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SLAC Modulator System Improvements and Reliability Results

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A. Abstract

In 1995, an improvement project was completed on the 244 klystron modulators in the linear accelerator. The modulator system has been previously described [1]. This article offers project details and their resulting effect on modulator and component reliability. Prior to the project, we had collected four operating cycles (1991 through 1995) of MTTF data [2]. In this discussion, the '91 data will be excluded since the modulators operated at 60 Hz. The five periods following the '91 run were reviewed due to the common repetition rate at 120 Hz.

B. Introduction

The project objective aimed at improving modulator reliability and increasing mean time to failure (MTTF) for specific components through the replacement of the old thyratron trigger chassis and the installation of a hybrid anode reactor [3]. MTTF data from '92 and '93, considered as "base" data, will be compared with data from '96 and '97/8, or accelerator runs after the improvement completion. These periods are based on the SLC/SLD experimental program because operation was especially critical and required a high degree of stability from every station. The 1994/5 accelerator run was the period when the thyratron trigger improvement project was partially accomplished. Hence, a transitional off-set appears in the '94/5 MTTF data.

The SLC/SLD program uses 244 modulator-klystron stations in the linear accelerator which are spaced at approximately 12.5 m intervals over a total distance of 3000 m.

TABLE I: SLC Klystron-modulator Deployment

LOCATION	QUANTITY	E [GeV]
Injector Stations	**5**	0.2
Sector 1 Stations	**5**	1.15
N & S Damping Rings:		1.15
NRTL Compressor #	**1**	
SLTR Compressor #	**1**	
SRTL Compressor #	**1**	
Sectors 2 to 18 Stations	135	32.8
Sector 19 Stations	7	34.5
Positron Source:		
e^- to Target Station #	**1**	30.5-31.5
e^+ Accelerate Station #	**1**	0.2
Sector 20 Stations	7	36
Sectors 21 to 30 Stations	80	55
Energy to SLC Arcs		47
Energy to SLD Detector		46
Total Station Count	244	

Stations that compress the beam without energy gain.

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From Table I, it is apparent that SLAC has more modulators than needed for the energy required by the SLD experiment. This allows the modulators to be repaired by substituting operational, but "off-beam" modulators to avoid lost beam time. At any given time, there may be as many as 14 modulators available as spares. However, there are 15 critical modulators (indicated in bold type) which do not have substitutes, hence their critical designation.

Table II offers the specifications for the typical klystron–modulator station.

TABLE II: Klystron and Modulator Characteristics

Klystron Peak Power Out	67	MW
RF Pulse Width	3.5	μs
Klystron Beam Voltage	350	kV
Klystron Beam Current	414	A
Modulator Peak Power Out	150	MW
Repetition Rate	120	Hz (max)
Thyratron Anode Voltage	46.7	kV
Thyratron Anode Current	6225	A
Pulse Transformer Ratio	1:15	
Voltage Pulse Width	5.0	μs (ESW)
Pulse Flattop Ripple	±0.25	%
Nominal PFN Impedance	4	Ω
Total PFN Capacitance	0.70	μF

C. Improvements

Operational experience from the early 80's indicated that the thyratron triggering scheme was overdue for improvement due to safety concerns and poor reliability. A small thyratron, positioned below the main thyratron, fired the main unit. The combination of the small thyratron, large PFN, pulse transformer and 5 kV power supply was called the thyratron driver, which weighed approximately 40 pounds. The PFN on this chassis was a vintage 60's type in a large capacitor case, weighing about 10 pounds. The small thyratron was triggered by a blocking oscillator circuit that consisted of two vacuum tubes.

The thyratron driver chassis was located within the modulator. Chassis or small thyratron replacement was performed by first turning the modulator off, and then by opening the appropriate modulator compartment using mandated safety procedures to access a high voltage (HV) enclosure. The blocking oscillator was located in the control panel area of the modulator; however, any vacuum tube replacement required turning off the modulator and, once again, all of the HV safety procedures had to be executed for a tube replacement. The mean time to repair (MTTR) for this triggering scheme could easily be reduced if the HV safety procedures could be eliminated; the reliability could easily be increased through the use of a solid state trigger circuit.

The trigger scheme that was developed uses an SCR and PFN with an ensemble of integrated circuits to drive the SCR and provide the interlock functions. The new trigger circuit is housed in a small chassis that occupies the former space of the old blocking oscillator chassis. The unit was designed and developed at SLAC, but is manufactured commercially [4]. The SCR unit can be replaced after the modulator is turned off without having to execute any HV safety procedures.

