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Analysis of Lifetime Data

For the

Linac 201 MHz Power Amplifiers

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Introduction

This document analyzes data on the lifetime of the 201-MHz triode power amplifier (PA) vacuum tube, model number 7835, used in the low-energy half of the Linac. The Linac staff, particularly Larry Allen, has collected data on these tubes since the beginning of operation in 1969. No one has conducted a careful analysis of the accumulated data until now. With these data, it is possible to estimate how often we should be prepared to change these tubes and the number of spare tubes required for smooth Linac operation.

First, we present some background information on the 7835. Then we describe and count the various failure modes of this device. Next, we examine the lifetime of these tubes. Finally, we make some conclusions on the lifetime data and on how many tube we need to operate reliably.

A recent summary of the status of the entire 201-MHz Linac system may be found in the reference[1].

[1] C. W. Schmidt, et al., "Status of the Low-Energy Linac 200 MHz Stations," Fermilab TM-2166, March 2002.

Background on the 7835s

The 7835 tubes provide the final amplification that drives the five 201-MHz resonant drift-tube cavities to 4.5 MW in the low-energy half of the Fermilab Linac. These tubes were originally manufactured by RCA in the 1950s for radar applications in the military. Now, Burle Industries' Electron Tube Division in Lancaster, Pennsylvania, manufactures and rebuilds them.

➢ Nomenclature

These tubes are known by their serial number, which takes the form:

`<Letter><number>`**`R`**`<number>`, *e.g.*, **`X12R7.`**

The initial letter(s) and number, in this case "**`X12`**," is the serial number of the tube assigned by the manufacturer. The second combination represents the number of times a tube has been rebuilt, in this case seven times. On a new tube the **`Rn`** part is not included, e.g., **`AZ4`**. The serial number is stamped on a label attached to the tube.

The original model number for this style of tube was the "4617," a match to the driver tube, the 4616, which we use as our driver tube today. Modifications to the design of the 4617 were made to increase the lifetime of this tube and the resulting tube was called the 7835.

We present here the definition of a few basic terms.

- A tube that doesn't work anymore is called a "dud."
- A "carcass" is a dud that cannot be rebuilt. The manufacturer scraps carcasses, and uses them for parts.
- As with any other vacuum tube, the place in which the tube is placed for it to operate is called a "socket."

➢ Tubes Received at Fermilab

Table 1 shows the number of new or rebuilt tubes we have received over the years:

Rebuild Num.	# Tubes	In Inventory	Scrapped	% Scrapped
New	35	2	1	3%
1	33	1	3	9%
2	32	1	6	19%
3	24	2	2	8%
4	19	1	2	11%
5	14	2	0	0%
6	11	5	0	0%
7	6	3	0	0%
8	3	3	0	0%
9+	0	0	0	
Total	*177*	*20*	*14*	8%

Table 1. Tubes received at Fermilab

As of this writing, we have 20 tubes presently in our inventory: five operating tubes, two spares, six failed tubes in storage in the Linac basement, and seven tubes at Burle waiting for work there.

➢ Other Sockets in the World

According to Burle, there are 29 sockets for 7835-like tubes in the world:

- Brookhaven (AGS): 9 sockets,
- Argonne: 1 socket,
- Los Alamos (LAMPF): 5 sockets,
- Quadulan Island (a military installation in the South Pacific): 4 sockets (these are sockets for 4617s).

Thus, our five sockets represent about 17% of the sockets in the world. None of the sockets at the other national laboratories are run as long each year as the tubes at Fermilab, so in some sense, our demand for 7835's is greater than our 17% of the world's sockets.

➢ Burle's Role

Burle's plant in Pennsylvania is responsible for all work on the 7835, 4617 and 4616 power amplifier tubes. (They also manufacture a variety of other power tubes, big and small, including one called the 7651, which we use to drive our 4616 tubes.) Tubes are tested, built and rebuilt in the same facility by a single group of engineers and technicians. Most of the work is done at their plant in Lancaster, although outside contractors do some mechanical work. Burle cannot perform power tests on the tubes. Burle is the sole source for new and rebuilt tubes of this type.

