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They Will Soon Be Gone, But Not Forgotten

Tube amplifiers, the foundation of modern broadcasting, now disappearing

By **Michael LeClair**

Michael LeClair Manager of Broadcast Systems, WBUR, Boston, CPBE and editor emeritus, Radio World Engineering Extra

When the topic of tube transmitters comes up, it causes broadcast engineers of a certain age to look back fondly to their past. To understand their nostalgia, it doesn't hurt to remember that tubes have been in use for over a century in the broadcast industry.

Tube transmitters have always had their elements of "romantic" appeal. The oldest tube versions, with their glass envelopes surrounding a mysterious physical Erector Set of metal plates and wires, even emitted a warm glow like a comforting campfire. Modern versions retained the strange mechanical shapes that visibly expressed the physics of tube operation, with individual ceramic insulated rings for grid, anode and plate. Silver-coated heat sinks are welded to the plate itself, suggesting that these things are built for speed and, more importantly, huge amounts of raw power. Maybe that's part of what explains the mysterious appeal of tubes: the ability of something that can be held in two hands to control such an enormous quantity of electromagnetic power.

As we look at the landscape of radio transmitters in use today, it's hard to find many of these amplifiers still around, and the number is declining with every year's replacement budgets. Dave Supplee, Northeast regional engineer at Cumulus Broadcasting, is responsible for about 75 stations. He summarized the situation succinctly: "We have been purchasing new transmitters across the company to replace transmitters that are no longer supported or are troublesome. We are not buying new tube transmitters."

EARLY SUCCESS

It's important to reflect on the fact that tubes were

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Have You Bought Your Last Tube?

If you're running an older tube transmitter, you might have had the thought: Should you continue buying tubes or would you be better off with a new transmitter? It's a question that faces many broadcast managers. Radio World's September ebook explores the topic.

What factors should be considered when making this important investment decision? Are tube transmitters more rugged and forgiving? How much more efficient are solid-state designs? How do tube and solid-state compare in terms of failure modes, frequency agility and ongoing maintenance costs? What is the expected life of a tube today? And what else should engineers know about the costs of ongoing tube operation today?

In two articles, longtime Radio World contributor Michael LeClair and Nautel's Jeff Welton, winner of multiple engineering awards, took on this topic.

This is number 60 in Radio World's series of ebooks exploring important topics for radio broadcast technologists and other managers. Find recent issues at **radioworld.com/ebooks**.

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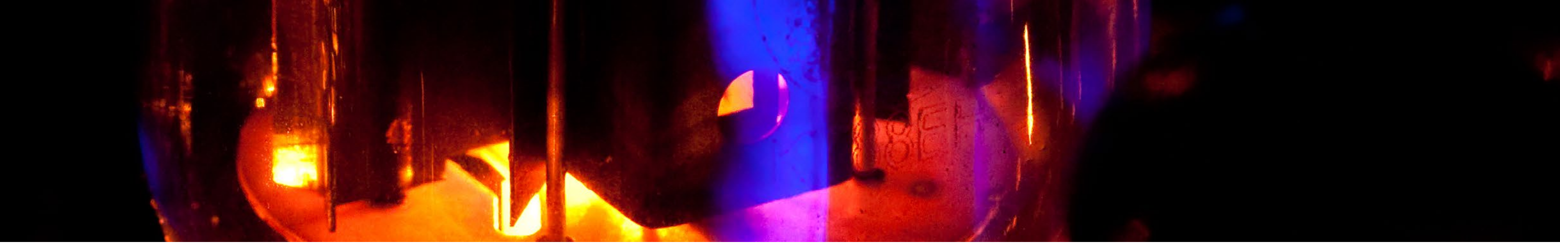

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themselves the result of a hundred years of theoretical and empirical science. At the time they were invented, it would have been difficult for the average graduate student in physics to even explain the mechanisms which allowed the tube to be the basic building block of a new science that would come to be known as "Electronics." Only a few understood the modern model of the atom with its loosely attached and massless electrons. Radio communications at the time were believed to occur through an invisible medium known as "ether" which allowed actions to travel at speeds that were invisible to the human eye.

