Quantitative reliability demonstration from production to operation on the example of the new radiation tolerant power converter controller for the Large Hadron Collider

Tamer Tevetoğlu[a*], Slawosz Uznanksi[b], Benjamin Todd[b] Bernd Bertsche[a]
[a] University of Stuttgart, Stuttgart, Germany
[b] CERN (TE-EPC), Geneva, Switzerland

Abstract: Highly reliable systems rely on methodical procedure during the design phase, production and deployment. This paper presents a methodology that covers production quality, reception tests and field analysis on the example of the mass-produced accelerator control system for the LHC. The production quality analysis of each board consists of functional tests based on the PXI test platform. Accelerated life tests at elevated temperature ("burn-in") are then used to accumulate mission time in order to demonstrate a certain reliability level before deployment. Both production quality analysis and burn-in lower the number of post-deployment infant mortality failures significantly. In order to assess the FGClite's reliability after deployment, the instantaneous failure rate is monitored quantitatively. This allows to detect possible early wear-out failures and forecast the number of failures for the next period of time. It is then discussed whether a constant failure rate is observed after deployment and appropriate to model electronic systems, since the applied Weibull Analysis is sensitive to certain assumptions.

Keywords: Electronic Systems, Control Systems, Electrical Reliability, Weibull Analysis, Weibayes, Field Failure Data, Reception Tests, Production Quality Analysis

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1. INTRODUCTION

In order to explore the fundamental structure of the universe, the European Organization for Nuclear Research (CERN) has built eight accelerators so far. In this accelerator complex, the Large Hadron Collider (LHC) is the last element in the chain. Two high-energy beams, travelling in opposite directions in the LHC, are accelerated and then collided at four crossing points. Superconducting electromagnets generate a strong magnetic field, which is used to guide the particles around the LHC.

These magnets need high precision control of the current. The power converters that feed power to the magnetic circuit in the LHC consist of a voltage source, a current transducer and a function generator controller (FGC). These FGCs are developed in the Converter Controls sections of the Electrical Power Converters group (EPC) at CERN. The LHC power converters are controlled by the so-called 'FGC2'. 1094 FGC2s are intended to be replaced with the newly developed FGClite, which is more radiation tolerant than its predecessor (especially against single event effects (SEE)).

In order to guarantee a high availability of the LHC, the electrical reliability of the FGClite needs to be assessed before and after its deployment. Therefore, reliability methods (e.g. FMEA, FTA, etc.) were already applied during the design phase in a previous work. In order to develop a complete methodology for assessing the reliability of electronic systems, all subsequent life cycle phases need to be addressed as well.

Hence, this paper aims to establish a comprehensive methodology that complements the reliability methods for the design phase with quantitative methods for all remaining phases of a product's life cycle. Therefore, quantitative reliability methods covering production quality, screening tests in the laboratory, and field failures are introduced and evaluated.

As only the electrical reliability of the FGClite is considered in this paper, the following specification are targeted for the FGClite:

- Maximum 10 electrical failures per year in operation (operational temperature: 30°C)
- Guarantee a lifetime of 20 years in operation (useful lifetime)
- Production quality goal: < 1% failures

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*tamer.tevetoglu@ima.uni-stuttgart.de

- 1094 FGClites in operation and 377 spares (total of 1471 devices)
- Proven lifetime of 100K device hours prior to deployment

1.1 Symbols

Symbols	Meaning	Unit
AF	Acceleration Factor	-
B(x; n, p)	Cumulative Binomial Distribution	-
C, CL	Confidence level, e.g. 5%	-
e	2.71828… (Euler's number)	-
E_a	Activation energy	[eV]
k	Boltzmann's constant $(8.617 \cdot 10^{-5})$	$[eV/K]$
MTTF	Mean Time To Failure	hours [h], no. of cycles
N	Total number of devices (failures and suspensions)	-
n	Number of trials, e.g. sample size	-
P(X)	Poisson distribution	-
ppm	Parts per million	-
r	The total number of failures	-
R(t)	Reliability (probability of success)	-
t	Any point in time or number of cycles, (random) variable	hours [h], no. of cycles
T, T_U; T_{AF}	Temperature; U: at normal use conditions; AF: at accelerated conditions	Kelvin $[K]$
X, x	Random variable	-
β	Weibull shape parameter	-
γ	Location parameter or failure free time	hours [h], no. of cycles
$\Gamma()$	Gamma function	-
η	Weibull scale parameter or characteristic life	hours [h], no. of cycles
$\chi^2()$	Chi-square distribution	-

2. MOTIVATION

A preceding reliability analysis of the FGClite was done during its design phase. Part of this analysis was the reliability prediction (e.g. failure rate or Mean Time To Failure (MTTF)) of the FGClite and its predecessor FGC2 according to MIL-HDBK-217F [1]. The subsequent sections briefly discuss the results and their usefulness for the methodology presented in this paper.