The anode reactor was specifically designed to increase the lifetime of the pulse cable — the component which connects the modulator PFN to the pulse transformer — and was also expected to improve the lifetime of the main thyratron [3]. Operating data collected in '91, '92 and '93 indicated the pulse cable failure rate was excessive. The failures were a result of overshoot voltage breakdown between the center conductor and the inner shield of the tri-axial cable at the termination in the modulator. The reactor consists of a combination of ferrite materials and shapes, eight torroids and four window shapes. The reactor uses both MnZn and NiZn ferrites. The reactor was designed to reduce the voltage overshoot on the pulse cable at the onset of a thyratron turn-on. A secondary objective was to increase thyratron lifetime by decreasing the switching losses and, consequently, thyratron anode temperature.

D. Method

The success of the improvement will be gauged by comparing the '92 and '93 runs with the most recent '96 and '97/8 runs. The '94/5 run is considered a transition period because one third of the improvement work was performed during this period.

As previously stated, the linear accelerator employs 244 modulators. The technician crew that maintains the units functions 24 hours per day and seven days per week during an experimental physics run. All duties that the technicians perform, referred to as "interventions," are recorded in a daily log book. This information is then transferred to a Microsoft Access database. The data has been classified according to three principle categories: "Class," "Section" and "Intervention."

The "Class" field, consisting of three values, indicates the operational status of the modulator:

- Non-scheduled: a specific accelerator program requiring modulator usage; the modulator directly affects program performance.
- Scheduled: an accelerator program not requiring modulator usage because the modulator is either in maintenance or available as a spare.
- Other: a log book entry that refers to a modulator but does not indicate any intervention or action taken.

The "Section" field includes six values – Modulator, External, Interface, Klystron, KMC and Other – to distinguish modulator interventions from problems associated with klystrons, accelerator structures, computer interface and low level RF.

Only the "Non-scheduled" and "Modulator" data was used for the current reliability calculations. This methodology does not necessarily represent a "true" indication of system reliability; however, it does offer a valid approach for calculating global system availability.

Finally, the "Intervention" field defines the actual problem. Within the modulator section are 110 intervention types. The real times for interventions are not recorded; instead, repair time is based on 30 years of modulator troubleshooting, repair and operation. The time to repair includes technician travel as well as troubleshooting time. When multiple actions are taken while troubleshooting, all of the appropriate interventions are entered as unique database records. Their inclusion consequently leads to a reduction of the actual MTTF for the modulator system and components.

To gauge the improvement project's success, the data collected prior to the improvements was compared to the '96 and '97/8 data. The total operating hours were determined for the five operational periods, and modulator intervention counts were then tallied to calculate the modulator system MTTF.

The MTTF bar charts are divided into three types: "component replacements," "component repairs" and "resets and adjustments." The "component replacements" category serves as the best indication for the success of the improvement program. Benefits from this program might also affect the MTTF for "component repairs" and "resets & adjustments." Figure 1 represents the "component replacements" MTTF chart for the modulator system. The x-axis displays five of the replacement categories. The bars denote the accelerator operating years -- '92, '93, '94/5, '96 and '97/8 -- for each category. The y-axis denotes the system MTTF in hours, indicating how often component replacements occur on a system basis.

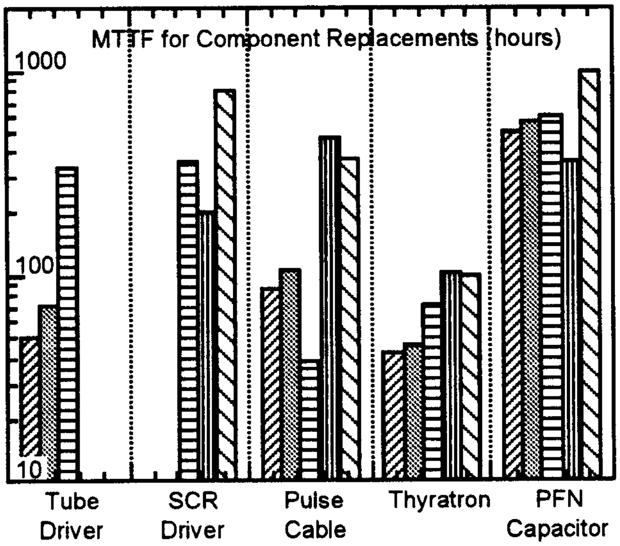

Figure 1. MTTF for five modulator components based on five operating periods.