Burle usually can rebuild a dud and the resulting tube is generally believed to be as good as new. We send several duds per year back to Burle to be rebuilt. When Burle receives a dud, they first perform a task called "TC&A", which stands for "test, cut and analyze." This task reveals whether a dud is repairable and, if so, the extent of repairs required. Generally, a TC&A takes about three weeks, after which time we receive a memo stating the cost of and time to rebuild the tube. According to the data presented in Table 1, we have observed that about 8% of the duds we send to Burle cannot be repaired. Burle uses carcasses to provide materials for future rebuilds. It is generally believed that there is a limit to the number of times a tube can be rebuilt—that limit was once thought to be four rebuilds, but clearly this is not true anymore.

Depending on the complexity of the rebuild task, it takes between two and nine months for a tube to be rebuilt. Today, the lead-time for a brand new tube is said to be about eight months. We currently have one new tube on order, our first since 1996 and only the second since 1986. In recent years, Burle has produced ten to fifteen new and rebuilt 7835-class tubes per year for the world customer base[2].

[2] Personal communication with Bob Rutherford at Burle, May 29, 2002

Data Analysis of Tube Lifetimes and Failure Modes

Failure Modes

The reasons why we remove a tube from service are listed and counted in Table 2.

Reason	**Explanation**	**Num**
Low Emission	This is the way a tube is supposed to fail. The cathode is no longer able to provide the flow of electrons necessary to sustain the required amplification and power levels.	118
Sparking	This can be external sparks across the ceramic or internal sparks. A tube that fails with external sparks can often be sandblasted (to clear away the carbon tracks from the ceramic) and put back into service. A failure from an internal spark is fatal.	59
Removed without failure	Sometimes we need to shuffle the tubes around, for example, when we decommissioned tanks 6 through 9. Also, Tank 1 can use a weaker tube, so we might remove a tube that is still operating in another system, but is having trouble making power, and put it into Tank 1	30
Grid/Cathode short	This is a fatal failure. It is often a failure that comes early in the expected life of the tube.	14
Unknown		10
Gassy	For a vacuum vessel that has no active pumping, it is satisfying that this problem occurs rarely.	8
Water Leak	Usually, this is a leak on a connection that causes water to accumulate into the cavity in which the PA sits. The cavity usually can be repaired and the tube can be cleaned up and put back into service.	6

Table 2. Reasons for removing a tube from service

Recorded Lifetimes

There are two relevant lifetimes for a tube: The hours a tube gets in a single socket (the "socket lifetime") and the total lifetime a tube accumulates in multiple sockets (the "tube lifetime"). (We have no data on the shelf life of a 7835. We have not observed any problems with tubes in storage, as long as they are kept clean.)

A histogram of the socket lifetime for all tubes is shown in Figure 1.

