

TUBE MANUFACTURING AT WESTERN ELECTRIC: THE WE 300B

Attila R. Balaton
Summit, NJ

This paper is dedicated to the members of the tube assembly line at the KC Works. "Good tubes are made by good people."

INTRODUCTION

The WE 300B is the successor to the 300A, a medium-power filamentary triode which was first developed in the mid-1930s for a new generation of movie-theater sound amplifiers (86A, 91A) and produced by the Western Electric Co., the manufacturing arm of the American Telephone & Telegraph Co. (AT&T). A legendary product, embodying all the qualities attributed to Western Electric tubes, the 300B is considered by perfectionist audiophiles to be the "king" of triodes. The 300A was first manufactured in 1935, the 300B three years later. (The only known difference between the two is the base, in order to accommodate a different socket: the 300A had an ordinary UX base with side pin; the 300B used the WE transmitting-tube base, which rotated the pin about 30 degrees.)

Few readers might know that until the fall of 1988 the 300B was still manufactured in an AT&T Technologies plant located on the outskirts of Kansas City, Missouri. It was the last thermionic tube left in production within the AT&T system. This is 53 years of continuous production: quite a tribute to the astonishing longevity of the triode design and the determination of audiophiles around the world who, in the interests of high quality sound reproduction, have refused to give up tubes [1].

To get a better perspective on this historic event, the end of tube production at AT&T, a short history of AT&T and tube manufacturing at Western Electric will be sketched; after which, a look at the actual process of making a 300B will be taken.

THE AT&T SYSTEM

Few will question the fact that the corporate system that was designed to foster and administer the growth of telephone communication in the United States has been extraordinarily successful. This success can be explained by adherence to two fundamental ideas: making science a full-time partner of the corporate venture [2] and continu-

ously focusing on one business, communications.

A lot of credit must be given to the early leaders of AT&T who, faced with the spectacular growth of the telephone as a local facility, realized that Bell's vision of "a man in one part of the country communicating by word of mouth with another in a distant place" was bound to happen, and then embarked on the necessary course of action [3]. Recognizing that the telephone, a product of scientific research, could not develop itself without science, they made a key decision: they identified the need for systematically pursuing scientific knowledge in-house in order to foster advances in telephony. As early as 1885 they put this fundamental corporate policy of supporting research and development in place [4].

By 1925, the corporate structure supporting the growth of telephony had reached maturity and consisted of the following components:

- a corporate entity controlling the fundamental telephone patents, owning the major long-distance lines, and holding stocks in the other companies constituting the Bell System: the AT&T Company;
- a manufacturing arm providing design and manufacturing facilities for the equipment needed by the affiliated companies: the Western Electric Company [5];
- a research entity providing fundamental and applied research to the affiliated companies, jointly owned by AT&T and WE: Bell Telephone Laboratories Inc. [6];
- operating companies providing basic telephone services to the consumers: the local Bell companies. These numbered 17 (later 19), plus two partially owned companies. [7]

The corporate motto, the common objective bonding all the parts of the Bell System together, was a commitment to provide the best possible communication services [8]. This focus on communications, in time, led to another fundamental AT&T corporate policy: the divestiture of "peripheral" activities. Several times in its history, AT&T sold and left business lines it had originally created as spin-offs of some research undertaken in its laboratories. They were sold not because they were unprofitable but because they were not in the main business line of AT&T and had outlived their usefulness from that standpoint [9].

This is the proper perspective to understand AT&T's decision to discontinue thermionic-tube manufacturing: notwithstanding the tremendous impact that vacuum tubes had on the development of AT&T and on world history, AT&T scarcely needs them in its current operations.

TUBE MANUFACTURING AT WESTERN ELECTRIC CO.

While the thermionic tube was not invented by Western Electric, the company was always at the forefront of the efforts to harness its full potential. Throughout the history of vacuum tubes, WE distinguished itself by its constant drive to improve their consistency, reliability and efficiency.

The Beginning

At the dawn of the 20th century, AT&T urgently needed a scientific breakthrough fostering new amplification devices in order to develop its long-distance telephone network. In 1911 Dr. H. D. Arnold joined the research branch of the Engineering Department at Western Electric with the mission of finding such devices [10]. There, in October 1912, he witnessed a demonstration given by de Forest of an audio amplifier using the audion [11]. Its performance was erratic but the potential did not escape the attendants.

Immediately, AT&T embarked on a concerted effort to develop vacuum-tube technology. Arrangements were made to secure the necessary basic patent rights from de Forest (triode) and Lowenstein (C battery or grid bias). Arnold was put at the head of a team of scientists with the charge of improving the performance of the audion [12] and designing basic circuit applications.

He quickly recognized that the imperfect vacuum in the audion was detrimental to performance and remedied that situation by the spring of 1913 [13]. At the same time, several of his colleagues were attacking the problem of emission of electrons from heated cathodes (thermionic emission) and the problem of electrode geometry [14] while other workers were setting forth the design parameters of elementary tube circuits [15].

The Triode Era (1913-1935)

In October 1913 the first electronic repeaters (amplifiers) were put into service on a telephone line between New York and Washington, D.C., with code "A" vacuum tubes consisting of an unbased glass envelope, a barium-coated platinum-iridium filament, a nickel plate, and a nickel grid.

In January 1915 the first transcontinental service was inaugurated. Code 101A tubes were used. They had a longer filament, an improved grid made of parallel tungsten wires welded to nickel side rods, and a four-pin metal base. At 400 hours, average life had already increased by a factor of ten over code A.

The period of World War I produced marked improvements in the rigidity of the electrode assembly to satisfy military applications (codes VT-1 and VT-2) and spurred the manufacturing of tubes with a (then) very high plate dissipation for transoceanic communications (codes S and W, having plate dissipations of 50 and 250 watts, respectively) [16]. By the end of the war the goals set by AT&T management were reached. The design parameters of a triode tube were known. Mass production of reliable, uniform-quality tubes was underway (the output of commercial vacuum tubes, i. e., codes VT-1 and VT-2, from the tube shop at 463 West Street in New York went from less than 200 per week in August 1917 to 25,000 per week in November 1918). Development engineers could choose from several circuit designs for their applications.

The following years brought a constant flow of improvements aimed at increasing the average life of tubes and their efficiency (reducing the power requirements). The progress achieved can be charted with the help of Table 1.

By 1925 life expectancy of the typical repeater tube had increased fiftyfold to 20,000 hours and filament power had been reduced by four-fifths (to 2 W). A few years later, code 102F would reach an average expected life of 70,000 hours [17].

Efficiency was also sought in specialization. By 1925 15 different codes were produced at the new tube shop located at 395 Hudson Street in New York or at the Hawthorne plant in Illinois.