To broadly summarize this early era, the goal was to develop a method of controlling something large with something small. If a small signal could be reproduced accurately, only larger, amplification of power would be possible. The tube did exactly that by using static potential and virtually no current to control the size of a large stream of electrons flowing from cathode to plate. The world quickly embraced the possibilities.

GOLDEN AGE

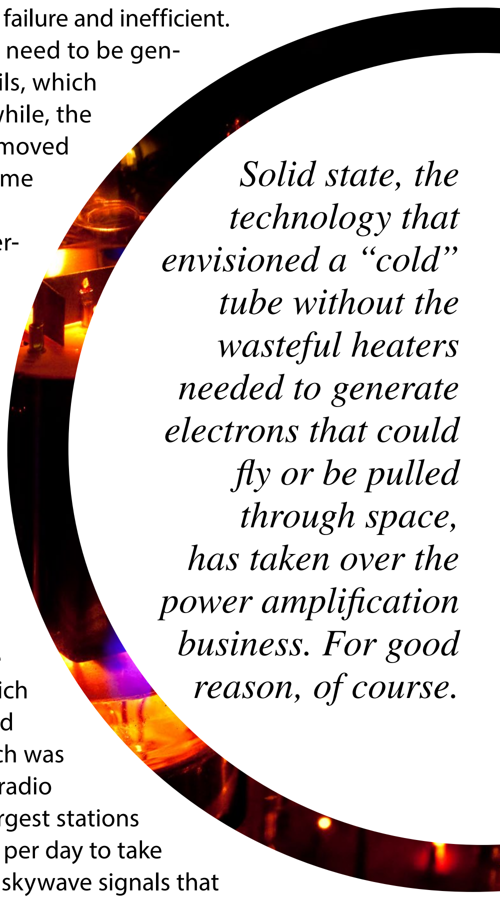
From the development of the first working experimental tubes, by Lee de Forest in 1906, electronics developed rapidly with radio being one its most important applications. About 20 years later the Federal Radio Act of 1927 was formed to regulate the rapid growth of radio stations attempting to operate in this new exciting world of electromagnetic communications. Less than 10 years later (1934), radio station WLW became the most powerful commercial radio station ever built in the US, designed to generate a half-million watts of signal to cover the earth with signal. Water-cooled tubes five feet tall were at the heart of a system that used enough energy to supply a small city.

There seemed to be no limit to the power of tubes. But in fact change for the industry was just around the corner. In that same year, 1934, the Communications Act was passed that created the Federal Communications Commission and the beginning of a standardized and rationed industry. Instead of monster, one-of-a-kind creations, radio stations were allocated to geographic coverage areas and sizes that allowed many signals instead of a few. It also allowed manufacturers to begin to develop standardized amplifier designs that would set the stage for a modern manufacturing business.

THE DRAWBACKS

Radio grew dramatically in those early years, capturing the imagination and interest of a public that had no other means of communication across wide distances. But this rapid growth actually concealed the drawbacks of tubes in the world of electronics. First of all, the need to create a vacuum inside a tube meant initial designs used glass and were very fragile. Second, to enable the creation of freely flowing electrons in space required a combination of special materials and quite a lot of heat, which made tube amplifiers both prone to failure and inefficient.

Not only did the heat need to be generated using electric coils, which became brittle after a while, the same heat had to be removed from the amplifier in some way before it grew hot enough to melt the internal metal grids. Electronic circuit designs were themselves inefficient and dissipated large amounts of energy in the tube plate or cathode, and this waste heat contributed to the inefficiency of early tube transmitters.



Solid state, the technology that envisioned a "cold" tube without the wasteful heaters needed to generate electrons that could fly or be pulled through space, has taken over the power amplification business. For good reason, of course.