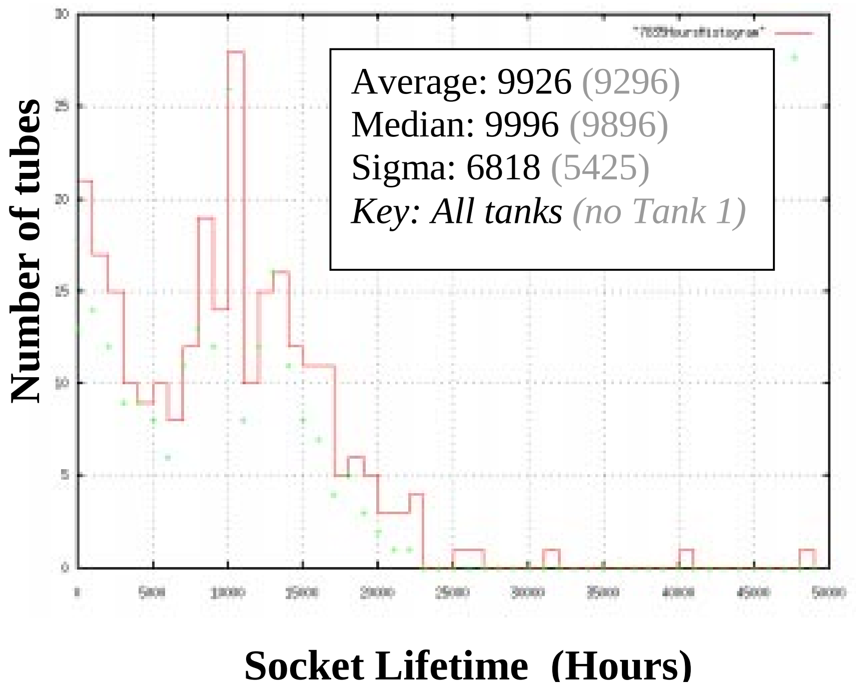

Figure 1. Socket lifetimes of 7835 PA tubes at Fermilab

Many short socket lifetimes are observed. Omitting Tank 1 socket data eliminates the longest socket lifetimes. The expected socket life of a tube is about 10000 hours, or 59 weeks.

A histogram of the tube lifetimes is presented in Figure 2.

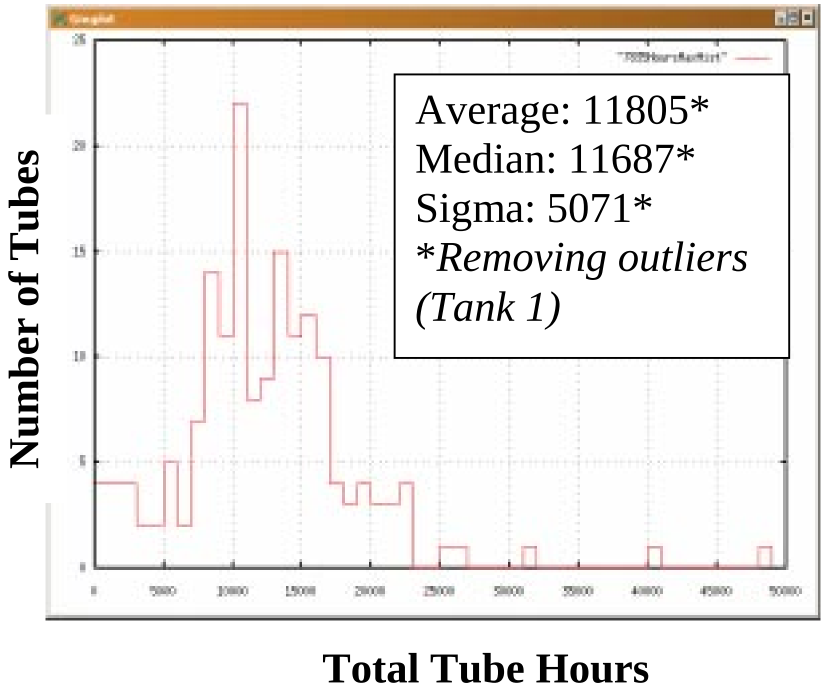

Figure 2. Total tube lifetimes of all the 7835 tubes at Fermilab

There are several important observations that can be made from these two figures:

- Most of the early "failures," apparent in Figure 1, are not fatal tube failures.
- The total expected lifetime of a single tube is about 12000 hours (70 weeks, 1.3 years).
- The standard deviation on this mean lifetime is about 5000 hours (30 weeks, 0.6 years).
- The peak of the distribution does not change much from Figure 1 to Figure 2.
- If a tube fails in a non-fatal way, it generally does so before 7000 hours (42 weeks) of service.
- Tubes in Station 1 last at least three times longer than tubes in other sockets.

Are the Tubes Failing Earlier Now?

