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Development of a RAMI Model for LANSCE and High Power APT Accelerators*

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Abstract

Assessment of the reliability, availability, maintainability and inspectability (RAMI) of all high power, high cost systems is important to justify and improve the cost effectiveness of these systems. For the very large (over 100 MW) accelerator systems associated with APT, a RAMI model is very valuable in guiding the design and allocation of resources. A RAMI model of an existing machine is also valuable, since machine improvement funds must be allocated to increase the availability by the largest amount. We have developed a RAMI model using the critical subsystems of the LANSCE accelerator and beam delivery complex as an example and to evaluate the effectiveness for estimating reliability and beam availability. LAMPF and LANSCE together provide most of the features required for the accelerator and beam delivery part of a high-power APT machine, but LANSCE is pulsed, rather than CW. This complex is capable of a 1-MW average power H^- beam, and it is the most powerful proton accelerator in the US built to date.

Introduction

The reliability of the LANSCE beam delivery system is the probability that the system will perform its intended beam delivery for a run cycle, about 1000 hours. The reliability must be estimated to include all possible sources of downtime, such as operator errors, main power failures, and other disruptive actions of both man and nature. The availability is the fraction of the scheduled time for which experiments at LANSCE could be done, i.e., the beam has been delivered to the start of the LANSCE target complex. In the steady state, the availability is the ratio of the time the system is operating to specification, divided by the total scheduled time. Thus the availability depends not only on the frequency of breakdowns, but also on the time that it takes to repair these breakdowns. Maintainability is the ease of diagnosing and repairing breakdowns. Inspectability is the procedures or tests that may be carried out prior to an operating period to assure that the system will operate properly. The inspectability goal is done at LANSCE by the many tests and inspections that are done before and during each run cycle. Many of these inspections and tests are required by regulations.

The general approach taken is to examine the LAMPF historical records, and then construct a mathematical model that approximates the historical records. The model is based on statistical analysis and calculations with the existing reliability data. An advantage of this type of approach is that all the variables in the operating environment are taken into account, even the non-obvious variables like operator errors and power outages. Once good agreement is obtained, the model

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will be used to examine future scenarios for improvements to LAMPF, with the overall goal of improving the reliability and availability of LANSCE in a cost-effective manner. The model can also be used for future accelerators, such as APT, to evaluate the reliability and maintainability as a function of the design parameters.

Description of the LANSCE Beam Delivery System

The beam delivery system to LANSCE is a serial connection of subsystems, starting at the H⁻ source, proceeding through the 201 MHz and 805 MHz accelerators, and then through the Proton Storage Ring to LANSCE. The H⁻ beam is accelerated to 750 keV by a dc column, and then it is accelerated to 100 MeV by the 201 MHz accelerator, and to the final energy of 800 MeV by the 805 MHz accelerator. There are also some other constraints on operation, such as availability of facilities and administrative requirements such as formality of operations and testing that also effect availability. A block diagram of the LANSCE beam delivery system is shown in Fig. 1, where the solid lines denote the beam flow, and the light lines are requirements that affect many segments of the machine. The diagram is by no means unique, but it is used to illustrate the major parts of the system, and reflects the historical methods of recording reliability data. One can consider the facilities and administrative requirements to be in series with all the other subsystems, since they must also be available (or performed) before the beam can be delivered to LANSCE. The LANSCE target system is not considered here. The goal is to formulate a mathematical model to

Figure 1. Block diagram of the LANSCE beam delivery system.

describe the reliability, availability, maintainability, and inspectability for the beam at LANSCE. The longer term goal is to improve all aspects of RAMI for LANSCE, and to evaluate RAMI for the APT accelerator systems.

The eleven blocks in Fig. 1 correspond to one of the ways that reliability and availability data is collected for the LANSCE beam delivery system. The beam delivery system for LANSCE includes several kicker magnets and their power circuits and the RF bunchers for the Proton Storage Ring (PSR). These components are referred to as the pulsed power system. The intent is to expand on each of the modules as data is collected, and to eventually be able to determine the unreliable components and subsystems within each of the major systems. The injector system is the ion source, dc accelerator, plus bunchers, a beam deflector, and a low energy beam transport system. The RF accelerator systems are composed of the RF accelerator, focusing and steering magnets, ion pumps, the RF amplifiers, and RF transport systems. A practical problem with any data collection system is that it is very difficult to assess the cause of a particular down time. For instance, any vacuum leak in the accelerator will result in many arc downs in the accelerator, which are considered RF system problems until the leak is so big that it is obvious, and then it is called a vacuum problem. One must also be careful not to count the down time twice, since when there is a vacuum problem, for example, there also is a problem with the accelerator, and the vacuum leak may be in a magnet or an RF window.

