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A Novel Approach to Increasing the Reliability of Accelerator Magnets

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Abstract— When a very large particle accelerator with about 8000 electromagnets, such as the proposed Next Linear Collider (NLC), has an 85% overall availability goal, then all these magnets and their power supplies must be highly reliable and/or quickly repairable. An interdisciplinary reliability engineering approach, more commonly applied to aircraft and space vehicles, has been taken to design maximum reliability in the NLC main linac quadrupoles, while maintaining magnetic field performance and reducing cost. A specially assembled team of engineers with a variety of experiences with magnets carried out a Failure Mode and Effects Analysis (FMEA) on a standard SLAC quadrupole magnet system. This process helped them identify which components were less reliable. Then they redesigned the quadrupole to avoid all the potential problems. A prototype magnet will be made and tested to ensure that functionality has not been lost.

Index Terms—Magnet, reliability, FMEA.

I. INTRODUCTION

The Next Linear Collider (NLC), as proposed, would collide electron and positron beams from two linear accelerators with center-of-mass energy of 10^{12} electron volts (1 TeV) and luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The beam lines that create, accelerate, and collide the beams total 35 kilometers in length, and are populated with about 60 000 components including 8000 electromagnets of about 90 different styles. The availability goal for the whole accelerator complex is 85%. Therefore every component must be highly reliable or quickly repairable. The overall design philosophy is to achieve an appropriate balance between performance, reliability and cost.

Reliability must be considered at all stages of such a project. Engineering techniques must be found to manage reliability as early as possible. By dealing with potential reliability problems early, development time can be shortened, the costs reduced, and reliability improved. Consequently, even though the NLC is still in the R&D phase, all its engineers will be engaged in reliability engineering from the conceptual development stage, through engineering and design, prototyping, production and operation of systems and their components.

The NLC engineers are adapting the concepts of reliability engineering as used in the military, government and industry to the needs of designing the NLC [1]. The reliability engineering process makes use of many tools ranging from general software packages (i.e. Microsoft Excel, MathCAD, etc.) to dedicated reliability analysis models. These tools are employed in the iterative process shown in Fig. 1 that has been developed recently using a complete DC magnet system (DC magnet, power supply, controller, transductor, AC distribution and cables) as a test case. We tried using each tool to ascertain which ones were most effective for designing the technical systems of a research accelerator. The tools we evaluated included mathematical modeling, Failure Mode and Effects Analysis (FMEA), Reliability Block Diagrams (RBD), and availability budgeting.

II. RELIABILITY ANALYSIS

In general, reliability analysis starts by listing all the major components of the magnet system and making a block diagram showing how their functions are interrelated. Then

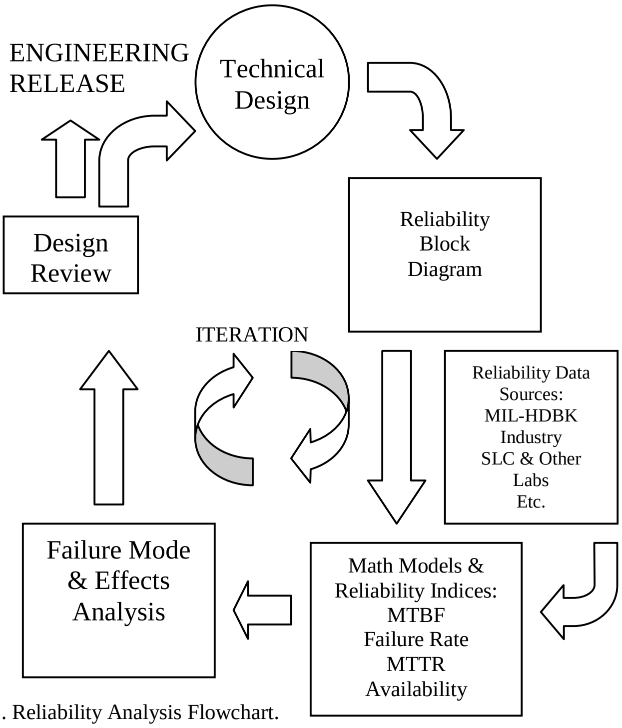

Fig. 1. Reliability Analysis Flowchart.

