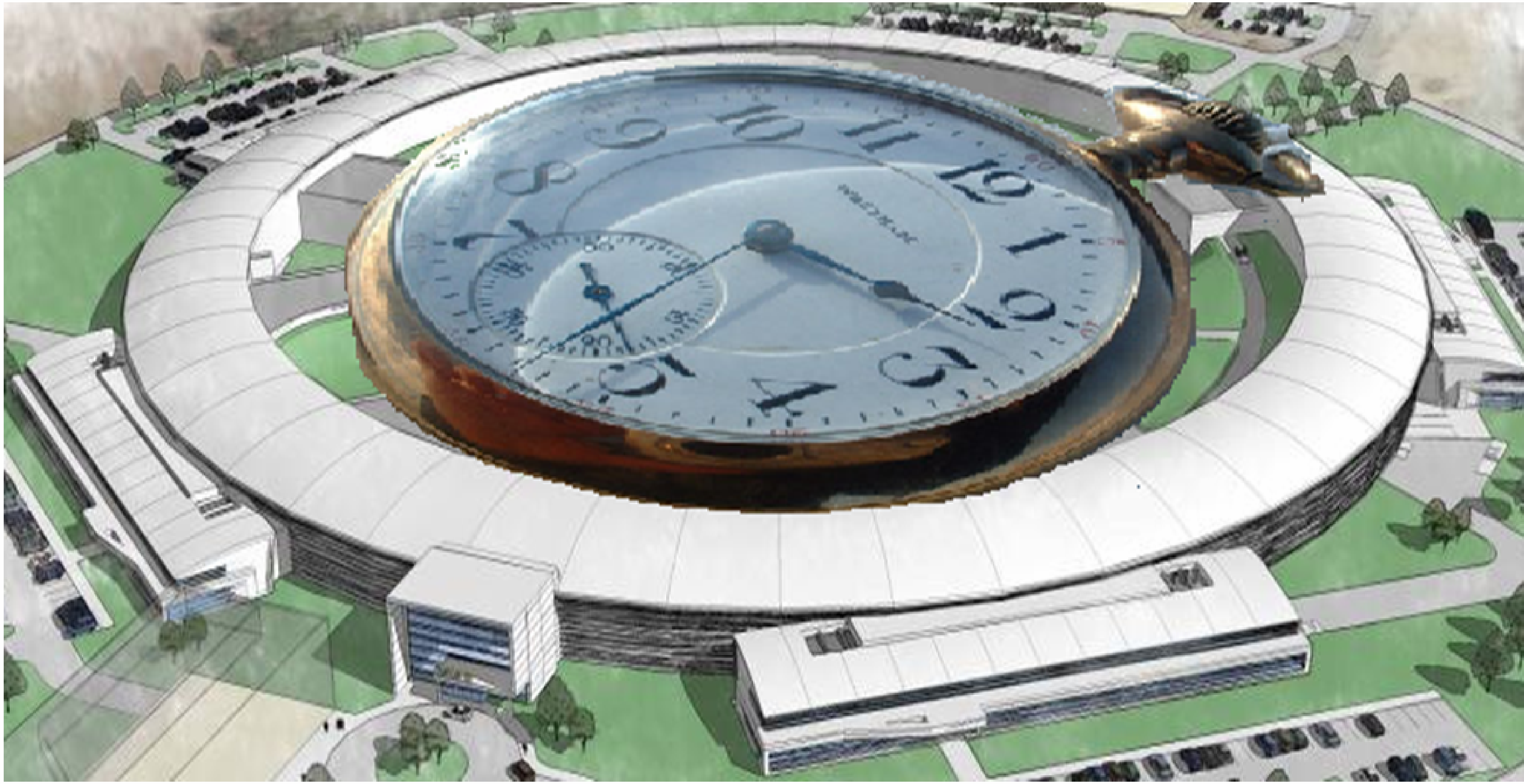
Designing and Running for High Accelerator Availability



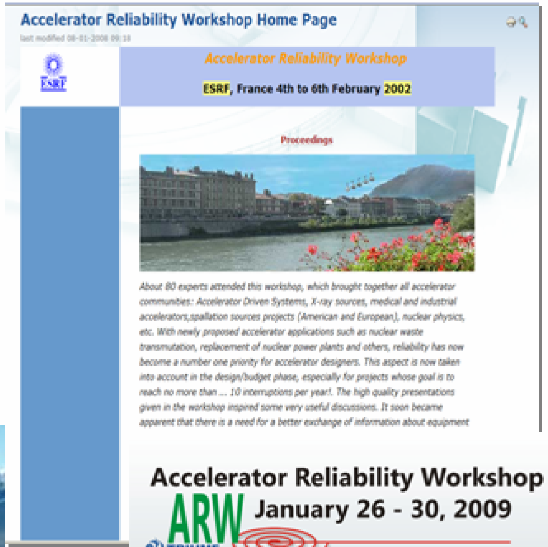
F. Willeke, Brookhaven National Laboratory
IEEE Particle Accelerator Conference, Vancouver
May 4-9, 2009

