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SLAC Modulator Operation and Reliability in the SLC Era *

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Abstract

A discussion of the operation and reliability of the 244 modulators in the SLAC linac with an emphasis on the past three years of operation. The linac modulators were designed and built in the 60's, upgraded for the SLAC Linear Collider (SLC) in the mid 80s, and despite their age are still reliable accelerator components. The 60s modulator operated at 65 MW peak and 83 kW average power. The upgrade resulted in 150 MW peak output at an average power of 87 kW, a modest increase since the repetition rate was dropped from 360 to 120 Hz [1]. In the present accelerator configuration, the Linac operates as a source of electrons and positrons to a <u>single pass collider.</u> The classic collider is a storage ring filled with oppositely charged, counter-rotating particles which are allowed to collide until an accelerator fault occurs and the stored beams are aborted. A reasonable storage ring can store and collide particles for as long as eight hours with a 10 or 20 minute filling time. A single pass collider, on the other hand, can only produce e^- and e^+ collisions at whatever rate the source operates. To be effective the SLC must operate at 120 Hz with a very high degree of reliability and on a continuous basis. Fortunately, the linac has a modest excess of modulator/klystron systems which allows some measure of redundancy and hence some freedom from the constraint that all 244 modulator/klystrons operate simultaneously. Nonetheless, high importance is placed on modulator MTBF and MTTR or, in the parlance of reliability experts and accelerator physicists, availability. This is especially true of the modulators associated with the fundamental requirements of a collider such as injection, compression and positron production. The past three years of high power operation will provide a reference for modulator design and reliability. The presentation of material related to modulator characteristics, system operation, problem frequency, repair times, adjustment interventions (e.g., thyratron ranging), component lifetimes (e.g., thyratrons), and improvements for present problems is based on detailed analysis of the 1991 SLC run.

I. MODULATOR/KLYSTRON DEPLOYMENT

The linear accelerator presently uses 244 modulator/klystron stations, but in 1991 only 243 stations were used to power accelerator structures. Table I presents the 1991 station deployment.

LOCATION	NO. OF STATIONS	ENERGY[1]
Injector Stations	5	200 MeV
Sector 1 Stations	5	1.15 GeV
N & S Damping Rings:		1.15 GeV
NRTL Compressor[2]	1	
SLTR Compressor[2]	1	
SRTL Compressor[2]	1	
Sector 2 Stations	7	2.80 GeV
Sectors 3 to 18 Stations	127	32.77 GeV
Sector 19 Stations	7	34.43 GeV
Positron Source:		
e^- To Target Station[2]	1	30.5-31.5 GeV
e^+ Accelerate Station[2]	1	200 MeV
Sector 20 Stations	7	36.01 GeV
Sectors 21 to 30 Stations	80	54.96 GeV
Energy to SLC Arcs		47 GeV
Energy to Detector		46 GeV
Total Station Count	243	

[1] Indicates the maximum possible energy (phase aligned) and does not include losses due to:
15 degree offset for BNS Damping
overhead for energy feedback
modulators down for maintenance
klystrons down for maintenance.

[2] Indicates stations which compress the beam but add no energy gain.

TABLE I. Modulator/klystron deployment in the SLC for 1991.

From Table I it is almost apparent that SLC has more modulators than needed for the required detector energy [2]. This allows modulators to be repaired by substituting operational but off beam modulators to avoid long repair times. At any given time there may be as many as 14 modulators available as spares. However this is not a universal situation, and there are 15 critical modulators (indicated in bold type) which do not have substitutes, hence their critical designation. These are the Sector 0 and 1 modulators at the front or beginning of the linac, the three compressor stations, and the two positron source modulators. The availability of the accelerator is essentially dominated by the operational status of these 15 stations.

II. MODULATOR CHARACTERISTICS

The SLAC modulators were upgraded during 1985 through 1987 period to meet the requirements of a higher power klystron designed to increase the accelerator energy for the SLAC Linear Collider. Table II offers these specifications.

