Proceedings of the 2003 Particle Accelerator Conference

COST BASED FAILURE MODES AND EFFECTS ANALYSIS (FMEA) FOR SYSTEMS OF ACCELERATOR MAGNETS*

Cherrill M. Spencer, SLAC, Menlo Park, CA 94025
Seung J. Rhee, Dept. of Mechanical Engineering, Stanford University, Stanford, CA 94305

Abstract

The proposed Next Linear Collider (NLC) has a proposed 85% overall availability goal, the availability specifications for all its 7200 magnets and their 6167 power supplies are 97.5% each. Thus all of the electromagnets and their power supplies must be highly reliable or quickly repairable. Improved reliability or repairability comes at a higher cost. We have developed a set of analysis procedures for magnet designers to use as they decide how much effort to exert, i.e. how much money to spend, to improve the reliability of a particular style of magnet. We show these procedures being applied to a standard SLAC electromagnet design in order to make it reliable enough to meet the NLC availability specs. First, empirical data from SLAC's accelerator failure database plus design experience are used to calculate MTBF for failure modes identified through a FMEA. Availability for one particular magnet can be calculated. Next, labor and material costs to repair magnet failures are used in a Monte Carlo simulation to calculate the total cost of all failures over a 30-year lifetime. Opportunity costs are included. Engineers choose from amongst various designs by comparing lifecycle costs.

INTRODUCTION

There is worldwide consensus that a high-energy, high-luminosity, electron-positron linear collider, operating concurrently with the Large Hadron Collider, is necessary to explore and understand physics at the TeV scale. The linear collider (LC) is envisioned as a fully international project, thus there will be only one LC to serve the world particle physics community and it must meet its luminosity goal through a guaranteed availability over a 30 year lifetime. Therefore every LC component must be highly reliable and/or quickly repairable.

One viable manifestation of a 1TeV LC is the Next Linear Collider (NLC), based on normal conducting X-band cavities. The facility is roughly 32 km in length and uses about 70,000 components of which 7200 are magnets and 6167 are power supplies. We have developed a set of analysis procedures for engineers to use to decide how much money to spend on improving the availability of any LC component through design changes. The LC will not be built if it is "too expensive", we must find an appropriate balance between performance, reliability and cost. This paper uses the magnets and power supplies of the NLC to illustrate some useful modifications to the Failure Modes and Effects Analysis (FMEA) risk-identifying technique, which involve life cycle costs, from design to operation.

PROBLEMS WITH TRADITIONAL FMEA

A team of engineers following the traditional FMEA process consider all the possible failures modes of a system component, from design through operation, identify all their causes, and rank their severity, expected frequency and likelihood of detection. A multidisciplinary team at SLAC carried out a FMEA of a standard SLAC electromagnet [1] and identified 10 design changes that would improve its reliability. A prototype NLC quadrupole that incorporated most of these changes was fabricated in 2000 [2] and has been run for about 10,000 hours since without any failures. The degree of risk of each failure is represented by the product of these 3 ranked indices, called the Risk Priority Number (RPN). But inconsistent definitions result in questionable risk priorities, and the use of failure modes rather than cause and effect fault chains inhibits ones understanding of the true causes of failures [3]. Furthermore traditional FMEA ends with the calculation of RPNs, the team does not consider the consequences of the failures in terms of costs. They do not check that their design changes for avoiding failures cost less than the failures [4].

LIFETIME COST: A MEASURE OF RISK

Risk contains 2 basic elements (1) chance, measured by probability, and (2) consequence, measured by cost. A new methodology has been developed to overcome these shortcomings, it is called "Life Cost-based FMEA" [3,4] It measures risk of failure in terms of cost. Cost is a universal language understood by engineers without ambiguity. Expected failure cost is defined as the product of the probability of a particular failure and the cost associated with that failure. Lifetime failure cost is the sum of all the expected costs for all failure scenarios at all stages of a system component's life: design, manufacture, installation, and operation. The probability of a failure can be characterized as the frequency of such failures in a system containing multiple components, e.g. in an accelerator with 4965 water-cooled magnets there will be 9 water leaks a year that cause a severe enough magnet failure to bring down the beam. The cost of each water leak includes labor costs to detect it, repair it and get beam running again, which are proportional to the times these tasks take, and the costs of parts that have to be replaced, e.g. a piece of *Synflex* hose with fittings carrying cooling water.