Accelerator Availability and Reliability

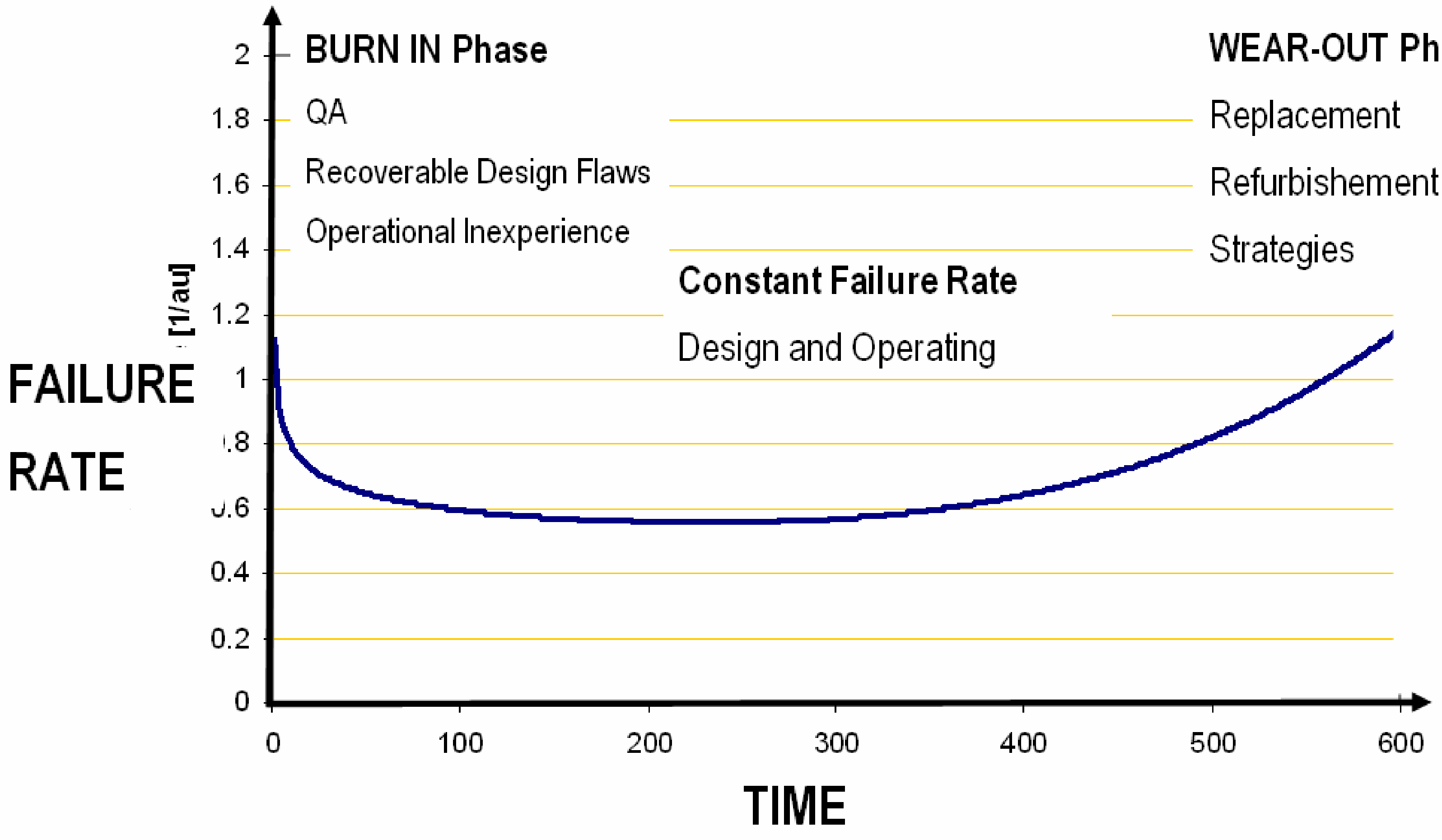
From Energy Frontier Colliders to

- Particle Factories
- Light Sources
- Medical Accelerators

→ Increased importance of high availability



Failure Rate



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

Maintenance Interval

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

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 Δt,

λ = failure rate

If λ constant →

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

$$MTBF = \lambda^{-1}$$

Basic Relationships

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

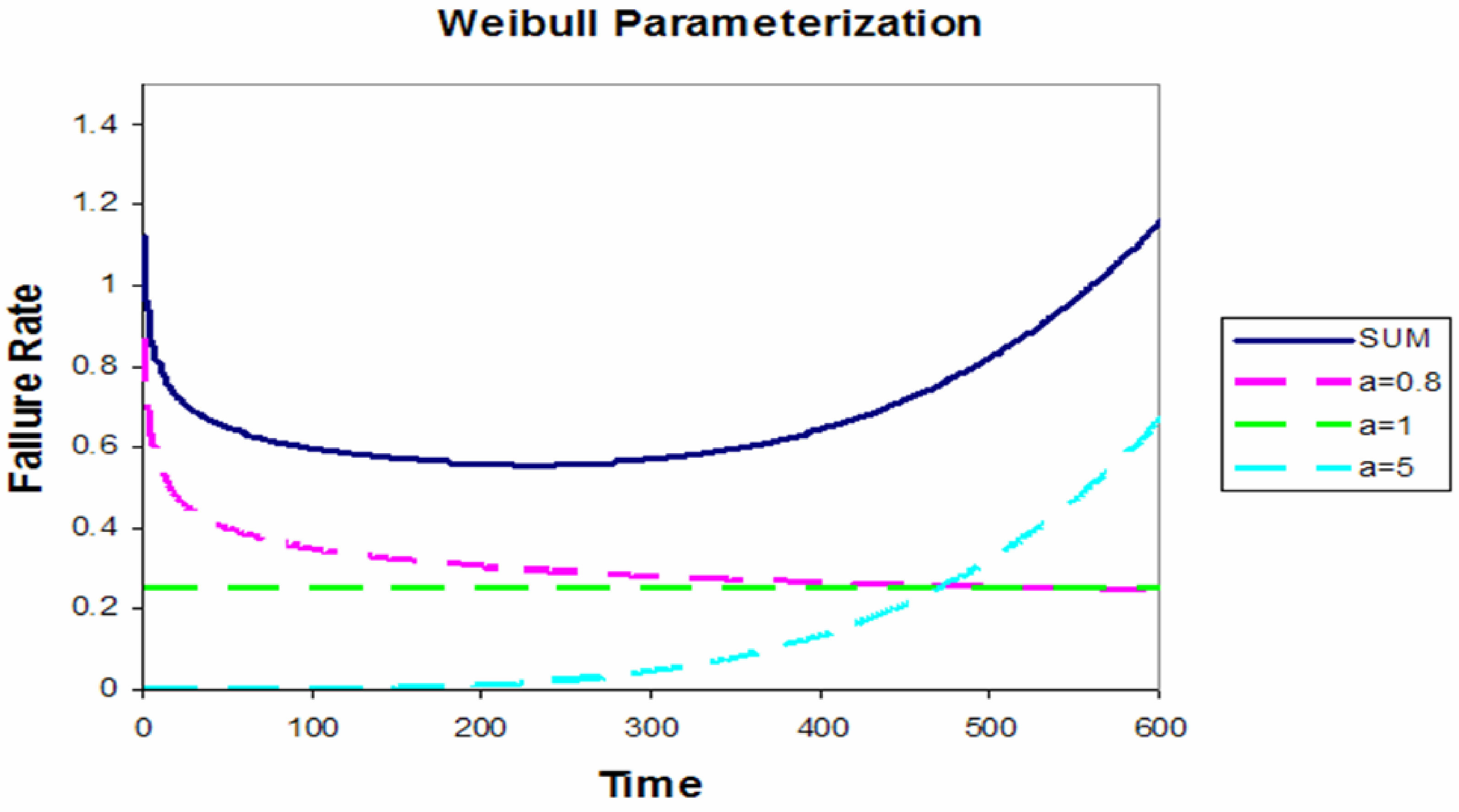
Basic Relationships

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

$$\lambda(t) = \frac{a}{b}\left(\frac{t}{b}\right)^{a-1} \Rightarrow MTBF = b \cdot \Gamma\left(1 + \frac{1}{a}\right)$$



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 down
- 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

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DESIGN DECISIONS

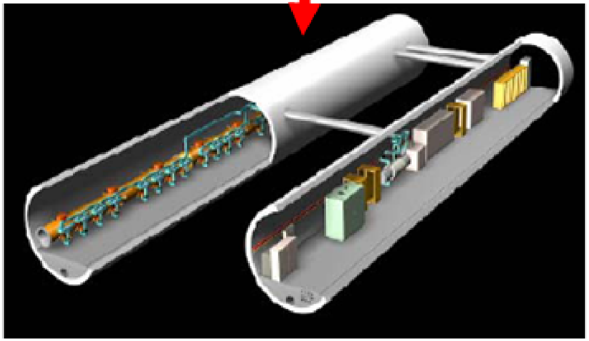
OPERATING DECISIONS

MANAGEMENT DECISIONS

<u>Example:</u>

Main Arguments for ILC Equipment and Service Tunnel (0.5B$+)

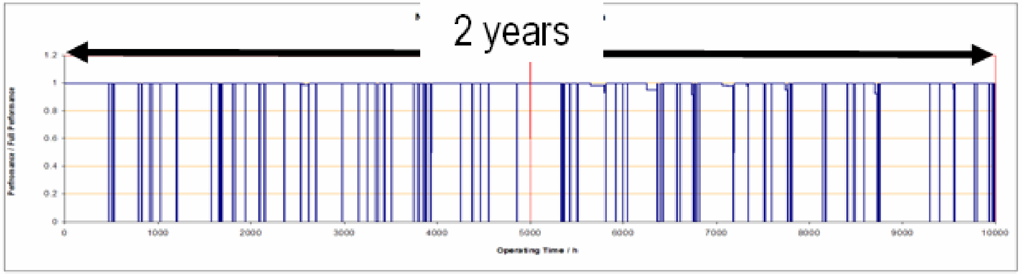
Based on Performance Simulation with "AVAILSIM" (T. Himel, SLAC, PAC'07

