Radio FAQ Part Six: The Vacuum Tube Timeline

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with additions and amendments by Rick Boatright

The radio FAQs through part five took us only up to early 1633. Much has happened since then, and in mid-2012 we are writing stories set in early 1636.

It's time for a substantial update. This document brings together the work of Jack Carroll, Wood Hughes and Rick Boatright into a single timeline.

Canon events

In June 1631 Gayle Mason founded Voice of America (VOA), and was on the air within a month. Some time within the next year the 100 foot cell phone tower was moved to a site behind the studio and set up as the broadcast antenna, with her 1 KW ham transmitter initially running at the high end of the AM[1] broadcast band, and later modified to run on 650 KHz. The transmitter was built using used 810A triodes collected by Gayle over several years, as they were taken out of service by broadcasting stations in West Virginia and Pennsylvania. At the time of the RoF, VOA had a total stock of 16 of these power amplifier tubes. This is enough to keep the station on the air for several years, if they're operated conservatively. (Radio FAQ's and the early chapters of "*Turn Your Radio On*" by Wood Hughes (GG 19 and 20) .)

In September 1632 Gayle Mason and John Grover formally founded General Electronics, Inc. (GE) They immediately obtained military contracts to manufacture communication transmitters and receivers from whatever up-time parts they could salvage, build additional equipment from materials currently available down-time, and launch a crash project to recreate the design and manufacture of vacuum tubes so that the electronics industry could be put onto a sustainable basis as soon as possible.

In "*Canst Thou Send Lightnings*" (GG7) Rick Boatright introduced John Grover and the radio communications projects to canon. In the context of tubes, it was noted that: "*Everything depended on tubes. Everything. The sniping and the infighting at the staff meetings was starting to move from sarcastic to vitriolic. If they didn't make some real progress soon, he didn't know what he was going to do, especially since his only real tube-head, Gayle Mason, was stuck in the Tower of London.*"

It's projected that the lab was built and occupied early in 1633 by jewelers and glassblowers who were developing the tools and techniques to make tubes.

1 http://en.wikipedia.org/wiki/Amplitude_modulation (The AM broadcast band covers 535 to 1705 KHz, with channel centers on multiples of 10 KHz from 540 to 1700 KHz.)

Training of supporting personnel was to start at the same time. The recruiting effort for that lab resulted in the recruiting of Father Nicholas Smithson to work in Grantville, eventually as a library researcher and scholar of the up-time technical literature. (“*Cans't Thou...”*)

In late 1633 the first prototype Alexanderson alternator was completed, and the frequency doubling and modulation transformers were wound. Voice of Luther (VOL) in Magdeburg went on the air in early 1634 with the second prototype alternator, with orders for two more from the Jesuits. (Implied by several of the stories set in Magdeburg plus novels-in-progress but not yet published.)

In *1633* (Flint and Weber) Gayle Mason was selected in May of 1633 as part of the embassy team to go to London and was subsequently imprisoned in the Tower of London, and from there diverted to Ireland with Oliver Cromwell. It is unknown when, or if she will ever return to Grantville. (1632 Timeframes document maintained for the Ed Board available at 1632.org) After Gayle left in mid 1633 there was a short-lived diversion of the tube team to the RF alternator[1] project until the intervention of Father Smithson brought it to fruition. At that time Gunter Peck moved from being the head of the tube project to the alternator project and Conrad Müller took over the tube engineering group. (Cans't thou... GG7.) By the time of “*Turn Your Radio On*” (GG19-23) and “*Breakthroughs*” (GG15) Gunter Peck had moved on to head the materials group.

Meanwhile, all of Grantville's industries were coping with a crippling shortage of technically trained people, especially engineers. The high school and tech center faculties had been raided to staff critical projects, which left a shortage of teachers to educate new engineers and scientists. In “*Stepping Up”* (GG 14) Jack Carroll introduced one of the education community's temporary expedients. Some of the most capable and talented students, who were able to study independently, organized private study groups in various subjects. Overworked teachers, engineers, and other professionals found some time to advise these groups and help them past rough spots. In late 1633 we saw a group of four young down-timer physics students, who had completed the math and science courses the schools were able to offer, and gone on to master English sufficiently to study second-year physics on their own.

In “*Breakthroughs*” (GG 15) Jack Carroll developed the details of the miniature Manhattan project[2] to develop vacuum tubes, previously mentioned in passing so that Grantville and the USE wouldn't lose their military communication advantage as the up-time radio communication equipment gradually wore out. That story put a few key events into canon and determined roughly when they occur. “*Turn Your Radio On*”, especially Episode 2 (GG 20) by Wood Hughes dated some of the key events that set the stage for “*Breakthroughs*”.

By February 1634 the previously mentioned study group had completed its course in introductory electrodynamics. They were then capable of absorbing on-the-job training in electrical engineering, electronics, or any of several related fields.