The requirements of specialized applications spurred the study of non-microphonic and low-noise tubes, which were needed for the high-gain preamplifiers used in movie-theater sound equipment. These were the 244A and 262A, the first tubes at Western Electric to use A. M. Nicolson's indirectly-heated cathode.

The same search for efficiency was pursued for power vacuum tubes; in that case, higher output power with less current consumption. For instance, when the WE 300A was first presented to the public, its efficiency was emphasized by a direct comparison with its predecessor, the 242A, in a typical application:

	<u>242A</u>	<u>300A</u>
Operating plate voltage (V)	800	325
Operating plate current (mA)	67.5	60
Power output, push-pull (W)	12	15
Filament power per tube (W)	32.5	6

The 242A and its predecessor, the 211A (B, C, D), had been the "war horses" of early sound-movie and public-address applications. The 242A was used in push-pull in the output sections of the WE 43A amplifiers which had been installed in more than 15,000 movie theaters.

The Search for Efficiency at Higher Frequencies

In a way, the 300A was the swan song of conventional (filamentary) triode design, which really was suitable only for audio or high radio frequencies [18]. Then the focus and needs of AT&T had shifted to VHF, since greater bandwidths were required for the carrier transmission systems that were planned to accommodate the growth of telephone and network (radio-TV) systems. Consequently, the 1930s saw the beginning of the multigrid tube era and a focus away from triode research. Several generations of pentode followed with applications geared to ever-higher frequencies.

The first generation culminated with the WE 310A of 1937, which, technologically, was a direct descendant of the high-gain, low-noise audio tubes described earlier. Compared with the traditional triode repeater tube of the time (102F), for the same plate voltage, the 310A delivered 28 dB more gain, was usable at higher frequencies, and required less than one third the grid drive. For the first coaxial carrier system that followed (L1), a more radical tube design was achieved in 1939: code 386A, a tube with the plate lead brought out the top of the glass envelope and no base (shades of 1913!) [19].

By 1949 a new family of tubes (435A, 436A, 437A) was designed for the 8-MHz L3 coaxial system. Each had a flat-sleeve cathode. The grid wire was fire-glazed under tension onto a frame (side rods braced with cross-members for stability) in order to accommodate an extremely small spacing of about 0.0025 inch between grid and cathode. This process was carried to its limit with a microwave triode (416A) operating at 4 GHz, in which the grid-cathode spacing was reduced to 0.0006 inch. By then the process had gone full circle, back to the triode. The dimensions were actually so small that only one grid could be fitted, as for most of the RCA nuvistors.

At the same time, vacuum-tube production was moved to a new facility in Allentown, Pennsylvania, the first major plant entirely devoted to the manufacture of electronic components. In 1958, in order to free space at Allentown for the manufacture of semiconductors, portions of the tube line were moved to Kansas City, Missouri. Fourteen years later, Allentown transferred the last of its tube production to Kansas City. The advent of integrated circuits gave that 1.5 million-square-foot plant a feature probably unique in the world: the ability to witness the complete history of electronics under one roof, housing side by side the production of vacuum tubes, discrete semiconductors, and integrated microcircuit chips.

TABLE 1 - TRIODE DESIGNS AT WE: FROM TYPE "A" TO 300A

YEAR	LAB REF	WE REF	TYPE	DESCRIPTION	CHARACTERISTICS	APPLICATIONS
1913	A		F-3	Barium coated platinum-iridium "V" shaped filament, plate and grid made of nickel, no base		T 1st telephone repeater NY-Washington, Oct. 1913
1914	M	101A	F-3	longer twisted filament, new grid (tungst. ladder wire, nickel side rods), machined brass 4 pin base	Ef= 4 V, If= 1.45 A, Eb= 100 V, Ib= 10 mA, Rp= 5,000 Oh, μ = 5, average life= 400 hours	T 1st transcontinental line January 1915
1915	L	101B	F-3	amelioration of type "M" with an improved filament coating	Ef= 5 V, If= 1.3 A, Eb= 150 V, Ib= 15 mA, Rp= 4,000 Oh, μ = 5, average life= 4,000 hours	M, R, T
1916	V	102A	F-3	modification of type "L" for higher voltage amplification	μ = 30.0	M, P, R, S
1917	J	VT-1 (203A)	F-3	first "ruggedized" receiving tube, plate and grid of stamped sheet metal, new metal shell base	Ef= 2.5 V, If= 1.1 A, Eb= 40 V, Ec= 0, Ib= 1.5 mA, Rp= 20,000 Oh, μ = 6	M, R, S
1917	E	VT-2 (205B)	F-3	first "ruggedized" transmitting tube, plate and grid of nickel	Ef= 6.5 V, If= 1.35 A, Eb= 350 V, Ec= -20V, Ib= 30 mA, Pd= 10W	C, P, R
1919	G	VT-4 (211A)	F-3	transmitting tube, related to code "S" of 1915, in 1924 change from oxide coated to thoriated fil.	Ef= 10 V, If= 3 A, Eb= 750 V, Ec= -30 V, Ib= 65 mA, Rp= 3,200 Oh, μ = 12.5, Pd= 50W	P, R 10A amplifier
1920	N	215A	F-3	2" high, "peanut" tube, cylindrical plate, continuously wound spiral grid, special bayonet base	Ef= 1 V, If= .25 A, Eb= 67.5 V, Ec= -6 V, Ib= 1 mA, Rp= 18,000 Oh, μ = 6.0	M, R
1921		101D	F-3	improved 101B, "M" shaped flat barium-strontium coated platinum-nickel-base filament	Ef= 4.4 V, If= .97 A, Eb= 130 V, Ec= -9 V, Ib= 8 mA, Rp= 6,000 Oh, μ = 5.9, average life= 20,000 hours	C, M, R, T
1922		102D	F-3	improved 102A, "M" shaped flat barium-strontium coated platinum-nickel-base filament	Ef= 2 V, If= .97 A, Eb= 130 V, Ec= -1.5 V, Ib= .75 mA, Rp= 60,000 Oh, μ = 30.0	C, M, P, R, S, T
1922		205D	F-3	improved 205B, "M" shaped flat barium-strontium coated platinum-nickel-base filament	Ef= 4.5 V, If= 1.6 A, Eb= 130 V, Ec= -9 V, Ib= 5 mA, Rp= 6,600 Oh, μ = 6.8, Pd= 14W	C, P, R, N 8B, 9A, 25A, 42A amplifiers
1922		216A	F-3	electrically equivalent to 101D, but plate and grid look like VT-1	Ef= 6 V, If= .7 A, Eb= 130 V, Ec= -9 V, Ib= 8 mA, Rp= 6,000 Oh, μ = 5.9	P 7A amplifier
1927		101F	F-3	improved 101D, new more efficient filament, continuously wound spiral grid, molded compos. base	Ef= 4 V, If= .485 A, Eb= 130 V, Ec= -8 V, Ib= 7 mA, Rp= 6,000 Oh, μ = 6.5, Pd= 2W	C, M, T