Baked into the design itself was the limited life of cathode emission which led to failure after limited hours of operation, which was especially noticeable in radio operations where the largest stations would operate 24 hours per day to take advantage of nighttime skywave signals that could stretch thousands of miles. Engineers were trained in that era to keep detailed logs of the number of hours of actual tube operation, both to assist in the proper operation of the amplifier, but also to predict the inevitable failures. Tube life depends on the type and, more importantly, on the operating power. Robert Combs, Cumulus senior regional director of engineering in the Southeast, says, "If we use the HT-25 as an example, with the output power at 24 kW we might have to replace the tube once every year or two. The tube may last 3–4 years if the TPO is 21 kW or less."

Proper filament management allows tube life to be extended greatly if the power is 90% or less of the tube rating.

THE COLD TUBE

Tubes were the innovation that led to development of radio and electronics. But it was clear from the beginning they were not perfect. As the science of physics developed further, and partially driven by the World Wars, scientists became intrigued by the idea of developing a way of accomplishing the same actions as a tube amplifier but at *room temperature*, avoiding the heat problems of the vacuum tube as well as the vacuum itself. In 1947 the bipolar transistor was invented at Bell Labs by the team of Shockley, Brattain, and Bardeen. It did not itself operate identically to a vacuum tube with its high impedance grid, but Bell Labs demonstrated that the principal of using room temperature materials to control large electron flows with small signals was possible. Although these initial transistors were barely able to create even a modest gain, the development of semiconductor physics was the first step toward the replacement of the power tube.

From that moment onward, the future of the tube began to be questioned. The development of the digital computer, and the nascent field of Information Technology, would end up being a powerful impetus to replace most tube applications and lead to the massive growth of what we now call the semiconductor industry. This growth in turn drove the cost of solid-state components down rapidly.

THE CONTINUED DEVELOPMENT OF HIGH-FREQUENCY POWER AMPLIFIERS

While it quickly became apparent to designers that for low-power signal processing, and computing, silicon amplifiers were the best route forward, it was less clear that these designs were suited to applications that tubes had always excelled in: high-power amplifier designs — in particular, amplifiers like those used in transmission of high-power broadcast signals. As a result, work on tube designs were continued, in order to handle the higher frequency transmitters required by FM and UHF TV throughout the 1950s and 60s.

When the manufacturing techniques for bonding a metal case and ceramic to create a successful vacuum were finally perfected in the 1960s, new lines of very high power tubes were created that allowed a relatively small form factor to handle much larger amounts of power while maintaining the simplicity of air-cooling for modern transmitter designs. The 4CX350000 (weight 50 pounds) was a typical example of a tetrode tube that could *dissipate* waste heat up to 35,000 watts before the case would fail. In the power amplifier section with an efficiency of approximately 50% this meant one single tube could be used to generate as much as 70 kW of RF energy if driven properly (in practice designs were far more conservative to prevent overheating under less than ideal conditions). It remains unlikely that single, or even common wafer, silicon amplifiers will ever achieve anything like this power performance at high frequencies.

Instead of slowly dying out, the vacuum tube found itself a specialized niche in which to thrive for a few more decades: high-power transmission at high frequency.

FROM AUDIO TO SMALL AM

It was in the 1970s that the first solid-state designs for AM transmitters moved over from the audio field, in which it had been proven that kilowatt and higher-power designs were indeed possible. The mass production aspects of semiconductors that had been developed for the rapidly expanding Information Technology industry promised much less expensive transistors with costs declining even more over time. The promise of cheaper, more efficient and smaller designs proved to be a siren call to change.

As might be expected, these early designs sometimes suffered from reliability problems in the presence of high voltages from static electric fields or even resonant circuits. Tubes, after all, were designed to operate at plate voltages in the thousands, whereas it was difficult to build semiconductor designs that could withstand more than several hundred volts. But solid state offered an indefinite lifespan if well protected, higher efficiency and lower cooling requirements than tubes. Solid-state designs were largely wideband, allowing the same production amplifier to be used in any transmitter regardless of frequency of operation. Designers began to turn their focus on moving to higher-power transmitters and from MW to HF, VHF and even UHF designs.