5045 KLYSTRON DATA		
Klystron Frequency	2856	MHz
Klystron Beam Voltage	350	kV
Klystron Beam Current	414	A
Microperveance	2	
Peak Power Out	67	MW
Peak Input Power	500	W
Power Gain	50	dB (minimum)
RF Pulse Width	3.5	µs
150 MW MODULATOR DATA		
Repetition Rate	120	Hz (maximum)
Thyratron Anode Voltage	46.7	kV
Thyratron Anode Current	6225	A
Pulse Transformer Ratio	1:15	
Voltage Pulse Width	5.0	µs (ESW)
Pulse Rise Time	0.8	µs
Pulse Fall Time	1.8	µs
Pulse Flattop Ripple	± 0.25	%
Nominal PFN Impedance	4	Ω
Total PFN Capacitance	0.70	µF
Charging Inductance	2.4	H
PFN Charging Time	4.1	ms
Peak Charging Current	12.7	A

TABLE II 150 MW modulator and 67 MW klystron specifications.

The performance of the upgraded modulators is on a par with the pre-86 modulators except for a few problems related to higher energy operation of the thyratrons (one thyratron is used per modulator) and EOLC resistors as well as a higher voltage on the modulator to klystron cable.

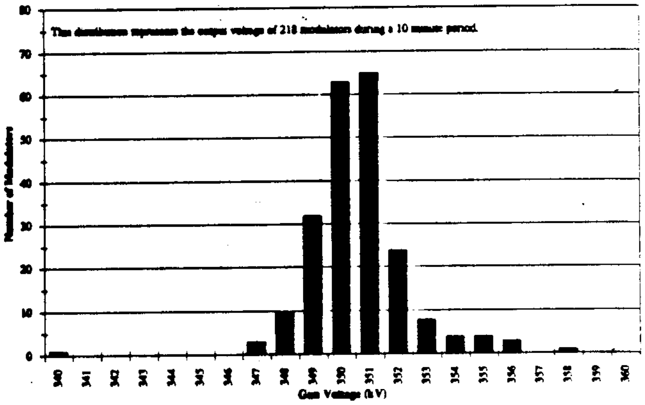

Figure 1. Output voltage on the secondary of the pulse transformer.

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- With 243 or 244 modulators on line it is interesting to report that the specified modulator voltage and current are as designed (a constraint posed by the klystron perveance). The secondary voltage of the 1:15 pulse transformer is presented in Figure 1 for 218 stations, and indicates the output range of the modulator. Thirteen modulators were operating at less than 330 kV as injector modulators or off beam time as operational spares, seven units were off beam time and were not measured, and five units were down for modulator or klystron maintenance.

The PFN design is dictated by the klystron perveance and peak output power. The plot in Figure 2 indicates the constraints placed on flattop pulse width as based on the 1% amplitude level. PFN tuning (for impedance and pulse width) is accomplished with variable inductors using a movable internal slug.

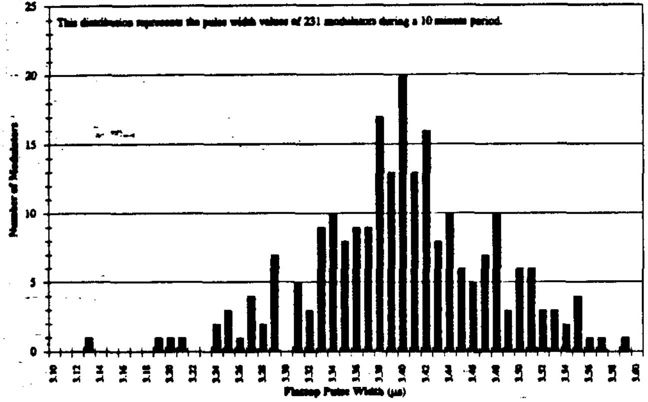

Figure 2. The flattop pulse width range for 1% amplitude at 120 Hz.

The flattop ripple is critical in many modulator applications, but in the SLAC case with energy compression cavities on the klystron, it can be relaxed to 0.5%. Figure 3 shows the ripple for a typical modulator as captured by the wave form sampler driven from the control system.

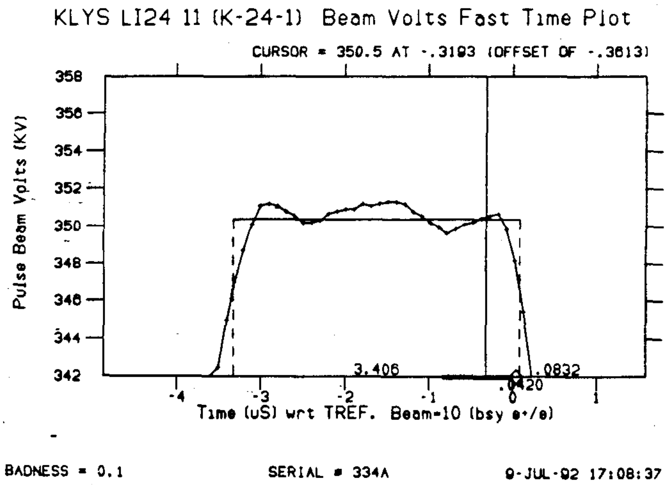

Figure 3. The flattop ripple performance for a typical modulator.

