RELIABILITY ASPECTS AND SYNCHROTRON LIGHT SOURCES

Emanuel Karantzoulis
ELETTRA, Sincrotrone Trieste, Italy

Abstract

Availability and Reliability definitions and aspects are presented. Their importance for x-ray sources is discussed and emphasis is given to the failure analysis where reliability serves as a tool. X-ray sources availability and their component failure are presented for different machines.

1 INTRODUCTION

Reliability is considered as a very important aspect of life including any enterprise such as financial, scientific, commercial or other. We often speak about a machine as reliable: "I have a reliable car" meaning that it doesn't break down often. Or, news people talk about an "usually reliable source". In both cases, the word reliable means "dependable" or "trustworthy." In research, the term reliability means "repeatability" or "consistency". A measurement is considered reliable if it would give the same result over and over again (assuming that what we are measuring isn't changing!). To explore in more detail, define a measure X, that might be a person's score on a achievement test, a measure of severity of illness or a measure of break downs of a machine. It is the value of X (numerical or otherwise) that is observed in the study. Now, to see how repeatable or consistent an observation is, the measurement has to be repeated many times. While we observe a score for what we're measuring, we usually think of that score as consisting of two parts, the 'true' score or actual level and the 'error' while measuring it for the i_{th} time (the error can be due to the observation) and therefore $X_i=T + e_i$ It is important to note that the X_i score is observed and not the true (T) or error (e) scores. The measure X is reliable if by repeating measurements the resulting scores are pretty much the same and the reliability in the layperson terms might be defined to be the ratio R= T/X Since T=X-e R=1-e/X and if e-> 0 R->1 or 100% whereas if e/X->1 (no T part) R=0. The reliability therefore has a value from 0 to 1 or from 0 to 100%. In general for X1,2 sets of measurements R=covariance (X1,X2) / sd(X1) * sd(X2)

2 RELIABILITY ASPECTS

2.1 Overview

Reliability theory is a mathematical framework comprising methods models and ideas in order to predict, estimate, understand and optimize the lifespan distribution of systems (living or not) and their components.

Started around the time of World War II, Reliability of a system refers to its ability to operate properly according to specified standards. Reliability is described by the Reliability function (also called survival function) S(t) which is the probability that a system will work through time t. This function evaluated at time x is just the probability P that the failure time T, is beyond time t. Thus the reliability function is defined as

S(t)=P(T>t)=1-P(T<t)=1-F(t) where F(t) (failure function) is a standard cumulative distribution function in the probability theory. In general reliability for systems is defined via the failure rate λ(t) (also called hazard rate h(t)) which is the relative rate for reliability function decline and it is expressed in fits (10^{-9} failure/hour).

$$\lambda(t) = \frac{\frac{dF(t)}{dt}}{S(t)} = -\frac{\frac{dS(t)}{S(t)}}{dt} = -\frac{d(\log_e S(x))}{dt}$$

For constant failure rate

$$S(t) = e^{-\lambda t}$$

Reliability is the probability that a system will work in a given time interval under specified conditions..

Availability represents the time a system meets its specification. A system must be designed for high availability when continuous service is important.

Failure is defined as F(t) = 1 - S(t) and a system can be classified as **Non-repairable** (e.g. satellites) or **Repairable** (e.g. car, particle accelerator).

Some other useful definitions are:

Mean Time To Failure (MTTF) (in hours) is defined as 1/λ and S(t) = exp(- 1) = 0.37 therefore it is the time the component has a probability of failure of 0.63 or 63%.**Mean Time Between Failures** (MTBF) is the mean number of time during which all parts of a system perform within specified limits, for a given time interval.

Mean Down Time (MDT), the average time a system is unavailable due to a failure

Mean Time To Repair (MTTR) is the sum of corrective maintenance time divided by the total number of failures during a given time interval.