THE COMBINER PROBLEM AND MODULAR AMPLIFIERS

As mentioned earlier, it remained unimaginable that single wafer or device designs could ever replace a modern, high-power tube with its huge power dissipation capacity. To solve this problem required amplifiers that were built around discrete amplifier modules at some more easily produced power level. To get to the high power levels required by broadcast transmitters, used by radio and TV stations, simple and efficient *combiners* were required. For example, if it became possible with

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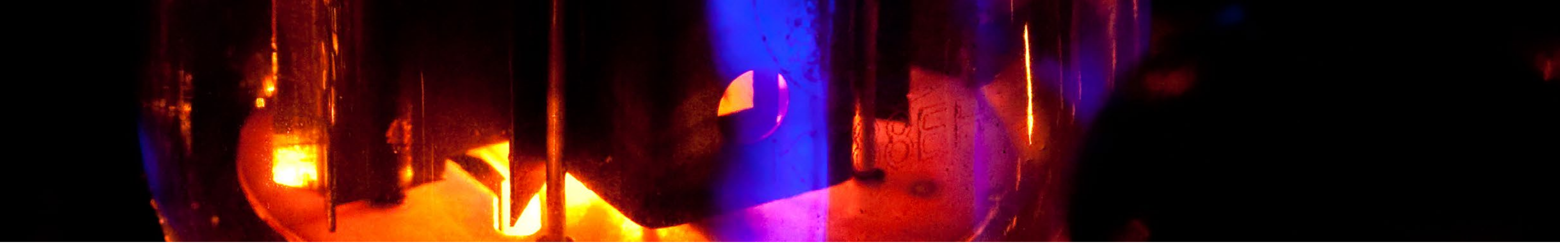

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advanced bipolar components to design a dual-device amplifier in push-pull configuration that could safely generate 500 watts, then combining two of these amplifiers into one output would allow the construction of a 1 kilowatt transmitter.

Extrapolating further, it would take approximately 20 of these 500 watt "pallets" to generate a full 10 kW solid state design, reaching a popular power level used by a large number of class B FM radio stations in the US (and similar allocations worldwide).

It took some time and experimentation to develop combiners that handled this task well; an RF combiner can't simply tie all the outputs of the amplifiers together into a copper bus bar (this technique doesn't even really work well for audio amplifiers). With the complex effects of impedance at high frequencies the combiner design must allow all the amplifiers to couple the maximum energy, which requires a matching source and load impedance, into the output load. At the same time, isolation must be achieved to avoid reverse driving power into each other.

The basic Wilkinson combiner (and its variants) ended up offering the necessary efficiency and high performance. It comes with a weak point — to achieve high power levels the combiner itself becomes quite large and even prone to destruction under poor load conditions (e.g. high VSWR as seen at the transmitter output).

Transmitter engineers "back in the day" used to joke about their ability to tune a rig into a soda can. With solid-state designs, transmitters themselves are a bit more delicate than they used to be, and automatic protection circuits to reduce power, or even shut down, under poor load conditions are no longer optional. Handling "the combiner problem" is now one of the important learned skills of maintaining high-power amplifiers.

However, with high-power combiners the last real barrier to the development of arbitrarily high power levels was breached and starting in the 1990s solid-state designs began to displace tubes for the majority of new transmitter sales for models up to 10 kW in power.

MODERN DESIGNS AND TODAY'S TRANSMITTERS

It turns out that the going back to the principals developed in early vacuum tube design proved fruitful when it comes to high-power semiconductors. The physics of power tube construction present a very high impedance at its input because of the lack of a connection between the grid and the other tube components (cathode and anode on a triode).

The latest solid-state designs for transmitters have adopted a similar property, employing what are known as Field Effect Transistors (FETs) that also feature an isolated input with high impedance. This type of transistor offers the possibility of more gain at higher frequencies (and thus higher efficiency). The use of the latest FET designs now make transmitters cost effective at powers above 20 kW. Using combiners, manufacturers are now offering designs as large as required for broadcasters, 60 kW or even larger.

We're also seeing the revival of another old tube technique for high-power designs: the water-cooled semiconductor amplifier. These offer reduced operating costs over the life of a transmitter and have been used in the TV broadcast industry (with its UHF allocations at high power) for many years.