Work supported by Department of Energy contract DE-AC03-76SF00515

In order to be confident in one's expected failure costs, it is best to measure failure rates and typical fixing times using historical data on systems of components similar in design to the ones you are doing a FMEA on. The next part of this paper describes how we have used the SLAC accelerator failure database (CATER) to make predictions about the availability of the NLC electromagnet and power supply (PS) system. Availability is defined as the average ratio of the time a component or system is usable to the total amount of time it is needed. It is calculated as the ratio of the Mean Time Between Failures (MTBF) to the sum of MTBF and the Mean Time To Repair (MTTR).

ESTIMATE FAILURE OCCURRENCE RATES FOR NLC MAGNETS & PS

Our premise is that the design of the NLC magnets and PS, their fabrication techniques, installation and repair procedures will be very similar to those used at SLAC over the past 35 years, therefore they will have the same failure modes occurring at the same rates as SLAC failures. The methodology described here was developed by considering SLAC magnets and PS and predicting for NLC magnets and PS, but it is applicable to any accelerator component that may fail and abort the beam.

Find MTBF & Availability of SLAC Magnets

We scoured the CATER database to find all magnet and switching PS failures in any beamline at SLAC which brought down the beam in the 5 year period 1997 to 2001. We categorized failures by magnet type: solid wire or water cooled and PS type: "small" : <12A, <0.5KW and "large": >12A,>0.5kW. We carefully counted how many magnets and PS were running in each beamline, and established how many hours each beamline was scheduled to run in that 5 years, thus we calculated number of magnet hours = no. magnets x no. running hours. Then we calculated the MTBF for any one magnet in that beamline. = no. magnet hours / no. failures reported. Table 1 shows the data for water cooled magnets for selected beamlines.

Details of each failure in CATER yielded the total time the beam was down, which we called the time to repair, TR, and particulars on the failure so we could place each one into a specific failure scenario, e.g. water leak from split hose leading to coil overheating, or turn to turn coil short due to damaged insulation.

We found these failures: 70 water cooled magnets, 6 solid wire magnets, 92 large PS and 70 small PS in the stated period. Each failure took a different amount of time to detect, i.e. to realize which component's failure had brought down the beam, and to repair. The TRs of 23 "water leak" failures ranged from 1 to 32 hours, these ranges must be accounted for when one calculates the predicted costs of failures for the NLC. The mean time to repair, MTTR, for a certain category of failures is calculated by dividing their total repair time by the number of failures, this is 10 hours on average for SLAC water cooled magnets. To calculate the average SLAC water cooled magnet's MTBF we summed the magnet running hours from 15 beamline runs (=80,383,136 hrs) and divided that by the 70 failures to give 1,148,331 hours. Then the availability of one "average" SLAC water cooled magnet is 1,148,331/(1,148,331+10)=0.99999127.

Predict Availability of System of NLC Magnets.

To calculate the availability of a system of N equivalent components in series, one raises the availability of one component to the Nth degree. In the 2001 NLC configuration, there will be 4965 water cooled magnets. If we built them without any effort to improve their MTBF or MTTR over an average SLAC magnet their availability would be 0.9576. By the same process, we predict the 2202 solid wire magnets in NLC would be 0.9988 available, leading to an overall magnet availability of 0.9576 x 0.9988 = 0.9565, which is less than the required 0.975. By the same process, we predict the overall availability of the 6167 power supplies that will power the NLC magnets to be 0.9279, less than the required 0.975.