1927	102F	F-3	improved 102D, new more efficient filament, continuously wound spiral grid, molded compos. base	Ef= 2 V, If= .485 A, Eb= 130 V, C, M, S, T Ec= -1.5 V, Ib= .75 mA, Rp= 60,000 Oh μ = 30.0, average life= 70,000 hours
1927	239A	F-3	internal construction similar to 215A but with a standard molded composition 4 pin base	Ef= 1.1 V, If= .27 A, Eb= 100 V, M, P, R, N Ec= -8 V, Ib= 2.2 mA, Rp= 15,000 Oh, 41 amplifier μ = 6.0
1928	242A	F-3	power transmitting tube, better than 211E in audio applications, thoriated tungsten filament	Ef= 10 V, If= 3.2 A, Eb= 1,000 V, P, R, N Ec= -45 V, Ib= 94 mA, Rp= 3,500 Oh, 43A amplifier μ = 12.5, Pd= 75W
1929	244A	H-3	first triode with a heater type cathode, low noise	Ef= 2 V, If= 1.6 A, Eb= 135 V, P Ec= -6 V, Ib= 5.5 mA, Rp= 10,000 Oh, μ = 10.0
1930	252A	F-3	power output triode, oxide-coated filament, designed for audio applications	Ef= 5 V, If= 2 A, Eb= 450 V, P Ec= -65 V, Ib= 43 mA, Rp= 1,700 Oh, 57A amplifier μ = 5.1, Pd= 38W
1931	262A	H-3	heater type cathode, low noise, low microphony, designed for audio applications	Ef= 10 V, If= .32 A, Eb= 135 V, P, N Ec= -4.5 V, Ib= 2.8 mA, Rp= 16,600 Oh 86A amplifier μ = 15.4
1931	264A	F-3	improved 239A, low noise, low microphony, designed for audio applications	Ef= 1.35 V, If= .3 A, Eb= 100 V, M, P, R, N Ec= -8 V, Ib= 2.1 mA, Rp= 13,000 Oh, 41A amplifier μ = 7.0
1932	275A	F-3	power output triode, oxide-coated filament, designed for audio applications	Ef= 5 V, If= 1.2 A, Eb= 200 V, P, N Ec= -45 V, Ib= 46 mA, Rp= 1,000 Oh, μ = 2.9, Pd= 17W
1933	284A	F-3	power transmitting tube, thoriated tungsten filament, used in audio applications	Ef= 10 V, If= 3.25 A, Eb= 1,250 V, P, R, N Ec= -220 V, Ib= 64 mA, Rp= 2,000 Oh, 87A amplifier μ = 5.0, Pd= 85W
1935	300A	F-3	power output triode, oxide-coated filament, designed for audio applications	Ef= 5 V, If= 1.2 A, Eb= 300 V, P, N Ec= -61 V, Ib= 60 mA, Rp= 790 Oh, 86A and 91A amplifiers μ = 3.9, Pd= 40W

Code for "Type": F-3 Filament type triode
oxide-coated unless otherwise indicated
H-3 Heater type triode
("indirectly heated", "equipotential")

Code for "Applications": C - Carrier
M - Measurements
P - Public Address, Program Pickup
R - Radio Transmitters and Receivers
S - Signaling
T - Telephone repeaters
N - Non-associated applications, i.e.

MANUFACTURE OF THE WE 300B

The design and manufacture of the 300B are good examples of the consistently high standards promoted by Western Electric in thermionic vacuum-tube technology.

Most of the problems of designing a vacuum tube are created by the necessity of strictly maintaining the geometry of the electrode structure [20] and preserving a high vacuum, of the order of 10^{-6} mm of mercury or ten thousandths of atmospheric pressure, within the envelope during the lifetime of the tube in the presence of elevated temperatures [21]. High temperatures result in variations in mechanical strength for tube materials (dilation and warpage); in the release of various gases occluded in those materials, spoiling the internal vacuum; and in early depletion of electron emission from the cathode. The manufacture of vacuum tubes is the careful selection of component materials and tube-assembly techniques in an attempt to solve those challenging issues.

A. TUBE COMPONENTS

1. Tube Envelope

Essentially a vacuum container, the envelope must resist the pressure differential existing between the external atmosphere and the vacuum inside, have low vapor pressure, be chemically inert, and help dissipate electrode heat. Over the years, glass has been the most economical and widely used receiving-tube envelope material, while metal and ceramic envelopes have been used for critical military and VHF applications [22]. The designers of the 300B chose a ST-19 glass bulb, the largest of the new standard format introduced in 1932. Barely 1/16 inch thick, the bulb is made of soda-lime glass, also called "soft glass." It has a fairly low softening point, which makes the sealing-in operation (joining the bulb and stem together by fusion) easier, a distinct advantage for production. A soft glass is also slightly conductive, in order to leak off wall charges that might arise from stray electrons striking the glass surface. On the other hand, the tube stem is made of lead silicate glass which has a much higher electrical resistivity. The lead-in wires which are sealed into the stem are rather closely spaced. Good insulation between them is necessary in order to avoid electrolysis at high temperature, since this would release various gases at the electrodes [23]. The lead-in wires are made from a copper-clad iron-nickel alloy wire known as "Dumet," which has a thermal-expansion coefficient very similar to that of glass and therefore provides a good glass-to-metal seal in order to preserve the vacuum. Introduced in 1911 as a replacement for platinum in lead-in seals for incandescent lamps, Dumet wire is made by welding or fusing a 42% nickel-iron alloy into a copper tube

with an intermediate sheath of brass. The copper surface represents about 25% of the total weight of the wire.

2. Internal Components

Nickel and its alloys are the preferred materials for the construction of almost all internal components of receiving and low-to-medium-power tubes when cost is not critical [24]. Their only drawback, in a few applications, is their magnetic property. The plate of a tube fulfills two functions besides collecting electrons: dissipating the heat generated by the electrons which strike its surface, and securing the overall electrode geometry, since the plate generally forms the outside electrode structure. The plate of the 300B is formed from two stampings of Grade 1 sheet nickel welded together. Special attention was taken in the design of the plate to stiffen it as much as possible by incorporating side ribs and wide flanges at the junction of the two halves. Rigidity becomes an important consideration, since the sizes of the different electrodes and the reduced spacing between them increase the risk of electrical shorts. The plate is blackened by a carbonizing process to improve its heat-radiating ability [25].

The grid of a tube must meet several requirements. First, the wire must possess reasonably good tensile strength and great uniformity in order to be wound with consistency, without any shrinking or stretching. Also, the grid should retain its shape despite the ambient heat. Finally, it should emit a minimum number of electrons, even after being contaminated with barium migrating from the filament [26]. The grid of the WE 300B is formed by a molybdenum wire wound flat and peened to two notched Grade 2 nickel support wires (side rods).

