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Reliability Issues for the BaBar CsI(Tl) calorimeter front end readout

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The BaBar CsI(Tl) calorimeter contains approximately 6000 crystals in the barrel and 1000 crystals in the end cap. The end cap is readily accessible. However, the barrel crystals and associated front end readout components are inaccessible other than by a major disassembly of the detector. It is anticipated that this will not take place for at least 10 years after the commissioning of the detector. This note assesses the stringent reliability requirements that must be incorporated in the design of the system. It is shown that at least a two fold redundancy in the readout scheme is required to achieve the necessary reliability.

1 Brief Description of Calorimeter Front End Readout

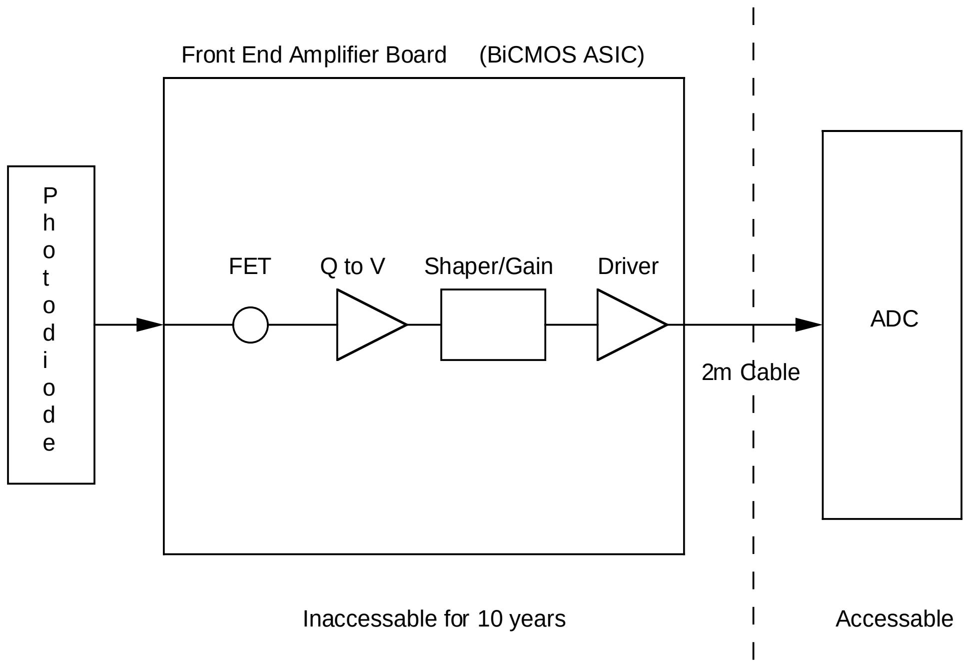

Figure 1: Schematic of front end Readout.

Figure 1 shows a schematic of the general setup which is described in reference [1]. The photodiode (Hamamatsu S3588-03) is coupled to the crystal using a wavelength shifter (WLS). It is affixed to the WLS using an optical epoxy. The diode is connected by a short cable to a preamplifier board which is mounted immediately behind the WLS. The preamplifier consists of a front-end discrete n-channel JFET for low noise performance. It is followed by charge to voltage conversion, amplification, shaping and a differential line driver. These functions in addition to calibration are all accomplished with a fully custom 1.2 μm biCMOS ASIC. The biCMOS ASIC has approximately 500 transistors. The ADC's are mounted near the barrel/endcap interface and connected to the preamplifiers by cables up to a few meters long. The endcap preamplifier/WLS/diode packages are readily accessible as are the

ADC's for both the Barrel and endcap. The front end package for the 6000 crystals in the barrel is not accessible other than by a major disassembly of the detector. This is unlikely to occur for at least 10 years after commissioning of the detector. This demands that all the front end components both mechanical and electronic are highly reliable. We state this design criteria as follows

- **The calorimeter should be designed so that after 10 years we should expect no crystal to be incapable of being read out.**