In other words, we cannot design, build and repair the NLC magnets and PS just the same as we have SLAC magnets if they are to meet our NLC availability goals. We choose to do a "Life Cost-based FMEA" to identify those failure scenarios that would be most costly to the project if not prevented. These will be the types of failures we will tackle first as we develop strategies to increase MTBF and decrease MTTR and thus improve availability.

Estimate Failure Occurrences and Frequencies.

We assume the NLC will run 9 months (=6480 hours) out of every year for 30 years, during the other 3 months preventative maintenance will be done on all components.

Table 1. Measuring Availability of Water Cooled Magnets at SLAC, 1997-2001. Selected beamlines

Dates Line Ran	Beam Line	Run Hours	No. of Magnets	Magnet Hours	No. of # Failures	MTBF (hr)	TR (hr)	MTTR (hr)	Availability 1 Mag	PPM
5/1/97 - 6/8/98	SLC	8828	2302	20,322,056	32	635,064	469.5	14.67	0.999976898	23.1
	HER	918	1240	1,138,320						
1/12/00 - 10/31/00	PEP II	6624	2602	17,235,648	7	2,462,235	34.6	4.94	0.999997993	2.0
	BSY/FFTB	2196	198	434,808						
	BSY/A-Line	630	520	327,600						
1/10/01 - 12/31/01	PEP II	7411	2602	19,283,422	7	2,754,775	37.9	5.41	0.999998035	2.0
	BSY/FFTB(e+)	2795	198	553,410	2	276,705	3.05	1.53	0.999994489	5.5
	BSY/A-Line	820	520	426,400						

Table 2. Life Cost-Based FMEA Table for Some Water Cooled Magnet Failures

		Input									Output			
Failure Scenario	**Ultimate Effect of Failure**	Origin	Detection Phase	Re-occuring	Frequency	Detection Time	Fixing Time (hr)	Delay Time (hr)	Recovery (hr)	Quantity	Parts Cost ($)	Labor Cost ($)	Material Cost ($)	Opportunity Cost
Too many loads on water circuit	Magnet overheats, is turned off	Oper	Oper	30	0.01	0.5	4		4.5	1	50	180	15	33,750
Conducter Sclerosis (hole gets too small)	Magnet overheats, is turned off	Oper	Oper	30	0.5	1	8		9	1	1,250	18,000	18750	3,375,000
Water passage is blocked due to foreign object	Magnet overheats, is turned off	Oper	Oper	30	2	1	4		5	1	50	38,400	3000	7,500,000
Damaged (crimped) coil	Shorted coil, magnet won't turn on	Inst	TR	1	4	0.5	2		0	1	1,250	1,280	5000	
Water sprayed onto the coil	Shorted coil, magnet is turned off	Oper	Oper	30	3	2	8		10	1	50	38,400	1500	7,500,000
LCW hose fails, water not cooling coil	Magnet overheats, is turned off	Oper	Oper	30	3	2	5.5		7.5	1	50	83,700	4500	16,875,000
Water fitting or braze connection fails	LCW not reaching coil overheats etc	Oper	Oper	30	1	2	4.5		6.5	1	50	23,700	1500	4,875,000
Loose Jumpers	Excessive heat lead to melting temp	Mfg	Test	1	4	0.5	2.5		0	1	100	1,560	400	
Poor terminal connection design	Excessive heat lead to melting temp	Des	Test	1	0.011	1	8		0	40	100	494	44	
Bad terminal Installation	Excessive heat lead to melting temp	Inst	TR	1	4	0.5	2.5		0	1	100	1,560	400	
Poor thermal contact: thermal switch & cond	Magnet destroyed	Inst	Oper	1	1	0.5	4		4.5	1	11,000	600	11000	112,500
Human Error - Magnet missing	Forgot to put back magnet	Oper	Oper	30	0.4	0.5	2.5		3	1		4,440		900,000
Out of tolerance dimensions	Insulation Failure	Des	Proto	1	0.3	0.5	4		0	1	1,250	180	375	