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those components that must operate properly for the system to operate are considered from a reliability point of view. These logical relationships are shown in the Reliability Block Diagram (RBD). Block Diagram (RBD) Fig. 2. The RBD is used to determine the effects of component failures on the system, and is used in conjunction with the FMEA as described below.

Next, the standard indices of reliability are estimated—Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and Availability (which is a function of both MTBF and MTTR). These are used to model the behavior of a system. This methodology is most useful on systems with few components or on systems with failure rates well-documented by industry, government or military sources (e.g. in MIL-HDBK-217, Bellcore Issue 5, NPRD-95, ISO 9000, Naval Surface Warfare Center Handbook, NASA documents, etc.). Some of the commercial power supply components have published MTBF data but most of the custom-made magnet components do not. Therefore operational experience with similar magnets is used to estimate reliability. For example, operational experience must be used to estimate the reliability of a resistive, water-cooled quadrupole. The next step in the process is to find ways to improve on the historical reliability. It was decided that the structured, qualitative approach called "Failure Mode and Effects Analysis" (FMEA) was best suited to our reliability engineering abilities and needs.

III. FAILURE MODE AND EFFECTS ANALYSIS

The FMEA process considers each mode of failure of every component of the system and ascertains the effects of each failure mode on system operation. The analyst must also identify the causes of the failures, and rank their severity and expected frequency. Only a team of engineers sharing a thorough knowledge of the system's design and application can perform an effective FMEA. For NLC components in their design phase, the ultimate usefulness of FMEA occurs when it points to design changes that eliminate the identified causes of failures, with a resulting improvement in reliability.

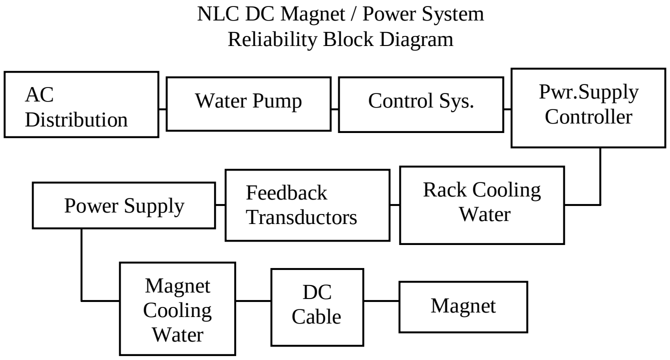

Fig. 2. Reliability Block Diagram

FMEA was first developed in the 1960s as part of the formalization of system engineering practices when demands for increased reliability drove engineers to take into account not only what the component failures were, but what their effects would be on the whole system. In the 1970s the US military formalized the approach further by developing and issuing US MIL-STD-1629, "Procedures For Performing A Failure Mode, Effects and Criticality Analysis" [2]. The standard included a special worksheet for compiling the failure mode and effects information. In turn, FMEA requires the completion of individual worksheets specific to the three major project phases of design, production and operation. In the design-phase FMEA one evaluates the most current design of a component and recommends actions that can be taken *during the design phase* to improve the design of the component. It is important to realize that each of the three FMEAs represent an interactive, iterative process. The worksheets are living documents to be nurtured and referenced repeatedly during the lifetime of a project.

Today, FMEA is being used in most if not all manufacturing industries in some form or another making it one of the most common reliability tools in use. However, the application of FMEA to accelerator magnet design might be unprecedented and the experiences described herein lead to the assertion that it is a worthwhile technique deserving of wider application in the world of accelerator engineering.

IV. FMEA AS USED BY THE NLC

The accelerator engineers and physicists in the NLC design group start new projects by drawing heavily on their collective experience that spans 35 years of development of conventional accelerator magnets at SLAC and at other Labs. That experience includes magnets designed with both reliable and unreliable features. With a reliability-based design methodology, hopefully only the better features will propagate in new designs.

The management and improvement of component designs outside this historical 'comfort zone' is a formidable challenge. It is in meeting this challenge that the promotion of reliability engineering is playing a significant role for the NLC. A reliability analysis process, as described above, is best carried out by a specially formed team with the collective experience to outline and plan the design of entire systems that span multiple functions and many engineering disciplines. The development of a reliability-based design process, centered on the FMEA method, was first attempted within the NLC project by an engineering team assembled to develop a more reliable design for the 1500 DC quadrupole magnets and associated power systems in the 20 km of linear accelerator in the NLC.