2 General discussion of Reliability

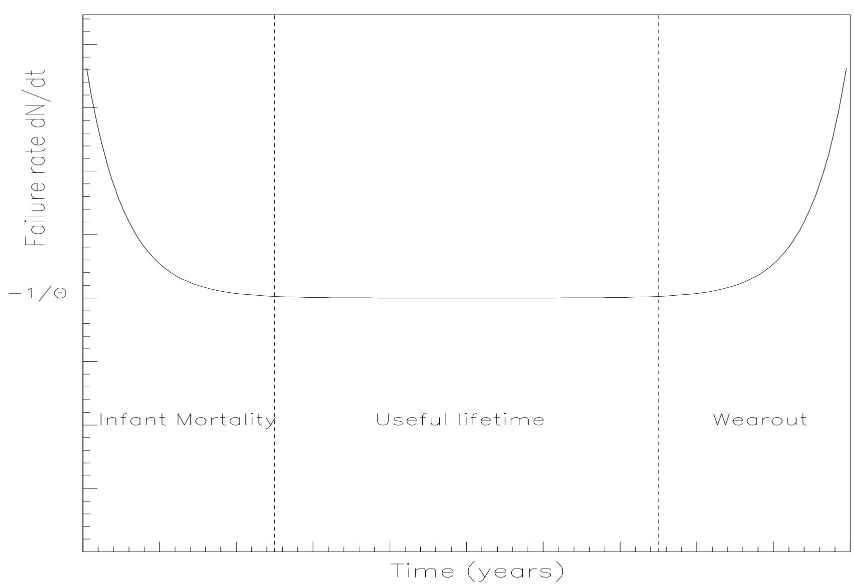

Figure 2: Component failure rate (dN/dt) in the limit of large N

The empirically observed behavior of a large number of components is summarized in figure 2. The failure rate (dN/dt) is plotted versus time. Initially there is a large failure rate which then tends to a constant $(1/\theta)$. This is known as the infant mortality period and indicates that most defective components will fail early. The period of constant failure rate is known as the useful life of the component and is typically of the order of a few hundred years for electronic components. The increase in failure rate after a long time is called the wearout period and is only relevant for moving mechanical parts such as bearings. During the useful lifetime the failure rate is constant

$$\frac{dN}{dt} = -\frac{1}{\theta} \tag{1}$$

$$N = N_0 e^{-\frac{t}{\theta}} \tag{2}$$

The time constant θ is known as the mean time before failure (MTBF). It is typically of the order of a few hundred years so that over a a short period Δt the number of failures ΔN.

$$\Delta N = \frac{N_0 \Delta t}{\theta} \tag{3}$$

The above considerations imply that in the design and construction of any system it is essential to

1. Test all components for a period so that all defective components can be removed before actual implementation. I.e getting past the infant mortality period. This is a process known as screening.

2. Establish the MTBF meets requirements for the screened components.

In order to establish the MBTF we must perform tests on screened components for an extended period. If we test N components for t years then the total duration of the test is T=Nt component years. In general the results of these tests will be a small number of failures and will be Poisson distributed. Such tests then allow us to set a confidence limit on the MTBF. Explicitly the lower bound confidence limit value of such a test is given by

$$MTBF_{lower} > \frac{2T}{\chi^2_\alpha(\nu)} \tag{4}$$

where α is the confidence level, ν is the number of degrees of freedom of the χ^2. If the number of failures is n then ν = 2n + 2. If we require 6000 crystals to be readout for 10 years with zero failures (<1) then from equation 3 this requires MTBF $>$ 60000 years. From equation 4 to establish this at 95 % confidence limit would require a test of 180000 component years with no failures (i.e 1000 components for 180 years or 10000 components for 18 years etc.). Clearly this is intractable and so we must resort to other means to establish the MTBF. There are three possibilities.

1. Use accelerated tests. Aging is due to chemical reactions and the Arrhenius rate reaction law states that the rate depends on a power of temperature R= kT^{α}. Hence by testing at a higher temperature the aging rate is enhanced and the time scale of tests can be shortened. Unfortunately the constant α is unknown and has to be estimated in order to translate the measurement into an estimate of MTBF at operating temperature. These tests are therefore extremely limited in their usefulness.

2. Use US Military failure rate tables [3] . The US Military has compiled statistics of failure rates for electronic components and translates them into formulas and tables that can be used to estimate the MTBF.

3. The CLEO experiment [4] has constructed and operated a CsI calorimeter for 5 years. The design is similar to that of the *BaBar* detector and so failure rate data is relevant.

The most effective way to approach estimation of MTBF is to use the CLEO data as far as possible. In addition we give estimates from the Military tables for comparison.

3 Screening

A screen is defined as a test which stresses the components in order to expose the defects yet does not cause fatigue. The US Military has defined sets of standard screens for components used in different applications [3]. The most stringent are for components used in spacecraft and the least for commercial applications. For components such as ASIC's they identify particular types of defects such as broken wire bonds,oxide shorts etc and list the types of screens that are effective in detecting such problems. From these tables it is apparent that the combination of two screens covers almost all listed defects. Firstly a detailed visual inspection that includes the mechanical checking of all connectors and bonds. Second is dynamic operation for an extended period at high temperature. The screens that might be used for the WLS/diode/preampfier package are as follows.

- Require vendors to perform standard industry screens on diodes and FETS
- Visual inspection of all components, connectors and wire bonds.
- Thermally cycle each preamplifier between -40 ^oC to 140 ^{o} C ten times. Operate overvoltage for short period at high T
- Operate diode + preamplifier at 75 ^{0} C for 1 week with diode over-biased. Require continued low noise performance over this period.

It is important to note that all components should be screened rather than sample batches.

4 Establishing MTBF

Time (Months)	Diode Failures	Noisy Diodes	Preamplifier Failures
0	48	0	17
5	48	2	58
12	48	7	85
24	48	12	100
32	48	12	112
38	48	12	119
50	48	13	128
60	48	14	142

Table 1: Cumulative diode and preamp failures for the CLEO-II calorimeter from 1989 to 1994.