The filament (cathode) is the key element of the vacuum tube. A surface emitting electrons under the influence of an activating energy (heat in most cases), the cathode must meet somewhat conflicting characteristics. It must provide a generous flow of electrons as efficiently (low current draw) and as steadily (slow depletion of the electron-emitting surface) as possible throughout the life of the tube. This requires careful attention to the characteristics of both the emitting material and the base filament material. Very early, Western Electric chose alkaline-earth metal oxides, the most efficient electron emitters, as the coating for a base filament. The metal alloy composition of the filament changed over the years as better understanding was gained of the complex phenomena involved in cathode emission [27]. The filament of the 300B is a flat ribbon of nickel alloy coated with a triple barium carbonate compound. It is arranged in a double M, the two Ms being wired in parallel instead of the more usual single M, since the filament must extend the full length and width of the plate in order to emit plate current onto as large a plate area as practical.

The getter fulfills two complementary functions: producing and preserving an adequate vacuum in the tube envelope after the pumping and sealing-off stages. It does this by releasing a metal element which has a high affinity for the various gases encountered in a vacuum tube and literally pumps them [28]. The WE 300B uses a so-called "flash" getter, consisting of a mix of barium and calcium carbonates with some magnesium added in order to ignite the compound and bring it rapidly to a temperature of approximately 300 deg C at which point the getter material is most effective. The getter support is made from nickel wire.

B. ASSEMBLY

The proper choice of materials for all components of a vacuum tube is not enough for optimal performance. The careful processing of these materials before assembly and the precautions taken during assembly are important considerations in order to obtain the expected performance and long life.

The materials used must be rigorously clean. Tube assembly is done wearing rubber gloves. Sulfur-free lubricants must be used during the various machining, drawing, stamping and grid-winding operations, as sulfur in the tube would poison the oxide-coated cathode and ruin it [29]. After chemical cleaning and just before pumping, all metal parts are "pretreated" by firing them in a hydrogen furnace near 1000 deg C in order to reduce remaining oxides and to outgas the bulk of the metal by replacing occluded gases with hydrogen. The hydrogen escapes easily at the pumping stage. A similar treatment (but at lower temperatures) is given to the other tube components, mica spacers and glass envelope. These are necessary precautions to obtain and preserve high vacuum in tubes.

Ultimately, the quality of the tube rests on the manual skills and experience of the assembly workers, as the construction of a large triode like the 300B largely consists of a succession of manual operations as described below. Indeed, the important proportion of labor in the fabrication of a WE 300B helps explain the high cost of such a tube.

The foundation of the tube is the stem-arbor assembly (Fig. 1). It is made in successive steps. A piece of glass tubing approximately 0.6" in diameter and 1.5" long is heated to a plastic state and the following operations performed: at one end a flared edge is reamed into the glass, forming the future area of sealing with the glass envelope; at the other end the glass is pressed around the four Dumet lead-in wires that will provide electrical connections with the filament, grid and plate; next, the two nickel lateral rods that will support the plate are inserted; finally, a piece of glass tubing approximately 2" long is sealed into the stem to serve as exhaust tip during the pumping stage. In the mean time, the glass is submitted to several annealing operations in order to

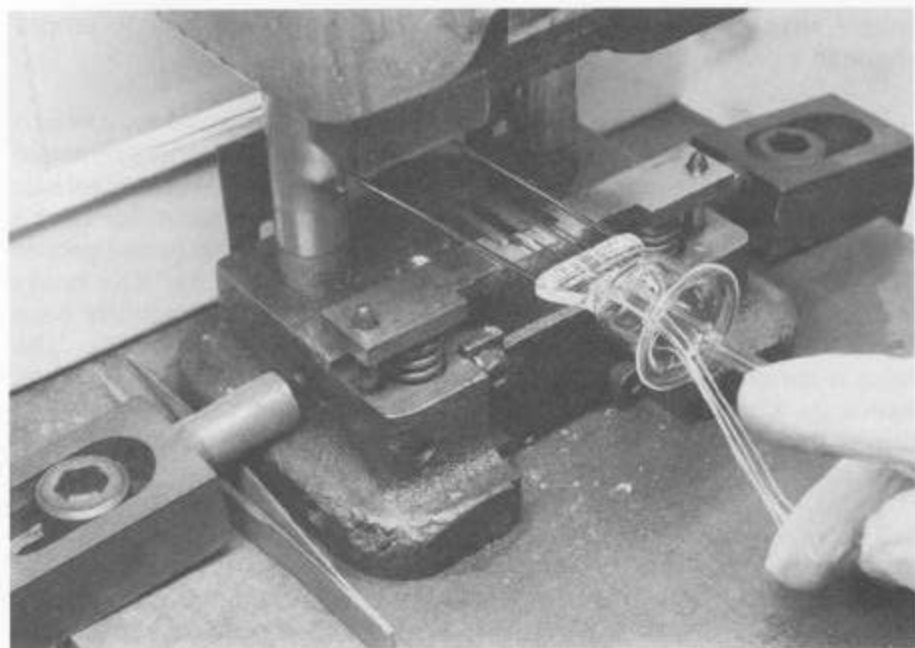


Fig. 1. The stem.

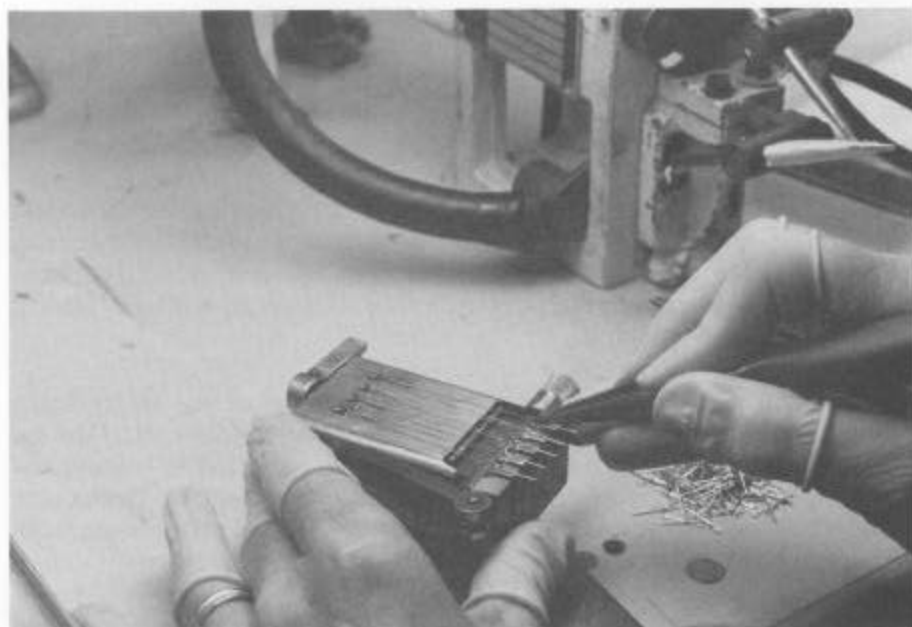


Fig. 2. Stringing the filament.

relieve stresses. Finally, the four connecting wires are bent to proper shape in a press.