The team consisted of technical managers, reliability trainers, mechanical and electrical engineers, designers, technicians, and accelerator physicists. The design process began with the definition of the magnet's functional requirements from the accelerator beam optics and a preliminary device specification. With some formal reliability engineering training and these requirements, the team set off to create and document a more reliable system design. Then the iterative process shown in Fig. 1 began. The team developed the functional block diagram and the RBD of the subsystems of the magnet and power system (Fig. 2.). Then they searched the literature for MTBF and MTTR data for these subsystems. As mentioned above, for those sub-systems without published MTBF data the team dug into SLAC operations data (and their own filing cabinets) to establish an MTBF and an MTTR for all sub-systems.

This data was manipulated with simple math models to calculate the reliability and availability of each subsystem assuming it was designed exactly the same as was done at SLAC these past fifteen years. Further, the gross analysis of sub system and component availability provided a starting point for comparisons of engineering design options. The ultimate goal of the exercise was to improve upon these initial reliability figures without impairing the magnetic performance.

The next phase of this process was to develop an appropriate FMEA worksheet that fit the accelerator world. It turned out to be a combination of automotive industry and US military worksheets. It has 18 columns and cannot be squeezed into this paper! A failure mode is defined as any way in which a component, sub-system or system could, historically or potentially, fail to meet design intent, performance requirements, or mission expectations. Based on their extensive experience with magnets and power supplies the team listed in one worksheet column all the envisaged failure modes for all the major components of these devices.

Next the potential effects of each failure were brought to mind and listed in an adjacent column. These effects spanned complete loss of function as well as changes in safety or increased risk of exceeding field uniformity requirements. Each effect was subsequently assessed for **severity** on a 5-point scale, with loss of function being most serious. Next, each failure mode was assigned one or more causes. Emphasis was placed on identifying only root causes and each entry was graded for likelihood of **occurrence,** again on a 5-point scale. The scale of failure rates generated was based on historical accelerator operations. In another column the team wrote an evaluation technique for each cause that could be applied during the design and testing phase. How successful the design evaluation technique would be in identifying a failure cause is also rated on a 5-point **detection** likelihood scale.

The product of the severity, occurrence and detection likelihoods for each cause was then calculated. This product is identified as the **Risk Priority Number** (RPN). When an RPN is high, the team must decide whether a threshold has been broken and, if so, recommend actions to reduce the risk. These actions are listed in another column. It is at this stage that a design change can be effectively attempted. A review committee studied the FMEA worksheets to decide which actions would be best for the whole system. They judged that if there are two or more possible design changes that could remove or ameliorate a failure mode, probably at different costs, that mode would have to be re-evaluated for each design change with new severity, occurrence and detection ratings. Then decisions between design changes would be made, based on the reduction of the RPN and the relative costs of the competing corrective design changes.

V. QUAD MAGNET DESIGN CHANGES

The team produced 10 magnet design changes on their first FMEA pass-through that took about one year of weekly meetings (including training and worksheet development). Much was also learned about the reliabilities of the power system components, but they will not be dealt with in this paper. The new magnet design generally differs from historical SLAC designs and actually overcame a number of long standing design prejudices. The new design not only offers improved availability, but also reduces fabrication cost. These positive results motivated the design team to apply some of these changes to other magnetic components required by the NLC.

The list of magnet design decisions, taken individually, may be not new or unique. The combination of these features into the total system is what is exciting. A summary of changes that were identified through the reliability–based design approach is shown in Table 1.

Fig. 3 is a 3-D sketch of the new quadrupole design.

This first pass design proposal has been released for prototype manufacture and will be tested for performance and validated for price by the early part of the year 2000.

Three of the many decisions that resulted from the reliability-based design process deserve some amplification. The selection of round hollow copper conductor would seem to go against the accepted need to maximize current and thus conductor cross section in the coil pocket. The selection of round conductor allowed us to balance the lower efficiency of fewer coil turns in a fixed size coil pocket with the need to radically improve reliability in the tolerance control of water joint brazes.

Coil protection from overheating remains a very active area of consideration. SLAC's coil thermal protection is typically provided via thermal switches mounted on individual water-cooled conductor leads. While these devices are considered

TABLE I.

CHANGES IN MAGNET DESIGN RESULTING FROM RELIABILITY-BASED APPROACH.

