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RELIABILITY AND LIFETIME PREDICTIONS OF SLC KLYSTRONS*

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Abstract

The energy upgrade of SLAC, with the first of the new 67 MW SLAC Linear Collider (SLC) klystrons, began over four years ago. Today there are over 200 of these klystrons in operation. As a result, there is a wealth of klystron performance and failure information that enables reasonable predictions to be made on life expectancy and reliability. Data from initial tests, follow-up tests and daily operation monitoring on the accelerator is stored for analysis. Presented here are life expectancy predictions with particular emphasis on cathode life. Also, based on this data, we will discuss some of the principal modes of failure.

1. Introduction

There have been approximately 514 of the SLC 5045 klystrons manufactured at SLAC. Many of these, particularly in the early part of this period, did not pass specifications or failed in bake or during initial tests. About 30% of the new starts were eventually rebuilt. To date, 372 of these klystrons were accepted for installation in the SLAC klystron gallery. The present compliment of 5045 klystrons in gallery sockets is 236.

There have been over 3,900,000 high voltage operating hours accrued in the klystron gallery. During this period there have been 110 failures resulting in a cumulative Mean Time Between Failures (MTBF) of 35,456 hours. It is important to realize that 25% of the klystrons that failed in the gallery did so in the first 1000 hours of high voltage operation. These so-called "infant deaths" represent about 8% of the total number of tubes that have been installed in the gallery. If we consider only the klystrons that survived these infant deaths, the MTBF is over 50,000 hours.

Impressive as these numbers are, they were achieved while the klystrons were pulsing much of the time at 60 pps and 10 pps. This was done as an energy cost saving measure. When full-time 120 pps operation is a reality, the failure rate will most likely go up. This pessimism, however, should be offset somewhat by design improvements that have greatly reduced the number of failures which are discussed later.

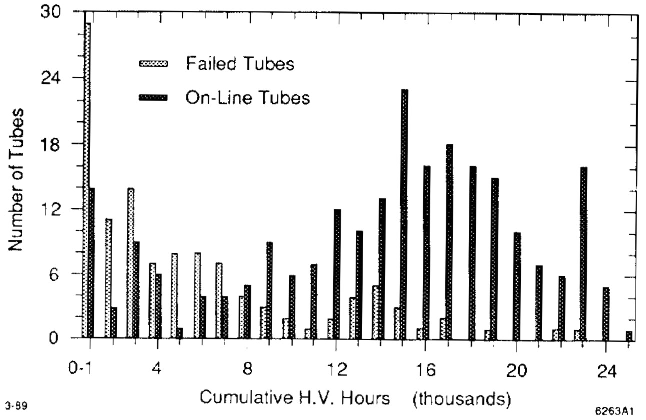

Fig. 1. The number of living and failed SLC klystrons in each high voltage age category.

The earliest of the SLC 5045 klystrons installed in the gallery are now approaching 25,000 hours of high voltage operation and 29,000 hours of filament time. The mean age of living tubes is 13,500 high voltage hours. The mean age at failure of failed tubes is 5,860 high voltage hours. The breakdown in age groups of both living and failed tubes is shown in Fig. 1. At any given time there are a few tubes in a limbo category in which their disposition has not yet been decided. These are usually tubes that are marginal in performance that may eventually be failed. At present there are seven in this group.

2. Principal Modes of Failure

A breakdown in the various modes of failure is shown in the table below:

Cause of Failure	Number of Tubes
High voltage seal puncture	37
RF window failure	30
Unstable RF, low-power output	21
Vacuum leak	10
Gassy cathode	7
Mechanical failure	5
Total failures	110

The failure of the high voltage gun ceramic insulator became the major concern as the failures mounted in the summer of 1986. A task force was formed to study this problem with several promising solutions proposed. Among these were

1. Redesign of the klystron seal corona shield geometry.
2. Change the resistive coating on the inside of the ceramic insulator.
3. Use only ceramic seals from the vendor whose seals had the lowest failure rate.
4. Shorten the solenoid focus electromagnet corona shield and improve its polish.

The adoption of proposal number 4 appears to have solved the high voltage seal puncture problem. This modification involved shortening by one inch, the outer upper corona shield, which is part of the electromagnet pole plate. A program to retrofit all existing tube magnets was instituted as well. No tubes have failed from punctured seals which have this modification which was instituted about 27 months ago. There have been a total of 37 high voltage seal failures from the group of those that have not yet received this modification. At present 65% of the klystron magnet corona shields have this modification.

The other principal mode of failure has been the puncture or cracking of one of the RF output ceramic windows. Very early R&D and production klystrons utilized a single output window. A design change to split the RF output power between two windows helped reduce the number of window failures to some extent but there were so few klystrons in the program at that time to attach a statistical significance.

The major breakthrough was achieved when the output window configuration was changed so that the plane of the alumina ceramic disks was changed from horizontal to vertical. It had been suspected that debris deposited on the horizontal windows either during klystron handling or from the gallery vertical waveguide feeds to the accelerator was causing RF electrical breakdown

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across the load side of the ceramic surface. The present configuration is such that it is more difficult for foreign debris to find its way into the circular pillbox housing the ceramic and, if it does, gravity causes it to rest in an area of the pillbox circular sleeve where the RF electric field is near zero.

