Accelerator Availability and Reliability

From Energy Frontier Colliders to

- Particle Factories
- Light Sources
- Medical Accelerators

→ Increased importance of high availability
Failure Rate

FAILURE RATE

TIME

BURN IN Phase
- QA
- Recoverable Design Flaws
- Operational Inexperience

WEAR-OUT Phase
- Replacement
- Refurbishment
- Strategies

Constant Failure Rate
- Design and Operating
Availability Modeling

Improvement Cycle:

- Monitor Operations
- Analyze Failures
- Propose Improvements
- Project Improvements
- Implement Improvements

Availability Modeling:

Failures are Statistical, Independent Events

Imperfect Model of Reality!
Availability

Availability (A):
(Total Scheduled Time – Lost Time due to Failures) / Total scheduled time

Mean Time between Failure (MTBF):
(Total Time – Lost Time ) / Average number of failures

Mean Time to Repair (MTTR):
Lost (+Recovery) Time / Average numbers of Failures

\[
A = 1 - \frac{MTTR}{MTBF + MTTR}
\]
Complementary Figure of Merit

Average Performance
Performance = Beam Current / Effective Beam Size

D: Relative Performance Reduction Due to Failure

\[
\langle P \rangle = \prod_{n=1}^{N} \left[ 1 - \frac{1}{2} \cdot \frac{\Delta T}{MTBF_n} \cdot D_n \right]
\]
Multi Components

Accelerator with N subsystems

\[ A = \prod_{n=1}^{N} \left[ 1 - \frac{MTTR_n}{MTBF_n + MTTR_n} \right] \]

or

\[ A = 1 - \sum_{n=1}^{N} \frac{MTTR_n}{MTBF_n + MTTR_n} \]
Basic Relationships

Probability for component failure within a time interval $\Delta t$,

$\lambda = \text{failure rate}$

If $\lambda$ constant $\Rightarrow$

$$p = \lambda \cdot \Delta t$$

$$MTBF = \lambda^{-1}$$
System with $N$ components

$$MTBF = \frac{1}{N \cdot \lambda}$$

→ The larger the system, the more reliable the components have to be to maintain availability
Basic Relationships

Non-constant Failure Rate

\[ MTBF = \int_{0}^{\infty} dt \cdot \exp \left[ - \int_{0}^{t} d\tau \cdot \lambda(\tau) \right] \]
Parameterization of the Failure Rate

\[ \hat{\lambda}(t) = \frac{a}{b} \left( \frac{t}{b} \right)^{a-1} \Rightarrow MTBF = b \cdot \Gamma \left( 1 + \frac{1}{a} \right) \]
Availability Simulations

To take into account operational strategy and deterministic aspects of failure rate → **MONTE CARLO SIMULATIONS** HELPFUL

- Work Around and Compromised Performance
- NearTerm Opportunity for Repair in the Shadow of planned downtime
- Opportunistic Accelerator Studies
- Controlling number of activities in same location
- Accessibility of the components for repair
- Coupling of Failure Rates
- Operation History dependent Failure Rate
- Failure Rate Dependence on Operational Parameters
- Enhanced Failure after Downtime
- Burn-in after maintenance and Trouble Shooting
- Improvement of failure rates due to preventive maintenance
- Learning Curve after Restart
- Spare strategies
- Impact of limited accessibility of the components for repair
- Radiation Safety Concerns dep. on operating history
- Partial or Limited Power Redundancy

**Example:**
Main Arguments for ILC Equipment and Service Tunnel (0.5B$+)
Based on Performance Simulation with “AVAILSIM” (T. Himel, SLAC, PAC’07)
NSLS-II Performance Simulation

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**Efficiency**
- Simulation: 0.957
- Analytic: 0.963495

**Availability**
- Simulation: 0.958
- Analytic: 0.963495

**Failures**
- Simulation: 45,000
- Analytic: 44.65032

**Time Without Beam**
- Simulation: 210,000
- Runtime: 5000

Lost Performance per System:

```
2 years
```
NSLS-II Performance Simulations

Question: Keep Running with Reduced Performance – OR – Break for Repair?