2.1 Reliability prediction

The reliability prediction according to the Military Handbook 217F shows a mean MTTF greater than or equal to 198,379 device hours for the FGClite. The expected number of failures for 1094 deployed FGClite units per year (≙8766 hours) is

$$1094 \text{ units} \cdot 8766 \, \frac{\text{hours}}{\text{unit}} \cdot \frac{1}{198{,}379 \, \frac{\text{hours}}{\text{failure}}} = 48.34 \; \approx 49 \text{ failures.} \tag{1}$$

Analogously, the prediction for the FGC2 results in an MTTF of 104,000 device hours. This allows an assessment of the accuracy of the prediction results, since there is actual field data available for the

FGC2 (see chapter 2.3). The expected number of failures in both cases is way higher than the declared maximum of 10 electrical failures in the design specification [2].

2.2 Design iterations

The design improvements for the FGClite involved upgrading to automotive grade capacitors (lower failure rate), changing PCB connectors, upgrading resistor and capacitor ratings, changing PCB layouts, and adding pin redundancies. Using qualitative reliability methods, like FMEA and FTA, in addition to the $MTTF$ prediction, helped to improve the design of the FGClite to an MTTF of 198,000 hours as stated in chapter 2.1. Without any improvements, the MTTF would have been equal or greater than 121,000 hours according to the prediction method (worse by a factor of 1.6).

2.3 Comparison to actual field data and problem description

Table 1 emphasizes the necessity for quantitative reliability methods through a comparison of actual field data of the FGC2 and predicted MTTFs of both FGClite and its predecessor FGC2.

Table 1: Comparison of actual field data and predicted MTTF

System	MTTF Prediction [h]	Field MTTF [h]	Magnitude
FGC2	104K	1.1M	x10.6
FGCLITE	198K	unknown	unknown

The actual field MTTF of the FGC2 is 1.1M device hours, which is about ten times higher than the predicted MTTF. Interpreting this data as a proof that the FGClite's MTTF will be higher by a factor of ten as well is risky, although the environmental conditions are the same for the FGClite and FGC2. Since there is neither an empirical nor a statistical proof for this assumption, a quantitative reliability demonstration is essential in order to assess the reliability of the FGClite.

3. QUANTITATIVE RELIABILITY DEMONSTRATION

The quantitative reliability demonstration covers the production quality analysis of the FGClite boards, reliability assessment before deployment (screening), and field reliability. They are necessary to lower the number of infant mortality failures and to detect potential design flaws of the FGClite before and after its installation in the LHC tunnel.

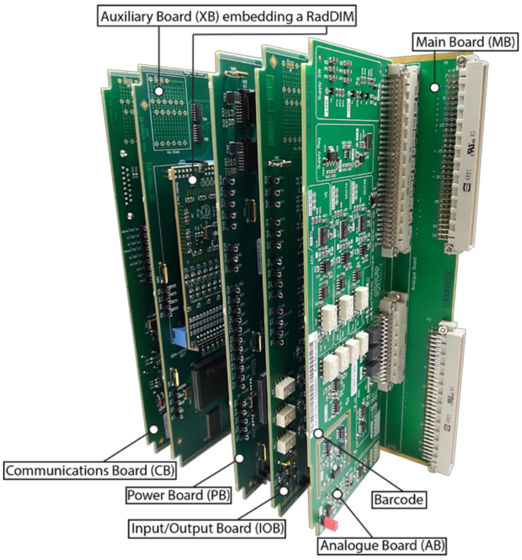
3.1 Production Quality

The production quality analysis of each printed circuit board of the FGClite consists of functional tests based on the National Instruments PXI (PCI eXtensions for Instrumentation) test platform. This board level testing before assembly is essential to lower infant mortality failures after deployment significantly. Additionally, failures that occurred during screening tests and after deployment can be diagnosed precisely through these functional tests. All manufactured PCBs for the FGClite are being tested, and not just a subset of a population of FGClites. The main goals of the production quality analysis are:

- less than 1% of faulty boards in production,
- discovery of production flaws, and
- assurance that enough functional boards are available for the FGClite deployment.

The FGClite consists of six boards as shown in figure 1.