The PFN mismatch is another important aspect of modulator operation as it relates to thyratron turn–off or deionization. In the SLAC modulators, a positive mismatch has been established as an effective way of deriving maximum lifetime from our thyratrons. The positive mismatch is probably beneficial because of our low repetition rate (60 and 120 Hz), and would not be useful or even desirable at kilo Hertz type operation. The positive mismatch plot for two repetition rates is shown in Figure 4. This data was compiled from the thyratron change reports, as no automated data collection exists for this parameter. A higher mismatch is possible at 60 Hz because the power supply can deliver slightly more energy at the lower rate.

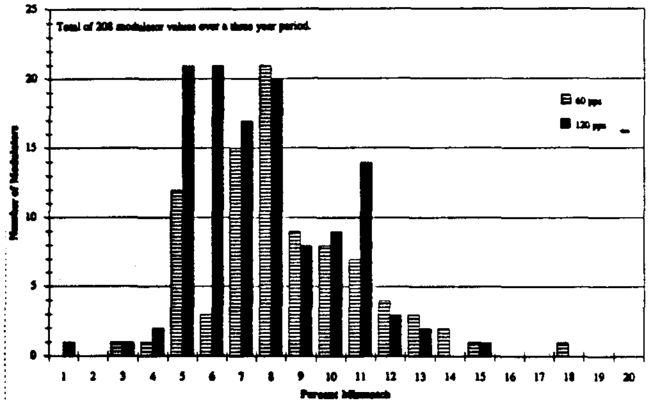

Figure 4. The distribution of positive mismatch at 60 and 120 Hz.

Modulator output voltage is regulated with a classic deQ'ing circuit using a SCR to deQ into a resistive load on the secondary of the PFN charging choke. The range of typical deQ'ing at 60 and 120 Hz is illustrated in Figure 5. DeQ'ing in the SLAC modulators regulates at 0.1% pulse to pulse.

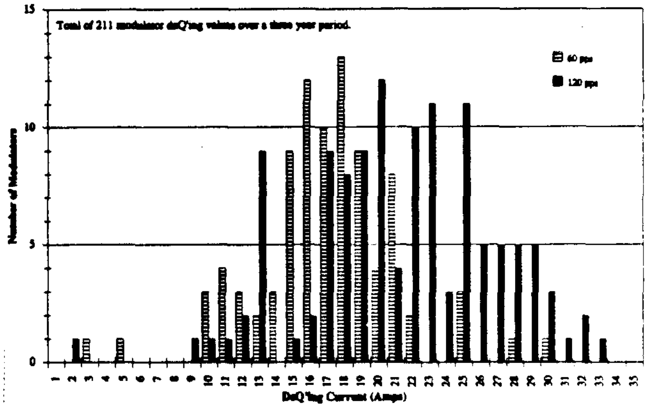

Figure 5. The typical range of deQ'ing current at 60 and 120 Hz.

III. MODULATOR RELIABILITY

The SLC must operate at 120 Hz with a very high degree of reliability and on a continuous basis. Fortunately, the linac has a modest excess of modulator/klystron systems which allows some measure of redundancy and hence some freedom from the constraint that all 244 modulator/klystrons operate simultaneously.

The modulator log book for 1991 was poured into a database in an effort to analyze the reliability and hence availability of the modulators. The log book also recorded station problems associated with the modulator computer interface, klystron (which included rf, water, and vacuum problems), accelerator structure and waveguide problems allied with vacuum and water interlocks, klystron dc magnet circuit, and 600 Vac variable voltage substation operation. The database was designed to reveal specific modulator problems (or interventions) and the frequency of those problems. These revelations while common knowledge among the modulator cognoscenti had not been quantified, accordingly they couldn't be used to provide evidence for improving the reliability of the modulators. The database also offered a measure of scheduled versus nonscheduled intervention time. In the category of scheduled time are thyratron ranging and PFN tuning, as well as major repairs, i.e., rectifier transformer replacement (T-20).