The category for PFN capacitor replacements is included for reference. It serves as a credibility check of the database and MTTF calculations. There are 16 PFN capacitors in each of the 244 modulators for a total of 3,904. The system MTTF average of 680 hours equates to a failure rate of approximately one per month.

E. Results

Refer to the bar graph in Figure 1. The "Tube Driver" category represents the old thyratron triggering scheme that used the small thyratron and vacuum tubes. The plot shows the MTTF for replacements to either chassis or tubes in this system over three periods of accelerator operation. The combined MTTF for the tube trigger was 61 hours in '92, and '93. For the 244 modulators, a technician was required to re-tube or replace, one or both of the chassis every 61 hours. The MTTF for the individual tube driver requires that the system MTTF be multiplied by 244. For '92 and '93, the MTTF for the tube trigger driver was 14.9 k-Hours. The figure is rather poor, but considering the age of the circuits and tube technology, the MTTF values are reasonably good. As the tube drivers were removed during the '94/5 transition period, the MTTF improved slightly.

The second category in Figure 1 is the "SCR Driver," the chassis which partially replaced the tube driver during the '94/5 operating period. Later, it completely replaced the "Tube Driver" during the down time between the '94/5 and '96 runs.

The '94/5 MTTF for the SCR Driver is much better than the '96 run because we discovered that a protection spark gap across the thyratron trigger grid would fail to arc if the thyratron fired through, thus occasionally killing the SCR Driver. Many spark gaps were readjusted during the '96 run: the remainder during the down-time period before the '97/8 run. When the tube driver was used, it was rarely damaged by a main thyratron fire-through. The system MTTF for the SCR Driver then jumped up to 800 hours for the '97/8 run. MTTF for the SCR Driver is then 195 k-Hours which exceeds the MTTF for the tube driver by a factor of 10.

The second element in the improvement upgrade was the installation of the anode reactor. The primary intent of installing this device was to improve the pulse cable lifetime. The wave forms in Figure 2 reveal the modulator output voltage on the pulse cable before and after the installation of the anode reactor. The anode reactor reduced the overshoot by approximately 50%.

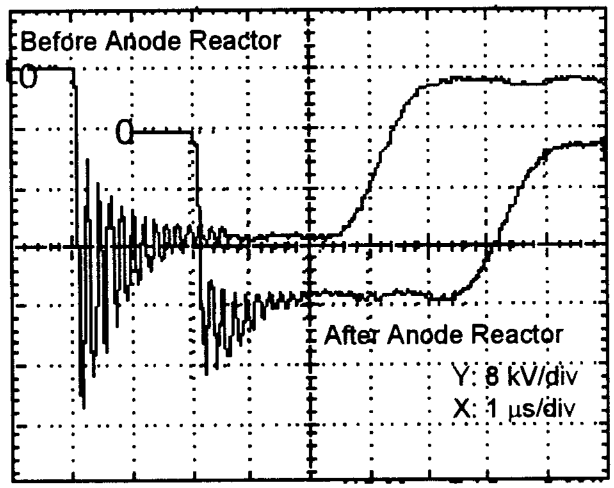

Figure 2. Modulator output voltage wave forms.

The third MTTF value in Figure 1 is for the pulse cable. System cable replacements for '92 and '93 averaged 96 hours. The average life for an individual cable in this period was 23.4 k-Hours. In the '94/5 run, the failure rate for the cable increased, and the system MTTF was only 40 hours. The modulator technicians were replacing four cables per week. It is possible that the cable termination and assembly may have been compromised at some point during the termination process, thereby reducing the voltage at which the dielectric failed. This may have been a cause, but no evidence was found to implicate an assembly defect.

The system MTTF for the pulse cable in '96 and '97/8 increased to 474 and 364 hours, respectively. This rise represents an average improvement by a factor of four for the '92 and '93 MTTF values, and a factor of ten for the '94/5 MTTFs. As the cables with the weakened or damaged dielectric are slowly replaced, the MTTF value may increase slightly.