There is a suspicion that the 7835 tubes are failing sooner now than they once did. Figure 3 shows the total life for a tube plotted against the delivery date of the tube.

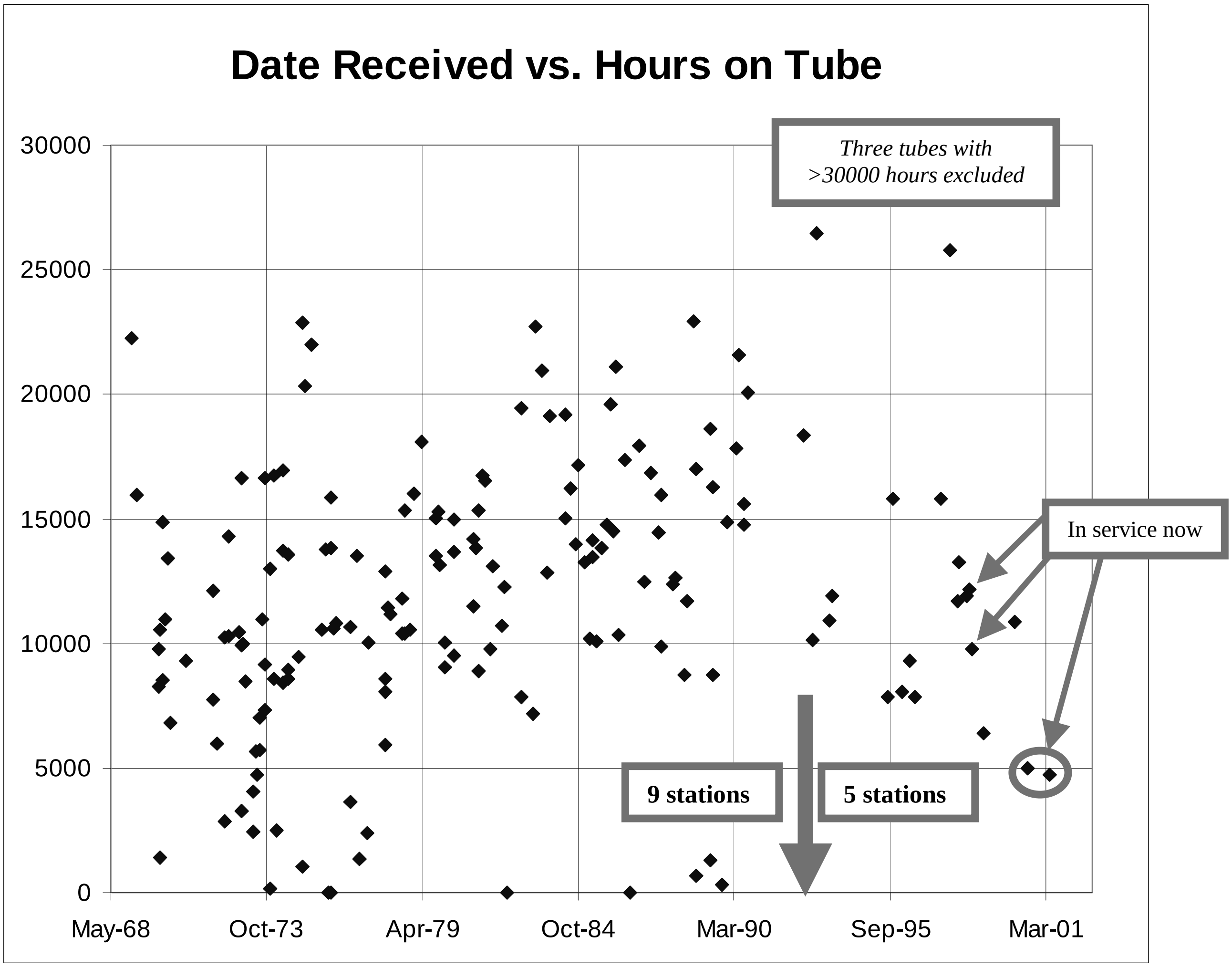

Figure 3. Tube lifetime as a function of date received.