The database was used to create a Pareto chart [3]. Figure 6 shows the Pareto chart for modulator problems divided into scheduled and nonscheduled interventions with a logarithmic y-axis for visual definition. The categories on the x-axis are ordered by counts, and where duplicate counts occur, the total time for the category. The total count for interventions was 2803, but the chart only displays 2776 grouped into 44 categories. The 27 remaining interventions (another 12 categories) were two count or single count interventions of very short duration, and were not deemed interesting because of the minimum counts, but they are included in the reliability calculations below. Superimposed on the Pareto bars are small dots which indicate total repair times for each category. The total time corresponding to these interventions was 1431 hours with 1031 scheduled and 401 nonscheduled over the 4000 hour operating period. These times will provide the grist for calculations that offer a perspective on modulator reliability and availability.

The thyratron ranging category was not accurately indicated in the database and was therefore calculated based on our 500 hour ranging schedule for each thyratron. The count for thyratron ranging as calculated was 1500 for the 4000 hour operating period. The y axis was limited to 1000 counts, again for good visual definition of the minor problems. The schedule for thyratron ranging as performed at SLAC is covered in more detail in the PREVENTIVE MAINTENANCE section.

We placed six other categories in the scheduled section because the repairs are only allowed when the linac is off, or the faulty modulator can be replaced with a spare to preserve the same beam energy. These repairs restore time measurements, timing interlock functions, and monitor circuits which do not impact the performance of the modulator. Accelerator Operations will only permit correction of these problems when spare modulators are available, and when the 15 critical units are considered, corrections are not allowed until a "repair opportunity day" or a scheduled downtime occurs. The Replace T-20 category falls into the scheduled section because of the time, since it takes four hours to replace one of these large devices. During the '91 operating period only one T-20 replacement was unscheduled, and that repair time raised the critical modulator downtime by four hours.

The nonscheduled section contains four categories worth discussion because of their frequency, 100 counts or greater. The Reset Relay Lock-up is a result of the relay age, and the lock-up occurs when relay contacts fail to close. This condition at the least, requires an intervention to exercise the relay chain, or at the worst, contact cleaning.

The Reset Main CB indicates an intervention to reset the main circuit breaker on the modulator. This circuit breaker can trip for several reasons, but the typical case involves thyratron latch up because of high reservoir voltage or a malfunctioning thyratron. Normally the circuit breaker trips because the overcurrent fault circuit fails to open the primary contactor for the hv power supply.

The Reset Interlock category specifies an intervention to merely reset the interlock circuitry without exercising or cleaning. Usually it indicates a fault that the Accelerator Operators can not reset from the control computer, but in some cases it might mask a computer interface problem. There are two other relay related categories in the low count area (< 100 counts). The Replace Relay category refers to a replacement and in some cases with a modern relay. The Relay Problem category is a catch–all for relay repairs and fixes which are not lock-ups, resets, or replacements.

The final high count category is the Reservoir Voltage Adjust which refers to those situations where modulator technicians adjust the reservoir voltage to correct an immediate problem. Problems such as main circuit breaker trips can be corrected by this adjustment. Accelerator Operators often request that adjustments be performed to improve the stability of an accelerator section because of actual and sometimes perceived phase or energy jitter.

The remaining 30 categories will not be described in detail, but several will be referenced below. The chart highlights our most obvious problems, hence we have established a program for improving the modulators based on these high count categories which will be described in the RELIABILITY IMPROVEMENTS section.

IV. RELIABILITY AND AVAILABILITY CALCULATIONS

The database contains 997 nonscheduled interventions with 401 hours of allied repaired time for the 4000 hour operating period. The operating period can not be accurately measured as the front end (the first 13 modulators) must always come on weeks before the rest of the modulators down the linac. The 4000 hour figure was determined by the SLC operating period for 1991 which was 3850 hours [4], and an additional 150 hours added to that for modulator turn on, tuning, and shake down prior to accelerating beam.

Total modulator–hours are then 243 modulators times 4000 hours for 972 k modulator-hours of operation.