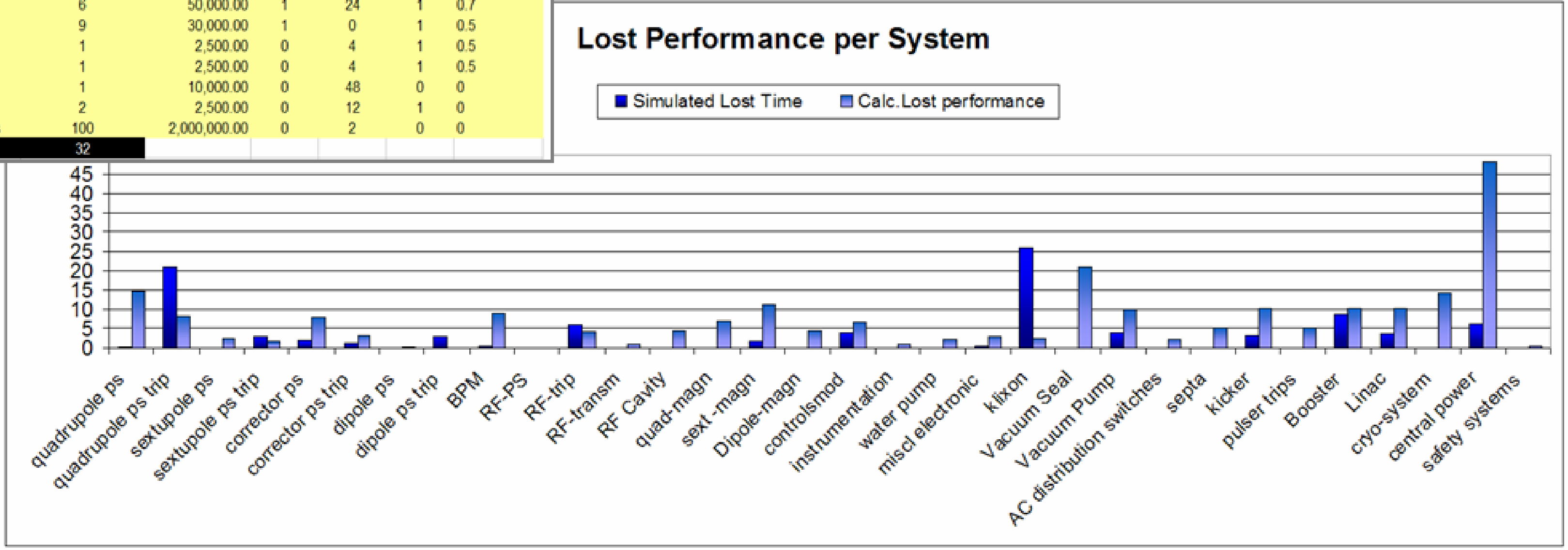


NSLS-II Performance Simulation

system	Count	mtbf	mttr	range	pr-max	pr-min
quadrupole ps	300	800,000.00	0	8	1	0.5
quadrupole ps trip	300	200,000.00	0	0	0	0
sextupole ps	60	820,000.00	0	8	1	0.6
sextupole ps trip	60	220,000.00	0	0	0	0
corrector ps	204	450,000.00	0	2	1	0.8
corrector ps trip	204	340,000.00	0	0	1	0
dipole ps	1	150,000.00	0	8	1	0.4
dipole ps trip	1	80,000.00	0	0	0	0
BPM	240	500,000.00	0	2	1	0.95
RF-PS	2	600,000.00	0	8	0	0.3
RF-trip	2	2,500.00	0	0	0	0
RF-transm	2	50,000.00	0	8	0.7	0
RF Cavity	4	100,000.00	8	24	0.7	0.4
quad-magn	300	1,500,000.00	0	8	1	0.4
sext -magn	300	1,000,000.00	0	8	1	0.4
Dipole-magn	60	1,000,000.00	0	24	1	0.4
controlsmod	1000	2,000,000.00	0	1	1	0.4
instrumentation	100	1,000,000.00	0	1	1	0.9
water pump	25	300,000.00	0	6	1	0
miscl electronic	500	2,000,000.00	0	1	1	0.4
klixon	1000	5,000,000.00	0	1	0	0
Vacuum Seal	400	2,000,000.00	4	24	0	0.4
Vacuum Pump	200	2,000,000.00	4	24	0.7	0.5
AC distribution sw	25	500,000.00	2	8	1	0
septa	3	50,000.00	2	24	1	0.7
kicker	6	50,000.00	1	24	1	0.7
pulser trips	9	30,000.00	1	0	1	0.5
Booster	1	2,500.00	0	4	1	0.5
Linac	1	2,500.00	0	4	1	0.5
cryo-system	1	10,000.00	0	48	0	0
central power	2	2,500.00	0	12	1	0
safety systems	100	2,000,000.00	0	2	0	0
Count	32					

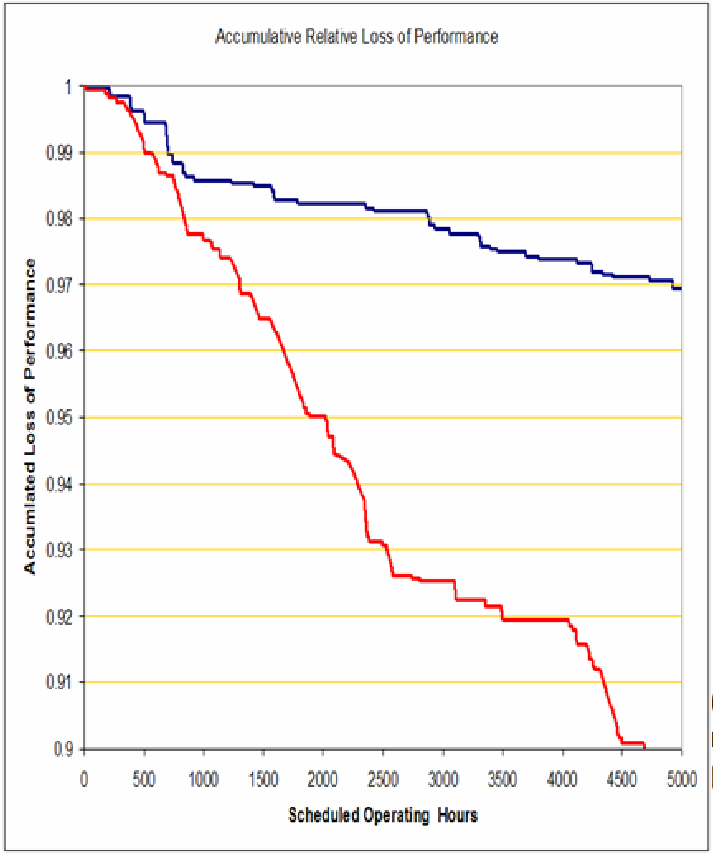
Efficiency	*simulation*	0.957	*Analytic*	0.953495
Availability	*Simulation*	0.958	*Analytic*	0.953495
Failures	*Simulation*	45.000	*Analytic*	44.65032
Time Without beam	*Simulation*	210.000	*Runtime*	5000