Answer (for NSLS-II assumptions): Don’t accept more than 10% reduction in performance, Don’t expect substantial increase in schedule safety by accepting running with reduced performance.
Accelerator Design

COST

PEAK PERFORMANCE

OPERATIONAL EFFICIENCY
Design for High Availability

Considerations:

- Overall Complexity
- Unavoidable Weakness
- Subsystem Architecture
- Fail Safe Design
- Overrated Design
- Environmental Impact
- Error Prone Solutions
- Build-in Redundancy and Hot Spares
- Built-in Diagnostics
- Repair and Maintenance Friendly Design
Achieved Availabilities

Colliders, Example HERA

**HERA Efficiencies**

DEFINITION: Time spent with collision divided by scheduled time

- Improvement of Redundancy 97/98
- Luminosity Upgrade
- Positron operation

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http://www.aps.anl.gov/Accelerator_Systems_Division/Operations_Analysis/logging/MonitorDataReview.html

Synchrotron Light Sources, Example APS

- APS 800m accelerator 20 cells, 0.5h fill cycle

⇒ Comparable component reliability leads to different availability
Subsystem Architecture

Monolithic versus Modular Design ➔
Case to Case Decision
Avoid coupling of the two types of architecture
Subsystem Architecture

Monolithic versus Modular Design ➔
Case to Case Decision
Avoid coupling of the two types of architecture

DC
“Mother” PS

Switched Mode “Daughter” PS
High Reliability Switched Mode PS

ATF Corrector Power Supply developed at SLAC

From P. Bellomo#, D. MacNair, SLAC
http://indico.triumf.ca/contributionDisplay.py?contribId=5 &sessionId=7&confId=749, Vancouver 2009
NSLS-II Solution: Small AC/DC Supplies

Courtesy G. Ganetis, BNL
Smart Fail Safe Design

Fail Safe Design = Good Engineering Practice

However: System Trips are an important factor in operational efficiency esp for accelerator with long injection cycles

Need to be conservative in early operation phase ➔ High false trip rate, but

Trip Thresholds could be higher with growing experience and confidence

- Need flexible internal trip thresholds
- Need flexible protection logics
- Needs to be included in the design phase
- Safe administration and management of the threshold must be integrated upfront!
Overrated Design

Overrating of Power Components:
- Reduced operating temperature
- Reduced temperature change when switching on/off
- Less mechanical and thermal stress on Components
- Operating further away from internal trip thresholds
  ➔ Lower Failure Rate

Difficult to optimize overrating

For magnet power supply gain in reliability varies from vendor to vendor
Example HERA Experience:
Beam Current @ 1996 Limited by RF Trip Rate <1996
After RF power margin of ~30% was added by adding an 8th 1.5MW klystron transmitter and fixing SC RF cavity problem
  ➔ Beam current increased from 35mA ➔ 50mA

Thermal Cycling

\[
\frac{\lambda}{\lambda_0} = \left( \frac{\Delta T}{\Delta T_0} \right)^2 \cdot \exp \left[ -\frac{E}{k} \cdot \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]

Temperature Failure Enhancement Factor for Electronics
Environmental Impact: Dust, Humidity, Temperature

Dust causing frequent failures on TEVATRON QP electronics (copied from H. Edwards/P. Czarapata, FNAL, Groenitz Miniworkshop 2005)

Lifetime of film capacitors vs int. temperature
C. Chen et al
IEEE PESC, Aachen 2004

This avoids error prone design
Error Prone Solutions

- Water Cooling
- Electrical Connectors
  Replace analog cable connections by serial digital links where ever feasible (gain reliability, save costs)
Build-in Redundancy and Hot Spares

Build in Redundancy will increase reliability significantly -- if failed modules are replaced continuously then needs access!

- “Hot Swap” Capability helps

Example:

TESLA/XFEL
Switched Mode
PS with Hot
Spare Redundant
Power Modules
Built-in diagnostics

- long term monitoring and onset of failure detection
- trouble shooting
- Cross correlations with external factors
Repair and Maintenance Friendly Design

Power Supply Rack System with Docking ➔ System for fast replacement of the entire unit

Good accessibility of components important to minimize troubleshooting and repair

However, is often compromised
Continuous Improvement
Data Logging (time stamped, well accessible on/off site)
Data Analysis Tools and Cross Correlation
(Example: check A/V on each magnet cycle)
Root Cause Analysis mandatory for large incidents
Commercial Software tools available to extent this technique for all failures

Illustration of Root Cause Analysis using Fault Tree Analysis
High Availability Operations

Operational Strategy to mitigate Impact of Failure

- Scheduled Maintenance: Opportunity for repair and preventive maintenance
- Back-up programs to operate with limited performance (accelerator studies)
- Management:
  - Clearly defined roles and accountabilities
  - Escalation strategy
  - Experts On-call
HIGH AVAILABILITY OPERATIONS

- **Preventive Maintenance**
  - Necessary: Rotating machinery (compressors)
  - Air Filters
  - UPS-systems
  - Desirable: clamped, bolted support systems in PS
  - Cooling Water Hoses
  - Difficult: Connectors