Redundancy is the existence of more than one way (component) for accomplishing a given task. In general components may be connected as follows:

In Series (cheap - repairable) all n components must work in order for the whole system to work S=S1*S2*S3*…Sn or S=ΠSi and λ = Σλi

In parallel (expensive – non-repairable or high redundancy - living) (**Active or Standby)**, the system

karantzoulis@elettra,trieste.it

will work as long as at least one component works $R=1-(1-S1)*(1-S2)*(1-S3)*\ldots*(1-Sn)$ thus $R=1-\Pi Fi$ and $1/\lambda \sim \Sigma 1/\lambda\iota$.
Mixed connection used for cost and reliability optimization.

2.2 Controlling Components Aging

The reliability function of non-aging systems (components) is described by the exponential distribution:
$\lambda(t)=\lambda=const$ è $S(t)=S_0 \exp(-\lambda t)$
This failure law describes “lifespan” distribution of atoms of radioactive elements, beam lifetime in accelerators etc.
If failure rate increases with time we have an aging system (component) that deteriorates with age. If failure rate decreases with time indicates that the system was not set up correctly or not all its subsystems were functioning properly.
In reality system failure rates may contain both non-aging and aging terms:

$$\lambda(t)=N \exp(-b\ t) + A + R \exp(a\ t)$$

with parameters N A R and a,b >0, where N and b are age dependent terns that indicate decrease with time (e.g. infant mortality), term A is aging independent term thus it is due to external causes like accidents, mishandlings etc. whereas R and a are the true aging terms. Their values depend amongst other on how the system components are connected. Such a function could be like in Figure 1 using $N=1$, $b=0.005$, $A=10$, $R=10^{-8}$ and $a = 0.0046$:

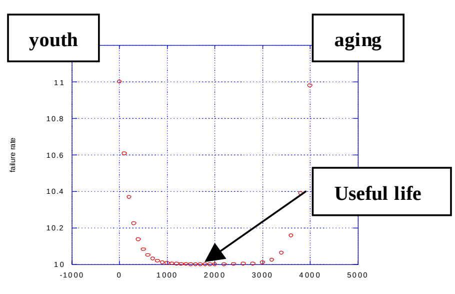

Figure 1: bath tube model

Since failure rates indicate the state of health of the components of a system the existence of any trends is of particular importance since if the failure rate increases with age we have an aging component that deteriorates. In order to see these trends one usually plots the cumulative number of failures against the cumulative time between failures (TBF). These graphs help to predict the behaviour of a system. Maintenance scheduling, spare part procurement and early detection of trends are essential in running a facility and planning for reliability improvement.

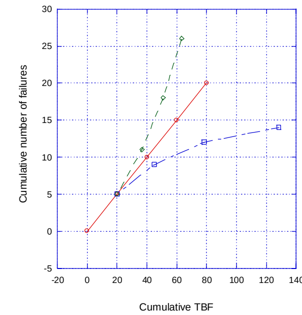

Figure 2: Cumulative number of failures vs. cumulative TFB (time between failures)

2.3 Fully repairable systems

They have a behaviour similar to non aging system for which

$$\lambda(t)=\lambda=const \text{ and } S(t)=S_0 \exp(-\lambda t)$$

However in repairable systems under continuous supervision, λ is a quasi-constant and reliability is not always a pure **exp** function. The cumulative number of failures oscillates around the line that indicates constant failure rate. Also plots of failure rates do not follow one bath tube diagram but are a combination of many such graphs. In this case the failure rate can be represented as a polynomial or even as a power function too.

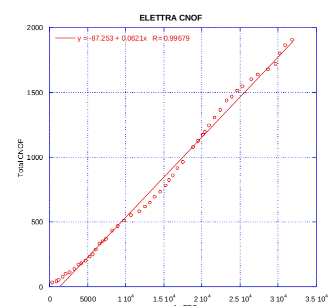

Figure 3: Cumulative number of failures for ELETTRA vs. cumulative TFB

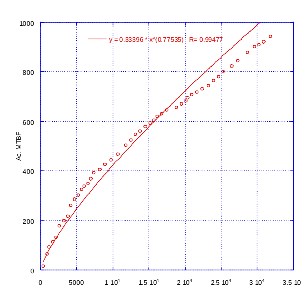

Figure 4: Cumulative MTBF for ELETTRA vs. cumulative TFB

where the TFB is from 1995 until now (about 35000 hours). Assuming a power relationship for MTBF one can estimate the evolution of the system. The fit gives

