches long, with a 1.5-inch section where no net gain could be obtained, and started 1.5 inches from

* To be described in a subsequent paper.

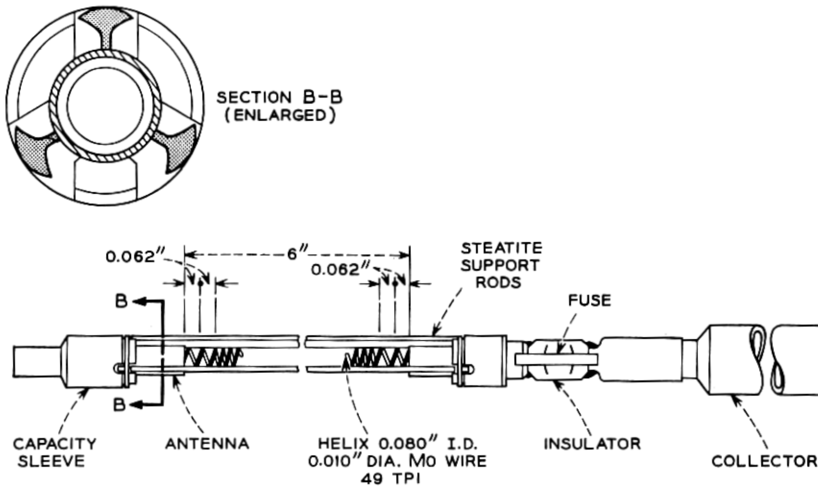

Fig. 6 — Helix assembly, showing cross section with special undercut F66 ceramic support rods.

the input coupler. It was found that the efficiency continued to improve as this section was shortened and moved closer to the input, as long as enough gain was maintained in the input section to establish the slow wave. The final loss pattern, as measured on a completed helix, is shown in Fig. 7. Moving the loss section towards the input and shortening it led to a considerable increase in the gain of the output section, where a maximum low-level gain of 46 to 49 db is produced. Since the tube must be short-circuit stable, this imposes a tremendous requirement on the return loss of the output edge of the loss pattern and the uniformity of the helix near this edge. A return loss of 52 db or more would have been desirable. It proved to be extremely difficult to maintain a return loss of better than 46 db. The short-circuit stability test was the most serious shrinkage factor on otherwise acceptable tubes for flight. Fig. 8 shows the hot and cold output match for an acceptable and a rejected tube, measured when the voltages are adjusted for maximum low-level gain.

The physical embodiment of the helix consists of a winding of 10-mil diameter molybdenum wire, wound with an inside diameter of 80 mils and a length of 6 inches at 49 TPI, except for two turns at each end which are at 66 TPI. Each turn of the winding is glazed to each of the three F66 steatite ceramic rods (spaced 120° apart) and then it is copper plated. After this, attenuation in the form of the aquadag is sprayed on. Fig. 9 shows schematically the means for applying and controlling this deposit.

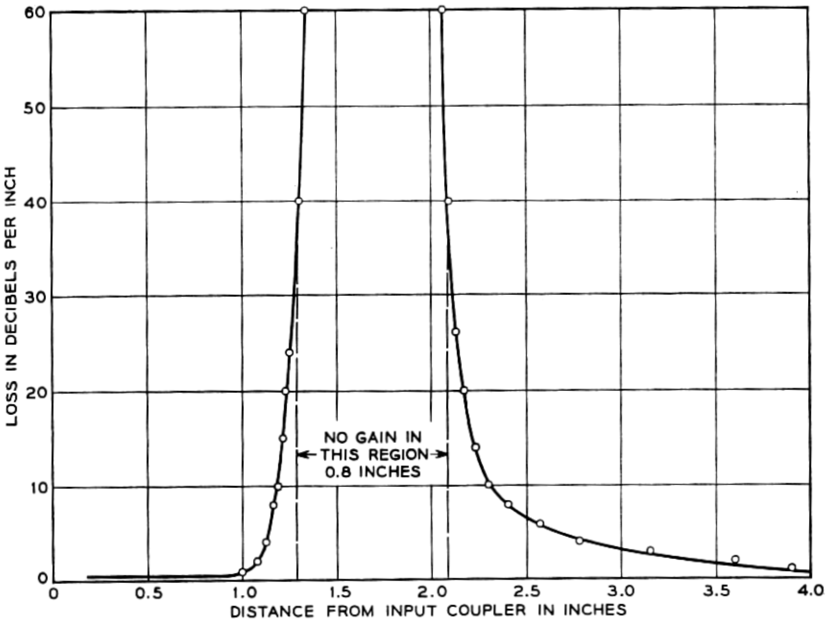

Fig. 7 — Final helix loss patterns of sprayed aquadag (intrinsic loss with Cu plating 2.78 db; total loss 83 db).

The glazed helix structure is shown in Fig. 6. The helix wire is wound to a maximum pitch variation of ±1 per cent (±0.0002 inch). Techniques developed at these Laboratories for fabricating glazed helices[4] make it possible to hold the outside diameter of the helix structure, defined by the outside of the ceramic support rods, to ±0.00075 inch. This is a maximum of 1.4 mils smaller than the inside bore diameter of the glass envelope within which it will be assembled later on. This close fit not only precisely aligns the helix, but also provides a support that enhances its resistance to shock and vibration. The helix structure is capable of withstanding thermal shock, extensive cleaning procedures, and outgassing in vacuum. The outgassing temperature is limited by the vapor pressure of the copper plating to 650°C.

4.3 *The Collector*

The collector in a high-efficiency TWT plays an important part. To improve the efficiency, the collector voltage is depressed below that of the helix until the maximum tolerable helix or accelerator interception is reached. For long-life tubes, it is desirable to keep this interception at

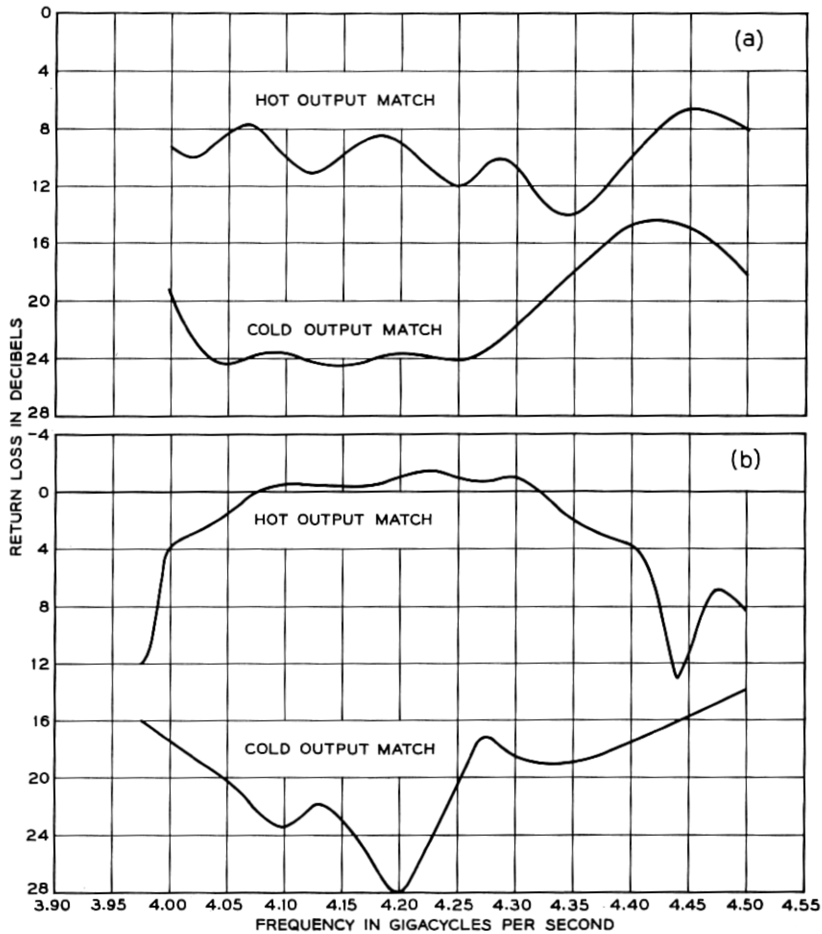

Fig. 8 — M4041, output matches measured at waveguide flange: (a) acceptable tube, (b) rejected tube (note return gain in band center).

the beginning of life to a maximum of 1 per cent of the beam current, since this interception increases slowly but steadily throughout life.

In Fig. 10, the helix current is shown as a function of collector voltage with no RF drive and with a drive to saturate the output power. When the collector voltage is depressed below the helix, the helix interception rises rapidly until it reaches a plateau. This current, called back-streaming, consists largely of secondary or reflected electrons, which finally terminate on the helix or accelerator. In addition, RF feedback that can

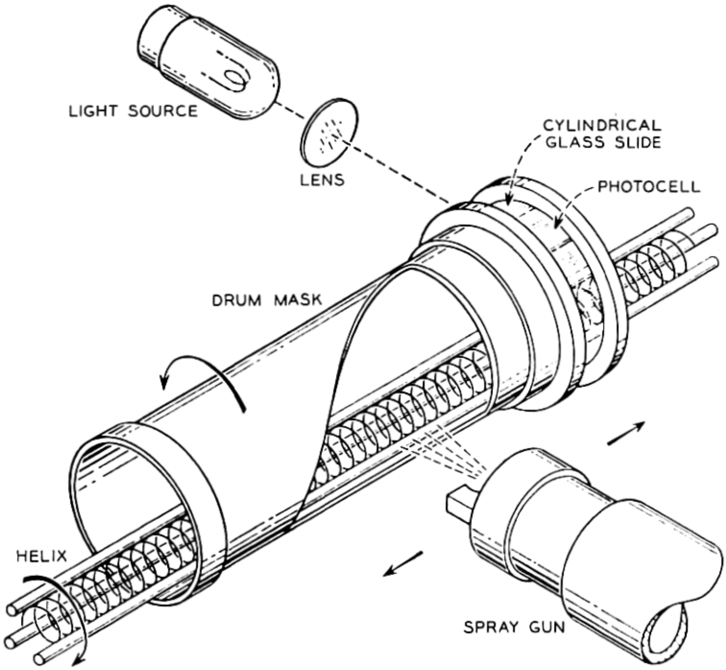

Fig. 9 — Schematic diagram of machine used for spraying aquadag loss section on helix.

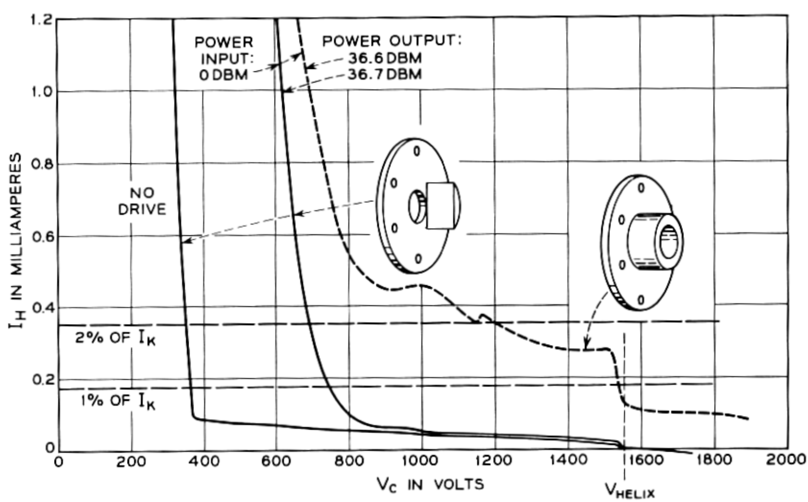

Fig. 10 — Depressed collector operation. Helix current vs collector voltage is shown for symmetrical and asymmetrical output pole-pieces. (Note the suppression of secondary and reflected electrons.) $I_k = 17.4$ ma, $V_{\text{helix}} = 1550$ v.

lead to internal oscillations is caused by the returning electrons, which provide a small amount of coupling between the output and input of the helix. The secondary and reflected electrons leave the collector on trajectories similar to those of the primaries, but in the reverse direction. The original collector pole-piece was shaped symmetrically, with a spreading magnetic field. To prevent back-streaming from the inside of the collector, a transverse field was produced in the area of the collector chamber by an asymmetry of the pole-piece. The returning electrons now follow different trajectories and are thereby prevented from leaving the collector again.