Especially for stations operating in less profitable locations outside of major markets, a tube auxiliary is a nice, low-cost backup to analog-only operations.

THRILL IS GONE

There is little case to still be made for tube amplifiers in new designs, and it's unlikely that anyone reading this article will ever buy another new tube amplifier for a broadcast station. Solid-state amplifiers have won this competition and represent the best solution for high-power transmission.

Although some specialty manufacturers remain, there are few options for newly manufactured power tubes and it appears to just be a matter of time before the venerable tube becomes nearly impossible to get. Most engineers are using a dwindling pool of rebuilds. Supplee notes, "Beginning about 10 years ago, we started to see a decrease in the rebuilt transmitter tube life, and when tubes are replaced we are seeing increased instances where a rebuild has to be sent back two or more times." Combs agrees. "As tube transmitters are being phased out and fewer new tubes are being purchased, the rebuilt tubes we are buying have been rebuilt multiple times and are not as reliable."

Another disadvantage for tubes is the increasingly compact size of solid-state amplifiers. “With a tower site that might have three high-power stations together, the tube transmitters would take up an entire room. Three 30 kW solid-state transmitters would fit in the same footprint as one 30 kW tube transmitter and high-voltage power supply cabinet.”

All engineers mentioned the greater flexibility of new modular designs. “With the new solid-state transmitters, if you lose one power supply or PA module you lose 1,000 watts or so and you keep right on broadcasting. If your tube goes out you are off the air,” says Combs.

Solid state, the technology that envisioned a “cold” tube without the wasteful heaters needed to generate electrons that could fly or be pulled through space, has taken over the power amplification business.

BUT NOT FORGOTTEN

This is not to suggest that I would recommend anyone go out and throw away a working tube transmitter, for example in use as an auxiliary on rare occasions. Especially for stations operating in less profitable locations outside of major markets, a tube auxiliary is a nice, low-cost backup to analog-only operations. Even with a limited tube lifetime of maybe 10,000 hours, at a few hundred hours operation per year that could last for centuries. Indeed, there are many instances of stations happily doing just that. Doug Irwin, iHeartMedia’s vice president of engineering for the Los Angeles region and the former editor of Radio magazine, notes, “We have three auxiliary transmitters still that use tubes. Since they’re in aux service now they last for years.” Inexpensive insurance for most stations if they have an operating tube transmitter around that can make full TPO.

SHOULD I BUY ANOTHER TUBE TOMORROW?

For most stations operating tube transmitters, if a key part, or the tube itself, were to fail, the choice of simply buying a solid-state amplifier (possibly at 50% of the licensed TPO) to replace a multi-thousand dollar tube or amplifier rebuild, is something most engineers should consider. The price of these smaller amplifiers, all of which can now be easily placed in a rack with room to spare for other equipment, has become much more affordable for even low-budget stations. If this is to replace an auxiliary transmitter and only expected to operate for short periods of time, a solid-state backup at reduced power is really all that one needs in many locations.

For those of us who grew up in the era of tubes the choice of solid state is understandably logical. But that doesn’t mean we have to forget this formative technology from over a hundred years ago. The concept of high-power transmitters owes its existence to the development of the power tube. Tubes will remain the foundational technology that led to a technological revolution and the development of the modern electronics industry, even as our transmitters hum along on solid-state power. ■

Factors to Weigh in Your Tube Talk

Q
A

We asked Jeff Welton about ROI and the role of tubes today

Jeff Welton is known for sharing great ideas. Recently, two important engineering organizations recognized that formally.

The Association of Public Radio Engineers saluted him with its 2019 APRE Engineering Achievement Award; and the Society of Broadcast Engineers recognized him with the 2018 James C. Wulliman Educator of the Year Award.

Welton is central U.S. regional sales manager for Nautel, sponsor of this ebook, but his technical expertise and hands-on approach go well beyond those of many salespeople.

We raised the tube question with him.