The database offered 997 nonscheduled interventions with a total of 401 hours of downtime. Assuming that a constant failure rate occurs

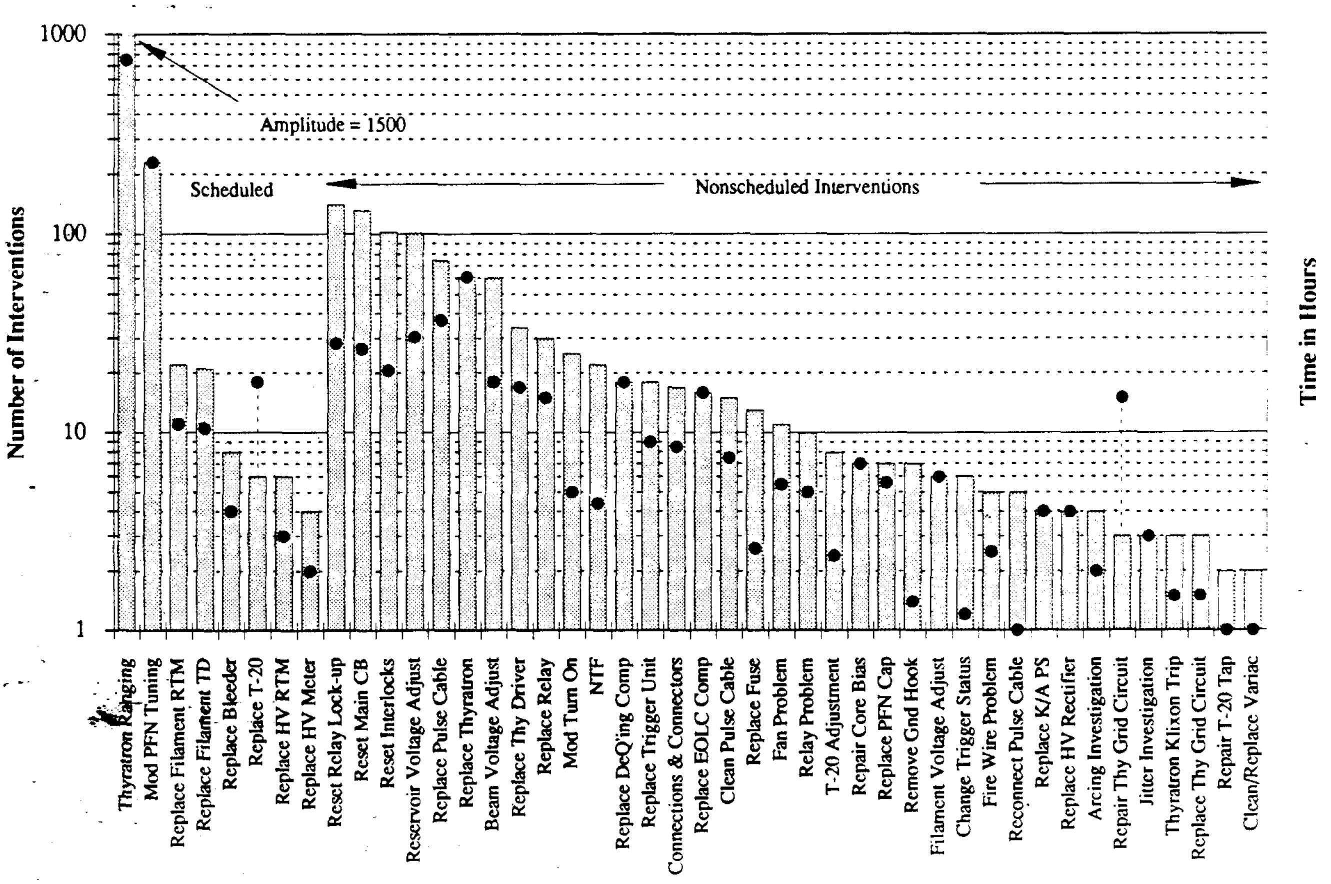

Figure 6. The Pareto chart with bars to indicate intervention frequency while dots offer total time for interventions.

for nonscheduled problems based on the 972 k modulator-hours and a typical Poisson distribution for electronic equipment failure [5],

Overall Modulator Failure Rate = 997/4000
Overall Modulator Failure Rate = 0.249 problems/hour,

or a modulator problem occurs about once every four hours for 243 modulators which requires the intervention of a modulator technician.

The overall mean time between failures is then,

Overall Modulator MTBF = 972,000/997
Overall Modulator MTBF = 975 hours,

which rounded off is 1000 hours per modulator, and considering the age of modulators, thyratron fault rate, and relay control circuitry seems appropriate (the database error could be as high as ±10%, a pessimistic MTBF is then 900 hours).