The most recent 55% of new tube starts utilized a newer set of gain cavity resonant frequencies which has helped to reduce but not eliminate the number of tubes that exhibit RF instabilities. The most common RF instability exhibits itself as low frequency (about 15 MHz) amplitude modulation superimposed on the RF output pulse. The former set of cavity frequencies resulted in the production of some tubes that were marginally acceptable initially, but gradually RF instabilities became more severe as operating hours were accrued. Some edge emission from the earlier vintage cathodes required that some klystrons run with the cathodes temperature limited in order to meet acceptance stability criteria. Normal cathode aging later on dictated increased heater power which resulted in some of these klystrons experiencing edge emission and becoming unstable.

3. Cathode Life

The beam voltage and current are monitored continuously on the klystrons operating in the gallery. The automatic monitoring of klystron heater power is not yet operational. The acquisition of cathode emission information is not usually possible because it is necessary to remove the klystron from the on-line condition for about four hours to obtain the data.

However, there has been occasion to remove many healthy klystrons from on-line in the gallery because of malfunctions in the pulse transformer tank, focusing magnet, water cooling, and temperature sensors. These klystrons must be returned to the test laboratory to repair the faulty ancillary equipment. When the repair is complete, a klystron must be retested with its new or repaired compliment of accessories and it is at this time that a complete new set of cathode emission data is obtained — sometimes many thousands of hours of filament time later. Sometimes the "knee" of the emission curve is very close to that recorded during acceptance and the nominal heater power for resumed operation is identical to that used in the beginning. Often, however, there has been some degradation in perveance at the "old" heater setting and an increase is in order to bring the perveance and output power up to optimum.

It is the data on these klystrons which were removed from the gallery for reasons other than klystron failure that have enabled the reasonable prediction of cathode life. About 75 klystrons in this category were available for this type of analysis. Many of them were returned from the gallery in the first thousand hours of operation and therefore the time lapse between sets of emission data were too short to provide statistically significant data. Others were ruled out because irregularities in the data acquisition or suspected calibration error in the heater power instrumentation. There were, however, 38 klystrons with emission data that was taken at two intervals separated by 5000 hours to 19,000 hours. Since the emission data in some cases were taken at 320 kV instead of 350 kV μ-perveance is more useful to use than beam current.

Figure 2 shows a plot of four groups of perveance data taken in the test laboratory after several thousand hours of high voltage operation. The perveances are normalized to their original values upon acceptance. These are plotted as a function of filament time accrued between the two sets of data. As mentioned earlier, data sets with fewer than 5000 hours between them were not considered. In some cases the perveance appeared to have increased — possibly a measurement error. It is assumed that these points will average out with those errors made in the other direction. Mathematical models have been developed by several authors[2,3] to predict cathode life based on limited data such as this. Our emission data comes from essentially four time groups at 5,000, 7,000, 12,000 and 17,000 hours and are shown below with a curve fit based on the Longo model.[3] Each data point represents the average for that group.

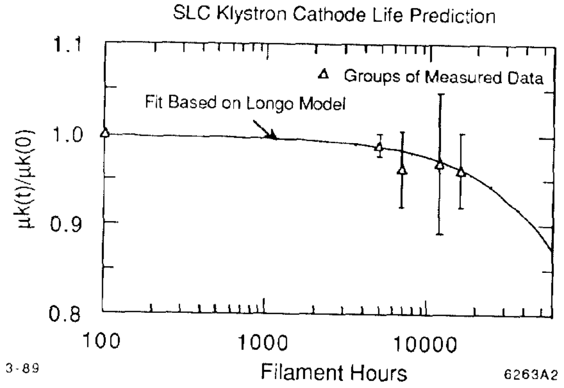

Fig. 2. The mean perveances of SLC klystrons from four different age groups normalized to their initial values upon acceptance.

It should be noted that since, even after 17,000 hours, little cathode deterioration has occurred, it is still too early to obtain an accurate estimate of cathode lifetimes. If the cathode end of life is defined as the perveance dropping to 90% of its value at $t = 0$, one can make a reasonable prediction of 45,000 hours. This extrapolation should be taken as a best guess. Also it is assumed that all of the cathodes are operating at the same temperature. Earlier failure can be expected if a higher temperature is required to raise a dropping perveance.

4. Conclusion

Future performance of SLC 5045 klystrons looks very optimistic. Klystron MTBF presently exceeds 35,000 hours and is increasing as more operational time is accrued. Although most of the operating hours have been at reduced pulse repetition rate, no cathode failures due to aging have been seen. RF instability problems have been reduced by changing the gain cavity frequencies. Output window problems have also been reduced by modifying the window orientation to minimize the effect of contaminants and by replacing the single window with a two-window output. High voltage ceramic insulator failures have been solved by modifying the electromagnet corona shield. Long life cathodes and modifications mentioned have combined to achieve a very reliable long-life klystron which meets SLAC's SLC requirements.

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