Figure 1: FGClite Boards

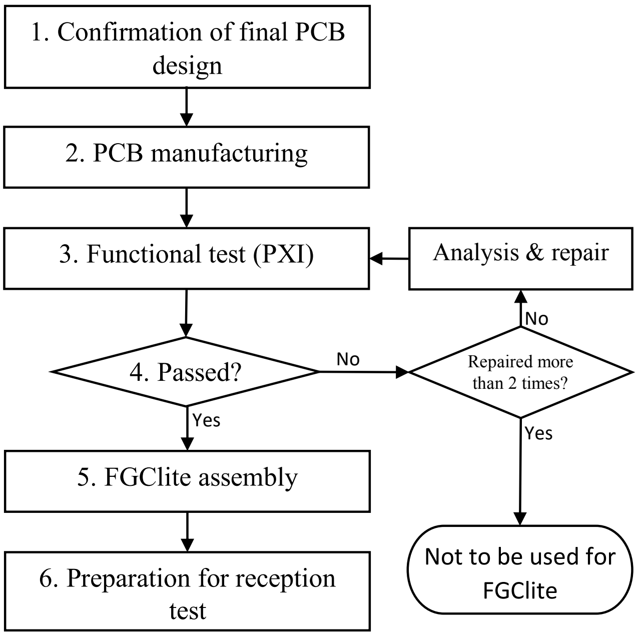


Functional Test Setup and Strategy

As stated above, the whole population of boards for the FGClite is being tested in order to assess the production quality. Therefore, for each board a dedicated Test Control Card (TCC) and tester software based on the LabWindows™/CVI development environment is developed. In this setup, the device under test (DUT) is one of the FGClite's boards, which is connected to the PXI chassis via the TCC. The GUI displays the status and outcome of the test, before creating a log file. This log file is then being uploaded to the CERN internal database. Boards that failed are analyzed, repaired and retested.

All boards for the FGClite undergo the same procedure, which is presented in figure 2 as a flowchart. After confirmation of the final design, the boards' components are delivered to the PCB manufacturer. The finished boards are then transferred to CERN in batches, where they are tested according to the setup mentioned above. If a board passes the functional test, it is installed in an FGClite. However, if the board fails the test, it will be analyzed (i.e. visual inspection, multimeter measurements, etc.) and repaired according to the standards IPC J-STD-001F and IPC-A-610F in order to guarantee printed boards conform to IPC Class 3 for high reliability electronics. IPC Class 3 requires a higher standard of production quality, e.g. minimum of 75% vertical solder fill in the through holes instead of 50% (IPC Class 2), etc. [3]. It was decided by the TE-EPC that no more than three repairs ought to be attempted for boards that are intended for the FGClite.

Figure 2: Functional Test Strategy



Results and Failure Forecasting of Boards

Following test results are obtained from all tested boards until August 2017. The number of tested boards exceeds the number of needed FGClites (1471), since more boards than FGClites have been tested in order to have a buffer during the cassette assembly. Table 2 summarizes the results of the board level tests. For each board around 1500 units were produced and tested. The RadDIM is not listed in this table, since it is a specification of the power converters. Therefore, it is not considered as one of the interconnected boards of the FGClite itself.

Table 2: Production Quality at Board Level

Board	Produced and tested until August 2017	No. of failures until August 2017	Probability of failure (failed/tested)	Prediction in February 2017
AB	1481	62	4.19%	$52 \leq r \leq 82$
CB	1534	20	1.30%	$13 \leq r \leq 30$
PB	1550	19	1.23%	$10 \leq r \leq 26$
MB	1498	5	0.33%	$4 \leq r \leq 16$
IOB	1472	4	0.27%	$2 \leq r \leq 12$
XB	1506	4	0.27%	$2 \leq r \leq 9$
One Population	9041	114	1.26%	$96 \leq r \leq 138$

Gathered data from the first tested units can be used to extrapolate the number of failures for the whole population of produced boards, if the sample is large enough to compute conclusive results.

In February 2017, the number of expected faulty boards was predicted after having tested around 1000 units of each board (see column on the far right). Basis of the predicted number of failures is the cumulative binomial distribution

$$B(x;n,p) = \sum_{x=0}^{n} \binom{n}{x} p^{x} \, (1-p)^{n-x}, \tag{2}$$

which is also used in the AQL method [4].

If p is defined as the probability of a trial being unsuccessful, then X is a random variable for the number of failures. In the following, p stands for the probability of failure during the functional tests. As an example, the forecasted number of failures for the Analogue Boards are shown step by step, when 46 out of 1050 Analogue Boards had failed already. The calculations for the other boards individually and as one population are done in the same manner.

The probability p that an Analogue Board is faulty, is being calculated as follows:

$$\frac{\text{number of failed Analogue Boards}}{\text{number of tested Analogue Boards}} = \frac{46}{1050} = 4.38\% \triangleq 43809{,}52\,ppm \tag{3}$$

The probability p is transformed to parts per million (ppm). In order to calculate the 90% confidence interval, one has to find a parameter p so that the cumulative binomial distribution is B(46;1050,p)=0.05 and B(46;1050,p)=0.95, respectively. The calculation is done iteratively. The lower and upper limits for p are

$$34700\text{ppm}\ (3.47\%) \leq \text{p} \leq 55670\text{ppm}\ (5.57\%). \tag{4}$$