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

Overall Modulator MTTR = 401/997
Overall Modulator MTTR = 0.402 hours/problem

or the average problem (a repair or intervention) requires about 25 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 [6].

Overall Modulator Availability = 1 – (Failure Rate)(MTTR)
Overall Modulator Availability = 0.900

This would be the "availability" if there were no spares for the modulators, however as mentioned earlier there are up to 14 spares available and they can be activated within 12 minutes to replace a faulty unit. Using the 12 minute or 0.2 hour repair/replacement as the MTTR, then increases the "availability" to 0.950, a respectable increase that verifies the advantages of available spares.

The database contained 62 nonscheduled interventions for the 15 critical modulators with a total time for repair of 35.7 hours. Applying the calculations as above for the critical modulators gives 60,000 modulator-hours of operation,

Critical Modulator Failure Rate = 62/4000
Critical Modulator Failure Rate = 0.015 problems/hour,

Critical Modulator MTBF = 60,000/62
Critical Modulator MTBF = 968 hours,

Critical Modulator MTTR = 35.7/62
Critical Modulator MTTR = 0.576 hour/problem,

Critical Mod Availability = 1 – (Crit. Failure Rate)(MTTR)
Critical Mod Availability = 0.991

The Accelerator Operations Group defines availability as [7],

$$A = \frac{\text{Scheduled Operating Time} - \text{Unscheduled Downtime}}{\text{Scheduled Operating Time}}$$

If we establish that the 15 critical modulators were scheduled for 4000 hours of Operating Time, and their operation resulted in 35.7 hours of Unscheduled Downtime then, A = 0.991, which is identical to the result of a variation of the above equation for Critical Modulator Availability, and it sets the actual overall availability for the 243 modulators.

This number indicates that modulator availability was better than either of the above two calculations for Overall Modulator Availability which offered 0.900 for the no spares case, and 0.950 for the spares case, but it portends that the expected availability would be no better than 0.900 since there are no spares for the 15 critical modulators.

V. Preventive Maintenance

Great importance is indeed placed on modulator MTBF and MTTR because the beneficiary of "availability" would prefer that the calculation for "A" produce a whole number rather than a decimal. There is reason to believe that A = 0.900 can be improved upon. Whatever is achieved in the future will be buttressed by preventive maintenance just as the current statistic has been.

Preventive maintenance (PM), in general, occurs during long shutdown periods between running cycles. These exercises have the greatest impact on modulator reliability because there is time to be thorough. Whereas both the incidence and duration of "scheduled maintenance" during an accelerator running cycle are unpredictable. The operating philosophy is to allow overall performance degradation until running isn't feasible (which is to say, no useful physics can be done) then, "schedule" a maintenance period or an aforementioned "repair opportunity day."

MODULATOR PM SIGN-OFF LIST

SECTOR____ DONE BY______ DATE____

I. INSPECTION	1	2	3	4	5	6	7	8
A. GROUND HOOKS								
B. DOOR LATCHES & SWITCHES								
C. LAMPS								
D. FANS								
E. PFN COILS & STRAPS								
F. MAIN CONTACTORS								
G. OIL LEAKS								
H. BNC FEED-THROUGHS								
I. BLEEDER RESISTORS								
J. SCR ASSY & RESISTOR STRAPS								
K. RFI FILTERS								
L. TRIGGER CHASSIS 1 & 2								
M. T-20 & EOLC CONNECTIONS								
N. TRIAX & TANK SOCKET								
II. OPERATION								
A. K-28 SET								
B. SHUNT TRIP								
C. FAULT STEPPER								
D. K-14 (Min 2 sec delay)								
E. TUNE PFN								
F. THYRATRON RESERVOIR SET								
G. HIGH VOLTAGE STABILITY								
H. NOTIFY MCC OF COMPLETION								

Table III. The modulator PM sign-off list.

PM is done in two distinct phases during long shutdowns, 1) Cold PM when all parts of the modulator are accessible and safe, and 2) Hot Maintenance when various modulator parameters are established e.g., PFN tuning, in preparation for actual accelerator operation. Technicians work against a check list in the first case which is intended to produce a thorough examination of the modulator's component parts and provide a record of completed maintenance. In the second case, the Hot Maintenance phase, a separate data sheet records tuning parameters and other high voltage on conditions for each of the 243 (or 244) modulators.

Once the accelerator is operating, there are two maintenance routines which are essentially nondisruptive and will pre-empt certain failures.