4.4 *Envelope*

The vacuum envelope in Fig. 11 is made in two sections: the bulb, which consists of concentric details of Corning 7056 glass and Kovar; and the stem, made of the same materials. The stem provides leads and connections to all elements and a tubulation for evacuating the tube, while the bulb provides the surfaces which support the helix and gun assemblies in precise alignment. There are two accurately located reference surfaces. One is the bore of the glass tubing which will enclose the helix; it is held to a diameter tolerance of ±0.2 mil and a straightness of 3 mils maximum camber. The other surface, which later locates the gun, is machined to the inside of the large Kovar detail and is held with respect to the bore of the glass tubing to a total indicator reading (TIR) of 1 mil. The external reference surfaces, used later to assemble the tube to the circuit, are machined on the outside of the Kovar detail to a concentricity of 1 mil TIR with respect to the inner reference surfaces.

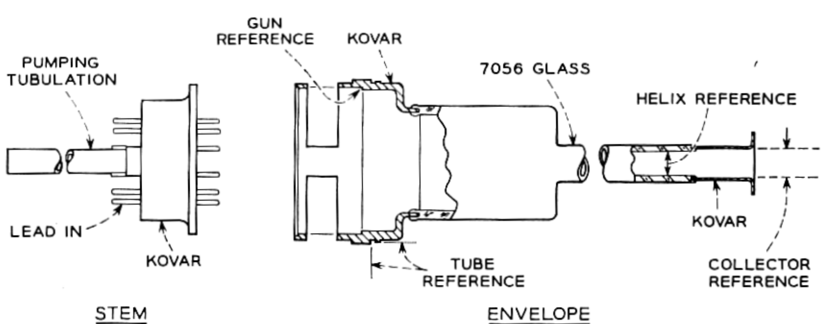

Fig. 11 — Envelope assembly with reference surfaces.

4.5 *The Focusing Circuit*

In a satellite system, weight is the controlling factor. The choice of the magnetic focusing circuit is intimately coupled to the problem of over-all system weight. In this connection, the solar plant with its supporting frame, the storage batteries, the regulator and the tube power supply contribute the majority of the weight. The average duty cycle of the tube is low, but because of long operating periods, the supply must be designed close to CW capacity. The solar plant, shielded for protection from particle radiation, and its support frame also add a considerable weight which is almost proportional to the power required by the TWT. To find the lightest over-all system, it was necessary to consider not only the weight of the tube package, but also the tube power requirements, or the tube efficiency. In the present satellite, several pounds must be allowed per watt of power supplied to the TWT.

The lightest focusing package would be a periodic permanent magnet circuit (PPM) which requires approximately one-half pound of magnetic material. The drawback is that it is relatively more difficult to focus the beam, which tends to scallop to a higher degree than in other magnetic circuits. This leads to higher beam interception and to a slightly higher collector voltage. It was estimated that this type of circuit might require 10 to 15 per cent more dc power than a straight field magnet.

From the viewpoint of life and efficiency, a straight field magnet (PM) would be the most desirable circuit since, with it, significant changes in cathode activity can be tolerated without degradation of the focusing. Its magnet weight of about 25 pounds is, however, prohibitive. A compromise is the single-reversal, permanent magnetic circuit (SRPM). It provides the excellence of focusing and high efficiency inherent in the PM design at a considerably lower weight. In common with the PM design, it has the disadvantage of some external magnetic leakage flux. The use of this design results in a magnet weight of 4 pounds, 3.5 pounds greater than the PPM circuit. On the other hand, the SRPM gives a power saving of about 1.5 watts over the PPM circuit. (See Table IV.)

TABLE IV — COMPARISON OF FOCUSING CIRCUITS

Focusing Circuit, Type	Magnet Weight, Pounds	Focus	Efficiency
PM	25	excellent; large leakage flux.	high
SRPM	4	excellent; some leakage flux.	high
PPM	0.5	more difficult; not for ultra-long life; no leakage flux.	lower

From these considerations, the SRPM was chosen for the Telstar satellite. It is comparatively new and has had little coverage in the literature.[5] In the form fully developed for this application, several objectionable qualities have been eliminated, and its operation is much better understood. A detailed description of this circuit and the improvements follows.

The weight of a magnet increases approximately with the third power of the length over which the field must be maintained if the length-to-diameter ratio is notably larger than one. By dividing the magnet in the middle and magnetizing the two halves so that their fields oppose each other, a weight saving of a factor of four can be realized. This is the result of a volume reduction of the leakage flux. The focusing of a traveling-wave tube in such a field should be a straightforward operation, provided the magnetic field can be reversed instantly. In practice, this is difficult to do unless a tapered reversal pole-piece is used between the two magnets, with a hole diameter only a small fraction of the scallop wavelength of the beam. In the present tube, the maximum diameter of the pencil type envelope is 0.319 inch and the measured scallop wavelength, 0.6 inch. The axial magnetic field of such a circuit is shown in Fig. 12. The reversal pole-piece used has a hole diameter of 0.35 inch; we can see that the reversal requires more than 0.6 inch. This means that a serious degradation of the beam focus will take place — the beam starts to scallop with a considerable increase in over-all diameter. Under these conditions, about 20 per cent of the beam current was intercepted by the helix in the reversal region.

A solution had to be found, since an interception of 20 per cent is intolerable. Before describing the solution, it is necessary to describe the behavior of a laminar beam in a uniform magnetic field which includes a small perturbation, as is shown in Fig. 13(a). The perturbation disturbs the laminar flow and forces the beam into a scallop mode. This is, however, reversible; and again observing Fig. 13(a), going from right to left, we can state: a scalloping beam in a uniform magnetic field can be forced back into laminar flow by a field perturbation of the right magnitude and the right phase with respect to the scallop. In Fig. 13(b), two perturbations of the same magnitude are placed a half-scallop wavelength apart. The beam begins to scallop at the first perturbation and is forced back into laminar flow at the second perturbation. Similarly, the second perturbation could be placed $(n + \frac{1}{2})\lambda_{sc}$ away. (If n is even, the perturbation has the same sign; if n is odd, the opposite sign.)* From now on, we will consider the field reversal as nothing but

* An analog can be found in a transmission line with discontinuities or mismatches, where the beam diameter would correspond to the VSWR and the per-

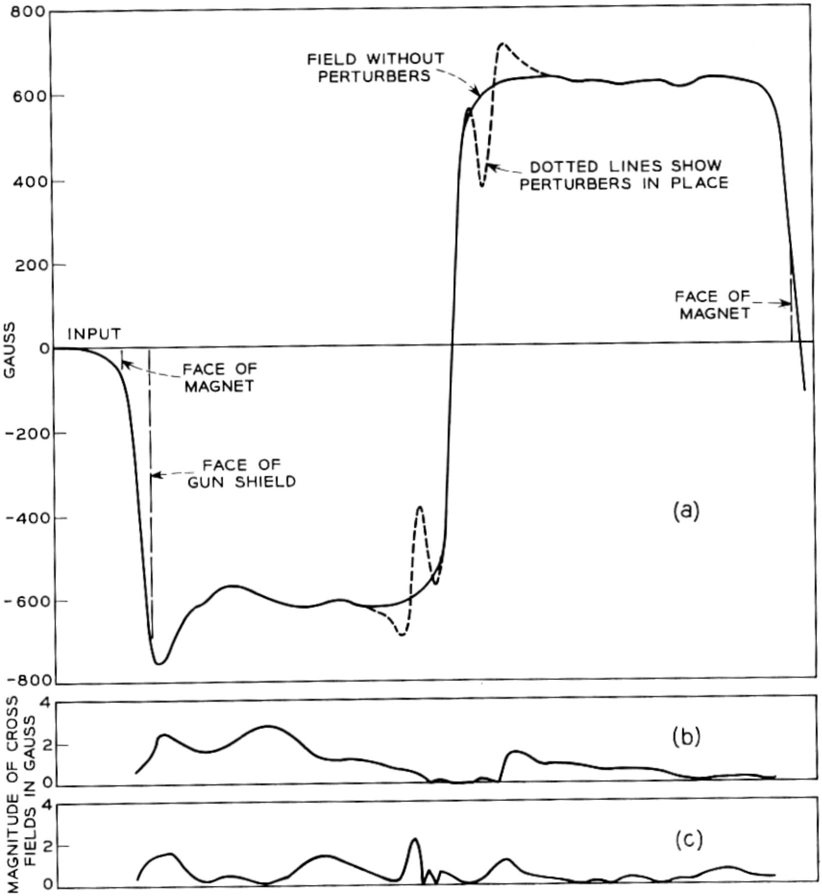

Fig. 12 — Magnetic fields in the single-reversal circuit: (a) axial magnetic field shown without perturbers, and modified field with magnetic perturbers in place; (b) horizontal cross fields; (c) vertical cross fields.

a large perturbation. Earlier SRPM circuits did not use perturbers to counteract the effect of the reversal plane. By mismatching the beam entrance from the gun to the uniform field, one can obtain a scalloping beam, which is shown in Fig. 13(c). If the phasing of the scallop is correct, it can counteract a further beam expansion at the reversal plane. This phasing or phase angle depends on the product of the distance between gun and reversal and the reciprocal of the beam velocity. The

turbations would represent the mismatches. The standing wave produced by one discontinuity can be canceled out by placing a second discontinuity of identical magnitude one-half wavelength away.