LANSCE Historical Data

The first step is to gather enough reliability and availability data from LANSCE to determine what the problems have been in the past. Fig. 2 [1] shows the availability of LANSCE for the past 15 years, with the points for contiguous operating cycles connected. The three straight lines are various averages of the availability. The overall availability average is almost 75% (the central dotted line), but the first cycle after a long down time average availability is slightly under 70%. The average availability calculated with only the best operation cycle in each major set of run cycles is almost 80%. This result shows that the machine is difficult to turn on after an extended down time, and that better availability will be realized by operating LANSCE more in each year. Much of this initial turn on problem is due to new software and hardware installed, but not sufficiently tested and inspected, between major operating cycles. This problem may be reduced by requiring strict controls and reviews on changes to the machine, i.e., stricter administrative change controls. It is also well known that electronic and mechanical equipment is subject to failure during the turn on transients. Many highly reliable systems such as commercial radio and television transmitters are only rarely shut down to minimize this mode of failure.

Figure 2. Availability of LANSCE beam delivery system for the years 1979 to 1993.

The second step is to subdivide each system in Fig 1 into its major subsystems, and gather reliability and availability data at the major subsystem and even component level. This task is difficult, since most of the existing LANSCE records were designed to calculate the machine's overall availability, and not the individual subsystem reliability or availability. The existing records were not taken with component or subsystem reliability in mind. Some of the data can be found in the main logbooks, but other data only exist in logbooks kept by the individuals doing repairs on the subsystems. We have been obtaining this data, but some of the components will have to have their lifetimes estimated by either the manufacturers or the experts who repair them. A summary of the major causes of downtime for LAMPF from the 15-year historical record is presented in Fig. 3. The pulsed power entry in Fig. 3 was found from the summary logs of LAMPF Run Cycles 51 to 62, from 1988 to 1993. The injector entry is for the H- injector that is actually used at LANSCE, but only for the years 1991 and 1992. The five major contributors of down time are the 201 MHz accelerator system, the vacuum system, the injector system, the pulsed power system, and the 805 MHz accelerator system. Previous RAMI work has been done on the injector system [2]. It is believed that the injector system has been improved significantly by this work, and these same techniques are now being applied to the other systems. Some results at the major component level have been obtained for the 201 and 805 MHz RF systems, and these results are included below.

Figure 3. Leading causes of LANSCE beam delivery downtime, 1978 to 1993.

Availability Analysis

The availability is determined both by the reliability of all the individual components, and the maintainability of these components. In addition, administrative requirements can influence the time to maintain, or even to diagnose, a system, especially when high powers, high voltages, and radioactivity are involved, as is the case for large accelerators or reactors. The reliability function is determined from the distribution of times to failure, and the simplest measure is the mean time to failure (MTF), which is constant if the component exhibits a random failure mechanism. Real components often suffer both from infant mortality and wear out, so a bathtub shaped curve shown in Fig. 4 usually is a better approximation to the failure rate. The parameters for the failure distribution may be obtained from life testing, field data, manufactures estimates, or ab-initio calculations on the component. The two-parameter Weibull distribution is often a good approximation to failure rates for electronic equipment, especially when the equipment is maintained by replacing components, so the wear out phase is approached, but never reached. Two possible failure (sometimes call hazard) rate curves for Weibull distributions are also shown in Fig. 4. The failure rate is the probability per unit time of failure for a component or system. The Weibull distribution has two characteristic parameters, m , the shape parameter, and θ , the time parameter. These failure distributions may either rise or fall with time, depending on the shape parameter, m . We generally use the field data to establish the failure distribution for

components and sub systems. For high power electron tubes, m is less than one (often from 0.6 to 0.7), and the failure distribution has many early failures. When $m=1$, the failure rate is constant with time, and the system operates on the flat part of the bathtub curve. For $m>1$, the failure rate grows with time. This type of failure distribution is likely with mechanical systems, such as pumps, but in accelerator service, the pumps are usually made redundant, since there are not many of them. Although some klystron vendors hope that early failures may be eliminated, there is no evidence that this has ever been done. The MTF for pulsed klystrons in accelerator service [3] is very good, and averages over 50,000 hours, and for CW klystron in accelerators [3], the MTF averages over 25,000 hours. When the MTF is large, over 50,000 hours, the early failure times may range above 10,000 hours, so it is not practical to burn in the components this long.

Figure 4. The bathtub and Weibull failure rate curves versus normalized time.

The maintainability data falls into two classes for a machine like LANSCE or APT. The large components, such as the largest power supplies and power transformers, must be maintained in place, since it is not practical to have spares available. For these components, the repair time varies greatly, depending on the complexity of the repair, and the amount of diagnostics that must precede the repair to establish what is wrong. From the historical records, we can estimate the distribution function of the repair times. Again, the mean value, the mean time to repair (MTR), is sometimes used to describe the repair process, but this is a gross

simplification. It is better to record repair times, and then fit a Weibull or log-normal distribution function to this data, and use the distribution function in calculations. The smaller components at LANSCE have spares that are located close to the component. When these components fail, a replacement is used. There is less variability to this process, but there still is variability, since the failed component must first be diagnosed. In this case the repair is done off-line, and the time it takes to make the repair does not matter for LAMPF's reliability and availability, but it affects the number of people required to operate the machine. For these components we are concerned with the mean time to replace, and the distributions of diagnostic and replacement times. We still use the concept of the time to replace and use the same abbreviation for the mean time to replace.