CLASSIC DESIGN	RELIABILITY-BASED DESIGN
Square hollow conductor	Round hollow conductor
Wet lay-up design	Potted racetrack coils
Additional water compression joints	Monolithic coil lead to water interface
Quadrants of thin Laminations	Solid, EDM profiled, modular steel core
Same Input & Output hose fittings	Sexed Input and Output water hoses
PPS Interlocked supplies	Complete lead end safety/protection cover
Expensive multifunction components	Separate current and water connections
Torque carrying connection	Current quick disconnect to long haul cables
Exposed core bolts	Recessed core bolts
Thermal switch with no intelligence	Coil protection

to be highly reliable, their circuitry is not! Thermal switches forward only single point data and are usually not useful in diagnosing root causes or improving MTTR because they do not give precise location data prior to maintenance technicians entering the accelerator. The NLC magnet design group is currently evaluating a number of options that provide more operational information with higher reliability at an equal or lower system cost.

SLAC has had a long history of making very economical magnet coils with predetermined lifetimes to match expected accelerator lifetimes, but particle physics research can sometimes take longer than planned. So failures and susceptibilities of SLAC's recent coil designs and the NLC emphasis on higher availability for magnetic components directed our team back to a potted configuration with a minimal number of water compression joints. It was a combination of assembly tolerance investigations and slowing down insulation degradation that allowed the design team to demonstrate that potted coils were really a cost improvement over wet lay-up designs. The additional volume required by potted epoxy insulation and a realistic manufacturing analysis, suggested and supported by our FMEA document, allowed us to secure additional beamline space by showing it would improve reliability and lower magnet cost. This result is in sharp contrast to the general perception that a smaller magnet is always cheaper and larger conductor cross-sections are always better.

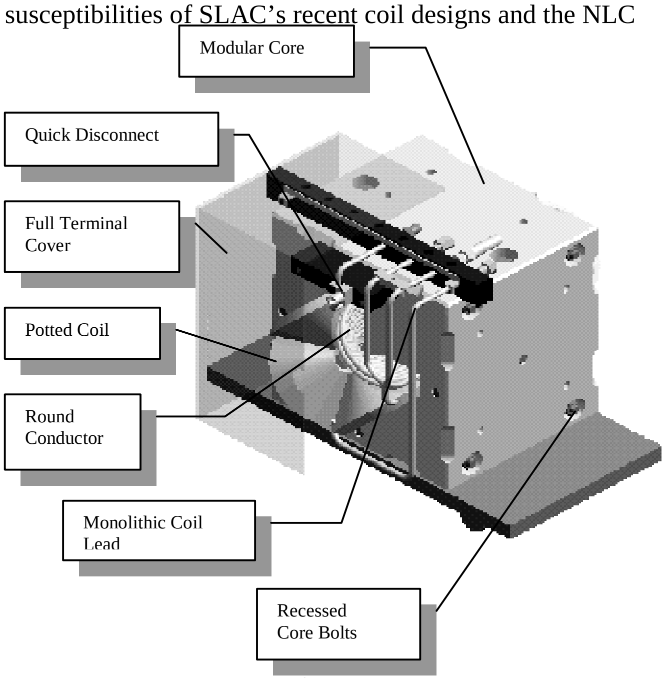

Fig. 3. NLC Linac Quad resulting from a reliability-based design approach.

VI. SUMMARY

Some conclusions can be drawn at this stage of the project. The introduction of reliability tools required minimal to moderate training and did not overwhelm the team. Quantifying risk by FMEA is simple and intuitive. The tools developed are useful enough that they already being used to improve the reliability of other components such as klystrons and vacuum components. While the magnet design FMEA is not yet complete it has already succeeded in encouraging people from different disciplines to work and problem solve as a team and to communicate effectively with each other. This positively affects the overall engineering process of this proposed large project.

The reasons for doing a FMEA are many, but some of the major benefits are: (1) It provides engineers with an understanding of the structure of a system and the factors that influence reliability. (2) It obliges engineers to collect failure and repair experiences and document them in a preserved way. (3) It helps to identify items that are reliability sensitive and rank them with regard to risk of disrupting the mission, and so gives a means of deciding priorities for corrective action. (4) It establishes if there are any operational constraints resulting from the design. (5) It gives the assurance that reliability is being or has been properly addressed early in the project. (6) It improves insight into cost versus performance trade-off. (7) It moves a project towards the most reliable device designs.

ACKNOWLEDGMENT

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