$$MTFB(t)=0.334* t^{0.77535}$$

and it is evident that the machine runs better now than in the beginning

3 RELIABILITY AND AVAILABILITY IN ACCELERATORS

These are relatively new issues, concerning more X-ray sources and spallation sources (for different reasons). X ray sources are are multi user storage rings that produce synchrotron radiation. There reliability has an increased importance exactly due to their nature i.e. many users work in parallel and plan their experiments long in advance (usually over one year). The demand for beam time is still unsaturated and new x-ray sources are emerging (e.g. Soleil , Diamond). In these establishments work typically 600 - 6000 users per year for about 5000 hours of machine time for user operation. Usually a machine can break as long as it has high Availability, otherwise will loose its users. One can distinguish between:

- High reliability -> the machine breaks seldom
- High Serviceability -> the machine can break more often but has short recovery time.

As a rule of thumb many short failures are tolerated better than a long one. Thus Availability comprises such issues as reliability, serviceability and others.
The availability qualitatively depends on

- Budget (personnel, redundancy of equipment, maintenance)
- Operations (operators, experts/on call, troubleshooting, modes of operation)
- Management (personnel, equipments, statistics)
- Planning (new installations, coordinating shut down work, careful control before start up)

and is measured with the usable up-time (=beam on with agreed quality) and the MFD (mean fault duration).
Additional information is given by: CNF (Cumulative number of failures), MTBF,
Failure rates (Faults / hour) and MTTR (mean time to repair)

In the next, 3 x-ray sources (APS 7GeV, ELETTRA 2-2.4GeV, ESRF 6 GeV) will be considered for the only reason that they seem different since use 3 different modes of operating. Thus APS has full energy booster and top-up with many individual power supplies, ESRF full energy booster and ELETTRA injects from a linac at 1 GeV while the machine operates for the users at 2 or 2.4 GeV (25% of user time).

3.1 Up-time statistics

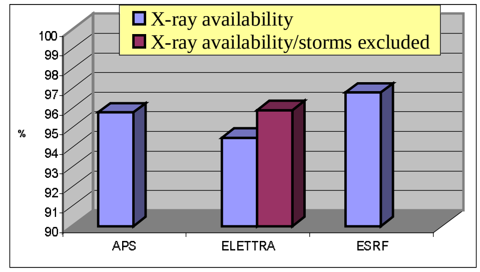

Figure 5: X-ray sources availability for 2001

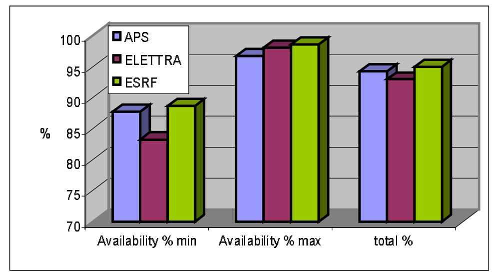

Figure 6: Maximum, minimum and average availability since 1995 (APS since 1997)

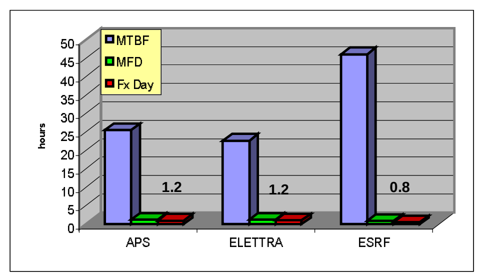

Figure 7: X-ray sources Mean Time Between Faults (MTBF) , Mean Fault Duration (MFD) and Faults per Day (FxD) for 2001

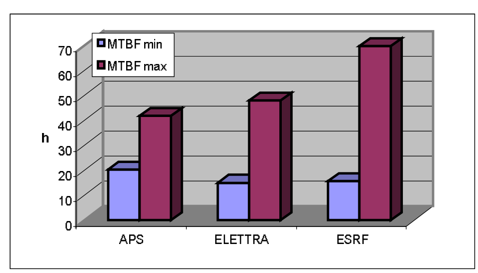

Figure 8: Maximum and minimum Mean Time between Faults since 1995 (APS 1997)