Radio World: *As you talk to transmitter users and prospective buyers in your work, what's your feeling about how tubes fit into the overall transmitter picture today?*

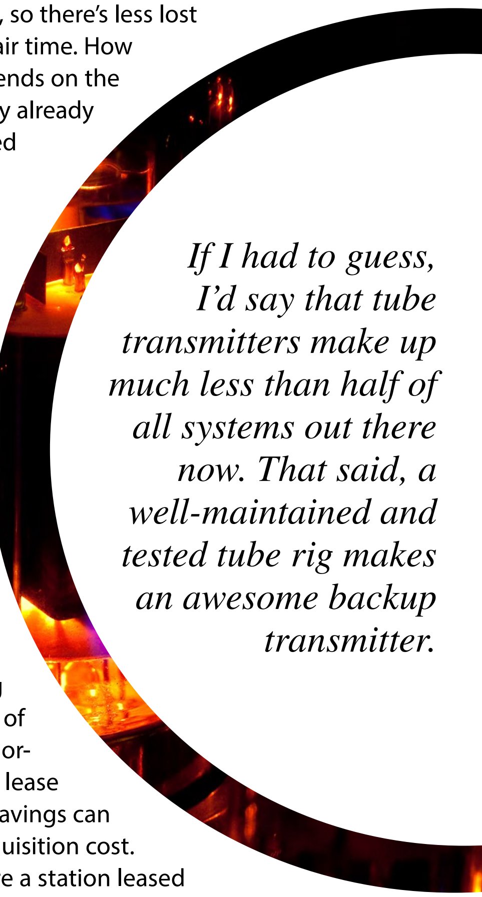
Jeff Welton: As time marches on, they'll eventually go away — in higher-power FM, there are still quite a few out there; however, as the engineering talent that has familiarity with the intricacies of working with glassFETs slowly dwindles, I think you'll see those numbers declining, as well.

There are definite advantages to using solid-state (of course, I may be biased). If I had to guess, I'd say that tube transmitters make up much less than half of all systems out there now.

That said, a well-maintained and tested tube rig makes an awesome backup transmitter; so if you have one, unless space dictates otherwise, it's not a bad idea to keep it as long as it can be maintained.

RW: *Users may have older tube transmitters and wonder whether they'd be better off buying new. So let's start with the plusses of new: What are the advantages of solid-state over tube type designs?*

Welton: The obvious advantages are cost of operation and redundancy. As a rule (not always, but almost always) a solid-state transmitter will be more efficient, so it will consume less power from the grid for any particular output. It will also produce less heat in the process, so there are savings to be had in two areas. Multiple power supplies and amplifiers mean that a failure doesn't take you off air, like it would if you arced a plate blocker or blew a doorknob capacitor, so there's less lost revenue due to off air time. How much, though, depends on the levels of redundancy already employed (well-maintained backup transmitter with automatic switching, etc.)



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RW: *But do you find that many users are attached to their tube systems, both because of familiarity as well as cost factors? What do you hear in the field?*

Welton: Very, very few — and it's a rapidly decreasing number.

There are some who are quite apprehensive about the cost of acquiring a new box, as it's a big number. However, in a lot of cases, especially if you amortize it over the period of a lease or bank loan, the overall savings can actually outweigh the acquisition cost.

I've had situations where a station leased a solid-state transmitter to replace a tube rig, and the savings in operating costs actually made the lease payments. Obviously that's not always the case, but it's something to consider, especially if the current rig is eating you out of house and home, electrically speaking!

***RW:** What considerations then should an engineer or manager use to assess the ROI on a new purchase?*

Welton: It's not enough to just look at purchase price. Look at the power bill now — and get the manufacturer to use that to provide you with a ballpark of what it would be with the new rig. Remember that this will just be an estimate — demand costs and overage charges can be hard to calculate without an intimate knowledge of the specific utility.

Also factor in the amount of time your engineer spends doing repairs — or if you have a contract engineer, what it's costing in emergency calls. Don't expect engineering costs to go away; if you're not doing maintenance, it's the same as owning a car and never changing the oil ... it's not if you'll have a failure, but when. However, you can factor in the cost of emergency repairs and tube costs; those alone can make up several thousand dollars a year.