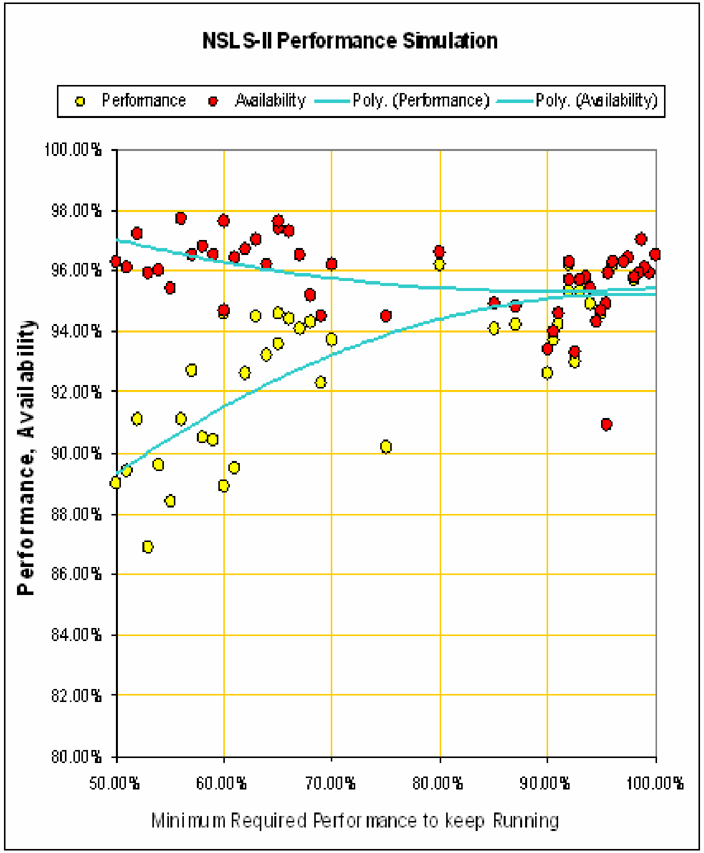




NSLS-II Performance Simulations

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

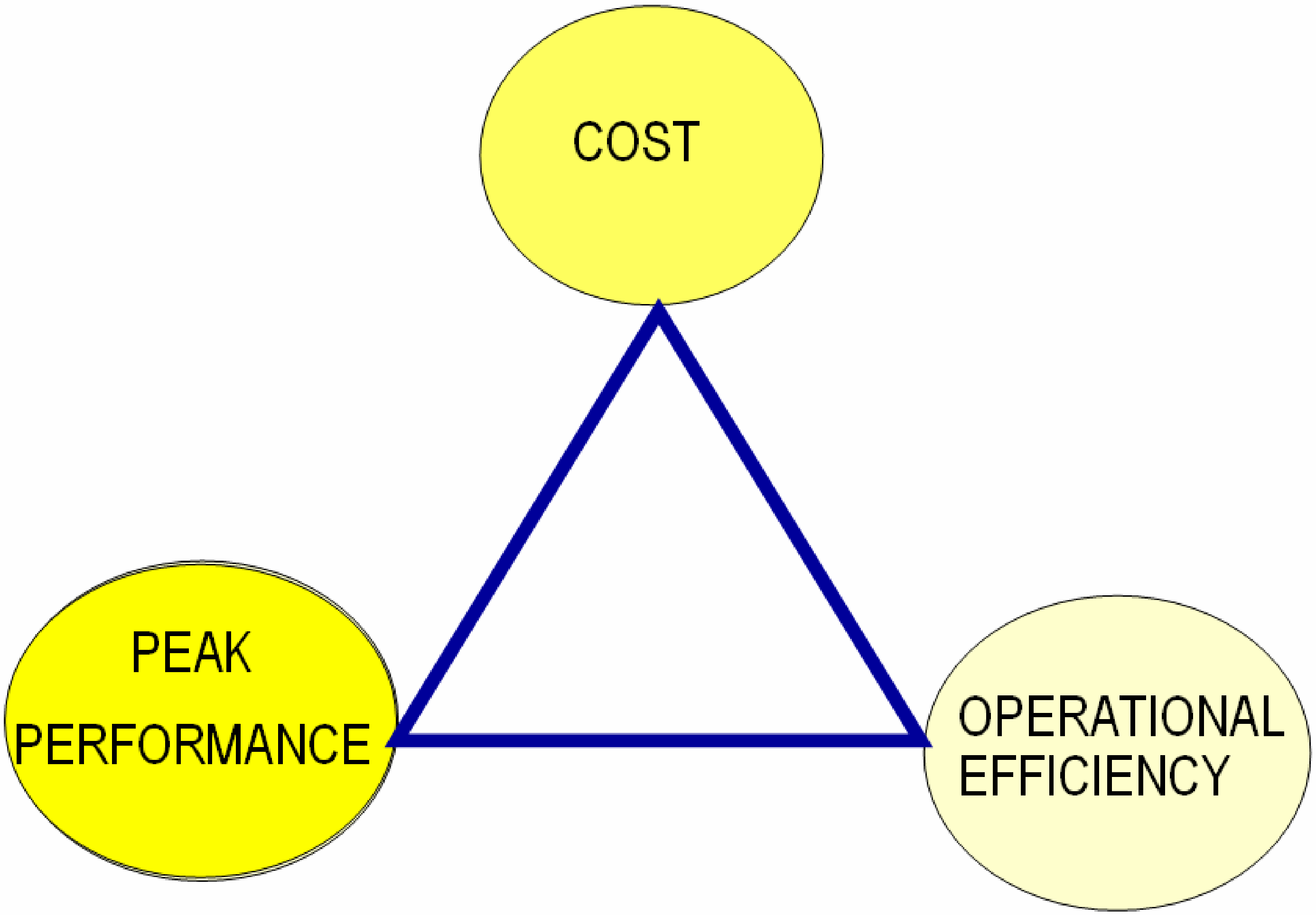




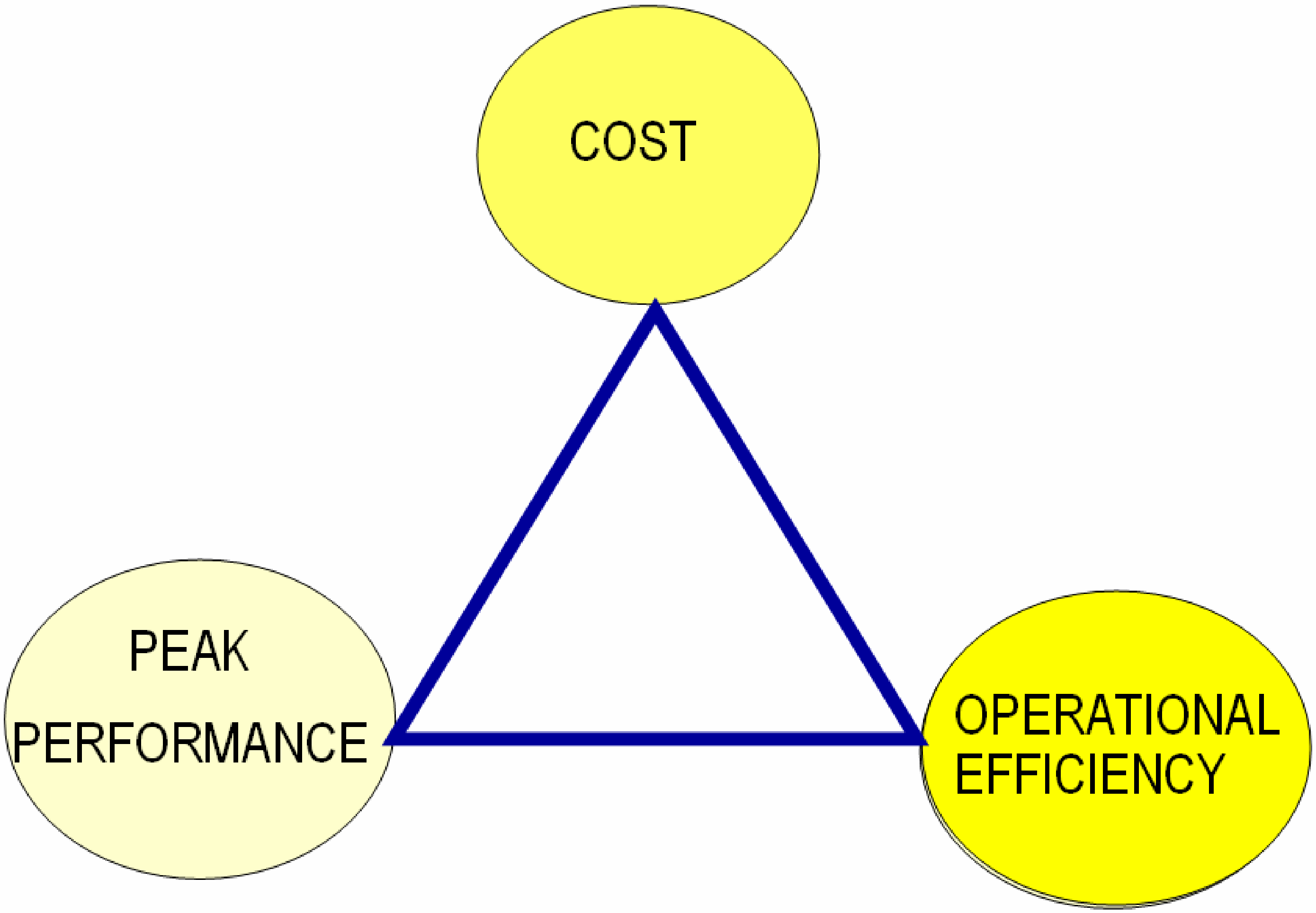
Answer (for NSLS-II assumptions): Don't accept more than 10% reduction in performance,

Don't expect substantial increase in schedule safety by accepting running with reduced performance