All considered machines had a high reliability >95% in 2001. Extending the statistics over many years one sees that in general the average lays above 93% . Looking at

MTBF, MFD and Faults per Day, for 2001 APS and ELETTRA seem to be close however ESRF does factor of two better. Seen all statistics since 1995 (APS 1997) whereas the minimum mean time between faults is in the order of 15-20 hours the maximum is still by 30% higher for ESRF (a very good achievement). It is useful to observe that 95% is practically a non stop mode. For 5000 hours of user operation, 250 hours is down time. A MFD of 1.2 h means that the machine in a year had 208 failures. (It was reported that Spring8 and ESRF are now approaching 99% meaning 50 hours of downtime in a year or about 50 faults). It is very important however that the faulty 5% should be smoothly distributed through the year (otherwise it might happen that some users do not work at all since 5% of 5000 is about 10 days) the figure of merit being MFD and it should be small. ESRF has it 0.8 meaning more faults at 95% but faster recovery.

3.2 Where to look for improving - Equipment failures

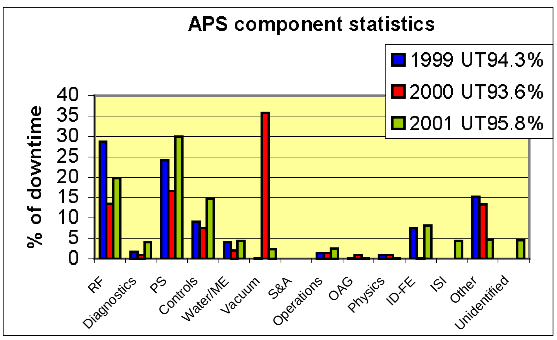

Figure 9: Three years of component failure analysis for APS

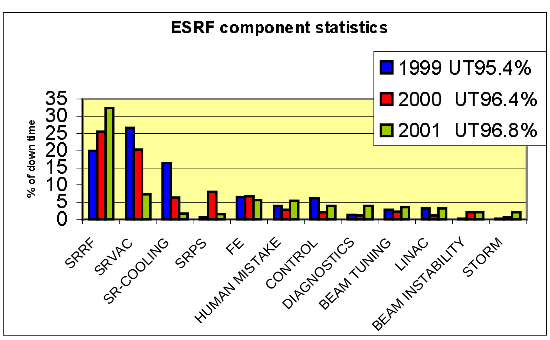

Figure 10: Three years of component failure analysis for ESRF

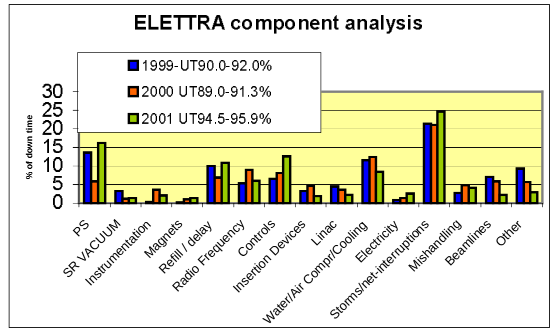

Figure 11: Three years of component failure analysis for ELETTRA

Table 1: Max. % of down-time for x-ray sources' subsystems

% of down-time	ALS	ELETTRA	ESRF
PS	>15	>15	>5
RF	>15	>5	>20
controls	>10	>10	>5
VAC	>35	<5	>25
Cooling	<5	>10	>15
BL	>5	>5	>5
other	>10	>5	<5