1. All modulators have 6 removable, disposable air filters which are routinely replaced to optimize cabinet cooling.
2. The most important PM routine, however, is thyratron ranging.

The thyratron requires adjustment to its reservoir to maintain the temperature of the hydrogen replenisher which results in a relatively constant plasma pressure within the tube. This process of finding the proper setting for the reservoir is thyratron ranging. To preserve the life of the tube and maintain stable operation it is necessary to range it, at least, every 500 hours. Too little reservoir voltage will produce overheating and shorten the life of the tube. Too much reservoir voltage will cause arc-over. Neither has a salutary effect on reliability so the center position must be found and tracked over time as the tube ages. Ranging information is collected on a sheet designed for the purpose. A resultant database is the source of reservoir history that follows every thyratron throughout its lifetime.

VI. Component Lifetimes

Referring to Pareto chart in Figure 6, notice that several "replace categories" are rather dismal because of high number of interventions and repair time involved. These are components or chassis that are obvious topics for lifetime or reliability discussion (and for eventual improvement). Keep in mind, that in 1991 the SLC operated at 60 Hz for 90% of the run. There is anecdotal confirmation that were the PM scheduled more conscientiously several categories could drop counts, but the two components about to be discussed below would be difficult to effect. However interventions due to the chassis element below could decrease by a factor of ten.

The Replace Pulse Cable category refers to the triaxial cable that delivers power from the PFN to the pulse transformer attached to the klystron. The MTBF for the cable was 13,300 hours as based on 972 k modulator-hours and 73 replacements. Cable survival has improved during the 92 run, but we don't have a specific answer for the increase in lifetime that seems to have doubled. One theory posits that the liquid dielectric filled cable was being improperly stored, allowing the oil to drain, and reducing the withstand voltage at the PFN inner shield connection. Another idea involves cable ground placement so the outer and inner shield are tied together. Cable storage has since been improved and intra-shield connections implemented. The shop that terminates the cable claims that no changes were introduced to the termination process, and furthermore states that the cable construction has not changed.

The Replace Thyratron category offers a direct calculation of thyratron lifetime. Sixty-one thyratrons were replaced during the 972 k modulator-hour operation. Denoting a thyratron lifetime of 16,000 hours for essentially 60 Hz operation at the power levels as indicated in Table II. Thyratron endurance has suffered during the 92 run with 120 Hz operation as the standard, consequently lifetime has been reduced to 12,000 hours. The modulators use one of four thyratron types, and this lifetime is an average of these four types. Specific type lifetimes will not be presented, but some idea of lifetime can be gleaned from Figure 7.

Figure 7 presents thyratron hv hours at a specific time for the modulators, and while it does allege age distribution, it doesn't indicate potential lifetime [8]. The total number of sockets indicated is 246, but two modulators are used as complete spares for any unexpected catastrophe.

The ITT F-241 was produced in response to the specifications required for the modulator upgrade [9]. Figure 7 indicates that 127 thyratrons of this type were in use. The F-241 is slowly superseding the remaining types of thyratrons. As our population of types increases in age, more F-241's will enter those sockets, unless another thyratron manufacturer offers a product to contest the F-241.

The ITT F-143 is a rebuilt Wagner thyratron, formerly labeled CH1191 by Wagner. ITT was contracted in the 70s to rebuild 300 of the spent CH-1191 structures, in testimony to ITTs remanufacturing ability 28 of the F-143 types are still functioning.

The CH1191 as mentioned is the original SLAC thyratron manufactured by Wagner, and 43 units remain functional.

The fourth thyratron is the Omni-Wave 1002 which again is a rebuild of a lifeless Wagner body. These units were contracted in the mid 80s because of SLAC concern for a second source of thyratrons, since Wagner had disappeared from the market place and other vendors were unable to compete with ITT on either performance or cost. While competitive, the Omni-Wave rebuild effort was not as successful as the 70s ITT endeavor. The 1002 types do not exhibit the turn on performance stability that we need in the modulators for reliability. The thyratron specifications demand that no more than three thyratron faults occur in any 24 hour period, unfortunately the 1002s have a difficult time with this requirement. There are nevertheless 48 Omni-Wave types working in the modulators with good performance.