These results show, with a confidence of 90%, that the parameter p for the whole population is between 34700ppm and 55670ppm. The forecasted number of failures are computed by multiplying the boundary p values with the total number of planned (functional) boards (1471 units per board):

$$52\text{ failures} \leq \text{expected total no. of failures} \leq 82\text{ failures}. \tag{5}$$

Conclusion

The actual number of failures for all boards lie well within the confidence limits predicted earlier that year. Hence, the assumption of a binomially distributed failure population fails to be rejected and can

be applied for other electronical systems as well. The production goal of having less than 1% failures was not met due to the high number of faulty Analogue Boards. The root cause of these failures is still being analyzed.
However, enough functional boards were produced to deploy 750 FGClites in the LHC early 2017. The remaining 344 devices for operation will be deployed by the end of 2018. The production of the spare devices is being continued as well.

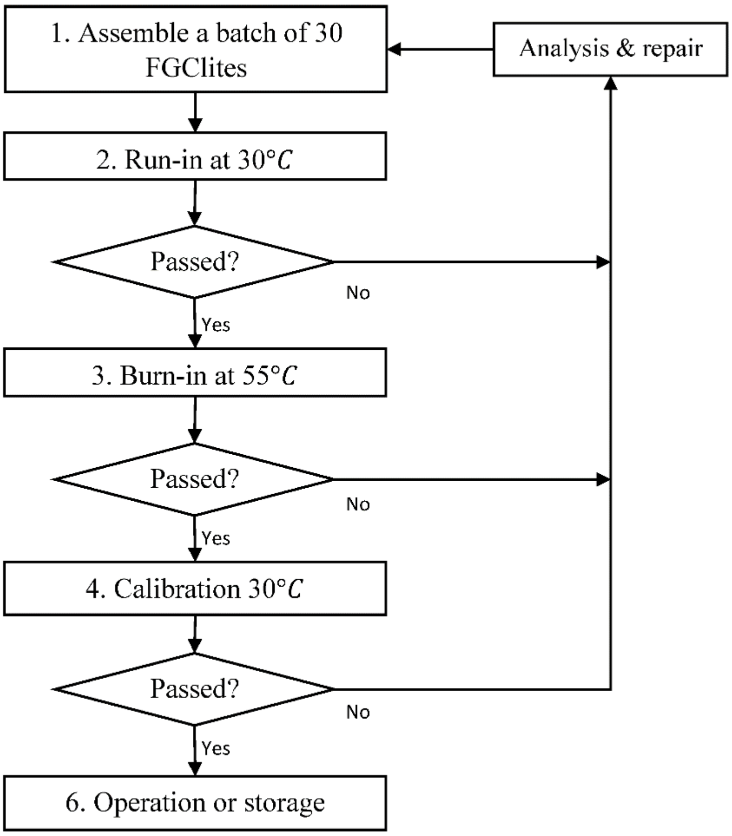
3.2 Reception Test (Screening)

All boards that pass the functional tests undergo a reliability screening and demonstration (in the following referred to as reception test) at assembly level. At assembly level, it is possible to test the functionality of interconnections between the boards and the FGClite as a whole. Thus, the screenings can be also regarded as an additional production quality assessment. The flowchart in figure 3 shows the whole reception procedure. The reception tests and calibration (not further specified in this paper) are performed in batches, each containing exactly 30 FGClites. After every test (the calibration counts also as a test), failed devices are sorted out and analyzed. The calibration is executed at $30°C$, which is the operational temperature of the FGClite in the LHC tunnel.

Goal

Screening tests allow to discover latent failure mechanisms (e.g. cracks in soldering, dielectric breakdown, etc.) that are not covered by the functional tests. Furthermore, these reception tests facilitate to force early failures that belong to the first section of the bathtub curve. Hence, these screening tests allow to minimize the number of faulty devices in operation. In addition, the accumulated mission time during these screenings is being used to determine the current MTTF of the FGClites before their installation in the LHC tunnel. The goal is to have an MTTF of 100K device hours prior to deployment (95% CL).
Ideally, all infant mortality failures are discovered before deployment so that the FGClite's failure rate is nearly constant and slightly decreasing (i.e. $\beta < 1$), respectively. Figure 4 shows the course of the failure rate the throughout the service life of the FGClite.