The second stage is the filament assembly. The long and narrow carbonate-coated ribbon is cut to length and the coating carefully removed at each connecting point. The ribbon is strung into the characteristic double-M shape on a jig (Fig. 2). The five lower extremities of the double M hold tiny nickel hooks which are then welded to the proper filament connections on the stem-arbor assembly (Fig. 3). The hooks are aligned via holes in a mica disk spacer which has previously been inserted on the stem-arbor assembly (see background of Fig. 3). The mica is sprayed with magnesium oxide to reduce stray current leakage, hence its white color. This last step originated in manufacturing of miniature tubes. While not absolutely necessary, it helps consistency in tube characteristics.

Two more holes in the mica disk spacer help align the grid side-rods and secure the geometry between the filament and the grid. A grid lathe winds the molybdenum grid wire at a constant pitch onto the notched nickel side-rods, forming the grid assembly. The resulting ladder is then inserted and spot-welded to the stem-arbor assembly (Fig. 4). Now the plate can be mounted over the other electrodes to complete the structure by carefully sliding it along the lateral rods (Fig. 5). It is then spot-welded to those rods (Fig. 6). Each plate has been individually sized to check for proper tolerance prior to assembly.

The finishing touches are done by inserting a mica spacer on top of the assembly (Fig. 7) in order to secure the other end of the electrode structure, and by spot-welding the getter support in place. At that stage the "mount" has been produced, a tube assembly ready to be evacuated on the vacuum pump and sealed (Fig. 8).

The glass bulb is sealed to the stem by carefully heating the two glass parts together with gas burners until they become plastic and readily fuse. The tube can then be exhausted (Fig. 9). For small receiving tubes, these two operations are combined and done by a single "sealex" (seal-in/exhaust) machine.

The tube, connected to the pump via the exhaust tip, is gradually pumped out on a series of rotating stations. Towards the end of the cycle the tube elements are heated by induction (Fig. 10) to release the gases occluded in various parts, to activate the cathode (transform barium carbonate into barium oxide), and to flash the getter in order to perfect the vacuum in the tube.

The final assembly stage is to mount the four-pin bakelite base which is secured to the glass bulb by a heat-cured adhesive (Fig. 11). The pins are made of tinned brass.

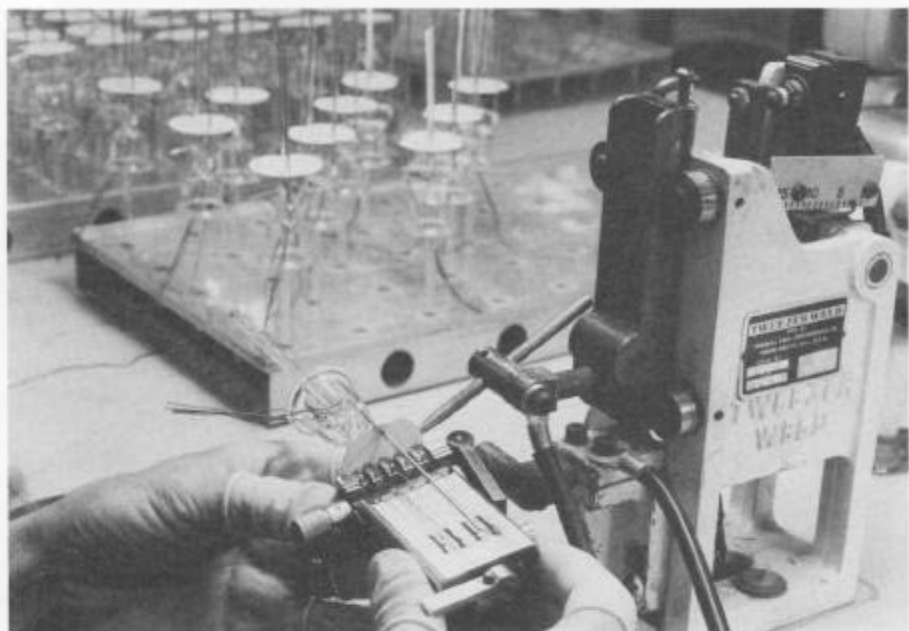


Fig. 3. Assembling the filament.

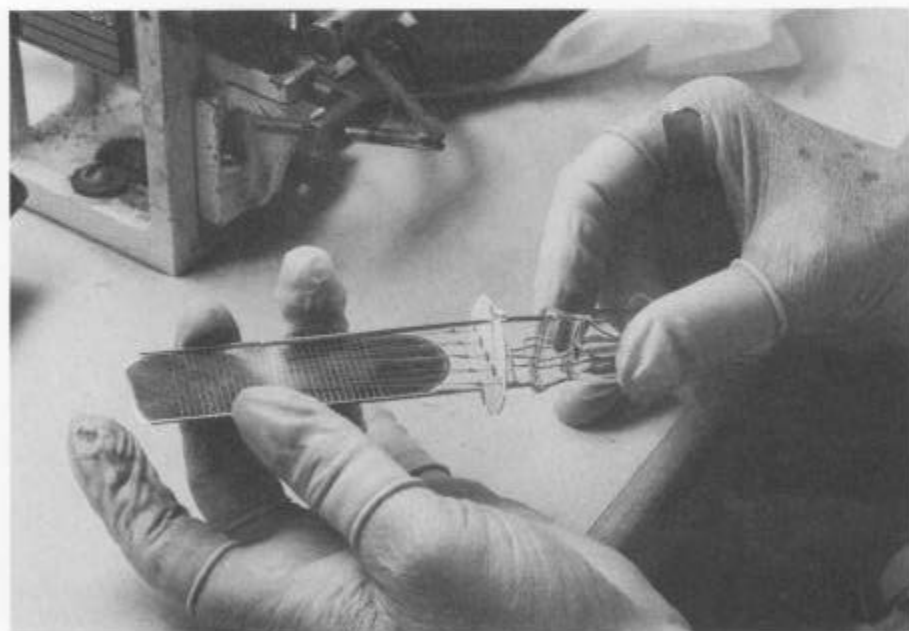


Fig. 4. Assembling the grid.