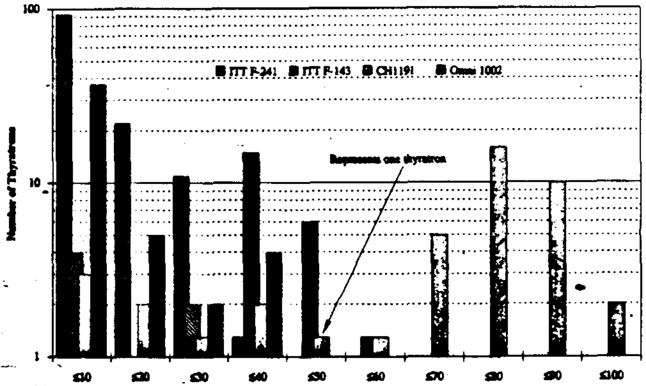

Figure 7. A distribution of 246 values for thyratron HV hours.

The third area for lifetime and reliability discussion is the Replace Thy Driver and Replace Trigger Unit which concerns the thyratron trigger generator. The trigger unit amplifies the timing pulse to drive the thyratron driver and the thyratron driver fires the main thyratron. This equipment ensemble is as designed in 1965. The MTBF for the trigger unit is 50,0000 hours which is a acceptable value, since it is determined by the two vacuum and VR tubes in the blocking oscillator that describe the circuitry in the unit. The MTBF for the driver is 30,000 hours which is essentially based on the lifetime of the small thyratron within the driver.

VII. RELIABILITY IMPROVEMENTS

The Pareto chart in Figure 6 suggests that several "replace categories" control the present state of "overall availability," A = 0.900. However at this level of availability or 0.950 as dominated by the spares situation, improvements can only be justified if the "overall modulator failure rate" is reduced to a half of the present value. This requires eliminating half of the unscheduled interventions and about 200 hours of unscheduled time. This has the effect of improving the "overall availability" to 0.950 (or a 5.5% improvement while MTBF doubles) which is equivalent to the availability with spare modulators. We claimed and calculated that without spares for the critical modulators that our expected availability should be 0.900, so this improvement is probably worthwhile. Improvements will be carried out to eliminate or reduce the interventions for the following categories,

1. Reset Main CB
2. Reset Interlocks
3. Reservoir Voltage Adjust
4. Replace Pulse Cable
5. Replace Thyratron driver
6. Replace Trigger Unit.

If unscheduled interventions could be decreased to 535 rather than 997, and the total repair time could drop to 261 hours as compared to 401, the reductions give A = 0.935 not the goal of 0.950, but then we expect to slightly reduce the interventions and time caused by the Replace Thyratron category as well.

The first three categories above can be reduced by regulating the thyratron reservoir voltage. A ferro-resonant regulator that was used for the reservoir was rewired during the upgrade to provide voltage for the klystron heater. We are investigating solid state as well transformer regulators for the reservoir regulator. Rectifying this mistake after five years should benefit modulator reliability as well as thyratron performance.

Category four interventions can be lowered (although they seem to be decreased as mentioned above) by reducing the voltage transient on the triaxial cable using a saturable reactor between the PFN and thyratron anode. This voltage ringing is a result of stray capacitance discharge and a cable impedance to load mismatch ($Z_{cable} > Z_{load}$). Stray capacitance is almost impossible to eliminate, and while it would help, lowering the impedance of the cable is also a difficult process. Successful reactors have been designed to reduce commutation losses in thyratrons so applying this idea to transient reduction offers a increase in thyratron lifetime and modulator reliability [10], [11].

Category five and six reductions require the replacement of tubes and thyratrons with solid state devices, simply put, changing the old driver and trigger unit to a modern circuit.

An additional decrease in the Reset Main CB category demands improvement to the high voltage overcurrent circuit so that the contactor opens before the main circuit breaker trips. These circuit improvements are also being designed.

VII. ACKNOWLEDGMENTS

Without the work of many people, equipment reliability as characterized herein, could not have been achieved. The authors are indebted to Ernest Howard, Perry Johnson, Fred Rouse and their respective crews in Power Conversion, for maintaining 243 modulators in a professional manner. Much of the reliability analysis could not have been done without information provided by C.W. Allen, Accelerator Department, (klystron data) and David Ficklin, Klystron Department, (thyratron data). Their contributions are gratefully acknowledged. Formulation of a reliability database would have been more difficult without Justine Mello who entered raw data. The authors would also like to thank John L. Brown, Maintenance Officer, Accelerator Department for his example and for focusing attention on the importance of improving reliability, as well as, Alfredo Saab, Department Head, Power Conversion, for his interest and encouragement.

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