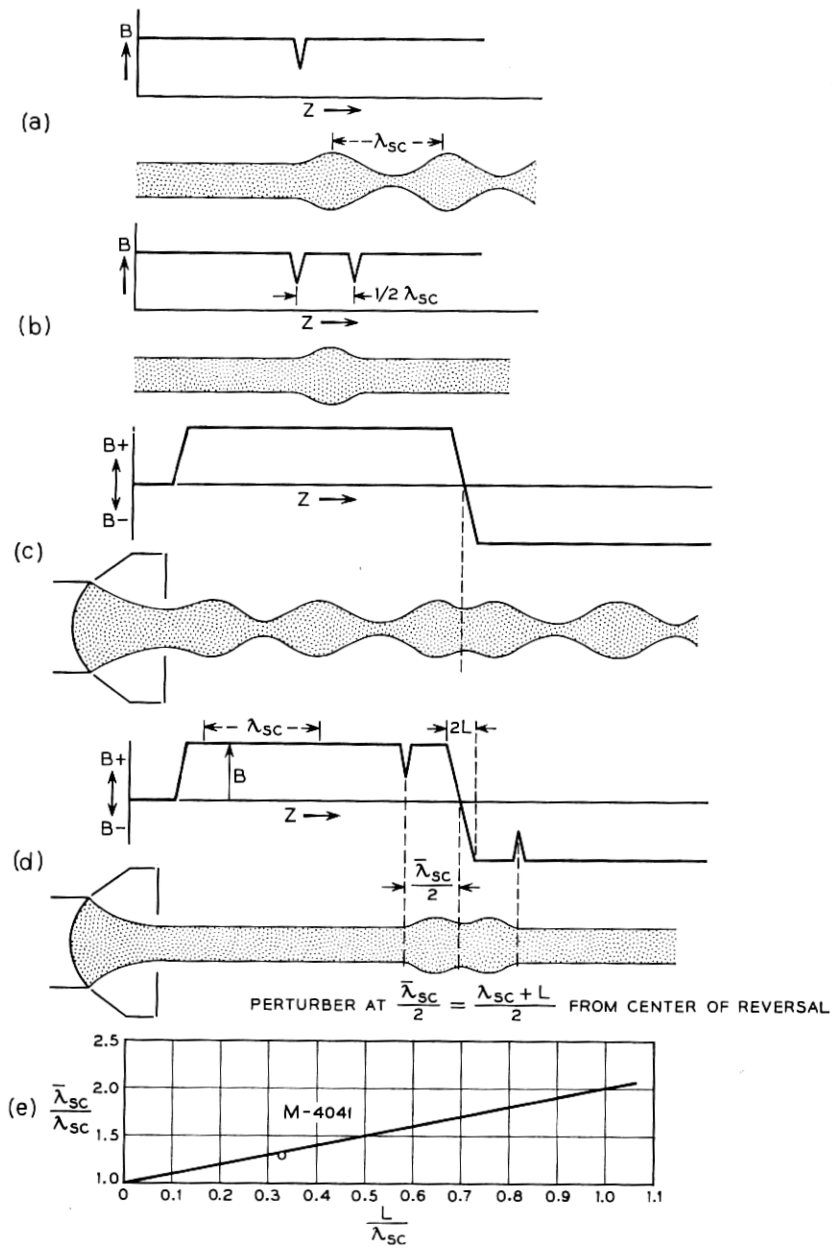

Fig. 13 — Focusing of beam with single-reversal circuit. (a) Laminar beam in uniform magnetic field with single perturbation. (b) Laminar beam in uniform magnetic field with two identical perturbations spaced by a half-scallop wavelength. (c) Focusing of beam through the reversal by pre-scalloping beam at start of magnetic field. (d) Focusing of beam through the reversal, using two magnetic perturbations, each spaced $\bar{\lambda}_{sc}/2$ from center plane. (e) Position of the perturbation computed for a linear field change in the reversal: normalized distance to the reversal plane is plotted vs the normalized length of the reversal. The measured value of the M4041 circuit is indicated and shows excellent agreement.

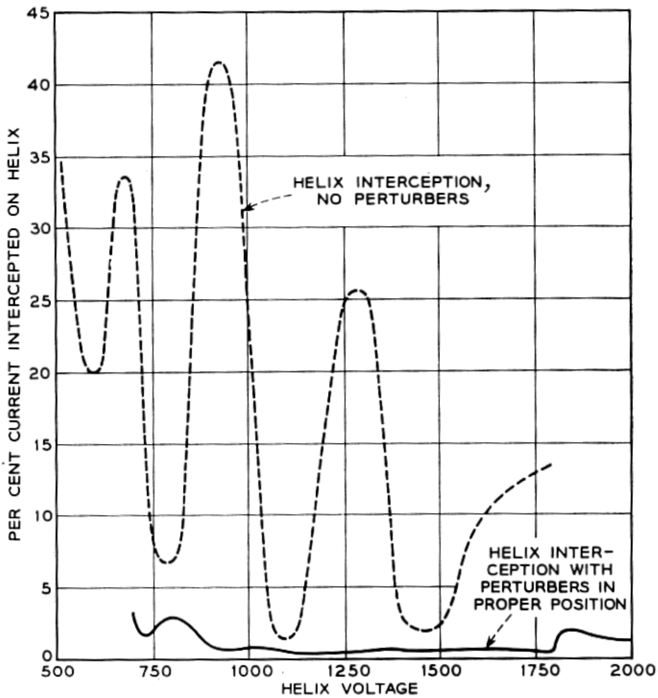

Fig. 14 — Single-reversal circuit, helix interception vs helix voltage.

helix interception measured on such a system is shown in Fig. 14 by the dotted line. The periodicity of the phasing between scallops and reversal is quite pronounced. The voltage passband is only 150 volts. To make the SRPM circuit usable, it is necessary to reduce the voltage dependence. This can be done by reducing the distance between the reversal plane and the point where the beam starts to scallop. For minimum scalloping, proper phasing is achieved with a distance of $(n + \frac{1}{2})\lambda_{cs}$ between perturbation and reversal. It is minimized for $n = -1$, which means that excess field would have to be placed at the reversal plane; this is inconsistent with the basic problem. For $n = 0$ and $n = -2$, we find two possible solutions. To obtain the smallest beam diameter at the reversal and least dependent on voltage, one should place one-half the perturbation, $\frac{1}{2}\lambda_{sc}$, before the reversal and one-half the perturbation, $\frac{1}{2}\lambda_{sc}$, after the reversal. This is shown diagrammatically in Fig. 13(d). In the reversal region, λ_{sc} is no longer constant; it depends on the magnetic field, which changes rapidly. The half-scallop wavelength measured from the center of the reversal and expressed as $\bar{\lambda}_{sc}/2$ can be calculated by integration. For the special case of a reversal with linear dependence of the magnetic field, $\bar{\lambda}_{sc}/2$ has been computed and the values are plotted versus the normalized length of the reversal in Fig. 13(e). The actual improvement in beam transmission and independence of beam voltage is shown in Fig. 14 with the solid line. If the interpretation is correct that the beam now enters and leaves the extended reversal in a laminar mode, one should be able to stack several of these reversals in succession. This has been demonstrated recently in a three-reversal circuit, where only a small degradation in the beam voltage passband had to be accepted. (The weight of the Alnico V magnets was further reduced from the 4 pounds for the SRPM to less than 1.5 pounds for the three-reversal circuit.)

The physical design of a focusing package depends to a large degree on how the RF connections to the tube are made. Since waveguide outputs were required by the system, RF connections were the first feature considered. Direct coupling of waveguide to helix would have required a penetration of the magnets by the waveguides, making for a bulkier and heavier package, and was therefore rejected. Coupled helix matches were considered, but also rejected, because the additional loss in the outputs would have reduced the over-all efficiency, though it would have been very easy to physically combine the SRPM with coupled helix input and output.

The solution finally adopted consisted of nonresonant coaxial couplers at both input and output. A sketch is shown in Fig. 15. The coaxial coupler has two coaxial lines connected symmetrically to the reentrance: one is a feed; the other is a line with a movable short circuit, the position of which determines the impedance of the coupler. These coaxial couplers have been made small enough in diameter to be inserted into a series of uniformly spaced field straightener rings which are needed to reduce the magnetic cross fields on the axis of the tube. These field straightener disks are made of permalloy 45 and are used throughout the length of the magnetic field. Geometrically, it is important that they be held square to the axis of the beam. The resulting crossfields are shown at the bottom of Fig. 12. Because waveguide inputs and outputs were required, a further transducer had to be provided. It consists of a standard coaxial antenna transducer with a specially shaped dielectric cylinder to support the center conductor and give the necessary impedance transform. The over-all cold match from waveguide to helix was quite good over a 10 per cent band, with a VSWR of less than 1.2.

The focusing circuit described is not magnetically shielded. The field has a rotational symmetry about the axis of the circuit. Some knowledge

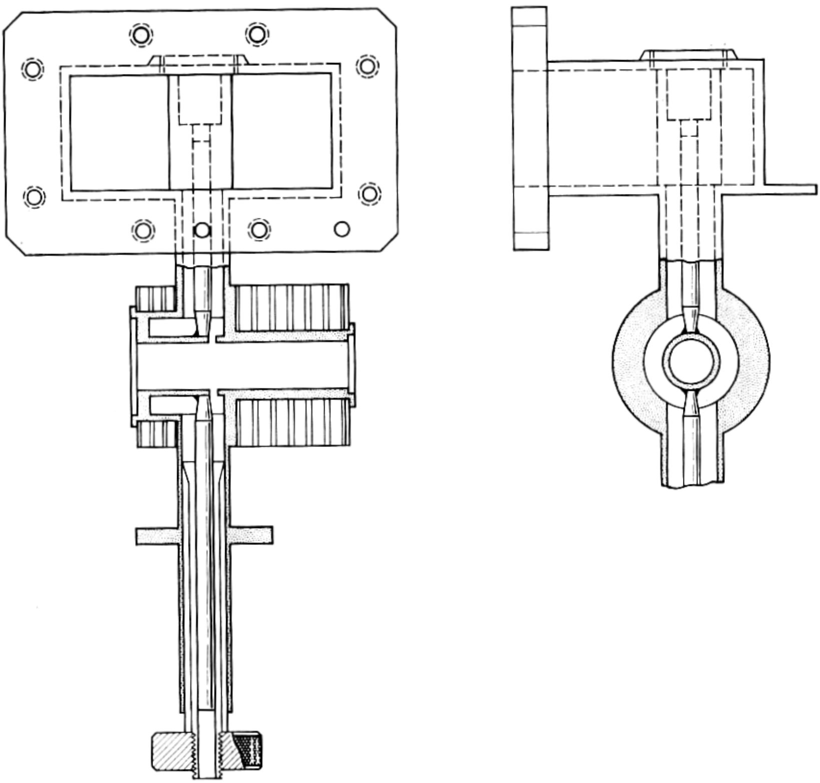

Fig. 15 — Nonresonant coaxial helix coupler with matching stub and transition to waveguide.

of the leakage flux was needed in order to evaluate its effects on other components in the tightly packaged satellite. The external fields are shown in a plane through this axis in Fig. 16. Little interference was experienced, except in the case of the telemetry package, which had to be shielded with permalloy 45.

V. PACKAGED DESIGN

The packaged traveling-wave tube consists of a tube with its magnetic circuit and RF couplers joined together to form a compact unit. This arrangement has many advantages to recommend it for satellite use. One of these is the optimization of tube characteristics by fine-grained adjustment, at the factory, of the relationship of the magnetic

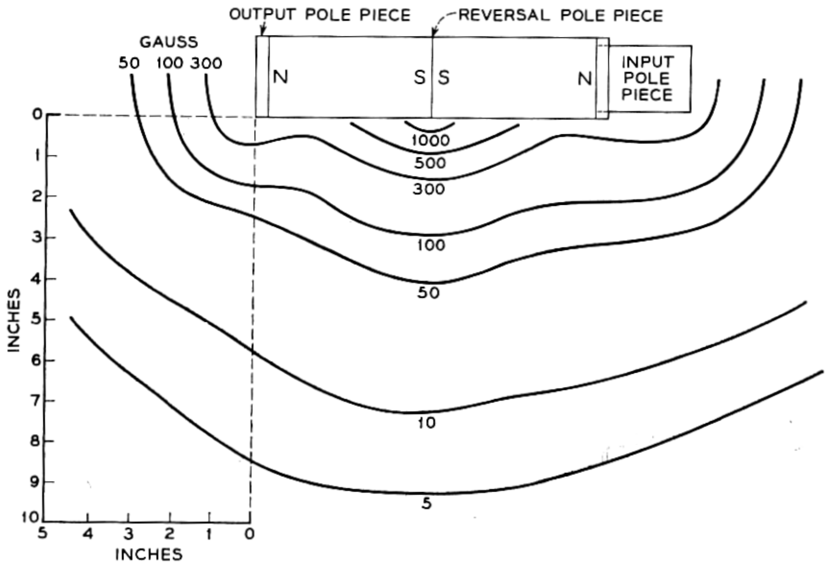

Fig. 16 — External magnetic leakage field of the single-reversal circuit.

field and RF matching sections to the tube. Another is the greater latitude permissible in designing the package to (a) ensure the stability of this relationship for the full life of the unit, (b) provide the ruggedness and support needed to protect the unit against shock and vibration, (c) provide an enclosure as protection against handling and environmental conditions, and finally, (d) provide the most elementary and rugged connections for securing the unit in the repeater.