The fourth category in Figure 1 gives the system MTTF for thyratrons. We had anticipated that the anode reactor would reduce thyratron switching losses and decrease the temperature of the anode (which was documented) [3], thereby increasing the life of the thyratron. The MTTF values for the periods following the installation of the reactor denote that thyratron lifetimes have increased by factor of two. The average lifetime for a generic (non-specific) thyratron has gone from 11,000 hours for '92 and '93, to 24,600 hours for '96 and '97/8, over equivalent operating periods. In the '92 and '93 physics runs, 253 thyratrons were consumed. Over the last two operating periods, only 105 thyratrons were used. Thyratron manufacturers should not concern themselves about going out of business. There is feeling on the part of the procurement team at SLAC that the manufacturers have also made some improvements to their products that have increased the lifetime.

The MTTF calculations for the thyratron do not include a cool-down failure that occurs with several models of thyratrons. These failures are the result of a manufacturing defect in the structure of the keep-alive electrode. When it cools down because of heater power being turned off or a power failure, the electrode either experiences an internal short or opens. The manufacturer(s) are aware of this problem and are working to remedy it.

The modulators use as many as eight different models of thyratrons that are or were produced by as many as six manufacturers. The lifetime of the entire set is affected by the anode reactor, but several models receive a higher degree of benefit than others. The actual thyratron lifetimes by model and manufacturer are reported in the proceedings [5].

F. Conclusions

The improvement program was effective in increasing the MTTF for the specific components. However, as the SLC/SLD program approached a critical stage in '96 and '97/8, technicians were requested to focus their attention on adjustments. Very stable modulator operation was required to insure that accelerated particle beams were ultra stable. The adjustment intervention rate increased for '96 and '97/8. The adjustment rate for beam (modulator output) voltage adjustment and PFN tuning increased by a factor of 2.5 and 4.4 respectively, from the base operating periods. Consequently, the system MTTF value remained almost constant without any significant improvement.

The appendix offers the MTTF and availability calculations, comparison tables and a set of MTTF charts that display 27 categories of modulator intervention.

An unfortunate weakness of the modulator database is the multiple reporting of interventions during the troubleshooting process. The cable use and purchasing records for the yearly cable consumption cables do not agree with the database records. There are several troubleshooting situations in which cable replacement might offer the solution, but symptoms still remain after replacement. The database denotes that more cables were used than were actually required. This is also true for thyratron use.

A misdiagnosis also affects the MTTF calculations, resulting in lower MTTF values at the system and component levels, since the record-keeping does not reflect a misdiagnosis. At the system level, the MTTF value is also affected by multiple interventions, as in the case of a lengthy repair situation. It probably gives a true idea of the difficulty to troubleshoot and repair our rather old modulator system.

Acknowledgments

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The modulator technicians deserve special recognition for their high quality work as well as for their accurate recording of every intervention.

References

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[3] A.R. Donaldson, "A Hybrid Anode Reactor for the SLAC Modulator," 1994 21st Power Modulator Symposium, 6/94, p.136.

[4] SCR Thyratron Driver, Model 727, BiRa Systems, Inc. Albuquerque, NM, http://www.bira.com/

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Appendix

The five year database contains 10,889 nonscheduled interventions with 4,314 hours of allied repaired time for the 28,219 hour SLC/SLD modulator operating period.

The 28,219 hour figure was determined from SLC operating periods for 1992 through 1998. It does not necessarily include scheduled maintenance periods of less than 24 hours.

Total modulator–hours are then 244 modulators times 28,219 hours for 6.88 Mega modulator-hours of operation.

Assuming that a constant failure rate occurs for non-scheduled problems based on the operating hours and a typical Poisson distribution for electronic equipment failure,

Modulator System Failure Rate = 10,889/28,219 hr

Modulator System Failure Rate = 0.386 problem/hour

or, a problem occurs about once every 2.6 hours for the 244 units configured as a "system." This forces the modulator technicians to enter the linac gallery every 2.6 hours to correct a modulator problem.

The modulator "mean time to failure" is then,

Modulator MTTF = 6.88 M hr./10,889

Modulator MTTF = 632 hours,

which, when considering the age of modulators, thyratron fault rate, and relay control circuitry, seems appropriate (the database error could be as high as ± 5%).

The calculation for the "mean time to repair" with our data gives,

Modulator MTTR = 4,314 hr./10,889

Modulator MTTR = 0.396 hr./problem

or, the average modulator problem (an intervention) requires about 24 minutes to correct.

The final calculation of interest to the accelerator operator and physicist is modulator availability, or "when can it be depended on to work." The reliability experts give several definitions for availability; we will use the following as it has been applied to other accelerator systems,

Mod System Availability = 1– (Failure Rate)(MTTR)

Modulator System Availability = 0.847

This would be the "availability" if there were no spares for the modulators; however, as previously mentioned, there are up to 14 spares available which can be activated within 12 minutes to replace a faulty unit. Using the 12 minute or 0.2 hour repair/replacement as the MTTR, the "availability" then increases to 0.931, a respectable rise that verifies the advantages of redundancy and available spares.