Accelerator Design



Accelerator Design



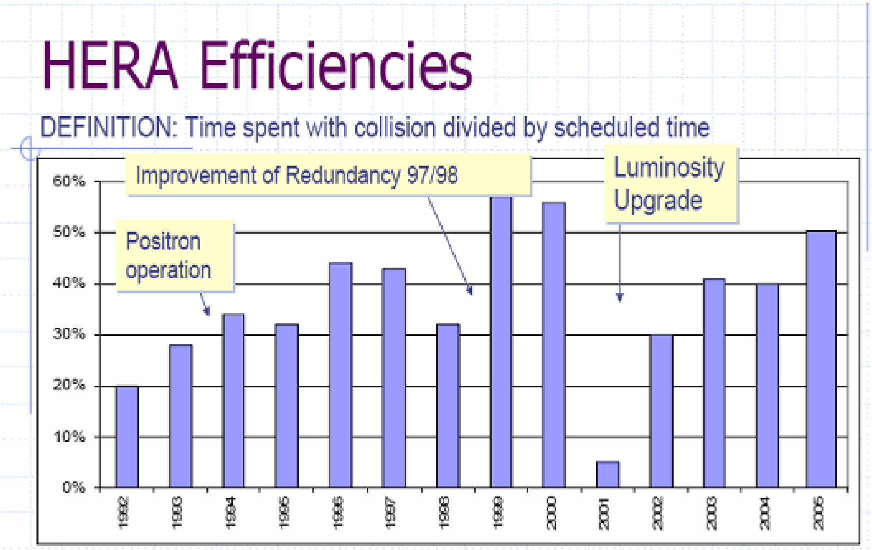
Design for High Availability

Considerations:

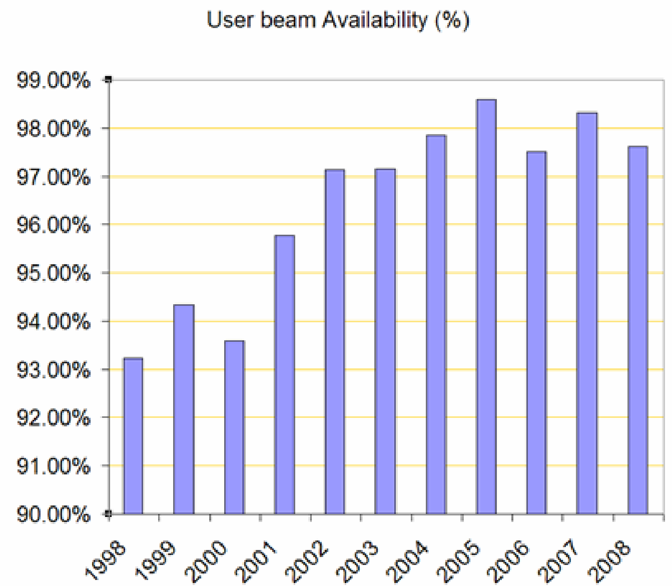
- Overall Complexity
- Unavoidable Weakness
- Subsystem Architecture
- Fail Safe Design
- Overrated Design
- Environmental Impact
- Error Prone Solutions
- Build-in Redundancy and Hot Spares
- Built-in Diagnostics
- Repair and Maintenance Friendly Design

Achieved Availabilities

Colliders, Example HERA



Synchrotron Light Sources, Example APS



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

HERA 12000 m accelerator, 600 cells, 3 h fill cycle

APS 800m accelerator 20 cells, 0.5h fill cycle

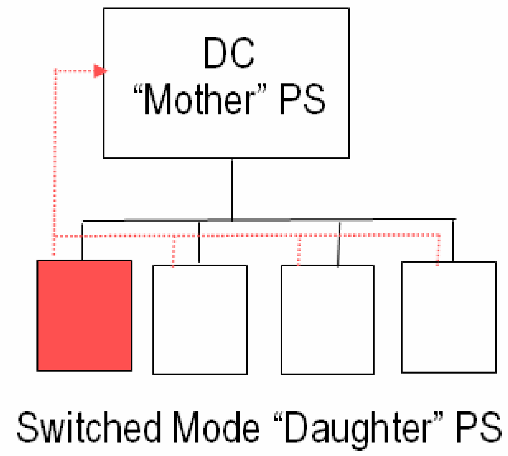
➔ Comparable component reliability leads to different availability