Fig. 17 shows a graphical cross section of the package. All elements are enclosed by, or mounted on, an aluminum tubular housing which forms the "backbone" of the structure. The tube is a pencil-like figure through the center of the unit. Between it and the inner wall of the housing are two Alnico V magnets and an array of field straighteners. The magnetic circuit is completed by a pole-piece at each end of the magnets and a Permendur septum with its perturber bushings separating the magnets. Mechanical support is given to the tube by means of the pole-pieces at each end, and by contact with two sets of four pins each which cradle the tube at points substantially equidistant between the end supports. Electrical connections are made to the elements by silicone rubber encapsulated leads at the gun end and a single lead at the collector end. Waveguide-to-coaxial transitions are shown at the respective input and output coupling points on the helix. An RF filter

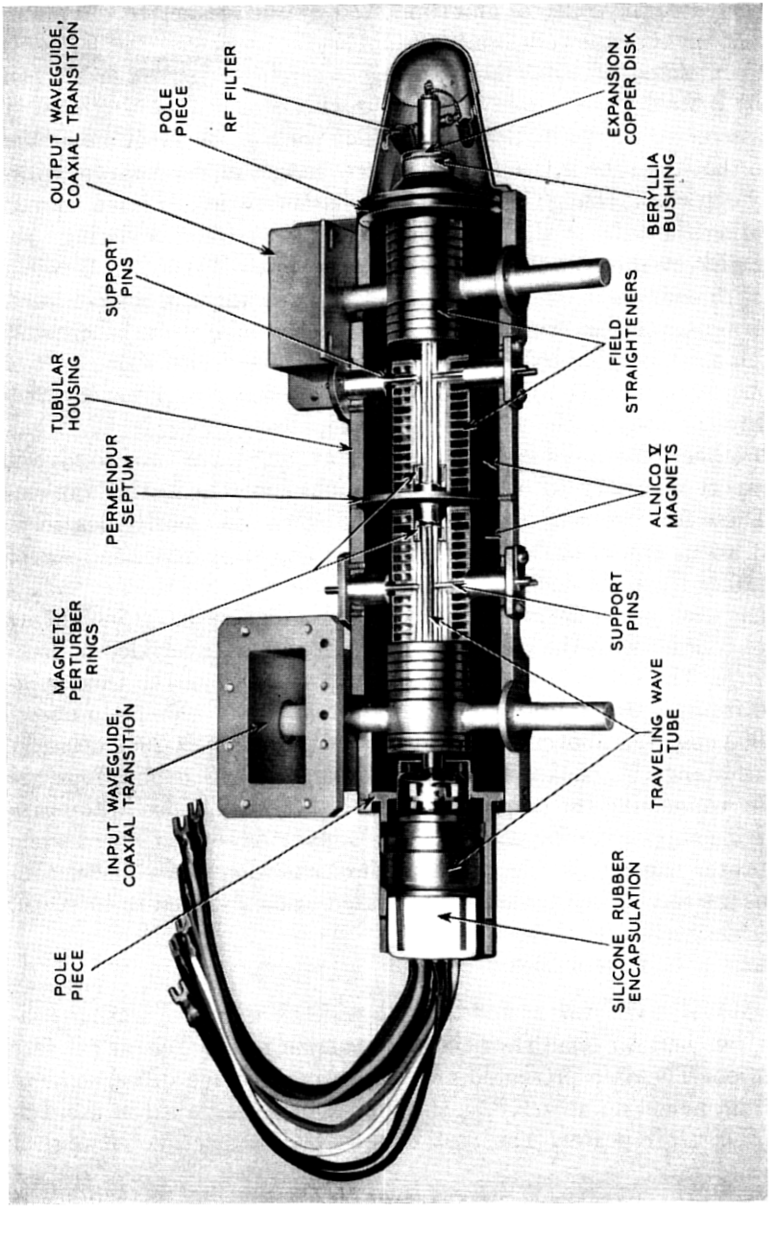

Fig. 17 — Cross-section view of completed amplifier package.

is connected to the collector and supported by the protective aluminum cone that encloses the collector.

The completed amplifier is a package wherein each part is kept in place by a weld or by a screw, and also with cement; the unit cannot be disassembled except by destruction. The package, in effect, floats the tube so that the tube is free to move with changes in temperature without any detectable change in its electrical characteristics. This is achieved by welding the tube to the package at the gun end and soldering to a copper disk at the collector end. The disk, which is 0.005 inch thick, flexes with changes in length brought about by changes in temperature. Furthermore, the disk, which is a part of a subassembly—the other parts of which are a beryllia bushing and a copper cone — also forms part of a thermal path through which some ten watts of collector power is transmitted to the body of the package and dissipated.

Two other constraints are put on the traveling-wave tube to give it the support necessary to resist the vibrations inherent in this application. These are two sets of four aluminum pins, previously identified, located about equidistant between the two end supports. Each set of pins cradles the 0.290-inch diameter glass tubing of the tube in such a way that each pin is deflected laterally approximately 0.002 inch at its point of contact with the glass, to ensure support over a wide temperature range. The result is that the resonant frequency of the tube is increased from an unacceptable value of approximately 700 cps to one of over 3000 cps, well above the specification requirement of 2000 cps.

In installing the package in the repeater, the RF connections are made by connecting the amplifier flanges to the waveguides in the canister giving support to the package. This support is supplemented when the repeater canister is filled with polyurethane foam. Electrical connections are established by flexible insulated leads attached to the tube.

VI. ELECTRICAL PERFORMANCE

The M4041 TWT was tested under a wide variety of operating conditions, but here we shall restrict the discussion to the Telstar satellite application. The data presented are taken from average tubes, some of them from model number KP24, the tube actually installed in the Telstar spacecraft repeater. The best values attained are quoted only if so indicated.

6.1 *The Tube Gain*

The tube gain for KP24 is plotted in Fig. 18 versus helix voltage. The low-level gain is 47 db and occurs at 1380 volts. Here, the maximum

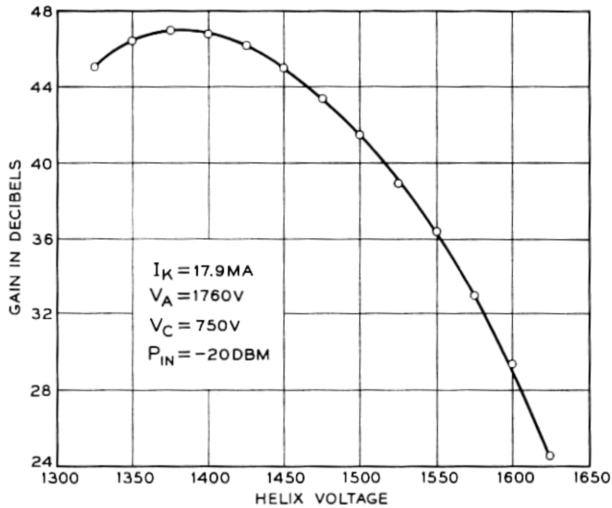

Fig. 18 — Small-signal gain vs helix voltage for KP24 installed in its final circuit.

power output and efficiency are low; to improve both, the tube is run at overvoltage. For the satellite repeater the operating point was chosen at 1520 volts. This point is indicated in the figure and shows a low level gain of 39 db. In Fig. 19 the power output and gain for this same tube are shown for a range of helix overvoltages. The tube was originally designed for an input drive of 0 dbm. Late in the development, a compromise had to be made to permit satisfactory two-signal operation, and to allow for a possible ±3 per cent voltage drift on all dc voltages. The gain versus frequency is shown in Fig. 20 for three different operating conditions. At the voltage for maximum low-level gain, the peak occurs at about 4.1 gc. Raising the voltage to the overvoltage condition lowers the frequency at which the maximum gain occurs, and thereby increases the gain slope; however, when the tube is driven into saturation, the gain drops off but the slope is greatly reduced. With an input level of −3 dbm, the gain slope is 0.5 db over the 4.0–4.2-gc band.

The TWT is not terminated by a well-matched load. The filters and antenna present somewhat of a mismatch. Gain measurements were performed with the tube operating into an attenuator followed by a sliding short circuit. For each attenuator setting, there were periodic positions of the short circuit for which the gain could be enhanced or reduced. In Fig. 21 the maximum and minimum values of the gain are plotted versus twice the attenuator setting, which is equal to the return loss of this load. The gain is not only periodic with the position of the

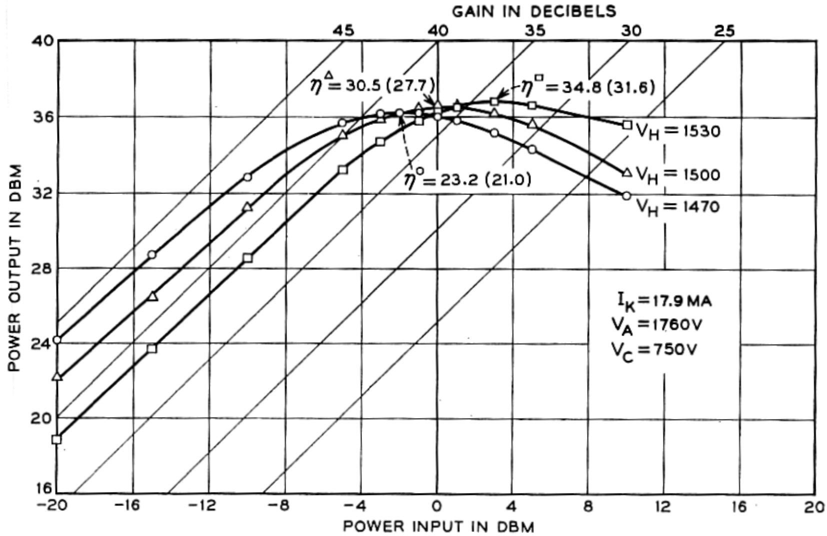

Fig. 19 — Output power vs input power with helix voltage as parameter for KP24. Depressed collector efficiencies are shown at maximum power points; overall efficiencies in brackets include heater power.