Figure 3: Reception Test Procedure



Approach

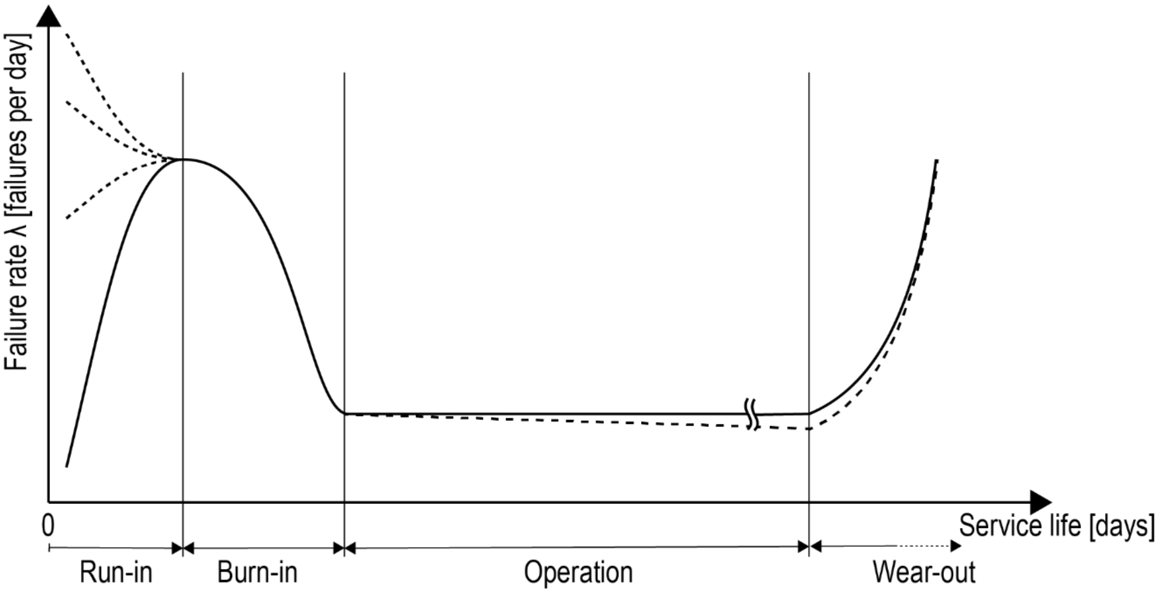
The screening is conducted on two run-in racks and two burn-in racks. The racks only differ in terms of heat generation. Each FGClite that passes the reception tests will be deployed or kept as a spare device. While conducting the tests, all necessary data of every FGClite (e.g. temperature inside the FGClite cassette, testing duration, etc.) is being tracked and evaluated.

The run-in is performed for at least 24 hours at the operational temperature of 30°C inside the cassette. The main goals of the run-in are to sort out dead-on-arrival devices, to assess the manufacturing quality, and to accumulate mission time. It is expected for the failure rate to increase rapidly during the run-in phase despite the functional tests, which are performed prior to the assembly of the FGClite [5]. The dashed lines in figure 4 during the run-in represent other possible courses of the failure rate, which depend, inter alia, on the number of dead-on-arrival devices. However, the bold line is the most commonly observed course for the run-in [5].

Since the run-in is executed at normal operational temperature, burn-in tests are needed in order trigger latent failure mechanisms that remain undetected until operation otherwise.

The minimum temperature in the cassette for the burn-in is chosen to be 50°C, which is derived from the FGC2 burn-in process. A failure mechanism (cracks) caused by thermo-mechanical stress in the vias of the FGC2 was observed at approximately 50°C [6], and therefore an even slightly higher burn-in temperature is preferred for the FGClite. Moreover, the burn-in duration is set to 24 hours.

Figure 4: Bathtub Curve with Run-in and Burn-in



The burn-in is an accelerated life test and allows to accumulate more mission time compared to the run-ins, which are performed at operational temperature. The formula for the acceleration factor

$$AF = e^{\left[\frac{E_a}{k}\cdot\left(\frac{1}{T_U}-\frac{1}{T_{AF}}\right)\right]} \tag{6}$$

is suggested by the JEDEC standard JESD74A [7], which is based on the Arrhenius equation.

The activation energy for semiconductors is between 0.3 and $1.4eV$ for various typical failure modes [8]. A lower activation energy results in a lower acceleration factor. Typically, 0.7eV is assumed for E_a in many scientific papers, regardless of the failure modes [8]. However, it was presumed that an activation energy equal to 0.35eV is suitable for the FGClite calculations. This gives a conservative estimation of the acceleration factor (in comparison to 0.7eV) and covers all failure modes greater than or equal to 0.35eV.

The overall accumulated mission time during both run-in and burn-in, are needed to assure a certain minimum MTTF before deployment. An MTTF (95% CL) around 100,000 hours was set as a goal to ensure a relatively low operational field failure rate right after deployment [6].

In the context of the reception test duration, a too long burn-in or run-in can result in a significant reduction of the FGClite's useful lifetime. In the short term, one can expect less infant mortality failures in operation, when the devices are tested for a longer period of time. In the long term however, wear-out failures would occur much earlier [9]. Thus, the reliability decreases faster, compared to a population that was not burned in. It is important to note that failure mechanisms with shape parameters lower than one benefit from longer run-in and burn-in processes, since the failure rate decreases over time.