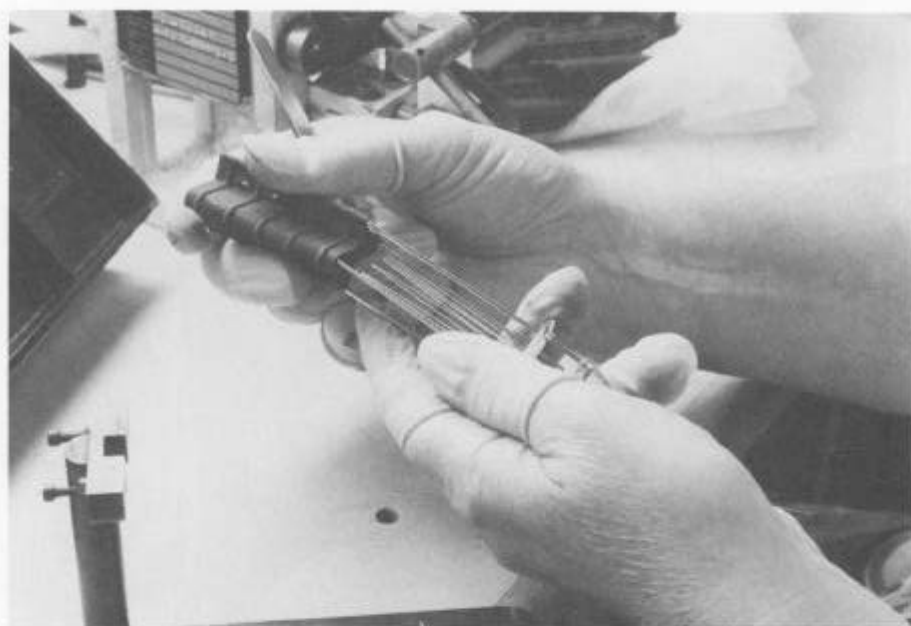


Fig. 5. Adding the plate.

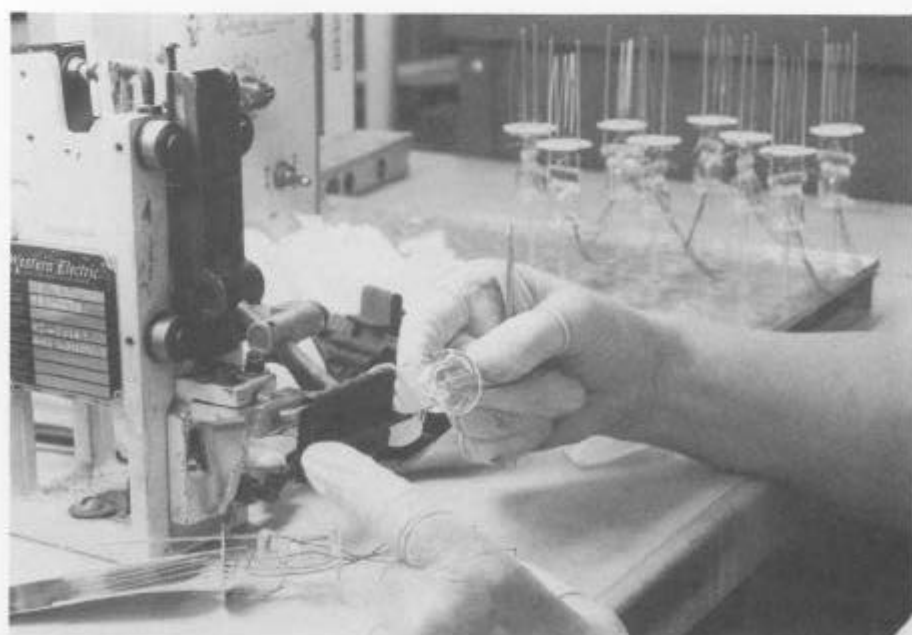


Fig. 6. Plate assembly.



Fig. 7. Adding the top mica.

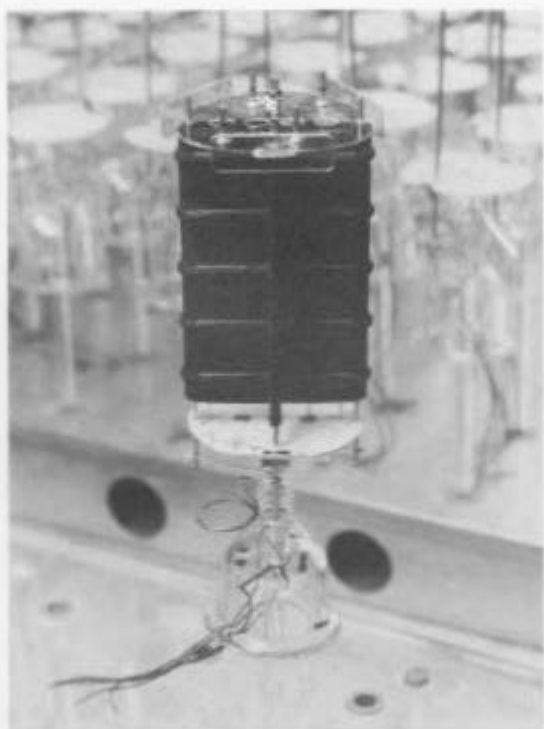


Fig. 8. The completed mount.



Fig. 9. A sealed tube.



Fig. 10. The exhaust operation.



Fig. 11. Adding the base.



Fig. 12. The aging rack.



Fig. 13. Test set.

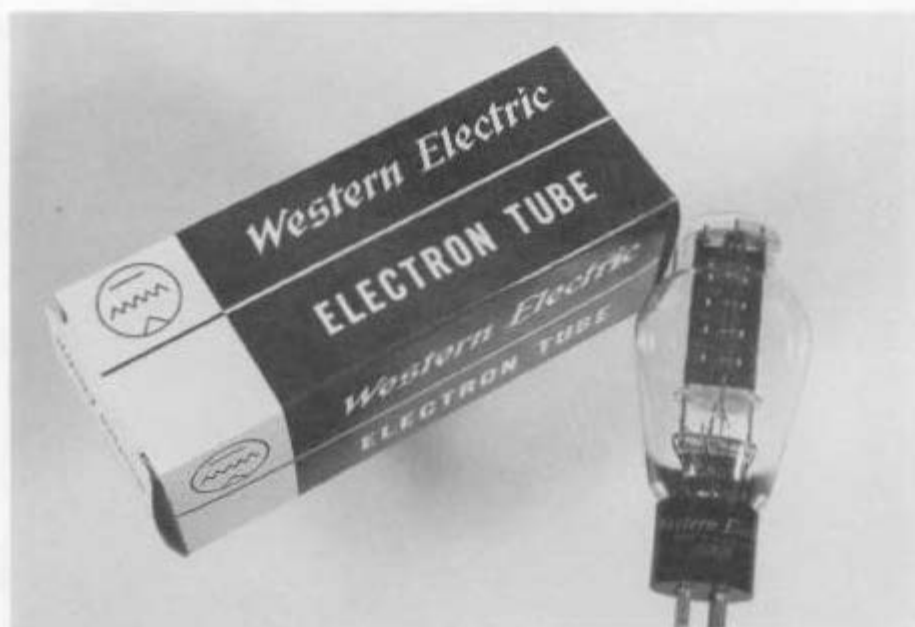


Fig. 14. A finished tube.