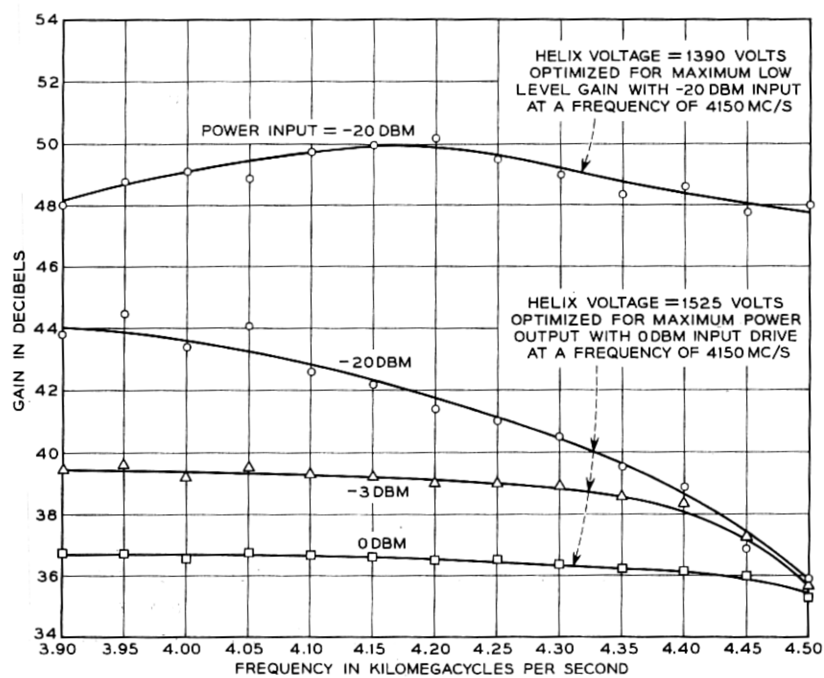

Fig. 20 — Amplifier gain vs frequency for different input power levels.

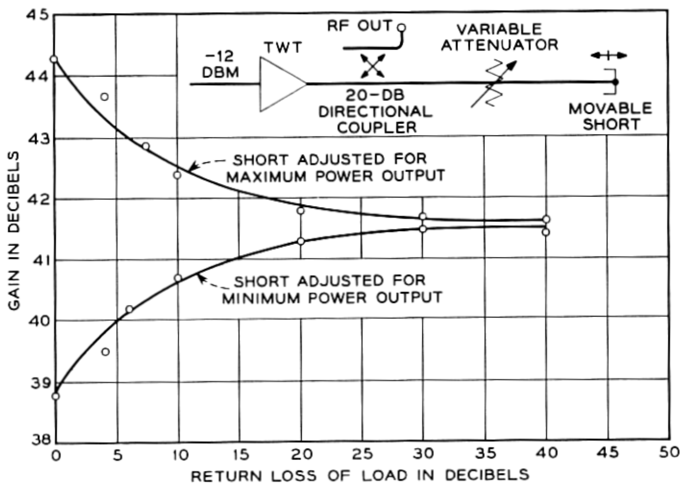

Fig. 21 — Effect of load mismatch on low level amplifier gain.

short circuit, but also with frequency, impressing a ripple on the gain curve. The frequency band between two maxima depends upon the electrical distance between the load and the TWT attenuator. In the region of saturation, these gain variations are considerably reduced.

6.2 *Power Output and Efficiency*

The power output and efficiency at 4.17 gc were studied as a function of the input drive and beam currents. The results are shown in Fig. 22. At each point the helix voltage was optimized and the collector depressed until the highest efficiency was obtained. It is interesting to note that the same TWT can maintain efficiencies of over 30 per cent for output powers from 0.3 to 10 watts. It must be remembered that the efficiency falls off much more rapidly when the helix and collector voltage have been set and only the input drive is varied. A curve of this type is shown for 17 ma as a dotted line in Fig. 22.

The highest efficiency measured with this tube type was 43 per cent at the output power level of 5.4 watts, giving an over-all efficiency of 38.5 per cent. Several other models reached 40 per cent, but most of the tubes gave approximately 38 per cent. These efficiencies look attractive; however, they are not realistic for actual satellite conditions, since they can be achieved only with high helix and accelerator interception not permissible in a long-life tube. From our life tests, we know that throughout the life of TWT's, the helix and accelerator interceptions

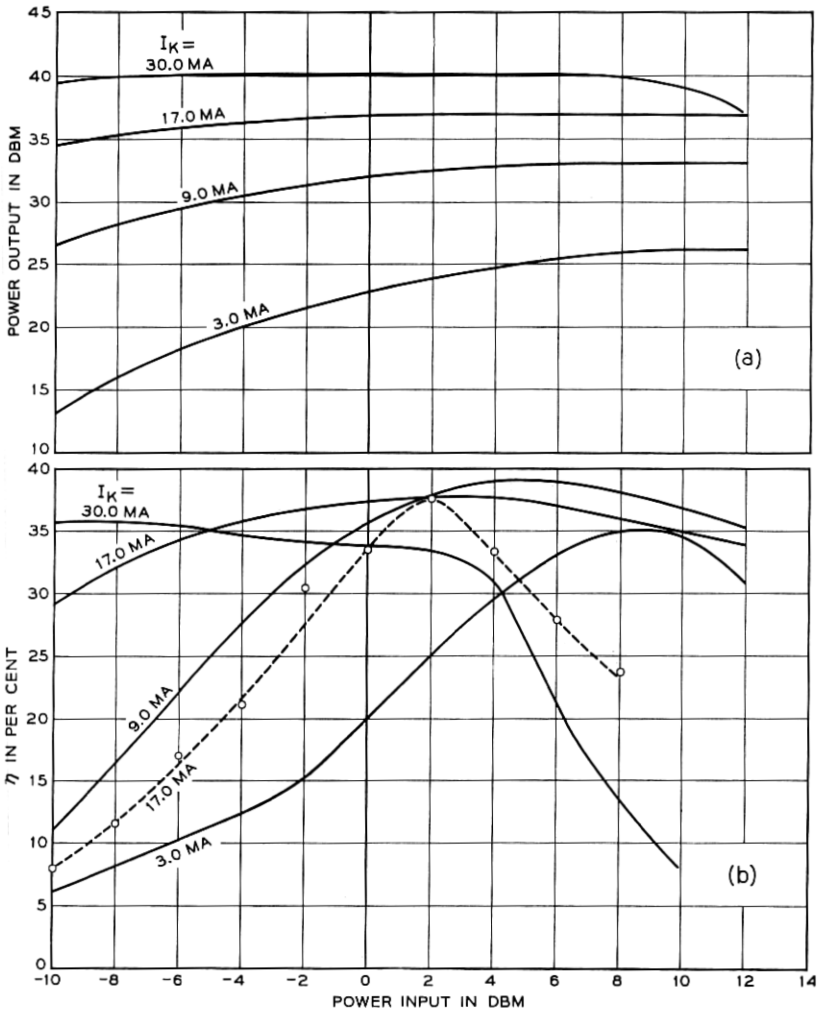

Fig. 22 — (a) Maximum saturated power vs input drive with cathode current as parameter. At each point, the helix voltage is optimized to obtain the maximum power output. (b) For each of the points in (a), the collector voltage is also optimized to achieve the maximum depressed collector efficiency. This efficiency is then plotted vs input drive. Operation with fixed helix and collector voltage is shown for comparison at 17 ma with a dashed line (helix and collector were optimized for highest efficiency with an input drive of +2 dbm).

increase and might eventually be the ultimate cause for tube failure; for this reason, they should be kept as low as possible when the tube is finally installed.

Fig. 23(a) shows both accelerator and helix interception at the oper-

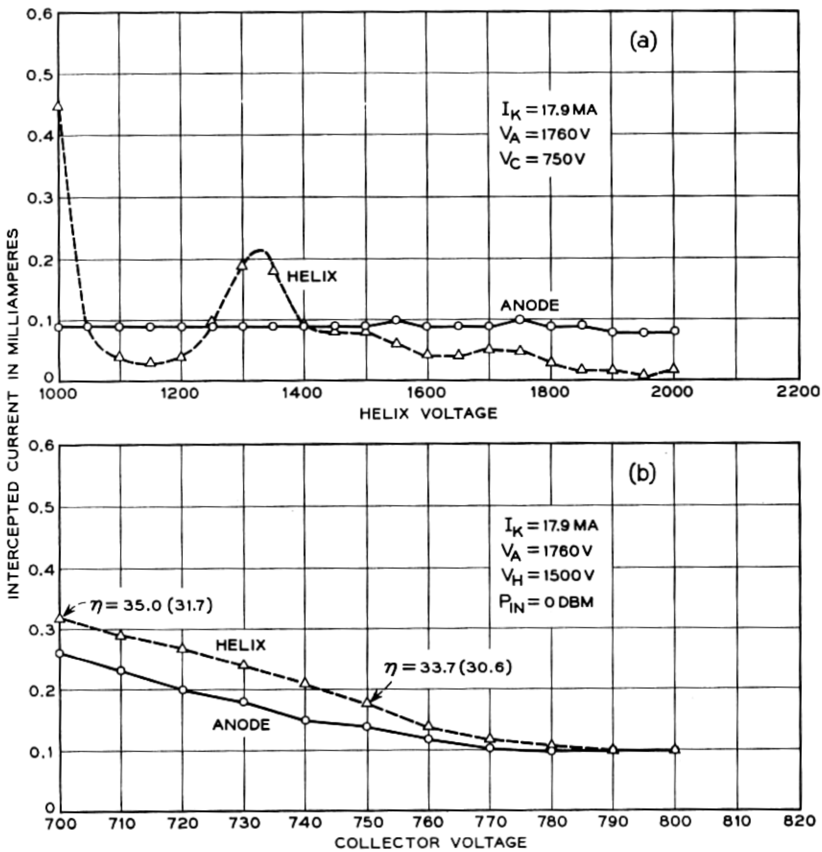

Fig. 23 — Beam current intercepted on helix and anode for KP24 in final package: (a) interception vs helix voltage without RF drive, (b) interception vs collector voltage with RF drive at saturation. Efficiencies, depressed collector and over-all (in brackets), are also shown at two points.

ating point without RF drive as a function of the helix voltage. These data stem from KP24 shortly before delivery for incorporation in the satellite with about 2800 hours of life. The accelerator interception was originally less, but has already climbed from its original value. This has been observed previously with many M1789 tubes on life tests. The hump in the helix interception at 1300 volts is not standard and is most likely caused by residual cross-fields. In Fig. 23(b), helix and accelerator interception is plotted versus collector voltage at full RF drive. Decreasing the collector voltage improves the efficiency, but the interception current exceeds the limit set for long life performance.