Subtracting the 0.9576 availability from 1 and multiplying the result by 6480 hours gives you the predicted downtime of the 4965 water cooled magnets per year, 274.9 hours; dividing this by the MTTR of 10 hours gives you the number of water cooled magnet failures per year in the NLC = 27.4, we call this the number of occurrences per year, or frequency. Using the information on the 70 magnet failures we found in SLAC's failure database we calculated the availabilities and hence the frequencies for many different types of magnet failure, which enabled us to complete a long FMEA table of all possible failure scenarios, a small part of which is shown in Table 2.

PREDICT EXPECTED FAILURE COSTS

Besides failures that occur during accelerator operations we also accounted for errors designers might make while designing a magnet, which would result in a failure when the magnet was first turned on while being tested in QC, for problems that might happen while a magnet was being installed, which would result in a later failure during operation. We gave educated estimates of such scenarios' frequencies and how many hours of labor it would take to recover. Failures that both originated and were detected during operations were assumed to continue to re-occur for 30 years, all others re-occurred just once. The values quantifying these various parameters are in the columns under "input" in Table 2. The lifetime costs associated with each failure scenario are calculated as explained below and the *median* costs in US dollars are shown in the columns under "output" in Table 2.

Calculate Expected Failure Costs.

Labor Cost = Frequency x {[Detection Time x Labor Rate x # of operators] + [Fixing Time x Labor rate x # of operators] + Delay Time Time x labor rate x # of operators] } x Re-occurring (1)

Material Cost = Frequency x Re-occurring x Quantity x Cost of Part (2)

The "Recovery" time has a strong influence on the failure costs, it is the sum of the other 3 listed times. It is used through an "Opportunity" cost, which is the cost incurred when a failure inhibits the main function of a system and prevents any creation of value; e.g. the beam is down and no luminosity is being accumulated. What to set this cost to per hour continues to be debated, we have used 3 values: $10,000, $25,000 and $50,000 per hour. All of them far exceed what any technician earns in an hour, so it is vital to minimize the recovery time to reduce costs.

We use a Monte Carlo simulation to estimate the possible range of failure costs. It is misleading to use only an average repair time, for e.g., when a wide variation has been observed. So triangular distributions with minimum, mode and maximum values were used for frequency, all times, and parts costs. We simulated the design, fab and installation stages plus 30 years of operations of all the NLC magnets and PS 5000 times to find the distributions of lifecycle failure costs, the maximum being over $1B.

CONCLUSIONS

In order to reach the NLC magnet system availability goals, we established we must both cut the repair time for water cooled magnets in half and run the large PSs in a redundant mode: 2 PS in parallel, ready to power magnets at all times. Such actions would yield an availability of 0.962, exceeding the goal of 0.95, and a worst-case lifecycle failure cost of $339M. The cost-based FMEA described here will continue to be used by NLC engineers to guide their engineering of all aspects of the NLC.

REFERENCES

[1] Paul Bellomo, Carl E. Rago, Cherrill M. Spencer, Zane J. Wilson, "A Novel Approach to Increasing the Reliability of Accelerator Magnets", IEEE Trans Appl. Superconductivity, 10 (1), (2000) p. 284

[2] C.E.Rago, C.M.Spencer, Z. Wolf, G.Yocky, "High Reliability Prototype Quadrupole for the NLC", IEEE Trans Appl. Superconductivity,12 (1), (2002) p.270

[3] S.Kmenta, K.Ishii, "Scenario-Based FMEA: A Life Cycle Cost Perspective", Proc. ASME Design Engineering Technical Conf. Baltimore, MD, 2000

[4] S.J.Rhee, K.Ishii, "Life Cost-Based FMEA Incorporating Data Uncertainty. ", Proc. ASME Design Engineering Technical Conf, Montreal, 2002