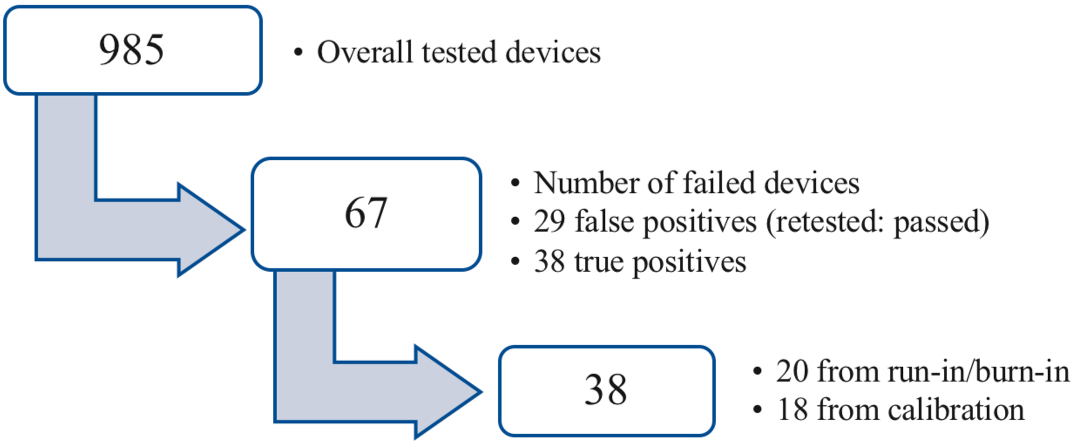
Results

Overall, 985 FGClites were tested during the whole reception process prior to the deployment of the first 750 devices in the LHC, from which initially 67 devices did not pass. However, not all failed devices were actually faulty. These 29, so called false positives, were surprisingly frequent and occurred only during the reception tests (not calibration). The most common reasons for these false positives were:

- FPGAs that were not updated to the latest firmware release
- Faulty power supply on one of the racks
- Random test script errors (depends on the maturity of the test software)
- Wrong assembly after the production quality tests

This leaves 38 'real' failures that would have lowered the MTTF of the FGClite during operation significantly, if there were no screening tests. 20 out 38 failures were detected during run-in and burn-in. The remaining 18 FGClites failed calibration. Figure 5 illustrates the substantial statistics gathered from December 2016 to February 2017 during the reception process.

Figure 5: Substantial Statistics of the Reception Process



As mentioned above, 38 failures are called 'real' in order to contrast them to false positives (which can be avoided). These FGClites are not considered in the MTTF calculation, since the main goal of the reception process is to sort out infant mortality failures in order to not take them into account. Including them in the calculation would result in the same or even lower field MTTF, as if there had not been any screenings prior to deployment at all (due to less accumulated total device hours).

Table 3 gives an overview of the failed checks during run-in and burn-in. Most frequently, the DIMS check was not passed. These six devices were repaired by replacing the faulty RadDIM with a functioning one.

There were four devices that failed the 1-Wire check, from which three were repaired by releasing a new firmware for the Auxiliary Board FPGA (XF). A faulty resistor was the cause for the fourth 1-Wire failure. Replacing it, fixed the FGClite.

One device had multiple failed checks, labeled as 'mixed' in the table. For the rest of the devices list, the repair process is still on-going.

Table 3: Run-in and Burn-in Failures

Quantity	Failed check	Repair	Comments
6	DIMS	Swap RadDIMs	Dead-on-arrival
4	1-Wire	3x Activate weak pull-up resistor in FPGA 1x Replace faulty transistor	Dead-on-arrival
3	ADC	On-going	Dead-on-arrival
2	INTERLOCK	On-going	Dead-on-arrival
2	CMD/STAT	On-going	Dead-on-arrival
1	MIXED	On-going	Dead-on-arrival
1	ROUND-ROBIN	On-going	Dead-on-arrival
1	Device is offline	On-going	Dead-on-arrival

In total, 18 devices failed during calibration. Since the analyses are still on-going and not relevant concerning the accumulated mission time, they are not further discussed.

Calculation of the MTTF prior to Deployment

For the calculation of the MTTF a Weibull shape parameter β of 1 is used. This type of analysis is called Weibayes Analysis, and for $\beta = 1$ the Weibull distribution equals the exponential distribution. The exponential distribution has a constant failure rate λ, which is commonly accepted as a failure property of electronic devices [10]. Since there is only one parameter (η) to be determined, the Weibayes Analysis is more robust to small sample sizes and uncertainties in parameter fitting (e.g. suspensions) than with two or more parameters. However, Weibayes needs a reasonable estimate of the shape parameter β. According to [10, 11, 12] the general MTTF formula

$$MTTF = E(X) = \int_0^\infty R(t)dt = \eta \cdot \Gamma\left(1 + \frac{1}{\beta}\right) + \gamma \tag{7}$$

can be determined by calculating the expected value E(X) of the random variable X of the Weibull reliability function R(t) in the interval [0, ∞), where Γ() is the gamma function. When assuming a constant failure rate ($\beta = 1$), the $MTTF$ is equal to the characteristic lifetime η (given: $\gamma = 0$) of the Weibull distribution and therefore the reciprocal of the failure rate λ. Using the maximum likelihood estimate of the characteristic lifetime in combination with the chi-squared distribution, gives following function for the MTTF:

$$\text{MTTF} = \frac{2 \cdot \sum_{i=1}^{N}(t_i \cdot AF_i)}{\chi^2(C, 2r+2)} \tag{8}$$