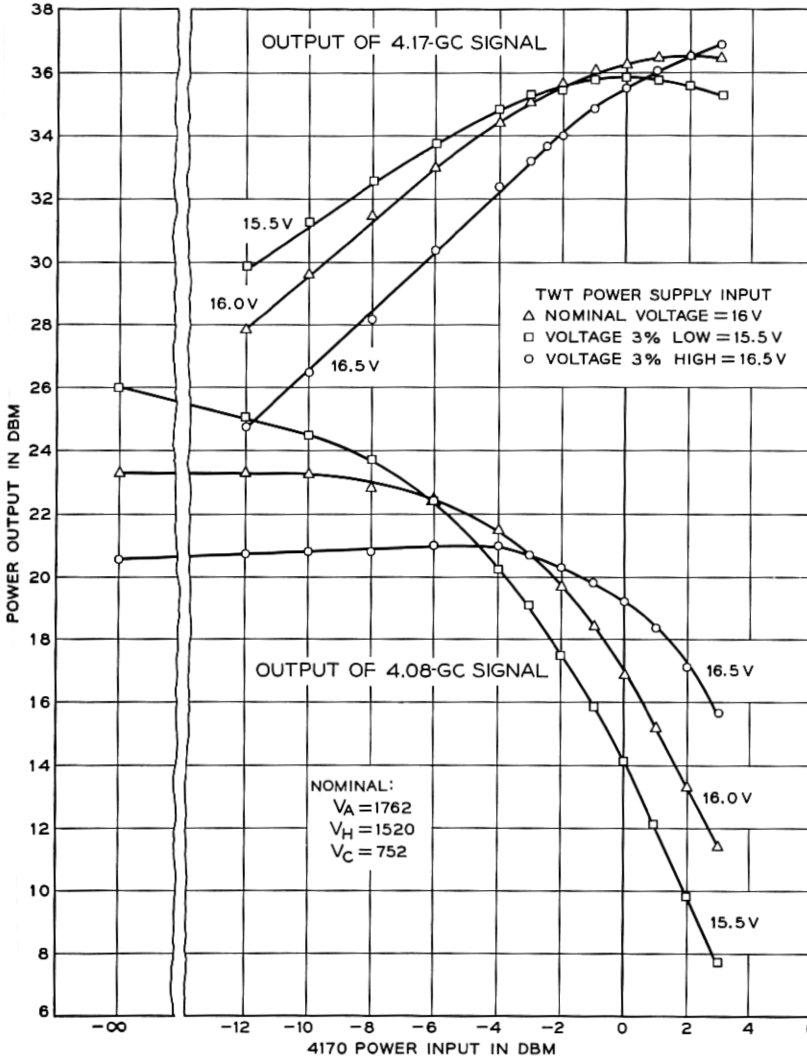

Fig. 24 — Two-signal operation of KP24 in final package. The 4.08-gc beacon input is held constant at −12 dbm as the 4.17-gc signal is varied. Power output is shown for both frequencies with the input voltage to the TWT power supply as a parameter.

6.3 *Two-Signal Operation*

After each tube had been tested and approved for flight, a two-signal test was made to determine the actual operating point (V_{helix}). In the satellite, the tube simultaneously amplifies the beacon and the communication signal. The beacon input is constant at 4.08 gc and −12 dbm. The signal at 4.17 gc has a variable level from −12 to 0 dbm. As the signal level increases, the output of the beacon drops off because the tube is driven into saturation. The beacon and signal outputs are shown in Fig. 24 as a function of the signal level. System limitations were imposed on the operating point to prevent envelope oscillation within the feedback loop of the converter. The limit imposed was that the beacon could not drop off more than 1 db if the signal level were raised by 1 db; this represents a 45° slope on the beacon output. At the nominal input voltage to the dc-to-dc converter, this occurs at −2.5 dbm. This, then, is the operating point chosen for the TWT. The efficiencies, depressed collector and over-all, have been computed for the −2.5- and 0-dbm input levels for the three cases of undervoltage, nominal and overvoltage. These figures are shown in Table V. To satisfy this late system requirement, a noticeable degradation in efficiency had to be accepted to guarantee a stable two-signal operation.

6.4 *AM-to-PM Conversion*

Instead of measuring the AM-to-PM conversion directly, a method described by Mr. H. L. MacDowell[6] has been used. Two signals of much different amplitude and frequency are amplified in the TWT. The intermodulation products are measured and the AM-to-PM conversion computed. These values are all plotted in Fig. 25 together with the output power against the input drive. The curves are from measurements made with different input voltages to the satellite dc-to-dc converter, for the nominal voltage of 16 volts, and for 16 volts ± 3 per cent. These are estimated limits of regulation throughout the life of the satellite. The maximum of 4°/db measured with 3 per cent overvoltage is less than the value encountered with the TH relay tube under similar drive conditions.

TABLE V — COMPUTED EFFICIENCIES FOR KP24 WITH TWO-SIGNAL OPERATION

Input η	−2.5 dbm		0 dbm	
	Depressed	Over-All	Depressed	Over-All
−3%	28.0	25.2	29.0	26.2
Nominal	27.0	24.4	32.0	29.0
+3%	17.3	15.7	24.2	22.0

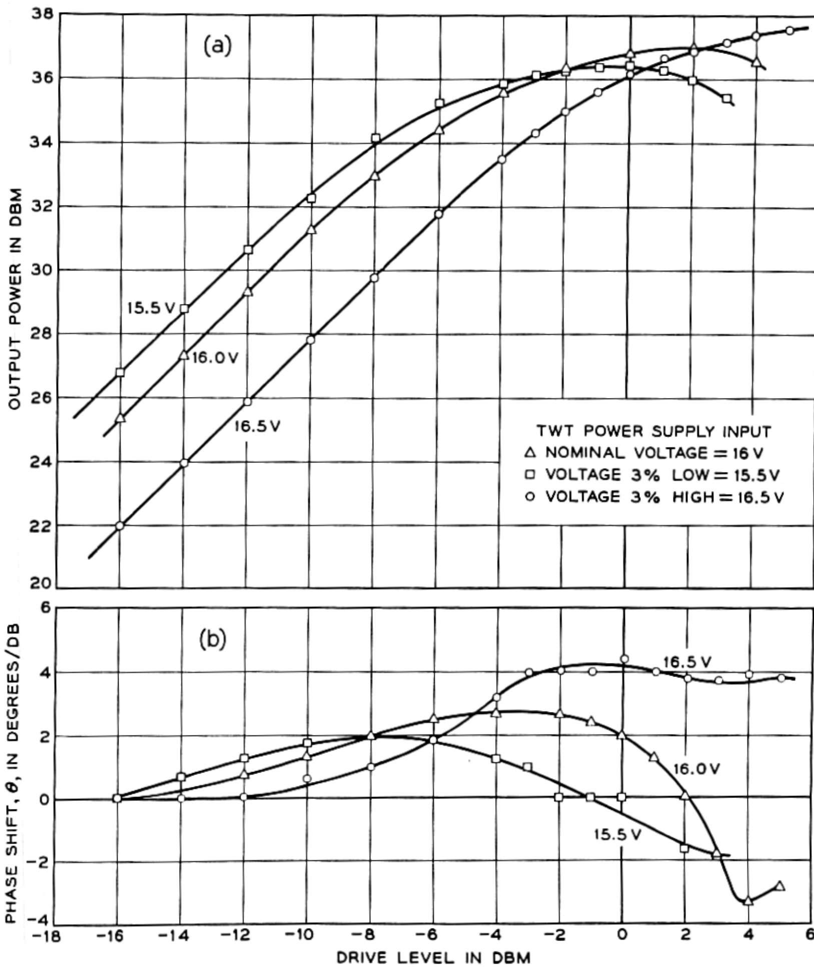

Fig. 25 — AM to PM conversion: (a) power output vs input drive, (b) phase shift vs input drive at 4.1 gc.

VII. MECHANICAL CAPABILITY

Mechanical capability, in the sense used here, is limited to the conditions the amplifier, or its components, have been shown to withstand by actual tests, and not the ultimate that it can withstand. In all cases, tests were defined to impose conditions more severe than were likely to be encountered in preparation for or in actual satellite flight.

Before a unit is passed for satellite use, it is subjected to the following vibration tests: 15-50-15 cps at 0.3 inch displacement (3.5-38-3.5 g), 50-100-50 cps at 20 g, 100-2000-1000 cps at 10 g.

During development, typical packages were subjected to mechanical and thermal tests as follows:

(1) Thermal cycle, three packages, heater off: $-30°F$ to $+105°F$ to $-30°F$.

(2) Thermal cycle, one package, heater operated on and off: $+15°F$ to 90°F to 15°F.

(3) Thermal cycle, six guns after 28,000 to 38,000 on-off cycles of heater: $-30°F$ to 150°F to $-30°F$.

(4) Vibration tested four guns after 11,000 on-off cycles of heater: 15–2000 cps from 4–20 g.

(5) Shock tested four guns after 11,000 on-off cycles of heater: three to 400 g without harm; one to destruction at 1600 g.

(6) Vibration check of five heater-cathode structures: 100-3000 cps at 40 g.

(7) Cycled 31 heaters in guns made exactly as in tube from 4000 to 44,000 on-off cycles with no losses. Fourteen were opened, carefully dissected and examined for deterioration at cathode and heater coatings. None was found. Seventeen still on cycling life.

(8) Two heaters same as item (7) put on continuous life. Satisfactory after 6100 hours and still on.

(9) Vibration (to remove foreign particles) applied to all guns and helices during fabrication: 50-2000-50 cps at 20 g.

VIII. BUILDING THE FINAL TUBES FOR SATELLITE USE

8.1 *General Cleaning and Processing Procedure*

To ensure an end product free of contamination and mechanical defects, procedures and processes are spelled out in great detail. All operations are inspected upon completion, and these inspections are supplemented by inspection of subassemblies. Assembly is done under pressurized hoods in areas where the atmosphere is controlled and personnel traffic is minimized. A general listing of these activities is:

(1) All piece parts and subassemblies are inspected for defects as received and again at several points in the assembly procedure.

(2) All subassemblies are inspected for particles, either airborne or by-products of fabrication, and particles are removed by hand or vacuum.

(3) All parts and subassemblies must pass an atomizer test, which is a very sensitive indicator of surface cleanliness, just prior to assembly.