Subsystem Architecture

Monolithic versus Modular Design ➔

Case to Case Decision

Avoid coupling of the two types of architecture

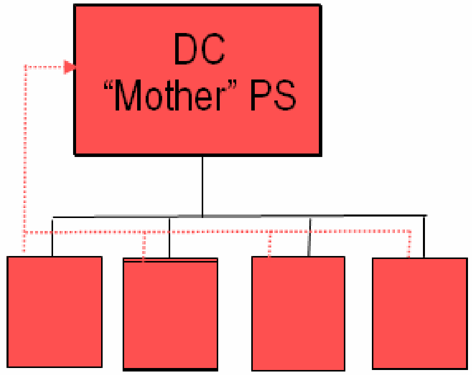


Subsystem Architecture

Monolithic versus Modular Design →

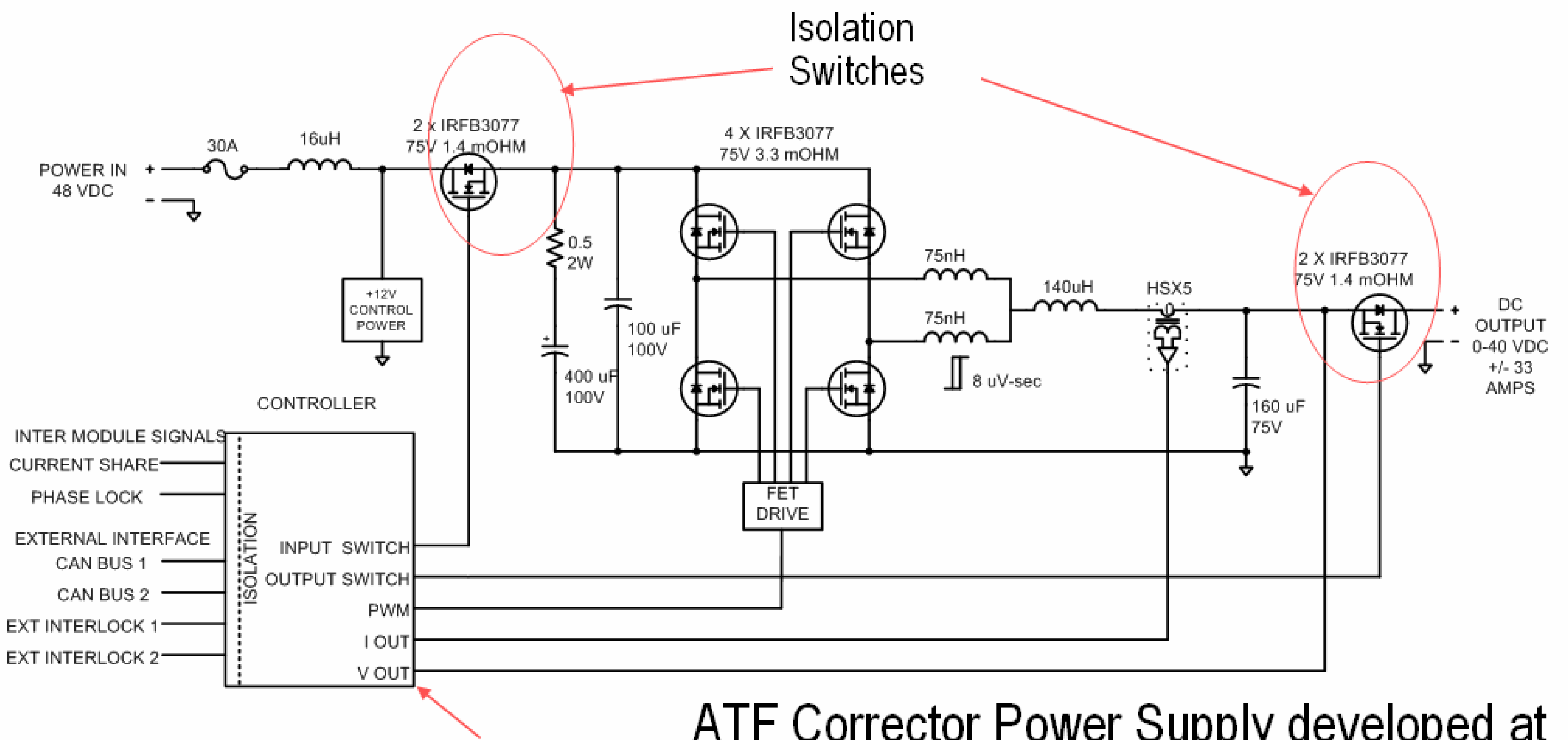
Case to Case Decision

Avoid coupling of the two types of architecture



Switched Mode "Daughter" PS

High Reliability Switched Mode PS

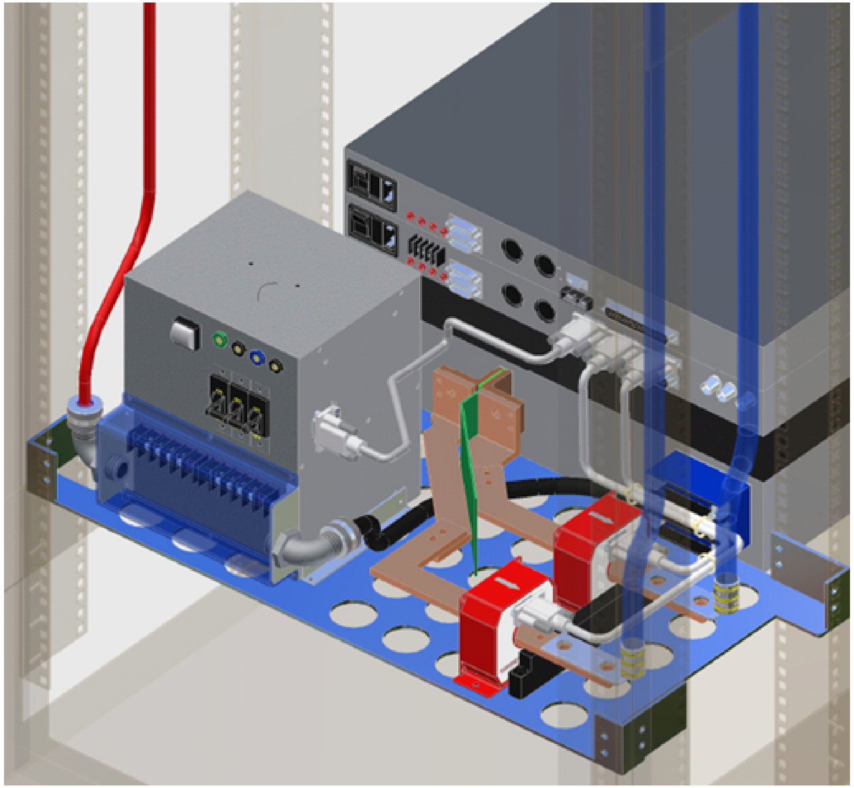


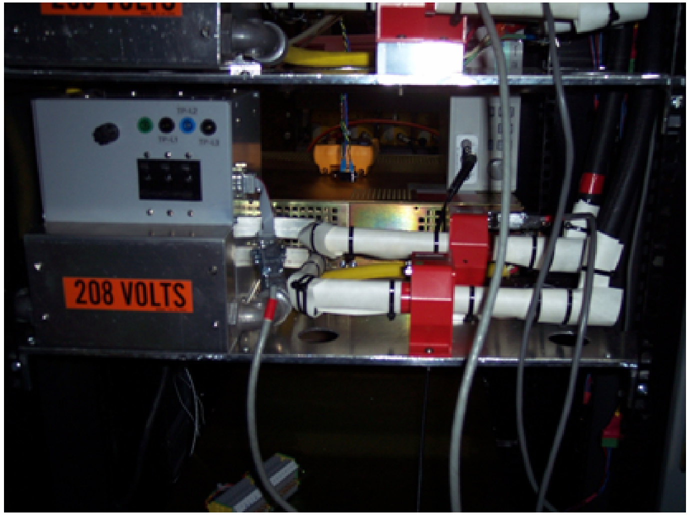
Smart Redundant Controller

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



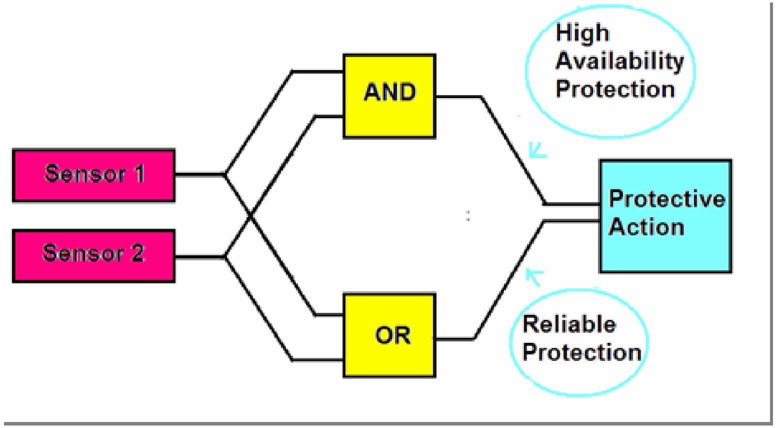


Courtesy G. Ganetis, BNL

Smart Fail Safe Design

Fail Safe Design = Good Engineering Practice

<u>However:</u> System Trips are an important factor in operational efficiency esp for accelerator with long injectin 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

Thermal Cycling   Thermal Stress

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

Temperature Failure Enhancement Factor for Electronics

Difficult to optimize overrating

For magnet power supply gain in reliability varies from vendor to vendor

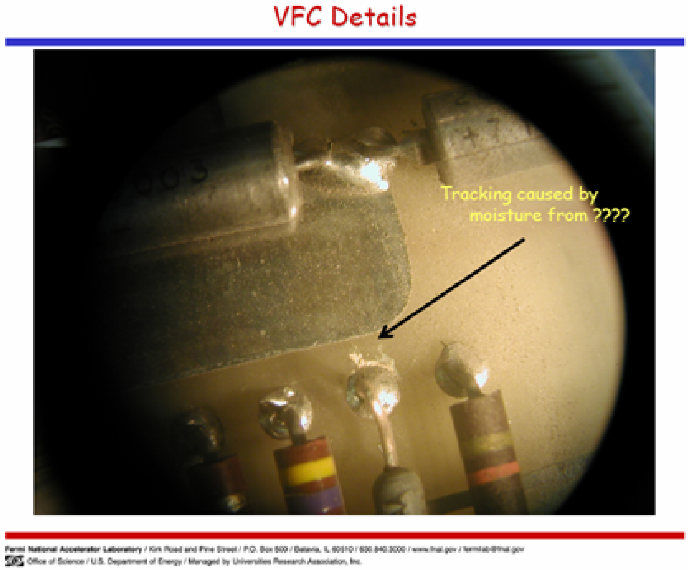
Example HERA Experience:

Beam Current @ 1996 Limited by RF Trip Rate <1996

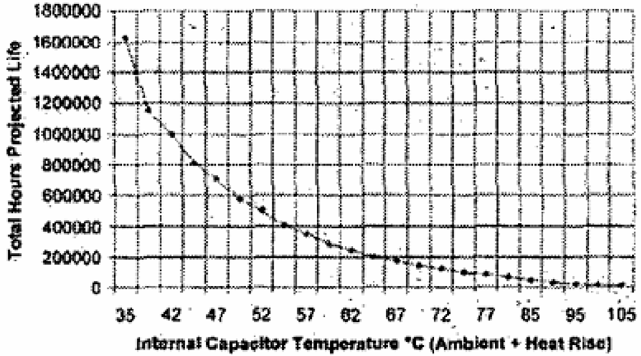
After RF power margin of ~30% was added by adding an 8th 1.5MW klystron transmitter and fixing SC RF cavity problem