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1 http://en.wikipedia.org/wiki/Alexanderson_alternator

2 http://en.wikipedia.org/wiki/Manhattan_Project

Else Berding was persuaded to interrupt her studies at that point and accept a job at GE as a research engineer in Conrad Müller's tube group. By this time GE had made considerable progress in vacuum technology, materials science and processing, mechanical engineering, and other necessary technology and equipment to develop tubes. But up to this time there wasn't anyone available to work on the project full-time who had the necessary background in math and physics to understand the theoretical basis of vacuum tube design. Thus, Else became the key person needed to complete the tube R&D team, but at this stage of her education she was barely capable of the task. She found herself stretching to her limits to master the knowledge as fast as possible, and begin the design work.

In early October 1634 the tube group accomplished its watershed milestone, the first successful lab demonstration of the working parts of an amplifier tube, in a lab vacuum chamber. (The fall foliage outside the lab window and other details in the text make the most probable date Friday, October 13, 1634.)

The date of the first complete glass-sealed vacuum tube isn't stated in the story; it would be around the beginning of November. At about that same time GE was also developing the capability to repair burned-out up-time tubes, especially the 810As that VOA relied on.

Around the end of 1634 Conrad and Else are seen on the way to a meeting with the machine designers at Marcantonio's machine shop, to brainstorm pilot production tooling.

Somewhere around that time, Else should finally be getting some help. At the end of 1634 she's still the only electronics engineer in the world, and she's literally working night and day to get tubes into production before too much of the up-time gear fails.

The story as first published doesn't adequately explain her motivation for this single-mindedness; this part was later expanded in the revised on-line download and the print edition. She was one of the refugees fleeing the Magdeburg massacre, and lost contact with her family in the chaos. She still has no idea what happened to them. Having just turned 17 while running from Tilly's troops, she ended up in Grantville by pure luck, and consequently survived. Given the chance at an education, she took in all the math and science the high school had to offer, and continued on in the study groups. Because of what Grover said during her job interview, she believes that getting tubes into production is probably essential to the survival of Grantville and the USE, and she's the only person who can do it. Worse, time may be very short. Since it's Grantville that saved her from the rampaging mercenaries, her continued survival depends on Grantville's survival, but Grantville's survival depends on her. Thus, mortal fear and a terrible sense of responsibility for her new countrymen are as much a part of her motivation as the sheer fascination with the problem.

The remaining members of that 1633 study group in electrodynamics launched their own careers. Manfred became a physics teacher and published a Latin translation of the second year physics textbook in "*Cap and Gown*" (Ring of Fire III). Anneke and Gottfried have never appeared in canon again, but the appearance on the commercial market of induction motors and steam turbine generators in "*An Electrifying Experience*" (GG 20), "*A Job Well Done*" (GG 24), and "*Storm Signals*" (GG31) suggests that they, or someone like them, hired on at American Electric Works as engineering trainees. Landon Reardon told his wife Sarah that he was assisting their study group in order to obtain job candidates for his company.

Timeline extrapolations

We can extrapolate from these stakes in the ground to the events that should logically follow.

Immediately after the end of "*Breakthroughs*", pilot production of simple triodes[1] should start about February 1635. These tubes would probably be usable up to around 10 MHz, possibly 15 MHz.

These would be suitable for the oscillator in a two-tube transmitter, or several different sockets in a receiver. The second tube design to be prototyped would be the final amplifier for the two-tube military CW[2] transmitter, probably in the 5 W range. Expect this maybe in March. The schedule calls for pilot production of two-tube CW transmitters around May. With just these two tube types a superhet[3] CW receiver would be possible, with about 5 tubes. GE's electronic designers have mostly a technician level of knowledge; John Grover and Jennifer Hanson have upper-level ham licenses, and lead the radio equipment group. They have taught some electronic designers who have high school educations. GE might go for a superregen[4] receiver first, or trade time for more efficient use of development resources, and choose to design a detector diode[5] and a pentagrid converter[6] tube first. That would probably give them a prototype military CW receiver around the end of the summer.

But by the end of 1634 many of the young up-timers have been back from the army long enough to go through some study groups themselves. The schools have also augmented their formal curricula, and some of the faculty have returned. Thus, we may expect a physics student or two to be available to join GE as an electronics engineering trainee and begin learning under Else's direction. Their physics consultant, Charnock Fielder, was killed in a riot "*Turn Your Radio On*" (GG 23), but Jim Saluzzo has been back for several months. John Grover might be able to arrange to retain him as a consultant, or even get him to reduce his course load so as to work part-time at GE and cross-train as an electronics engineer. With his physics degree and Amateur Extra ham license, Saluzzo would be the best candidate in Grantville for the job.