(At the time the data for this report were collected, four operating tubes appear in the data, and they are marked with an arrow or a circle in each chart presented here.)

It might appear that the total lifetime of the tubes began to fall off at about the time we decommissioned Tanks 6 through 9. We have had no tubes (that were not driving Tank 1) since 1993 last for more than 18,000 hours. But, as shown in Figure 4, there is a hidden correlation between the rebuild number and the delivery date. Tubes received recently are more likely to have high rebuild numbers that a few years ago. The line in Figure 4 is a simple linear fit to the data.

This relationship is likely to end since we are unlikely to get enough R7's and R8's (and higher) to continue the trend.

Figure 4. Tube rebuild number as a function of date received.

Figure 5 shows tube lifetime versus the rebuild number.

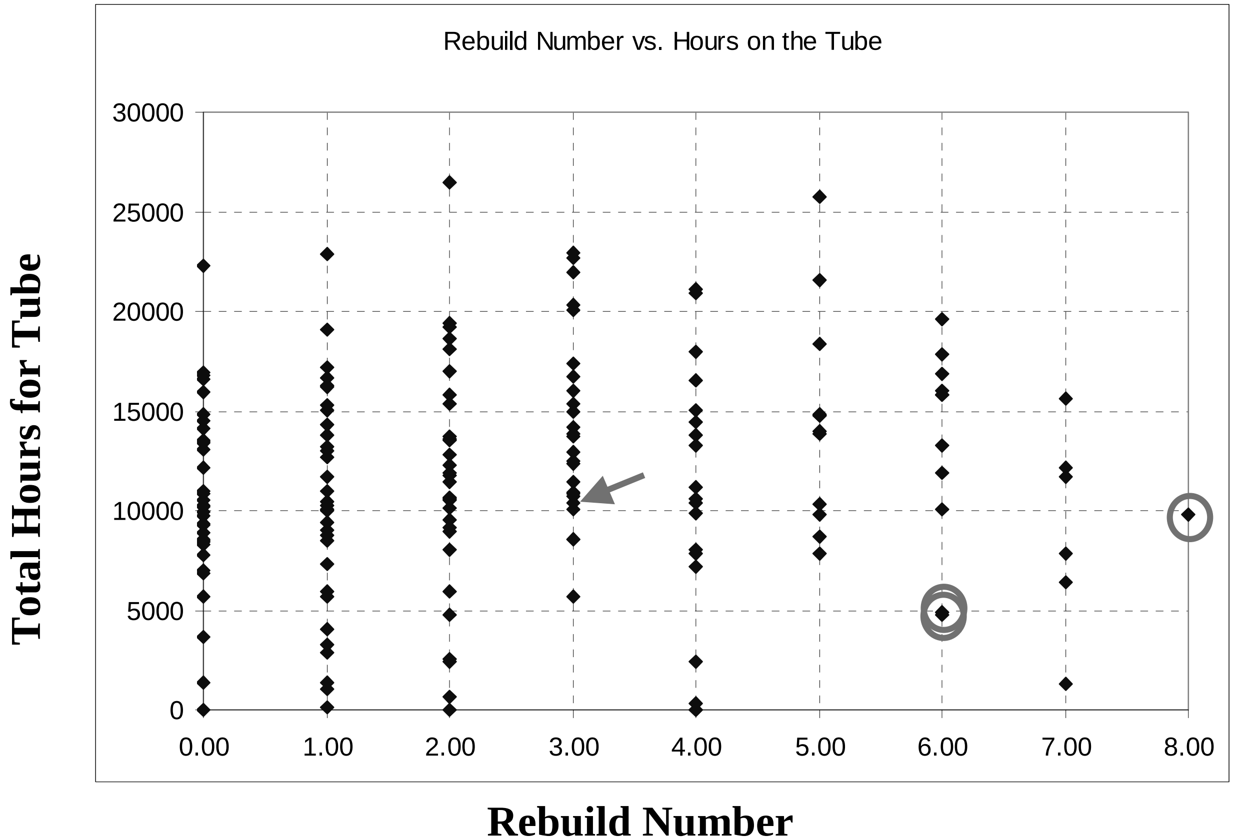

Figure 5. The rebuild number of the tube versus the total hours it achieved.