The conducted tests are time truncated, hence one imminent failure is always added to the actual number of failures. The confidence interval is 95%.

From December 2016 until February 2017, 947 properly working FGClites accumulated 276,538 device hours. The lower confidence limit for the MTTF is 92,311 device hours (10.53 years). In other words: 95% of all FGClites will have a greater $MTTF$ than $92{,}311h$.

As mentioned above, the failure rate of the FGClite is assumed to be constant for the MTTF calculations. The assumption of $\beta = 1$ has two main reasons:

1. The calculation of the MTTF is straightforward so that one only has to add up the individual mission time t_i in order to calculate the proven MTTF for the population of devices.
2. The FGClite is a solid-state device. Specialized literature and Weibull databases suggest that solid-state electronics have a shape parameter β close to 0.7-0.8 [11, 13] instead of 1. This results in a conservative MTTF estimation for the FGClite, when it is proved that the population of devices has indeed a shape parameter less than 1. For the purpose of the reliability analysis after deployment, the actual field shape parameter is determined in the subsequent chapter.

Conclusion

The goal of 100K hours as a proven MTTF for the FGClite is not met, however the number of needed functional FGClites (750) was met. The main reason for not accomplishing this goal were validation problems with the testing racks. It took nearly a month to troubleshoot and resolve issues concerning test script updates, cleaning connectors, etc. before the accumulation of mission started.

Each of the failure mechanisms that are observed during the reception process are checked, whether it is systematic or not. Systematic mechanisms lead to a higher number of failures during operation, since the screening process cannot detect all faulty devices prior to deployment. None of the run-in and burn-in failures looked alarming and required further preventive action. On one occasion, the information gathered from the reception tests led to a higher reliability of the FGClite, because one latent failure mechanism was discovered and preventively fixed with a firmware update for all devices.

3.3 Field Reliability

The field data is being used to assess the reliability of the FGClite as well as the effectiveness of the production quality analysis and reception process. Moreover, the observed failure mechanisms until mid-March 2018 are presented in this chapter. In addition, the real field failure rate and MTTF are plotted and calculated. Lastly, it is demonstrated how to forecast the number of needed spare devices.

The goals for the analysis of the field reliability are:

- Assessment of field reliability
    - o Monitoring the failure rate λ and MTTF, respectively
    - o Computing statistics for every observed failure mode
    - o Creating a failure database and conclusive failure reports
- Forecasting of needed spare FGClites
- Prove or disprove constant failure rate conjecture

The installation of the FGClites was conducted in February 2017. All 750 devices were in operation. Overall, 6 failures were observed from these 750 devices. Table 4 summarizes all observed failures with all necessary information for a reliability analysis.

Table 4: Field Failures

Useful lifetime [days] until failure	Temperature [K]	What failed?	Comments
9	303.15	1-Wire	Manufacturing issue
28		Reprogramming	Software maturity
44		Internal calibration	On-going
58		Internal calibration	On-going
80		1-Wire	Manufacturing issue
128		Internal calibration	On-going

The FGClites in operation as well as in the reception labs contribute to the proven MTTF, since the assumption of an exponential distribution allows to easily add up mission times. In March 2018, the currently proven MTTF equals 601K device hours with a confidence of 95%.

The shape parameter β is 0.8476 (median) for these field failures, which indicates a decreasing failure rate. Hence, 601K hours may be a conservative estimation as mentioned above. However, the Weibull plot as well as the failure rate need to be updated each time a field failure happens. The last failure in operation occurred in July 2017.