Also look at air handling; if you're air conditioning, you'll need less of it as a rule. Forced air is less a concern. Obviously you should look at extra costs that may come with a new rig, also; liquid-cooled systems, for example, tend to have much higher installation costs associated with the plumbing. That's a one-time thing, but it does need to be considered.

If you are using air cooling, you may decide to switch from forced air to air conditioned; that's also an impact on ROI.

Remember that manufacturers will typically be leaning toward the solutions they provide, so get a couple of different opinions, even if you already think you know what you are leaning toward.

Getty Images/hh5800

***RW:** What's the expected life of a tube these days?*

Welton: It varies, a lot. Some of the more popular systems out there are lucky to get 11 months out of a tube anymore, even with careful filament voltage management. Others are still good for a couple of years. I think the days of seeing 50,000 or more hours on a tube are pretty much gone. Part of that is systemic — the folks who know how to manage tuning for maximum tube life are slowly leaving us — and part of it seems to be related to material factors, but that's not an area I'm proficient in, for obvious reasons.

***RW:** How much more efficient are solid-state designs?*

Welton: For the most part, overall efficiency of a solid-state FM transmitter is around 72% these days — that's AC to RF. For tube transmitters, efficiency can vary from less than 50% for a grounded grid design, to 65% or higher for some of the other designs, so the efficiency of a solid-state design will be somewhere between 10 and 50% higher than that of the tube system, as a rule.

***RW:** How do tube and solid-state compare in terms of failure modes, frequency agility and ongoing maintenance costs?*

Welton: That's a loaded question — and a multi-part one!

In terms of failure modes, outside of exciter-generated spurs and distortion, almost any failure in a tube transmitter is off-air time. In a solid-state design, very few failures result in off-air … a controller failure, or in the case of liquid cooling, a heat exchanger failure or hose rupture, all of which are very rare, are about the only things that could take the system totally off-air. Obviously, I'm generalizing to things specifically inside the box.

Frequency agility is much higher in the solid-state rigs; I think pretty much every one being built today is front-panel changeable from any frequency in the broadcast band to any other. Obviously there may be external items that need to be tuned — antennas, combiners, mask filters, etc., but for the transmitters and exciters, it's basically "dial up the new frequency and hit <enter>."

It's not enough to just look at purchase price. Look at the power bill now … Also factor in the amount of time your engineer spends doing repairs.

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As to ongoing maintenance costs, you'll always need to replace fan filters, you'll always need to check and tighten hardware. Some like to argue that the higher number of fans in some solid-state transmitters is a higher cost; but a tube transmitter has a single blower that runs anywhere between 500.00 at Grainger to 2500.00 from the factory, compared to dozens of 40.00 muffin fans in the solid-state rig (or fewer 200.00 feather fans). Ultimately the end result is the same, except that losing a couple of the 40.00 muffin fans can't take you off-air. If your solid-state rig only has four or five fans, you're rolling the dice whenever one fails on a hot day. If your squirrel cage fails on the tube box, the airflow sensor will shut you off immediately, unless it's bypassed …

So, in short, maintenance costs, for a properly installed system, should be about the same.

One other thing to remember is that fans — and electrolytic capacitors for that matter — are highly temperature sensitive; the cooler the room is, the longer they'll live. This is true for virtually any electronics, so there are arguments to be made for keeping the room comfortable.

A tube that's been sitting on the shelf untouched for a few years could reward you with a raucous BANG the first time you bring it up.

RW: Nautel has a "cost of operation" spreadsheet, what's the link to that?

Welton: Yes, this handy tool will calculate the estimated cost of operation savings of switching from a tube transmitter to a Nautel solid-state transmitter year over year. You can find this Cost of Operation Comparison calculator at https://www.nautel.com/cost-of-operation/.

RW: *What else should engineers know about the costs of ongoing tube operation today?*

Welton: I think we've covered the bulk of it. One thing we didn't mention was that tubes need to be exercised consistently, or they'll gas up. So a tube that's been sitting on the shelf untouched for a few years could reward you with a raucous BANG the first time you bring it up … It's a good idea to cycle spare tubes through the system on a regular basis (adding to the maintenance costs, mentioned above). ■

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