SLC/SLD operation is compromised when we run out of modulator spares, or when one of the 15 critical modulators fails. The database contained 539 non-scheduled interventions for the 15 critical modulators with a total time for repair of 222 hours. We apply the above calculations for the critical modulators and then compare the data with the entire ensemble of 244 modulators in Table A-1.

TABLE A-I: System and Modulator Data for Five Runs

	244 System	15 Critical	
SLC Operating Period	28,219	28,219	Hr
SLC/Modulator-hours	6.88 e6	4.23 e5	
No. of Interventions	10,889	549	
Total Repair Time	4,314	222	Hr
System Failure Rate	0.386	0.019	P/hr
System MTTF	2.6	52.6	Hr
Modulator MTTF	632	771	Hr
Modulator MTTR	0.396	0.404	Hr
System "Availability"	0.847	0.992	
System "A" w/ Spares	0.931	not applicable	

The critical modulator value of 0.992 indicates that their availability was better than either of the above two calculations for the System Availability, which offered 0.847 for the no spares case, and 0.931 for the spares case; it indicates that the critical 15 must receive special attention through scheduled intervention.

Table A-2 shows the reliability and availability data for the modulator system for five SLC/SLD runs.

TABLE A-2: Reliability and Availability of Modulators

Run Period	1992	1993	94/5	1996	97/8
PRR (Hz)	120	120	120	120	120
Operating Hr	5568	5736	6070	2841	8004
244 Sys Interv.	2670	2095	1899	1358	2867
244 Sys MTTR	0.383	0.382	0.437	0.387	0.396
244 Sys MTTF	509	668	780	510	681
244 Sys "A"	0.816	0.860	0.863	0.815	0.858
15 Critical "A"	0.995	0.996	0.992	0.982	0.991

From Table A-2, it seems that in spite of the improvements, the modulator reliability (MTTF) and availability (A) remain unchanged in '97/8 as compared to previous runs. Figure A-1 displays the decrease in MTTF for adjustment interventions in '96, '97/8 and its consequent effect on the values in Table A-2. Ironically, the best values occurred in the '94/5 period when the cable failures hit their apogee. The major benefit derived from the improvement is that annual expenses for pulse cables and thyratrons have been reduced.

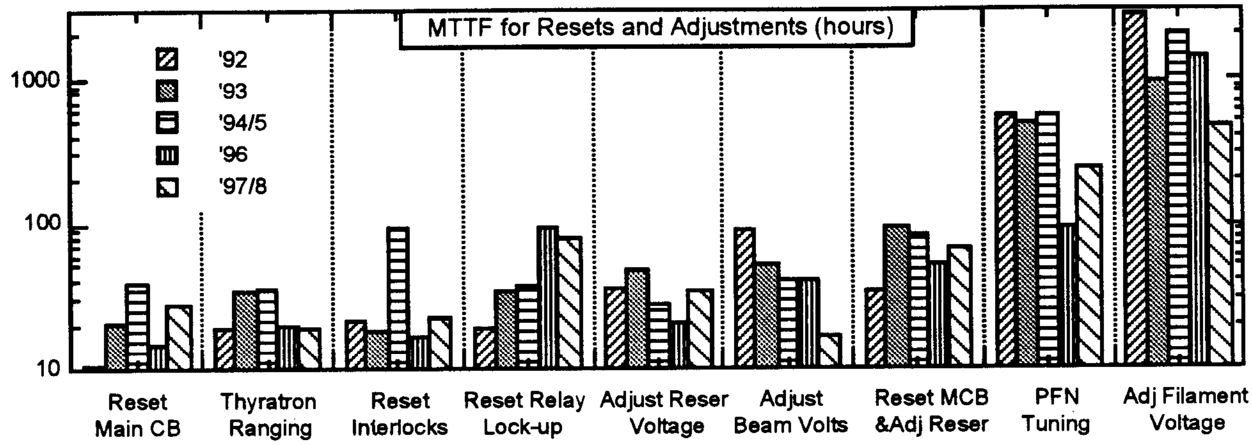

Figure A-1. System MTTF chart for nine reset and adjustment categories. Mark the MTTF's for Thyratron Ranging in '96 and '97/8 and Adjust Beam Voltage in '97/98 that have decreased dramatically because of increased intervention due to SLC/SLD operational demands for very stable modulator performance. This increase of the intervention rate is responsible for the lack of an increase in modulator reliability and availability in '96 and '97/8.