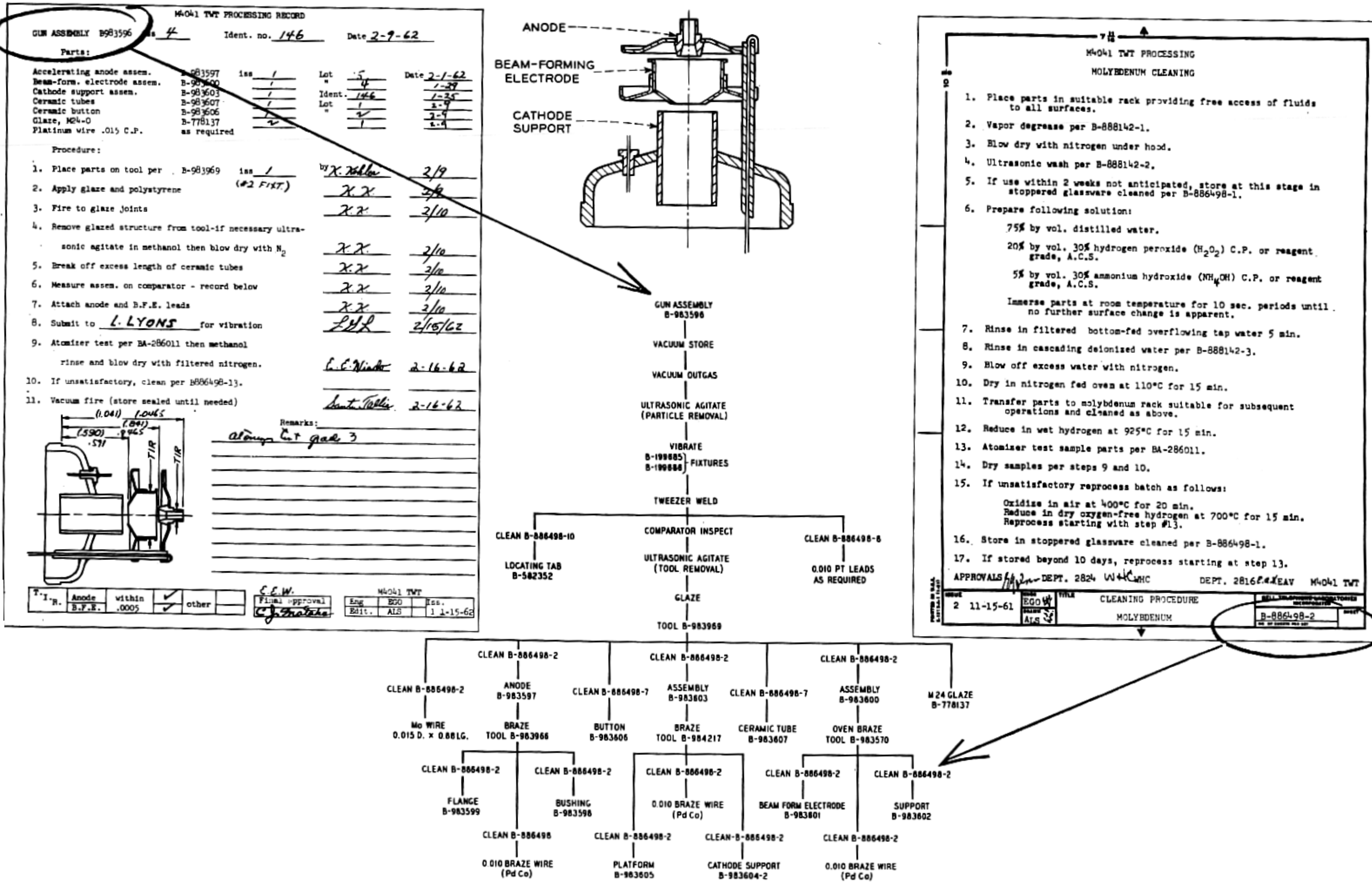

Fig. 26 — Typical flow chart of a subassembly procedure, with detailed specifications for a cleaning operation and the check sheet used to insure care-

(4) Cleaning operations:
   (a) trichloroethylene wash — liquid or a vapor (all metal parts)
   (b) hydrogen reduction (all metal parts)
   (c) air firing (all ceramics)
   (d) ultrasonic agitation in detergent or solvents (all parts and subassemblies)
   (e) cascade rinsing in deionized water — rinse used after operation (d)
   (f) chemically reactive immersion (some metal parts: i.e., cathode surface, gun parts)
   (g) oxidation-reduction (gun parts)
   (h) liquid honing (glass stem leads, cathode surface)
   (i) vacuum outgassing (all subassemblies)

(5) Storage

All cleaned parts are stored in containers which have passed an atomizer test. The limit of storage is ten days, after which they are automatically recleaned. The coated cathode is the only assembly that departs from this procedure; if held ten days, it is rejected.

(6) All fixtures and tools used in assembly are cleaned to the same standards as the parts.

(7) All vacuum outgassing containers are equipped with filters to entrap airborne particles when the container is open to air.

(8) Extraordinary "clean room" procedures are followed, in that assembly is done under a protective pressure hood in a dust-free temperature- and humidity-controlled room located within a similarly controlled area. The movement of personnel in the inner room is restricted to essentials.

The meticulous cleaning and assembly procedure is guided by a flow chart for the tube as a whole and subordinately for each subassembly. Each cleaning process is separately listed. This system is illustrated in Fig. 26 with a flow chart for the gun subassembly and the cleaning procedure for molybdenum. To prevent omission of any step, check lists are used for each individual component, small or large.

8.2 *Processing on the Pump Station*

To check for subsequent changes, the tube undergoes an additional inspection before it is sealed on the pump station. A similarly designed station was used for the M1789 TWT. This system uses a roughing pump, followed by an oil diffusion pump and two liquid N_2 cold traps. After a vacuum of 1×10^{-5} mm Hg is obtained, the tube is baked at slightly less than 450°C for a minimum of 16 hours. Subsequently, the helix is outgassed at 650°C by passing current through it, and the collector is baked in a small oven to higher temperatures to make sure all surfaces which are directly exposed to the beam have been freed from occluded gases. After the tube is thoroughly outgassed, the Ni-Zr cathode is broken down at a temperature of 1000°C for 4 minutes. Then a maximum of 500 volts is applied and a beam of about 2.3 ma drawn to helix and accelerator. The cathode temperature is gradually lowered, provided space-charge-limited emission can be maintained. The TTW is then sealed off.

8.3 *Preaging*

The TWT is now inserted into a focusing circuit and preaged. The cathode nickel is fairly inactive, and it takes the tube about one-half to one hour until full emission (20 ma) can be drawn with the nominal accelerator voltage, at a temperature of 900°C. For the next few hours the tube is permitted to age in before full RF drive is applied. Most of the tubes remain for about 100 hours on preaging. The tube is now removed from the aging circuit; the leads are attached and based in a silastic rubber cap. Thorough mechanical inspection follows, to eliminate further processing of a defective tube.

8.4 *RF Testing*

The tube is now ready to be checked for its RF performance. Thorough tests are made on all parameters to determine whether the tube passes the limits set for satellite use. At this point a considerable number of tubes are already marked "nonfly." The highest number of rejections are caused by a poor hot output match and an associated tendency to oscillate when the tube is short-circuit terminated. Some of these tubes, however, continue through this testing and are used for life studies.

8.5 *Aging and Life Tests*

All of the care in designing and building this tube is of little value if confidence in its life capability is not established. The aging-in phase is the only period in which the tube can be observed. Various observed characteristics can be used as indications of the later behavior and give confidence in the long-life abilities and reliability by eliminating poor or questionable tubes. An extremely sensitive method, the dip test,[7] was selected to measure relative changes in the average cathode work function, more commonly known as the "activity level." This test is initiated by a precisely timed interruption of the heater power to the tube under study while observing changes in cathode current, particularly the maximum drop which occurs shortly after the heater power is re-

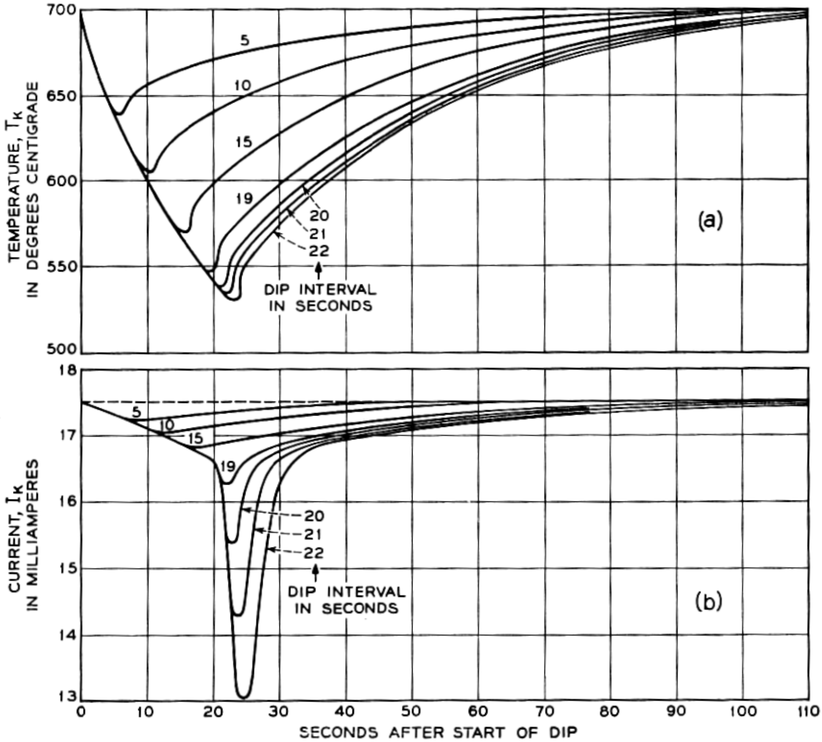

Fig. 27 — Dip test of typical M4041: (a) cathode temperature measured with built-in thermocouple during dip test, with dip interval as parameter; (b) corresponding cathode current.

stored to the tube. Fig. 27 shows composite plots of cathode currents and temperature, as measured with a built-in thermocouple, versus time. The sensitivity of the test can be increased by lengthening the timed dip interval and is shown for several values. This test basically gives a measure of how far below the set operating point the emission of the cathode changes from space charge to temperature limitation. The temperature at which the emission becomes temperature-limited changes downward in early life, reaches a minimum after several thousand hours, and eventually starts to climb again, until at the end of life it reaches the operating temperature of the cathode.

The shape of the dip curve reveals a further quality of the cathode, the uniformity of work function over the surface. A dip which breaks sharply indicates uniformity; one which is well rounded, a geometrical spread of different work function. These two dip curve types are shown in Fig. 28.

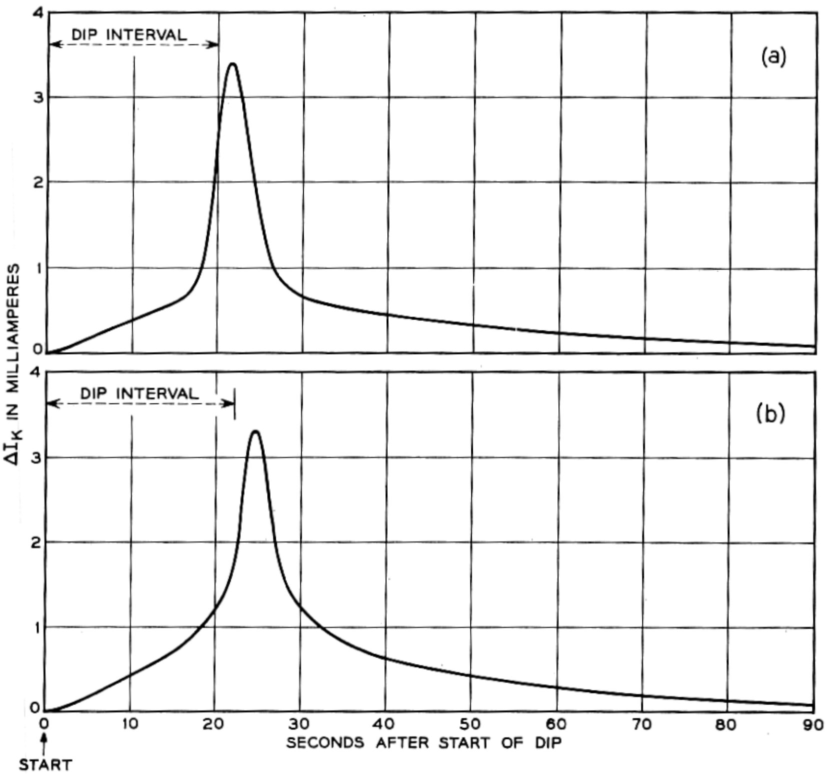

Fig. 28 — Shapes for cathode current dip curves: (a) uniform emission — uniform work function, (b) nonuniform emission caused by work function which is irregular throughout the cathode surface.