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1 http://en.wikipedia.org/wiki/Triode
2 http://en.wikipedia.org/wiki/Continuous_wave (typically used to transmit Morse code)
3 http://en.wikipedia.org/wiki/Superheterodyne_receiver
4 http://en.wikipedia.org/wiki/Superregenerative_receiver
5 http://en.wikipedia.org/wiki/Vacuum_tube (includes diode vacuum tubes)
6 http://en.wikipedia.org/wiki/Pentagrid_converter

Whoever the new engineers are, the added technical manpower will accelerate the tube project, as well as electronic design in general. They will begin to assist in designing new tube types within a few months, possibly around April or May of 1635. The next tube types in the development schedule will be slightly higher power transmitting/audio types, in the 25 W range. They would like to reverse-engineer the 6L6; it's not clear that they can do it that soon. Even if it's a triode, this next tube will be suitable for the RF finals and modulators of broadcast transmitters up to perhaps 200 W in a parallel/push-pull configuration. Modulation transformers for the 6L6 based AM transmitters will be a direct outgrowth of the modulation transformers for the AM alternators and will be available in good order. With a 25 watt tube, the design of small broadcasting transmitters up to, as mentioned, 200 watts should be technically possible in the third quarter of 1635, but GE's technical manpower will still be stretched too thin to help much. So anybody who wants to build that kind of transmitter will have to hit the books. It calls for somewhat advanced ham skills. (Ganging more than eight tubes in parallel for power amplifiers and modulating them all equally to avoid distortion is "hard.")

The long-planned VOA power upgrade could occur some time in 1635 by putting more of the up-time 810As on line. GE expects to be able repair burned-out 810As in the spring of 1635, but can't make new ones in the foreseeable future because of materials and fabrication problems with the graphite anodes.

Their first attempt at a high-power transmitting tube design will be a hybrid of several up-time concepts, with a copper external anode and cooling fins, but with a fairly simple triode structure internally. This may take them to 200-500 W in the broadcast and lower HF region (3 to 30 MHz), i.e. 50 to 125 watts per tube. In the absence of ionospheric skip, HF will be dominated by diffraction mode propagation in much the same way as VHF (30 to 300 MHz), and can be used for hilltop-based land networks, although with correspondingly larger antennas than VHF stations. Some military units may receive this type of gear in the 1635-1637 time frame.

Production is a separate problem from design. GE will need time to build up its plant and its manufacturing proficiency, and time to catch up to its backlog. Military orders are likely to absorb all its tube production throughout 1635, and well into 1636. We see CW tube gear in Navy shore stations and small vessels in 1636, in “*Storm Signals*”. After that it may be possible to start building communication gear for civilian markets, such as AT&L, mobile radio gear for public safety services, and a few broadcasting transmitters. Mass production of tube receivers for the consumer market wouldn't be possible that early. But since GE is willing to license its technology to raise cash, other tube manufacturers may be starting to appear in the 1637-1638 time frame. Radio equipment manufacturers may start to show up as soon as GE can make enough tubes to begin selling them as parts, since ham-level knowledge is enough for that purpose, and the Grantville Amateur Radio Club and the military training program have been teaching radio technology since at least 1633.

Although this is the ***tube timeline,*** it is not inappropriate to mention in this context that with the spread of GARC and military trained radio operators, there has been a spread of downtime built from all downtime parts spark-gap based Ham radios with crystal receivers and an active commerce in parts for them as shown in Huff and Goodlett's “*Waves of Change*” (GG 9.) These people and their radios form the core of the “European Radio Relay League” mentioned in past radio FAQ's and *“Paper Mate”* (GG 38), *“Catrin's Calling”* (GG 40). Spark transmitters will be suppressed as soon as possible primarily because they are very wasteful of bandwith, but also because they require vast power for the same outcome as CW transmitters.

RF alternators are at least a year ahead of high-power transmitting tubes both in terms of availability and in terms of absolute power produced. This continues for several years. In the OTL, production of alternators for extreme high power long-wave trans-oceanic communication continued up until World War II. In the NTL, two more alternator-based AM broadcasting transmitters are ordered and delivered after VOL, before tube transmitters make them obsolete; the first for the Jesuits at Muenster, and another in Würzburg in Franconia.

Alternator transmitters for CW are not obsoleted as soon. The navy orders a small number of high-power alternators (presumably five) for the backbone of a naval ground wave net covering the southern Baltic in late 1633, following the completion of the first prototype for VOL, even though Admiral Simpson knows all about the tube project. He reasons that the navy can't afford to wait, especially with the uncertainties in the development schedule, and that even after tubes begin to become available, they will be no match for the raw power of the alternators, particularly when used for long-wave cw. After the breakthroughs in October and November, it's unlikely that any new alternators would be ordered for radio communication, except possibly for anchor stations for trans-atlantic CW messaging.