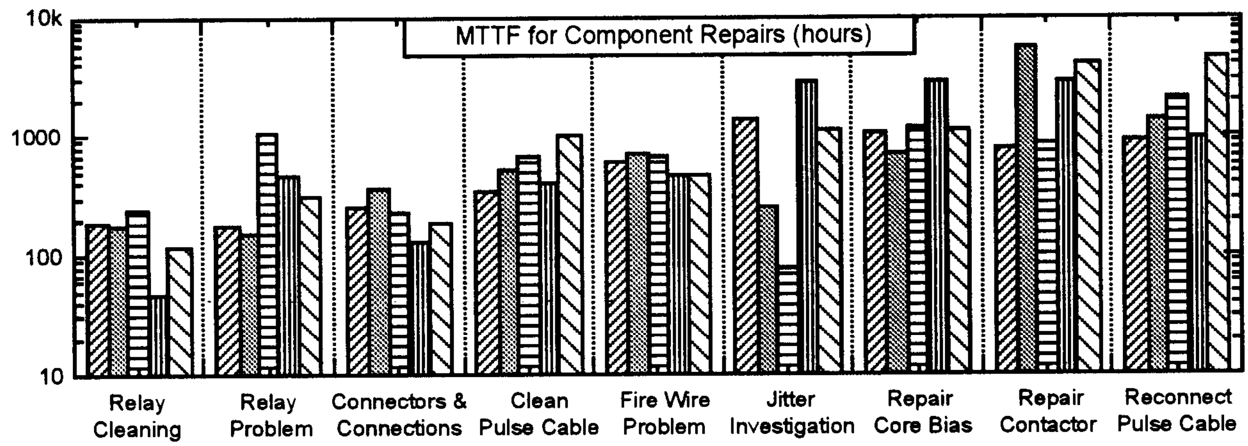

Figure A-2. System MTTF chart for repair categories. Notice that the MTTF values for repairs associated with the pulse cable (Clean and Reconnect Pulse Cable) have increased in '97/8 as a result of the anode reactor installation.

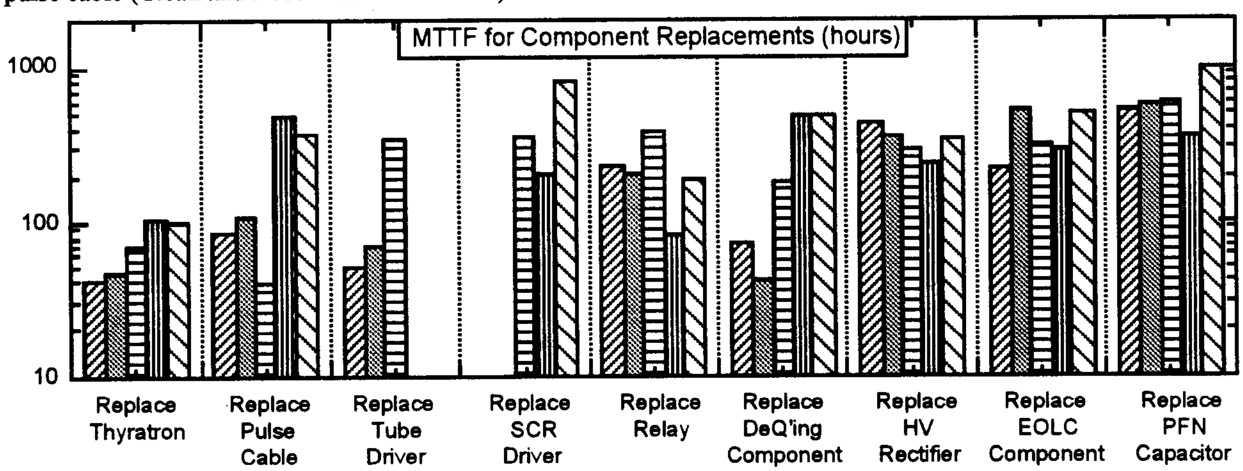

Figure A-3. System MTTF chart for nine component replacement categories. Regard the MTTF values for Thyratron and Pulse Cable replacements in '96 and '97/98 that have increased as a result of the anode reactor installation.