- **Preventive Refurbishment**
  - Fans, capacitors, small DC supplies
  - Fix before Fail

Was used successfully to improve HERA PS system

Some supplies: MTBF
15000h ➔ 50000h

Residual Lifetime Prediction

\[
MRL = \frac{1}{S(t)} \cdot \int_{0}^{\infty} dt' S(t + t')
\]
HIGH AVAILABILITY OPERATIONS

Speed Up Repair
• Transient Recording
• Integration of Operational Data Base and Asset Management
• Remote Access to Build-in Diagnostics
• Logged Data Analysis Tools
• Failure Scenario Data Base
• Start-up Check List

...
Human Factor

Human errors are unavoidable but can be minimized with reasonable effort

- Operations Briefings at shift change
- Written instructions
- Clearly defined line of command for routine/non-routine
- Automation of operating procedures highly desirable
- Software Interlock System to prevent wrong actions
- Operator Training and Qualification, Motivation
- On-line Technical and Procedural Informations
- Ergonomic Operation Software
- Functional alarm system (no false alarms)
- Management of access to accelerator controls
- Management of access to accelerator equipment
- Unambiguous naming
Human Factor

Entire Technical Staffs should have ownership of accelerator operations:

- Daily short operation briefings including technical staff
- Control center should be physically close to staff offices
- Monitoring Operations from out-site Control room
- Published e-Logbook
- Experts On-Call
- Remote Access to Hardware by off-site experts
Acknowledgements

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Kai Wittenburg, DESY
Tom Himel, SLAC,
Nan Phinney SLAC,
Eric Johnson, BNL
George Ganetis, BNL
Backup Slides
Basic Relationships

Probability for component failure within a time interval $\Delta t$, $\lambda =$ failure rate

If $\lambda$ constant, probability to fail at $t = n \cdot \Delta t$:

$\begin{align*}
    f_k &= (1 - p)^{k-1} \cdot p \\
    \text{(probability density function)}
\end{align*}$

$\Rightarrow$ **Mean Time Between Failure**

$MTBF = \langle k \rangle \cdot \Delta t = \sum_{k=1}^{\infty} k \cdot \Delta t \cdot f_k = \lambda^{-1}$

System with $N$ identical components:

Probability for $n$ failures in $\Delta t$:

$P_{N,n} = \binom{N}{n} \cdot (1 - p)^{N-n} \cdot p^n$

Expectation Value for $n$:

$\langle n \rangle = \sum_{n=1}^{N} n \cdot P_{N,n} = Np$

$\Rightarrow$ **System Mean Time Between Failure**

$MTBF = \sum_{k=1}^{\infty} k \cdot \Delta t \cdot (1 - Np)^{k-1} \cdot Np = \frac{1}{N \cdot \lambda}$

The larger the system, the more reliable the components for same availability.
Availability

\[ A = \frac{t - \sum_{i=1}^{k} \Delta t_i}{t} = 1 - \frac{\langle n \rangle \langle \Delta t \rangle}{t} = 1 - \frac{\langle n \rangle}{t} \cdot MTTR \]

\[ MTBF = \frac{t - \langle n \rangle \cdot MTTR}{\langle n \rangle} \quad \Rightarrow \quad \langle n \rangle = \frac{t}{MTBF + MTTR} \]

\[ A = 1 - \frac{MTTR}{MTTR + MTBF} \]
Non-Constant Failure Hazard

\[ \lambda_i \neq \text{const.} \Rightarrow \]

\[ f_k = \prod_{n=1}^{k-1} (1 - \lambda_n \cdot \Delta t) \cdot \lambda_k = \lambda_k \cdot \exp \left[ \sum_{n=1}^{k-1} \ln (1 - \lambda_n \cdot \Delta t) \right] \]

\[ \lim_{\Delta t \to 0} f_k \Rightarrow f(t) \]

---

Probability Density Function

\[ f(t) = \lambda(t) \cdot \exp \left( - \int_0^t d\tau \cdot \lambda(\tau) \right) \]
Failure and Survival Function

Probability for failure within time $t$

$$F(t) = \int_0^t d\tau \cdot f(\tau) = 1 - \exp\left(-\int_0^t d\tau \cdot \lambda(\tau)\right)$$

Probability for survival of a time $t$

$$S(t) = 1 - F(t) = \exp\left(-\int_0^t d\tau \cdot \lambda(\tau)\right)$$

$$MTBF = \int_0^\infty dt \cdot t \cdot \lambda(t) \cdot \exp\left[-\int_0^t d\tau \cdot \lambda(\tau)\right] = \int_0^\infty dt \cdot S(t)$$