Finally, RF alternators will find applications in industrial RF heating, since they will continue to out-pace tube amplifier designs for absolute raw RF power until materials science manages advanced graphite and advanced alloy materials.

Looking further forward

GE probably won't achieve VHF tubes much before 1637. They'll do it by reverse-engineering up-time tetrodes[1] and pentodes[2], especially the 6146. Once they reach that milestone, many things will suddenly become practical. VHF is ideal for land point-to-point and mobile communications. The army, police and fire departments, commercial transportation, point-to-point common carrier services, and hams would all be able to break out of the severe shortage of VHF equipment. Depending on terrain and siting, communication with mobile units up to 150 miles from a base station is possible. Mountaintops would become extremely desirable real estate. With higher power, fixed point-to-point links as long as 500 miles can

1 http://en.wikipedia.org/wiki/Tetrode
2 http://en.wikipedia.org/wiki/Pentode

deliver reliable full-time service using tropospheric scatter propagation[3]; this is likely to form the basis of intercity telephone trunks.

Among other advantages of VHF is bandwidth. If an AM broadcast signal needs 10 KHz to deliver acceptable audio fidelity, then only 100 “channels” are available in the traditional North American AM medium-wave band from 600 KHz to 1600 KHz, or 270 across the whole “medium frequency” MF band from 300 KHz to 3 MHz. On the other hand, the VHF bands from 30 to 300 MHz could support 27,000 such “channels” at the same time in the same place. (In practice, modes such as Morse code CW and slow-speed teletype dominate the very limited amount of spectrum space below the AM broadcast band, because their signals take up much less than 10 KHz—as little as 100 Hz—allowing many more channels to fit in. Similarly, FM[1], which suppresses natural noise much more effectively than AM or single sideband[2] at the cost of considerably greater channel width, becomes practical in the VHF and upper HF regions, where there's enough bandwidth available to accommodate these wider signals.)

RCE and AT&L will need to decide whether to extend their networks in the near term using lower frequency equipment, or conserve their capital until the more economical VHF equipment becomes available.

For a given channel width, each step “up” the frequency range results in a factor of 10 increase in the number of “channels” available in a band, from 27 in the “long wave” 30 to 300 KHz to 270 in the MF band, 2700 in the HF band from 3 to 30 MHz, 27,000 in the VHF band, and potentially 270,000 such channels in the UHF band (300 MHz to 3 GHz). It's easy to see why designers in the OTL keep increasing the frequency of our radios.

UHF capabilities, while exciting, are extremely difficult to manage with tubes since the tubes themselves are a substantial fraction of the wavelength of a UHF signal. The increasing mathematical sophistication and manufacturing complexity as tubes evolve to higher frequencies directly translates into a demand for better-educated and more experienced engineers, and many more of them. In OTL it took from 1907 until the mid-1930s to create decent UHF tubes, with a world-wide industrial base, and into the WW2 era to achieve high-power microwave transmitting tubes. Thus UHF and above work will doubtless wait until the latter half of the 1640's, and UHF semiconductors may not come until a couple of decades after that. (Microwave semiconductors are *much* more difficult than microwave tubes.) In the first quarter of the 21st century OTL, the VHF region is largely saturated with wall-to-wall signals, and much radio work is moving above the UHF bands into SHF (3 GHz to 30 GHz—1 cm to 10 cm wavelengths, common for WLAN and wireless USB connections, for example) and EHF (30 to 300 GHz—also known as “millimeter waves”. Do not expect large-scale use of UHF and above frequencies before the 1660's to 1670's, with the re-development of medium-power advanced transistors and FET devices.

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3 http://en.wikipedia.org/wiki/Tropospheric_scatter

1 http://en.wikipedia.org/wiki/Frequency_modulation

2 http://en.wikipedia.org/wiki/Single-sideband_modulation

Summarizing

October 1633	First Alexanderson Alternator
February 1634	VOL on the air
October 1634	First down-time experimental tube
November 1634	First sealed glass down-time tube
March 1634	First of five Naval CW alternator stations
December 1634	Second Alexanderson alternator station in Wuerzberg
February 1635	Pilot production of all downtime amplifier triodes
Spring 1635	“6L6” style 25 watt transmitter tubes
Spring 1635	Prototype military CW tube transmitter
Summer 1635	Prototype military CW tube receiver
Fall 1635	200 watt all downtime transmitters.
Fall 1635	“mass production” of low power tubes (hundreds/month)
circa 1637	True mass production of tubes allowing consumer products
late 1637	Downtime VHF capable tubes.
Circa 1640	True high power tubes (810A & larger)
1642-1645	effective “UHF” and “Microwave tubes
Circa 1650	last of the RF Alternators retired from active service.
Circa 1650	Spark transmitters banned in Europe.