The tubes are then placed in an aging rack (Fig. 12) and submitted to an aging cycle of several hours in order to stabilize their operating parameters.

Each 300B is checked individually on a test set (Fig. 13) to make sure that it meets the design parameters. (More specifically, with a plate voltage E_p of 300 V and a grid voltage E_c of -58 V, the tube should draw a plate current I_p of at least 62 mA.) Only then will it be labeled "Western Electric" and packaged (Fig. 14).

CONCLUSION

In conclusion, one cannot help wonder about fate and destiny when reviewing the long tradition of tube manufacturing at Western Electric: Born in 1913 under code "A," an audio amplifier tube designed to carry human voices over telephone wire lines, Western Electric's tube activities end exactly 75 years later with code 300B, another audio amplifier tube designed for high quality sound reproduction.

While vacuum-tube enthusiasts might be saddened by that ending, they should also feel indebted to all the AT&T pioneers, engineers and workers who, with their vision and their pursuit of excellence in design and manufacturing, have made possible vacuum-tube applications of the highest quality.

NOTES

[1] For the trivia buff, the all-time longevity record is probably held by the WE 215A ("peanut") tube which was conceived in late 1918 and, according to production personnel interviewed, was made for the U. S. Navy in small quantities until the mid-1970s. The tooling was finally scrapped in 1981.

[2] Alexander G. Bell was not the first one to balance the vision of science and the practicality of manufacturing. This honor should probably go to Thomas A. Edison, the "Wizard of Menlo Park," who set up the world's first industrial laboratory.

[3] Meeting the technological challenges that Bell's vision presented was a formidable task, as one can assess by surveying the numerous disciplines to be mastered: acoustics (sound, speech and hearing); electricity (transmission-line and network theory); mechanics; and science of materials (metallurgy, chemistry).

[4] This policy was implemented with the hiring of Dr. Hammond V. Hayes, a physicist trained at Harvard and MIT who became the head of American Bell's Mechanical Department, a direct ancestor of Bell

Telephone Laboratories (incorporated in 1925).

[5] Western Electric was acquired in 1881 after Western Union, its then-owner, lost a patent-infringement suit brought by AT&T, putting WU out of the telephone business. The original Hawthorne plant near Chicago was used to make telegraph and telephone parts for Western Union. In 1905 the headquarters of WE were moved to 463 West Street in downtown New York.

[6] Is the joint ownership due to the fact that Bell Labs, at its inception, was almost entirely staffed by the Engineering Department of Western Electric?

[7] This corporate system stayed in place until the early 1980s when the courts approved an antitrust settlement that ordered the breakup of AT&T and forced it to divest its stocks in the operating companies.

[8] The focus on communication was also urged by the regulators and the courts which carefully watched that the corporate giant did not stray out of its field and abuse its monopolistic situation.

[9] The main divestitures of interest in the audio field have been the following:

1925: licensing of the orthophonic phonograph to Victor;
1926: sale of WEA broadcasting studio to RCA (to become NBC);
1937: sale by ERPI of motion-picture sound leasing and servicing business to All Technical Products, Inc. (later to become Altec);
1948: sale of transmitting-tube activity to Machlett Laboratories, Inc.;
1949: sale of sound equipment lines (microphones, amplifiers, loudspeakers) to Altec Lansing Company;
1956: sale of the Westrex Company (motion-picture and studio sound equipment) to Litton Industries.

[10] Trained in the "new" physics at the University of Chicago under Professor Millikan (who first measured the charge of an electron), H. D. Arnold was familiar with electron theory and vacuum techniques. The latter proved invaluable, as we shall see.

[11] De Forest invented the audion (triode) in 1906 by inserting a third element between the two electrodes of Fleming's diode (1904). For several years its principal application was as a radio-wave detecting device; but the tubes were highly inconsistent in performance. It was while working at the Federal Telegraph Company in early 1912 that de Forest first presented an audio amplification device (to the U. S. Navy).

[12] The necessity of consistent performance can be better appreciated in the light of the fact that several dozens of tubes would have to be put in tandem on a transcontinental telephone line.

[13] He had to order a new type of vacuum pump that only Gaede in Germany was manufacturing at the time.

[14] It is interesting to note that, even though the work of Professor Wehnelt on oxide-coated filaments had been available since 1903, Western Electric was the only tube manufacturer to use it systematically for a number of years, the extensive experiments of its scientists having shown its superior electron-emission characteristics. Another result of early WE work on cathodes was Nicolson's 1915 patent application on the "equipotential" (indirectly heated) cathode which found its usefulness later in the 1930s.

[15] Two names on that team will instantly be recognized by readers familiar with electronic circuits: R. V. L. Hartley and E. H. Colpitts. A lesser known but pivotal figure was H. J. van der Bijl who, in 1914, derived the equation used to design the electrode geometry of all Western Electric triodes for many years. In 1920 he published a book, The Thermionic Vacuum Tube, which became the first reference in the field.

[16] Unfortunately, for lack of space, this paper will not be able to do justice to the contributions of Western Electric to the design and manufacture of high-power transmitting tubes. In that field WE also assumed a leadership role.

[17] The 5,000-hour average life for a typical commercial receiving tube is dismal in comparison; but one has to understand that operating as a regulated monopoly, AT&T was concerned with maximizing the economic life of its equipment rather than minimizing first cost. RCA or GE would have gone bankrupt had they tried to emulate Western Electric. For submarine telephone cables, Bell Laboratories itself manufactured a small series of special tubes (code 175HQ) which had an actual service life in excess of 190,000 hours (22 years!).

[18] The gain available at higher frequencies would naturally be limited by the various interelectrode capacitances and inductances resulting from the size of the elements in a filamentary triode and by the cathode-to-plate transit time (the time for an electron to travel from cathode to plate).

[19] An improved version of this tube (6AK5/403A) was made in very large quantities for WW II radar and other military systems. An extended-life version (code 408A) was manufactured by WE after the war. The war also spurred the development of the cavity magnetron (code 700A and others), Bell Laboratories perfecting what was originally a British discovery.

[20] Tube characteristics are dependent upon the electrode geometry. Grids which have fewer turns or which are closer to the plate decrease the amplification factor μ . Grids which are closer to the cathode, or cathodes which have a greater emitting area, increase the transconductance G_m . If heat or shock were to distort the electrode spacing, the impact on tube characteristics would be immediate.