Beyond a rebuild number of 5 or 6, it appears that perhaps tubes cannot be rebuilt very well.

The lifetime of recent tubes is less than historical averages, but this correlates with the high rebuild numbers of these tubes. We are unable, at this time, to distinguish whether this is due to the high rebuild number or if Burle has "lost their touch." Further information may be obtained by buying more new tubes or by sending in low rebuild number tubes. We intend to do both of these things.

Observations

Meeting Our Current and Future Tube Needs

Acquisition of new or rebuilt 7835 PAs is necessary to achieve each of three objectives:

1. To replace the steady state operational failures
2. To build up and maintain a sufficient spare stock to cover the periods of “bad luck”
3. To build up additional spares as a hedge against supplier problems or withdrawal

Assuming the lifetime of today’s tubes is the same as our historical average, a new 7835 tube should operate for about 1.3 years. A tube in Station 1 will work for about 3 years. Thus, from a steady state perspective, the estimated number of tubes we must replace per year is about:

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4*(1 tube/1.3 years) + (1 tube)/(3 years, tank 1)
                = 3.41 tubes/year
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The estimated error on the number of tubes we need per year, based solely on the measured standard deviation in the lifetime of these tubes of 0.6 years, is about one tube per year.

Ideally, this steady state objective is met by receiving a tube from Burle whenever an operating tube fails. Of course, this is impossible to achieve since we can control directly only when we send duds to Burle for TC&A and potential rebuild and when we place new tube orders. Assuming Burle can support a steady state pipeline and that the time for new tube production is comparable to time for rebuild, our normal replacement needs can be met by sending one dud for repair or placing one new tube order every three months. This covers the 3.4 failures per year plus the 8% of the tubes that fail to be repaired.

The number of tubes required on hand to cover the periods of “bad luck” is somewhat subjective. A “3σ” bad year would require replacing 3 tubes more than in a typical year (7.4 tubes). Therefore a spare stock of 4 or 5 tubes is not unreasonable insurance for this eventuality. Having these extra tubes in reserve also would provide a buffer if, in fact, current tubes do not live as long as the historical averages.

The Burle pipeline is about nine months long. Therefore, in the steady state situation where we return one failed tube every 3 months plus an occasional “bad luck” tube, we would typically have between 3 and 6 tubes at Burle at any time.

In this case the total steady state tube inventory would be 14 tubes: 5 operational, 4 at Burle in rebuild or manufacture, and 5 on-hand to cover “bad luck”.

As a hedge against supplier dropout, it has been recommended [Schmidt, ibid.] that an additional spare stock of 6 to 8 good tubes be acquired in the next few years and that the number be increased to 12-15 tubes in eight years. Since none of this stock currently exists, orders should be placed, above and beyond the steady state needs, for 3 new or rebuilt tubes per year for each of the next two years and for 2 tubes for each of the following four years.

Summary

We observe that a 7835 power amplifier vacuum tube has historically provided about one and one-third years service in the Linac. The lifetime of recently re-manufactured tubes is somewhat less, but it is not clear if this is because the manufacturer is "loosing their touch," or because tubes cannot be effectively rebuilt after a certain number of times.

Taking into account the expected tube lifetimes, the statistical fluctuations on this number, and the amount of time it takes for the manufacturer to make good tubes, we require about 14 tubes either operating, ready as good spares or being manufactured, in order to have sufficient spares to run the Linac. As a hedge against supplier drop out, we need to increase our inventory of good spare tubes by about three tubes per year for the next few years.