Essentially all the components in an accelerator system have to be operating to produce the desired beam, so the system is a series system. If we assume a constant failure rate, then the expected down time is given by

$$DT = n * MTR / MTF, \quad (1)$$

where n is the number of identical components. When MTF is the mean time to failure in days, and MTR is the mean time to repair in hours, then DT is in hours per day. The availability of a single component is then

$$A = (MTF / (MTF + MTR/24))^n. \quad (2)$$

In this model, the down time of the whole machine is the sum of the down times of the individual components, and the availability of the whole machine is the product of the availabilities of the individual components. More sophisticated models of the failure distributions may also be used, as can parallel connections of components. In these cases the algebra gets very difficult very quickly, but commercial software packages may be used to do the analysis numerically.

The reliability is also influenced by the stress levels, such as power density, electric fields, current density, and temperatures in the individual components. These stresses are built into the component at the design stage, but they may sometimes be relieved by operating the component at lower power or voltage levels. The major component in the 201 MHz RF system that has a short life is the final amplifier triode, but we cannot operate this triode at a lower power level since the accelerator requires a high peak power. We have made life better for these triodes by operating the 201 MHz RF system at the lower peak and average power required by the accelerator. We are also evaluating several replacement amplifiers that will generate the same power with lower stresses in the amplifiers, but there will be a penalty on capital costs, since each single amplifier will be replaced by a pair of lower power amplifiers plus a combining network. A major

problem with the LANSCE 201 MHz RF systems is that there are perhaps 12 high power amplifier and modulator tubes in each RF system. The system has been simplified recently, and this should improve the reliability, but two of the major tube types have had very bad life problems recently.

In the lowest order analysis, one assumes that the failures are all statistically independent, but we have seen that certain types of failures often cause a chain reaction of failures, or at least some long time to repair failures. The utilities and facilities failures are the most important common-mode cause for producing other failures. The loss of an air conditioning system, for example, increases the temperature of all the components in the building that used to be cooled, and secondary failures often result. Another type of failure that often causes secondary failures are power line faults, or even voltage dips on the main power lines. These types of outages, which are common during the summer thunderstorm season during which LANSCE operates, result in literally thousands of components switching off. Then the whole machine must be brought up from the off state, and typically there are a few components that fail during the turn-on process. Thus, there is a 'failure to start operations' failure mode that is almost independent of the failure rate during normal operation, and to assess this failure mode, we must have the failure to start probability as well as the probability of failure, given that the system is up and running. To minimize the downtime from this type of failure we need to reduce the frequency of power outages and dips, and also we must be sure that the components are robust to start-up transients in voltage, current, torque, etc. However, we must be aware in the analysis that statistical independence is not always justified on a real machine.

We are concentrating on hardware down time and are neglecting the down time caused by administrative procedures, formality of operations, and beam tune-up time. The scope of the project has to be limited to make measurable progress in the hardware area. We intend to expand into the other sources of beam delivery system downtime. We also are neglecting the very short down times that can be remedied by the manual or computer driven application of a reset pulse. These nuisance trips are usually caused by arcs, RF reflections, or other momentary overloads.

Accelerator Availability

In the 201 MHz accelerator systems, the major failure mechanism is the RF system, but vacuum problems and magnet problems are not negligible. Due to the difficulty of obtaining the component data, only two run cycles, totaling 1810 hours of operation have been analyzed. For this short time, all the accelerator components were lumped together, and the distributions of down times was examined, and a first model of the combined system was made. The distribution

of observed down times and the cumulative down time distribution for the 201 MHz accelerator system is shown in Fig. 5. Only down times of 5 minutes or longer are included in this chart. The surprising feature of the cumulative curve is that there is a large fraction of down time due to long outages of 12 hours or more. For the 805 MHz accelerator system, the same data base yielded the curves of Fig. 6. Once again we see a high fraction of long down times. In this case one long down time was caused by a large dc power supply that had to be repaired in place, and the second one was a vacuum leak. The short trips of the 805 MHz RF system are longer than those for the 201 MHz accelerator, since a loss of

Figure 5. Down time distribution and cumulative down time for the 201 MHz accelerator system.

resonance condition often occurs in the 805 MHz system due to the RF cavity's smaller size and faster cooling.

Conclusions

To summarize, the research on RAMI is showing that the reliability and availability of LANSCE may be modeled and improved by utilizing statistical methods and historical data. Baseline reliability data is being accumulated and applied to the individual subsystems that comprise the LANSCE beam delivery system, and individual subsystem models are also being developed. With these

Figure 6. Down time distribution and cumulative down time for the 805 MHz accelerator system.

subsystem models, a model of the entire facility is being developed and checked against historical data. Finally, the model of the facility will be used to assess the availability improvements for various proposed improvements to the facility. Then the cost effectiveness of the suggested improvements can be obtained from independent cost estimates and the availability analysis, the optimal improvements for the available budgets can be determined. The RAMI model is general enough to be applicable to other accelerators, both existing and proposed. In particular, this model is valuable to assess and improve the RAMI aspects of the high power accelerators being considered for APT and ATW applications. It also is applicable to evaluate the RAMI for the next linear collider accelerator.

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