Needed number of spare parts

The number of needed spares is calculated by assuming a constant failure rate. The Poisson distribution is the basis for the calculation of the number of needed spare FGClites. The number of failures over a time frame (e.g. number of failures over 20 years of usage) is a discrete random variable that can be modeled by the Poisson distribution. The period of time between these events (failures) is then exponentially distributed. For a more precise description of the relation between Poisson and exponential distribution, see [14]. The values of the Poisson distribution are discrete, therefore one has to sum each summand to calculate the probability of r failures:

$$P(x \le r) = \sum_{x=0}^{r} \frac{e^{-\lambda} \cdot \lambda^{x}}{x!} \tag{9}$$

The lower confidence limit for the MTTF is 601K hours. For a time frame of 20 years, 1094 devices in operation (in future), the constant failure rate λ is

$$\frac{8766 \cdot 20 \cdot 1094}{601\mathrm{K\,h}} = 319.13 \approx 320 \text{ failures in 20 years} \tag{10}$$

The result in equation 10 is just an average (point estimate), although the lower confidence limit for the MTTF is used for the calculation. In order to calculate the 95% confidence limit for number of spares, one has to find an r that solves $P(X \le r) = 0.95$ [15]. Thus, 349 spare devices are needed for the next 20 years of operation with an MTTF of 601K hours and a confidence level of 95%. According to the law of large numbers [15], the MTTF will reach its true value over time. It is expected that the goal of an MTTF equal to 1M device hours is achievable in early 2019.

4. CONCLUSION AND OUTLOOK

Overall, the FGClite project was a success in terms of needed number of boards, screening and deployment. Therefore, the proposed quantitative reliability methods were effective. The needed number of functioning FGClites were manufactured, tested and deployed. Generally speaking, the whole project was on time and no big design flaws were revealed, thanks to the reliability assessment, which was already started in the design phase of the FGClite.

The production quality goal was not met due to unexpected issues with one of the FGClite's boards. However, the functional tests were designed very well so that most of the faulty parts were detected before installing them in the FGClite.

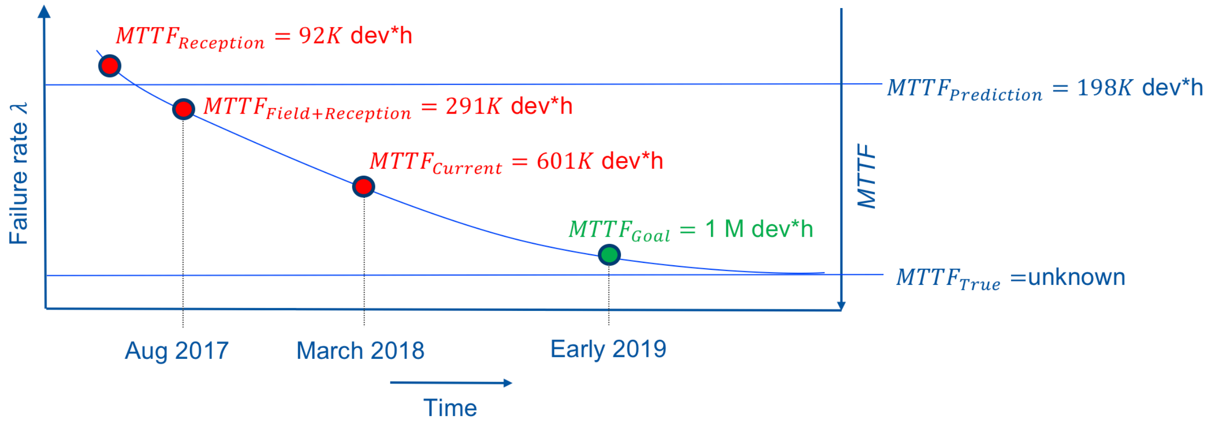
The data derived from the FGC2 contributed a lot to the success of the reception process. The estimated burn-in time and temperature were sufficient enough. The analysis procedure delivered conclusive and clear reports, which can be used for future projects.

The failure monitoring turned out to be very effective, when assessing failure modes and the overall reliability of the population. The constant monitoring of the failure rate enables to detect failure modes that appear to be systematic and distinguish them from random failures (e.g. remote reprogramming issues).

Furthermore, the first interpretation of the data from operation already indicates a shape parameter β of 0.85. If this is verified throughout its whole lifetime, the reception and design process would be slightly different for future projects. For instance, a proved continuously decreasing failure rate for the population would lead to longer infant mortality screenings. Hence, the production quality and burn-in process would be the key success factors for high reliability electronics.

Figure 6 shows an overview if the MTTF growth over time until the true inherent MTTF is reached.

Figure 6: Failure rate over time



As an outlook, one can conclude that the reliability analyses for electronic systems need to consider following recommendations based on the experience from the FGClite project:

- The whole population of devices is to be screened prior to deployment
- Screening tests can lead to preventive firmware updates that improve the overall reliability

- The assumption of a constant failure is sufficiently good and on the safe side, as the actual shape parameter for electronics seems to be less than 1
- The use of newer prediction methods is recommended like 217Plus or Fides. Other departments at CERN conclude that these newer methods have more precise predicted failure rates
- A demonstration of reliability prior to deployment through screening is essential and highly recommended. However, the temperature was static and therefore it was not possible to define a specific temperature profile instead. A temperature profile starting at run-in temperature and increasing to burn-in temperature triggers certain failure modes in a better way.

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