[21] Cathodes operate in the neighborhood of 750 deg C. Plate temperatures for receiving tubes range from 350 deg C to as high as 600 deg C. For optimum life and reliability, tube-envelope temperature should be below 175 deg C, preferably around 100 deg C.

[22] Vacuum-tube technology is directly related to incandescent-lamp technology. The progress made in the latter at the turn of the century helped create the former: for instance, the round shape of the early audion envelope was due to the use of readily available automobile light bulbs by McCandless, their manufacturer.

[23] The apparently superior quality of the Western Electric glass bulbs does not seem due to a special glass composition, as there is no evidence of Western Electric using anything but commercially available glass over the years. It is probably due to the care taken in secondary operations like annealing. (Annealing is the process of heating glass as much as possible without deformation and then slowly cooling it to room temperature in a special oven in order to relieve stresses created in the glass during manufacturing steps.)

[24] Nickel and its alloys possess adequate mechanical properties for all but the most demanding applications (the melting point of nickel is 1455 deg C). They can be readily outgassed and are highly resistant to corrosion. They can also be fabricated into any shape and spotwelded easily.

[25] Carbonizing nickel consists of heating the nickel to 925 deg C in an oven containing a hydrocarbon-gas atmosphere. For most commercial receiving tubes, carbonized nickel has been replaced by nickel-plated or nickel-clad steel and, more recently, by aluminum-clad iron on a copper core (General Electric Co.); the latter takes a dark color when fired at about 700 deg C in vacuum and thus does not need carbonizing. In high-power tubes, where the plate operates at 800 deg C or higher, it is usually made of more refractory materials such as molybdenum, tantalum or graphite.

[26] For most receiving tubes, nickel alloys using manganese, chromium or molybdenum (listed in order of increasing heat resistance) are employed for grid wire. To reduce unwanted electron emission from the grid, the wire may be coated with gold or platinum.

(Platinum has the ability to absorb a considerable quantity of thorium or barium that might migrate from the cathode.) For even higher temperature operations, grid wires are made of pure molybdenum or tungsten, which have melting points of 2625 and 3370 deg C respectively.

[27] The alkaline-earth metals used are barium, calcium, and strontium. They are generally applied in the form of double or triple carbonates which are heated at a later stage of tube manufacturing to produce the required oxides. The double carbonates are those of barium (a majority percentage) and strontium; the triple carbonates contain a few percent calcium in addition. Originally, Western Electric employed platinum-alloy filaments with the carbonate coating. Later it was found that special nickel alloys could be used effectively. Those alloys are made of very pure nickel, in the form of powder, to which are carefully added reducing agents (like tungsten and zirconium) in minute amounts of 0.01% to 0.2%. The role of these agents is to "activate" the barium oxide coating into emitting electrons. On a finished filament, the coating is approximately 0.001", or 1/5 the thickness of the base filament itself. It is applied by carefully "dragging" the filament in a succession of baths filled with the coating solution and letting it dry between stages until the proper thickness has built up.

[28] Conceptually, the getter acts like an auxiliary pump working in two successive stages: first, it lowers the pressure from about 10^{-4} to 10^{-6} mm of mercury; then it keeps pumping and maintaining that level of vacuum throughout the life of the tube. Alkaline-earth metals, principally barium, cerium, and strontium, have a great affinity for the most common gases released in vacuum tubes (oxygen, carbon monoxide, carbon dioxide, hydrogen, and nitrogen) and are commonly used as getters.

[29] While surface films of oil are readily removed in the degreasing and cleaning operations, some oil might be trapped in microscopic pockets of the material and released only much later once inside the tube. This is also true for other contaminants and explains the use of rubber gloves for assembly operations. VHF tubes are commonly built in special clean rooms.

ACKNOWLEDGEMENTS

The author wishes to thank AT&T Technologies, Inc., for allowing him to visit the Kansas City Works, particularly D. R. Dobson, Senior Product Manager, for organizing the visit and B. D. Magers, Senior Production Engineer, for answering the author's numerous questions. He is also greatly indebted to AT&T Archives and Records for providing access to original documents of interest.

While specific quotations have not been indicated in the text, the au-

thor borrowed heavily from the following books and articles, which are definitive references in their respective areas. Consequently, only the eventual inaccuracies in the text are claimed by the author.

A History of Engineering and Science in the Bell System. Bell Telephone Laboratories, Inc., 1975-1985. A multi-volume account of that prodigious history prepared collectively by past and present members of Bell Labs. Of particular interest are the following volumes: The Early Years (1875-1925), M. D. Fagen, Ed.; chaps. 2, 5, 8, and 10; Transmission Technology (1925-1975), E. F. O'Neill, Ed.; chaps. 8 and 17; and Electronics Technology (1925-1975), F. M. Smits, Ed.; chap. 3.

van der Bijl, H. J., The Thermionic Vacuum Tube (New York: McGraw-Hill Book Co., 1920). For many years, the "bible" for vacuum tube design, written by one of the original members of H. D. Arnold's team. Chapter VII, pp. 224-249, is of special interest, notably the section concerning "Tube constants as functions of the structural parameters."

Kelly, M. J., "The Manufacture of Vacuum Tubes," Bell Laboratories Record, July 1926, pp. 137-144. Precise account, by a future president of Bell Laboratories, of manufacturing by the Western Electric tube shop then located at 350 Hudson Street, New York.

Kohl, W. H., Materials and Techniques for Electron Tubes (New York: Rheinhold Publishing Corporation, 1960). An up-to-date reference book on tube design written by a senior engineer of GTE Sylvania. It contains a very extensive technical bibliography.

McNally, J. O., "The 300A Vacuum Tube," Bell Laboratories Record, July 1936, pp 365-368. Description of the WE 300A design by one of the engineers at the tube development department of Bell Laboratories.

Tyne, G. F. J., Saga of the Vacuum Tube (Indianapolis: Howard W. Sams & Co., Inc., 1977). The authoritative account of tube history until 1930 worldwide, by a former engineer of Bell Laboratories. Chapters 6 and 14 specifically cover Western Electric tubes.

Attila R. Balaton

A lifelong enthusiast for high-quality sound reproduction, Attila R. Balaton acquired an early appreciation for vacuum tubes by scratch-building audio amplifiers. Since his academic background (U. of Paris, UCLA) and work experience are in a different field of endeavor, he considers himself a dedicated amateur. An interest in researching, documenting, and preserving the early era of electrical sound reproduction (1920-1950) brought him into contact with several members of AWA who encouraged him to join. His particular area of interest is the research done at Bell Laboratories on high-quality sound reproduction and the resulting products manufactured by WE during those 30 years. He welcomes correspondence from any AWA member who can help him locate or document tubes or other artifacts for future publications on the subject.



Photos courtesy of AT&T Technologies, Inc.