Table 1 lists the cumulative diode and preamp failure rate from the CLEOII CsI(Tl) calorimeter [5]. These numbers are plotted in figure 3. There are

8000 crystals total with four diodes/preamps per crystal. The environment is closely controlled with a a temperature of 25 ± 1 °C and a humidity of 3 %. The initial 48 diodes are attributed to faulty connectors. It can be seen that the number of noisy diodes is negligible compared to preamplifier failures. Note that the failure rate is high at the beginning and tends to a constant as indicated in figure 2. This may indicate insufficient screening and consequently the screens listed previously are more stringent than those used by CLEO.

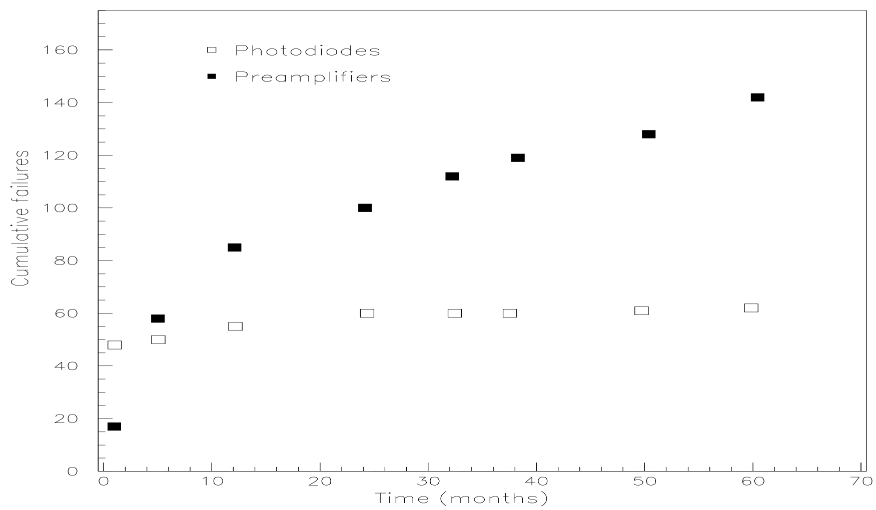

Figure 3: Cumulative Failure rate of photodiodes and preamplifiers in the CLEOII CsI(Tl) calorimeter.The failures are from a total of 32000 photodiodes and 32000 preamplifiers.

These numbers can be used to estimate an MTBF. Assuming that all 48+14 diodes are failures we then have 52 failures from 32000 diodes, and 142 failed preamplifiers from 32000 in five years. Using equation 4 we can compute the MTBF at 95 confidence limit

$\mathrm{MTBF}_{photodiode} > 1954$ years

$\mathrm{MTBF}_{preamplifier} > 832$ years

For two components in series the MTBF adds

$$\frac{1}{MTBF_{preamplifier+photodiode}} = \frac{1}{MTBF_{preamplifier}} + \frac{1}{MTBF_{photodiode}} \tag{5}$$

so that

$\mathrm{MTBF}_{photodiode+preamplifier} > 645$ years (95 % confidence limit)

Using MTBF > 645 years we can then compute the expected number of crystal readout failures for the *BaBar* calorimeter with 6000 crystals after 10 years. We consider the possibility of up to four fold redundancy. For example the probability of a diode failing in 10 years is p = 93/6000. If we have two fold redundancy then the probability of both diodes not failing is $(1\text{-p})^2$. The probability of one failing and the other not failing is 2p(1-p). It can be seen immediately that a single diode and single preamplifier is inadequate since 93 crystals will be incapable of being read out. A two fold redundancy will give only one dead crystal after 10 years. The other 184 crystals will halve the signal and give $1/(\sqrt{2})$ electronic noise (equivalent noise charge) so that the equivalent noise energy will increase by a factor of $\sqrt{2}$. It is clear that a two fold redundancy is necessary and adequate for The *BaBar* detector .

Failed Channels	1 Diode 1 Preamp	2 Diodes 2 Preamps	3 Diodes 3 Preamps	4 Diodes 4 Preamps
0	5907	5815	5275	5635
1	93	184	271	356
2		1	4	9
3			0	0
4				0

Table 2: Number of failed channels on a crystal for various levels of redundancy, after 5/10 years, assuming $MTBF_{diode+preamp} \geq 645\,\mathrm{yr}$.

Using the Military failure rate tables we can also estimate the failure rates. For opto-electronics from [3]

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E \; failures/10^6 hours \tag{6}$$

where

λ_b is a component type factor. For photodiodes = 0.0040

π_T is the temperature factor. At 25 ^{o}C = 1.0

π_Q is the quality factor. This is the level of screening used for the components. For standard commercial components = 8.0

π_E is the environment factor. For a low humidity constant temperature environment =1.0

This then gives MTBF$_{diode}$ = 3570 years. Similarly for the preamp we can combine predictions for the FET and the ASIC to give MTBF$_{preamplifier}$=925 years. Then MTBF$_{diode+preamplifier}$= 735 years. Note that no statistical significance is given for these numbers. This is to be compared with the number inferred from CLE0 MTBF$_{diode+preamplifier}$ $>$ 645 years. It would imply a slightly lower failure rate than in table 2

5 Conclusions

Stringent screening is required of the front end components. A two fold redundancy is necessary and adequate.

6 Acknowledgment

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References

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