Amongst the many different reasons that a subsystem can fail there may be a correlation to the energy, size or quantity of units and the operating mode of the source. Thus ESRF and APS both high energy storage rings suffer from failures of the rf system, whereas from failures of the power supplies suffer APS (too many) and ELETTRA (ramping to the final energy). This mode of operating is prone to faults during refills since the main ring power supplies and all other systems are stressed. In fact over 50% of failures happen during this period. The control system failures appear independent being almost the same for all machines. Human error can contribute also in a non-direct manner. For both ELETTRA and ESRF the evident mishandling is around the 5% of the down-time relatively low, no statistics exist for the indirect mishandling. "Other" is something to be eliminated, ELETTRA works towards this direction and no unspecified fault is tolerated. Finally all machines suffer from the users, the percentage is low >5% for all tree machine and peaks when new lines are installed. Storms and other external disturbances reduce the uptime at about 2%. ELETTRA suffers from storms and network micro-interruptions (20-25% of its down-time) with MFD of less than 2 hours. However although one could discuss whether it is worth spending some millions $ to get continuity generators for just a 2%, many forget that these interruptions can provoke major equipment failures

3.3 Detecting trends

Trends may be revealed plotting the CNOF (cumulative number of faults) of a subsystem against CTBF (cumulative time between faults). In general repairable systems have a quasi stable failure rate but trends are well visible.

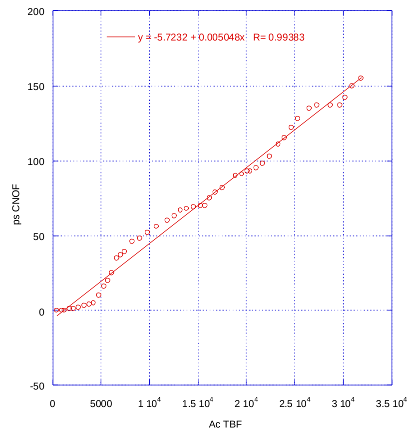

Figure 12: CNOF vs. CTBF for the PS of ELETTRA for 35000 hours of operation

This has to be well distinguished from stochastic (random external) disturbances that have similar trends and can greatly influence the failure behaviour of the system, like the graph below.

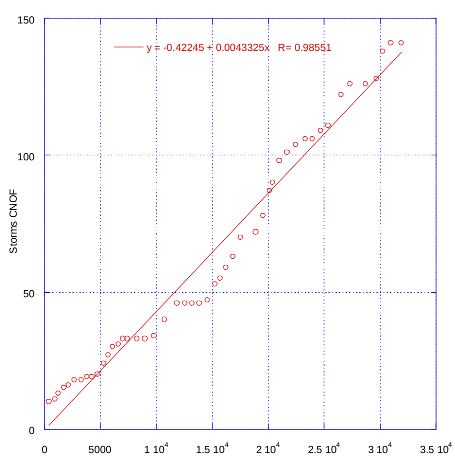

Figure 13: CNOF vs. CTBF for the storms and external disturbances at ELETTRA for 35000 hours of operation

It is very important to be able to distinguish between the two cases.

3.4 Modeling and predicting trends

This may be achieved plotting and fitting the failure rates (failures / hour) or MTBF against CTBF. One may use polynomial, power or exp fits.

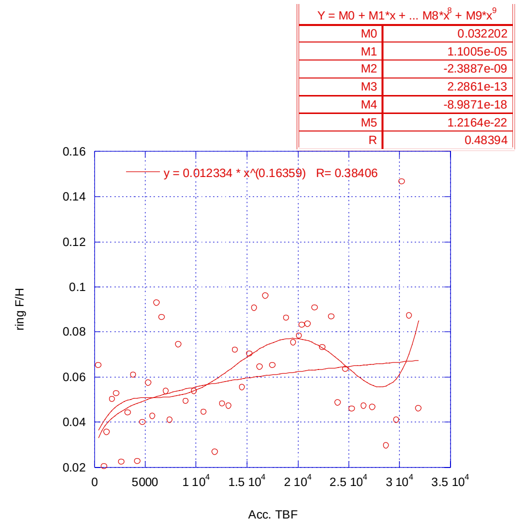

Figure 14: ELETTRA failure rate vs. CTBF for the for 35000 hours of operation and its polynomial and exp fits. Fit coefficients on the graph

External disturbances can be dominant for ELETTRA and when this occurs no good prediction can be achieved