➔ Beam current increased from 35mA ➔ 50mA

Environmental Impact: Dust, Humidity, Temperature

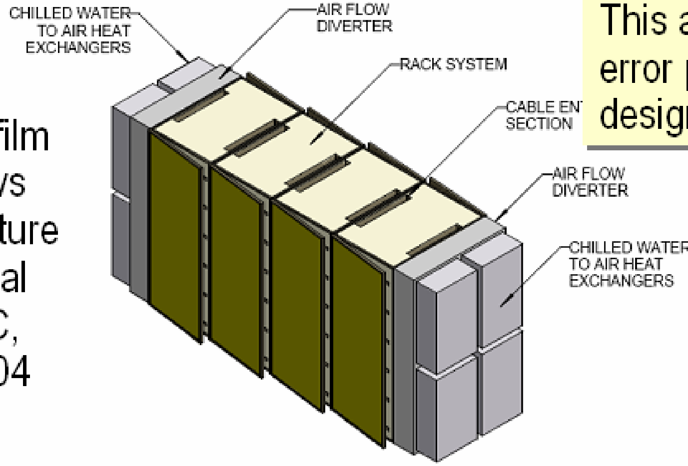


Dust causing frequent failures on TEVATRON QP electronics)copied from H. Edwards/P. Czarapata, FNAL, Groemitz Miniworkshop 2005



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

NSLS-II Electronics/PS Rack Solution



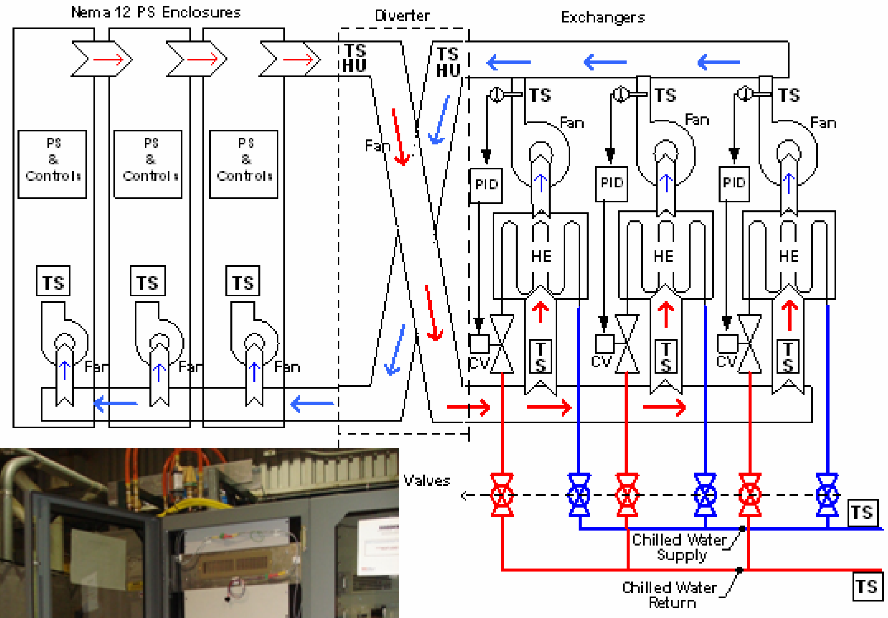
This avoids error prone design

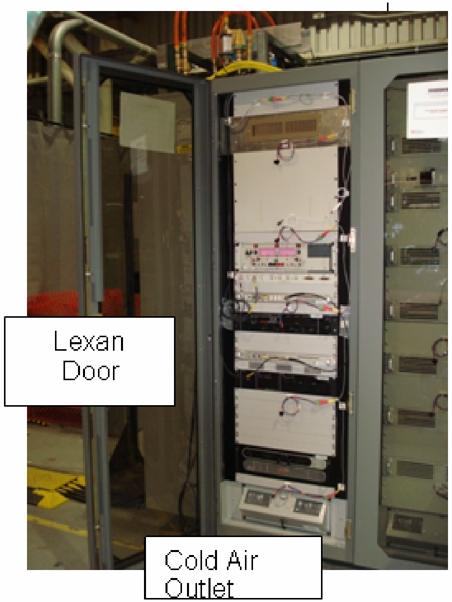
Error Prone Solutions

- Water Cooling
- Electrical Connectors

  Replace analog cable connections by serial digital links where ever feasible (gain reliability, save costs)

Schematics of the NSLS-II Air-Cooled Rack System

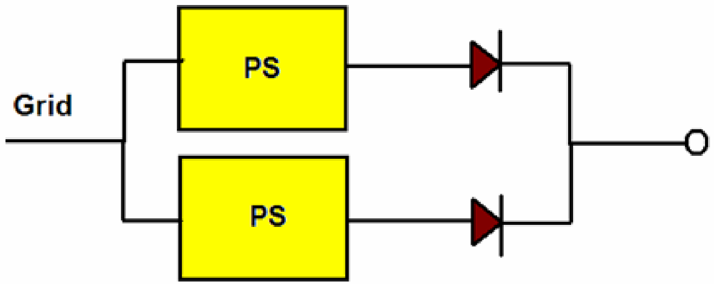




Build-in Redundancy and Hot Spares

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

➔ "Hot Swap" Capability helps



Example:

High Availability Power Supply Design Grömitz, 02.12.05

H.-J. Eckoldt

TESLA/XFEL

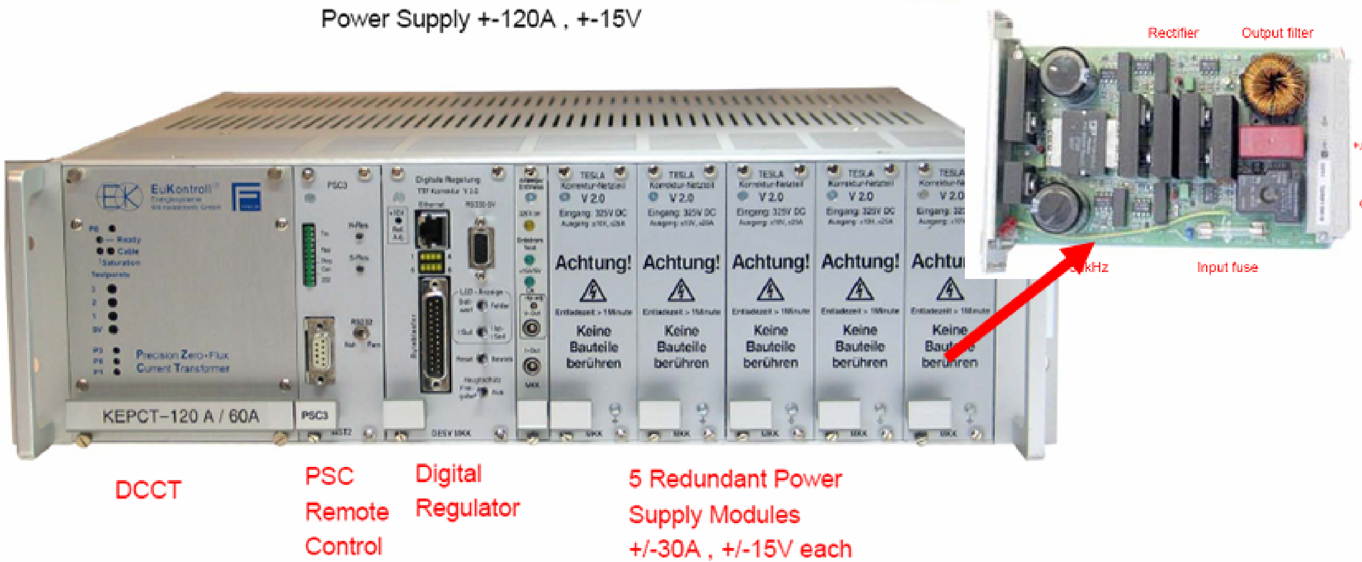
Switched Mode

PS with Hot

Spare Redundant

Power Modules

Power Supply +-120A , +-15V



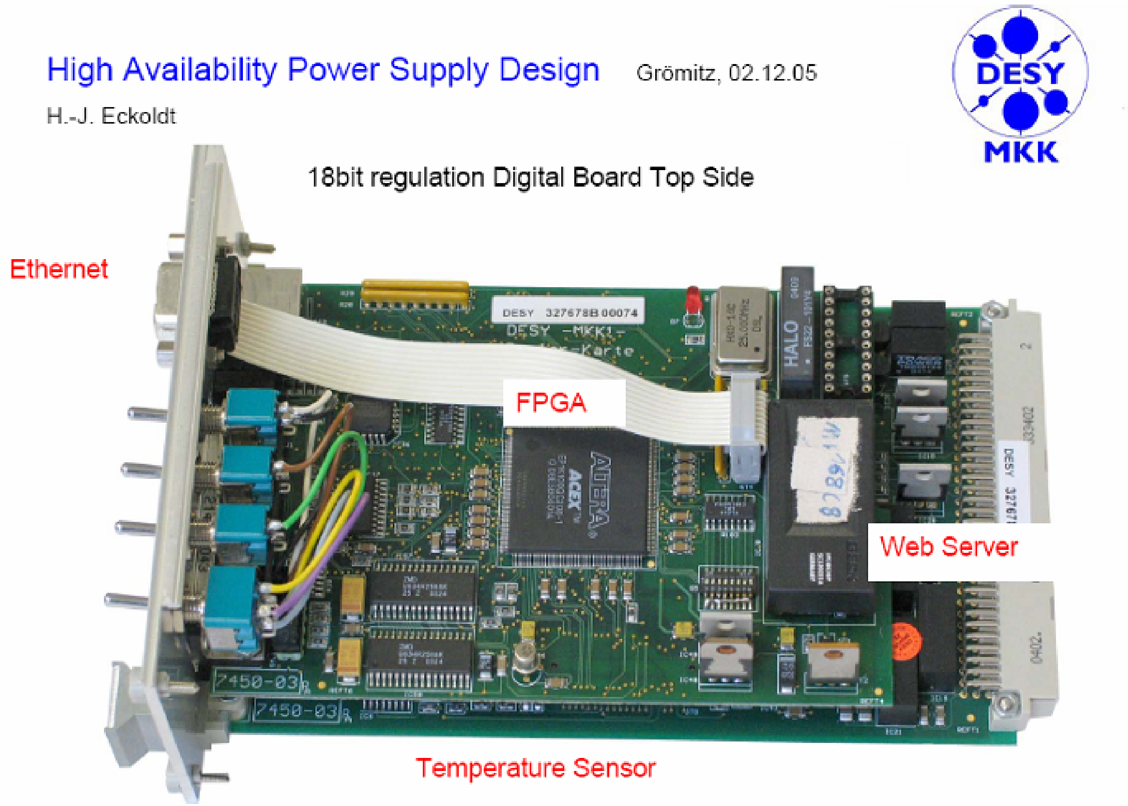
Built-in Diagnostics

Built-in diagnostics

- long term monitoring and onset of failure detection

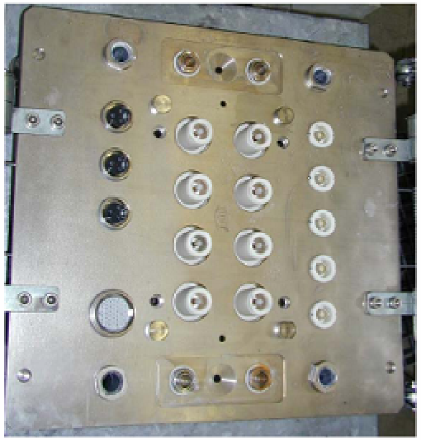
- trouble shooting

-Cross correlations with external factors



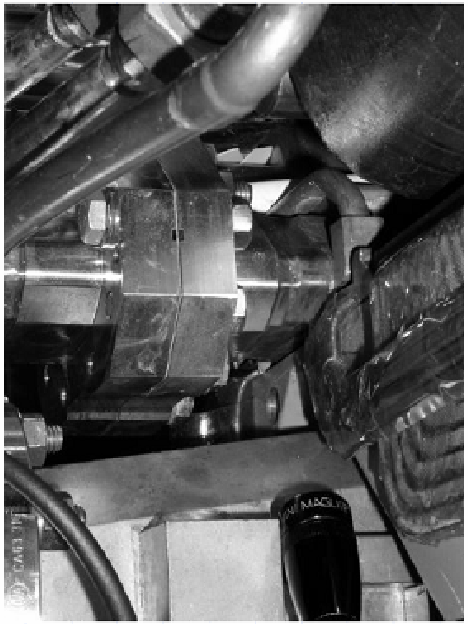
Repair and Maintenance Friendly Design

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



Good **accessibility** of components important to minimize trouble shooting and repair

However, is often compromised



HIGH AVAILABILITY OPERATIONS

Continuous Improvement

Data Logging (time stamped, well accessible on/off site)

Data Analysis Tools and Cross Correlatio

(*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

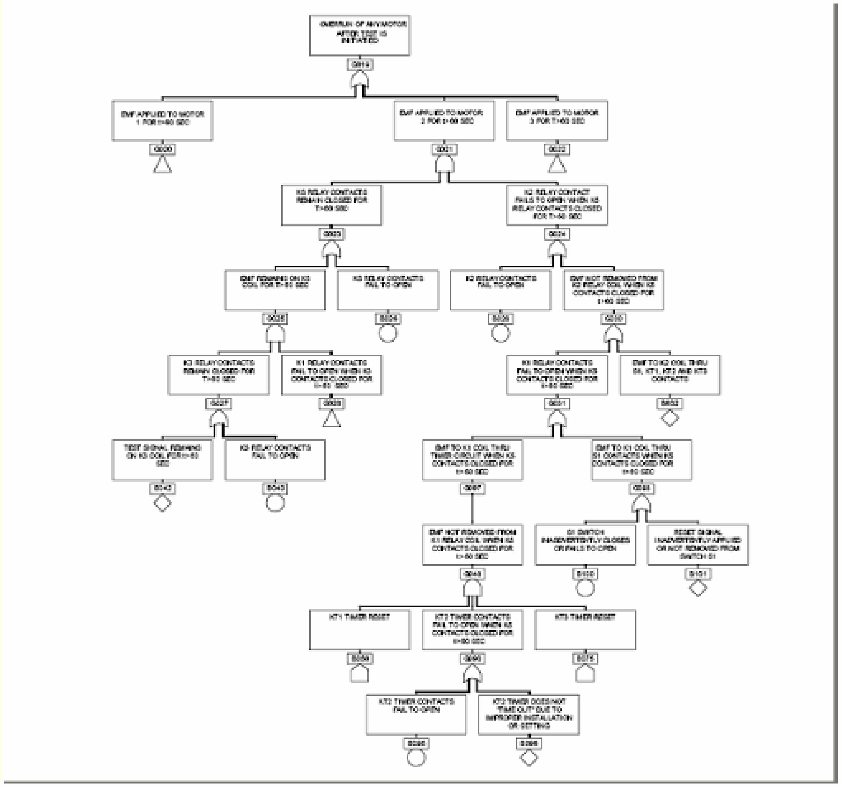


Illustration of Root Cause Analysis using Fault Tree Analysis

http://www.hq.nasa.gov/office/codeq/doctree/fthb.pdf

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:
  - Cleary 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

Was used successful to improve HERA PS system

Some supplies: MTBF 15000h→50000h

- **Preventive Refurbishment**

Fans, capacitors, small DC supplies

→ Fix before Fail

Residual Lifetime Prediction

$$MRL = \frac{1}{S(t)} \cdot \int_0^{\infty} dt' \, S(t+t')$$

HIGH AVAILABILITY OPERATIONS

<u>Speed Up Repair</u>

- 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

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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

ALS Reliability Information Board

Acknowledgements

I gratefully acknowledge many discussions and many hours spent together in trouble shooting, data analysis, and working out improvement plans:

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Tom Himel, SLAC,

Nan Phinney SLAC,

Eric Johnson, BNL

George Ganetis, BNL

Backup Slides

Basic Relationships

Probability for component failure within a time interval Δt, λ = failure rate

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

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

(probability density function)

$$f_k = (1-p)^{k-1} \cdot p$$

➔ **M**ean **T**ime **B**etween **F**ailure

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

System with **N** identical components:

Probability for n failures in Δt

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

Expectation Value for n

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

➔ **System M**ean **T**ime **B**etween **F**ailure

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

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

Availability

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

$$MTBF = \frac{t - \langle n \rangle \cdot MTTR}{\langle n \rangle} \Rightarrow \langle n \rangle = \frac{t}{MTBF + MTTR}$$

$$A = 1 - \frac{MTTR}{MTTR + MTBF}$$

Non-Constant Failure Hazard

$$\lambda_i \neq const. \qquad \rightarrow$$

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

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

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

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

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