The tubes which have gone through the RF testing are now ready for the aging phase. They are installed in an aging rack. Each tube is driven by an individual high-reliability power supply, which has a large number of safety controls to prevent damage to the tube in case of certain failures. The RF drive power to each tube is also individually controlled. The cathode temperature is set at about 750°C and the tubes adjusted for 4 watts output. The tubes are tested daily and their temperature and cathode current dips recorded on a strip chart. When the activity has improved and the 20-second dip no longer exceeds 2 ma, the cathode temperature is lowered. After 1000 hours of aging, the best tubes are selected for possible fly candidates. At this point, the tubes are removed from life test and taken out of their packages to be given the most thorough mechanical inspection. The good tubes are then installed in selected focusing circuits. A series of electrical tests follows to assure tube performance. The repackaged tubes, with their own circuits, are installed once more in the life area. Activity and stability of interception currents were especially observed. Even at this point it is found that the helix and accelerator interception change slightly with improving activity levels. This phase of the aging period extends over several hundred hours.

So far the tube was approved only for continuous operation. The next phase consisted of a switched life test. The voltages were switched on and off to simulate the actual satellite conditions: 3 minutes heater warmup, 15 minutes operation, and 12 minutes cool-off. At this point, an interesting phenomenon was observed. The cathode current climbed continuously at a very small rate as switching cycles were accumulated. This was first attributed to changes in mechanical tolerances due to the heat cycling, but precise measurements of the gun dimensions discredited this theory. The change had to be attributed to changes of the cathode itself. At the same time, it was discovered that test diodes in an entirely different vehicle displayed a similar behavior. Changes of 2 per cent were observed in cathode current and gun perveance over a period of 1000 switching cycles. For this reason, all fly tubes were cycled for an excess of 1000 cycles, when the time schedule permitted.

8.6 *Final Sealup of Tube and Circuit*

At the point where a tube and its focusing circuit had proven themselves by performance, the two were mated together, a process which is irreversible, since neither tube nor circuit can be recovered. The final steps in this operation are outlined below. First, the tube is rotated and input, as well as output, pole-pieces are slightly readjusted to obtain best focus at an input level of 0 dbm. The waveguide and coaxial transitions are moved longitudinally, and the coaxial plungers trimmed to obtain a match at input and output optimized for satellite performance. The unit is now ready for final packaging. It is positioned so that the central line of the tube is vertical and the gun end is up. The tube is gently lifted off its seat about 0.02 inch and allowed to fall back into position, after which it is lifted and held 1 mil off its seat, at which point it is locked in place by soldering the collector carefully to its collector support. The one-mil gap precludes the possibility of a bend in the tube as a result of pole-piece displacement during adjustment, or by the non-squareness of the reference surface, either on the tube or on the circuit. A bend would serve to bind the tube in its supports so that it would resist "falling" into place. As a result, the tube is fastened and supported in a free and unstressed state. All adjustments are pinned or locked. An epoxy resin is used as an additional bond so that all individual parts (housing, magnets, pole-pieces, waveguide tube, etc.) are locked together into an inseparable integrated unit. The resin is cured and the completed package subjected to the final vibration test.

Once more the tube is installed in the life rack to be observed for a few more days. The operating voltages are set accurately to the values which are expected at the beginning of life in the satellite. Interception and activity should now have stabilized. At this point, all the records of the tube are reviewed to make sure no detail or trend in its life history has been missed. The tube is now cleared for satellite use and remains on life until called for.

The final step consists of the marriage between the TWT and its power supply. For optimum performance, the TWT voltages are adjusted individually. For reasons of efficiency of the dc-to-dc converter, this is accomplished by selecting the best taps on the primary side of the transformers. The tube, converter and the assigned microwave network are assembled for tests. Subsequently, the helix voltage is chosen and the dc-to-dc converter completed. Once the taps are set, the converter is embedded in foam: no further changes are possible.

IX. CHOICE OF CATHODE TEMPERATURE

A word is advisable on the choice of the cathode temperature. It was pointed out earlier that the life of the tube is highly dependent on the cathode temperature. To be able to compare this cathode with those of other tubes, we have tried to find a parameter which would be independent of operating temperature and the dip interval chosen for the test. It is possible from the dip curves to obtain for each tube the actual point where the tube goes into temperature-limited operation by correlating the knee of the cathode current curve with the corresponding cathode temperature. On some tubes, estimates had to be made, since they were not dipped all the way into temperature-limited emission. For comparison, a point was chosen in life as a standard time for comparison: specifically, 1000 hours. In Fig. 29, the transition temperature from space charge limited emission to temperature-limited emission is plotted for each tube in chronological order. These values are not steady-state values, since they are taken on a transitional basis; however, they suffice for comparison with other dip tests. We see that these transition temperatures lie at 550° to 600°C. Where was the operating point now chosen? Similar points of the M1789 lie about 50° higher, namely 600° to 650°C. This difference can be attributed to the lower cathode current

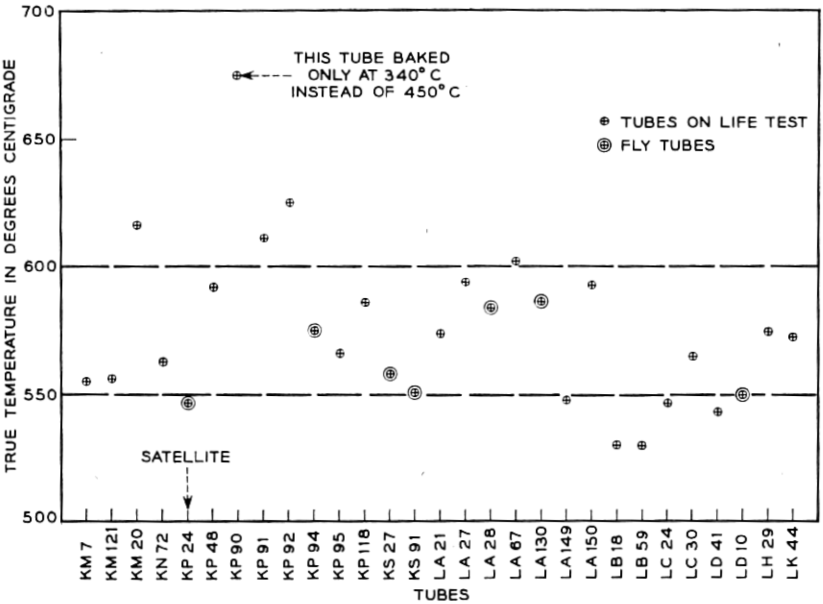

Fig. 29 — Transition temperature of cathodes for the 29 tubes put on life test (space-charge–temperature-limited emission).

loading and to the improvements in tube techniques and cleanliness. The point chosen for the M1789 was 775°, about 150° higher than the transition temperatures. It was found desirable to maintain about the same margin in the satellite tube. A lower cathode temperature would have extended the life but reduced the safety margin towards cathode deactivation; the choice was therefore made to favor reliability.

The data plotted in Fig. 29 are uniform to a high degree with the exception of tube KP90. This tube was accidentally baked at a lower temperature of 340°. This single deviation in processing resulted in an increase of the transition temperature by 100° from the average. No other tube shows such a large deviation. This test illustrates the true uniformity of all the tubes made, since no tubes were eliminated for activity reasons prior to the 1000-hour test. However, in most of the tubes the transition temperature continues to decrease with further aging; usually a minimum value is reached between 3000–10,000 hours.

X. KP24 DATA SINCE ITS INJECTION INTO ORBIT

The telemetry system in the Telstar satellite transmits once every minute the following data concerning the tube: heater voltage, helix

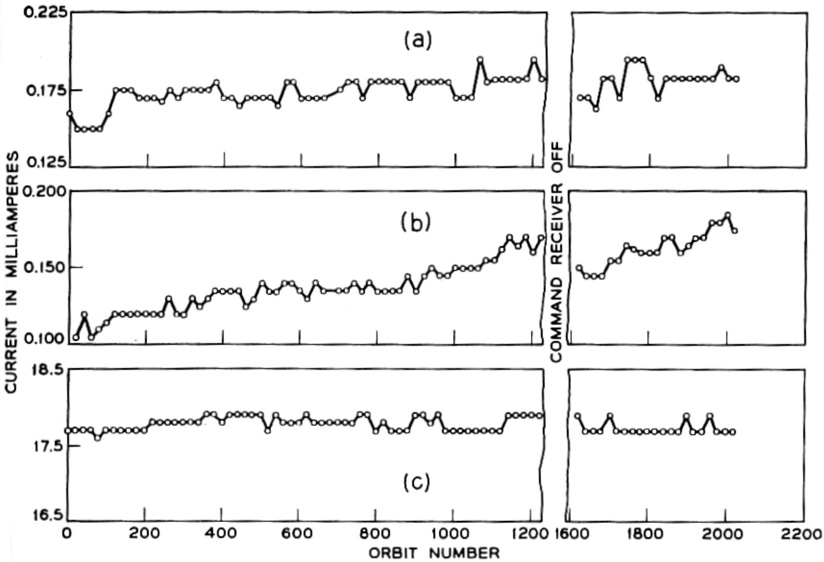

Fig. 30 — Telemetry data for KP24 after injection into orbit: (a) helix current, (b) anode current, (c) collector current.

current, accelerator current, collector current, and finally the temperature of the tube package as measured at the output waveguide flange. The values are transmitted in digital form and are therefore quantized. The smallest increments are: helix, 10 microamperes; accelerator, 5 microamperes; and collector, 200 microamperes.

In Fig. 30, the points represent data selected from active passes during which the TWT was operating under reasonably similar drive conditions. The intercepted currents on helix and accelerator vary to a certain degree; this is caused partly by the telemetry and partly by the varying experiments being performed with the satellite. Nevertheless, some trends can be observed. While the helix current remains steady, the accelerator current shows a slow but gradual increase, similar to that observed in the M1789. The collector or the cathode current (the sum of all three) shows a slight but noticeable increase, such as had been previously discussed under switched life tests. At the moment of writing (January, 1963) the tube has been turned on in excess of 400 times and has accumulated at least 100 hours of operation in orbit. There is no indication that the tube performs differently than if it had remained on the life rack.

XI. CONCLUSIONS

A high-reliability, long-life TWT has been designed, built, tested, and injected into orbit. The basic design philosophy of the conservative approach, based wherever possible on thoroughly proven experience, has paid off. There were only four new concepts used; these, however, had been thoroughly proof tested before incorporation. They are: (a) new cathode nickel (b) on-off operation (c) cathode heater structure (d) SRPM circuit. None has shown any undesirable side effects.

XII. ACKNOWLEDGMENTS

Many members of the Laboratories contributed to the successful development of the satellite traveling-wave tube amplifier. The authors wish to call attention to the excellent performance of all the highly skilled personnel involved in fabrication and assembly of the tube. Mr. C. J. Mataka was responsible for close supervision of the tube assembly line and resolution of the many problems arising from fabrication and assembly of the device. Mr. A. L. Stevens assisted in overseeing the many inspection points incident to ensuring the quality of fabrication. He also conducted tests to evaluate certain mechanical properties of the gun structure.

Mr. J. F. Milkosky undertook the mechanical development of the magnetic circuit and parts related to packaging the tube. In this work he was assisted by Mr. B. Smith. Mr. D. O. Melroy handled the interface problems which were encountered in associating the TWT with the microwave components and power supply in the satellite.

Messrs. A. J. Chick and A. C. Fodor took charge of conducting the life testing experiments. Messrs. H. J. Oudheusden, L. M. Reveron, and D. L. Van Haren were responsible for processing the completed tube on the pump station and for the complex electrical testing which immediately followed. Mr. D. L. Van Haren undertook the final development of the single-reversal magnetic circuit.

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