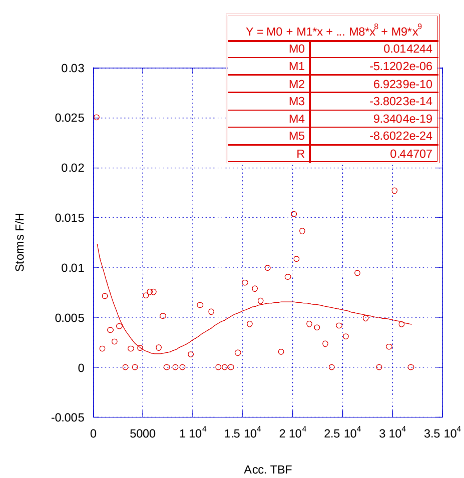

Figure 15: Storm and external disturbance failure rate vs. CTBF for the for 35000 hours of operation

From Fig. 14 we see that at about the end of 2002 a small increase in failure rate occurs that it is not in concomitance with external disturbances. The prediction and trends are correct since new equipments are installed (a 3rd harmonic super conducting rf system) and while it is commissioned the failure rate increases.

On the other hand other sub-systems reveal a tendency to not create problems in the close future as the RF system

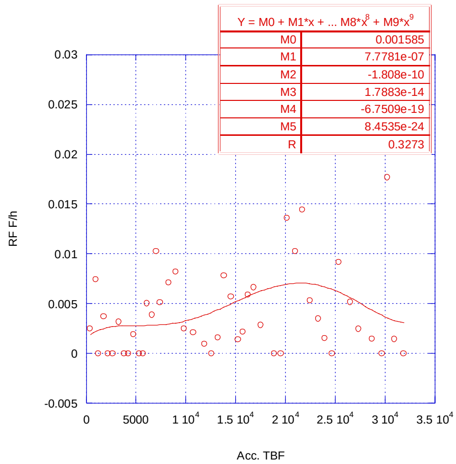

Figure 16: RF failure rate vs. CTBF for the for 35000 hours of operation

Fitting by parts exp functions tendencies can be better observed. Below the PS failure rates between 5 000 – 15 000 hours is plotted and a good exp fit is obtained

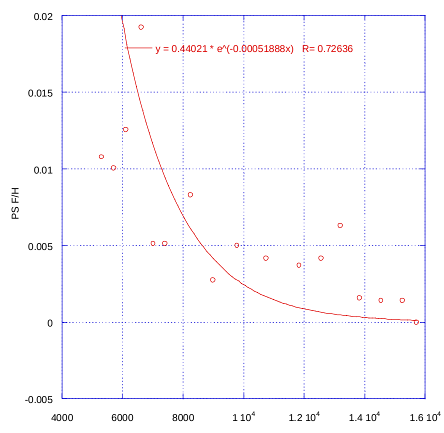

Figure 17: PS failure rate vs. CTBF for the period between 5000-15000 hours

4 CONCLUSIONS

Availability concepts can help to make accelerators more efficient. Early detection of trends and weak points are essential in running a facility. It also helps to optimize the availability services keeping costs low. For example intervention speed, on-call service, maintenance scheduling, service speed, spare parts procurement and availability, etc. can be optimized so that the usual accelerator operating mode "run it until it breaks" (being cheap) can also be efficient.

X-ray sources have in general high availability levels i.e. above 92% Three examined sources had more than 95% in the last years keeping also MFD low which is the aim of any operations group. Availability heavily depends on budget but not only. Actions that appear of administrative nature like seriously programming any activity, regular operations meetings, good statistical analysis not allowing for unspecified events, experienced and good operators team, good personnel management can help to gain a 2-3% in up-time. Maintenance and especially the preventive one is very important too (but enters into the budget question) however there the reliability analysis can greatly help in prioritizing work and optimizing costs.

Machines that do not do (or have) "exotic things" (like energy ramping, individual PSs for each magnet, many modes of operation) are prone to work better. Machines are always in evolution and during major evolution steps up-time suffers because not all aspects are known and usually not well analyzed. Availability can suffer by seemingly irrelevant actions. Thus careful planning and rigorous decisions on installations and innovations should not be taken without discussing with the Operations.

5 ACKNOWLEDGEMENTS

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