International Workshop on Small-Scale Satellite Testing Standardization Quick Summary

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Overview

60 participants (23 from abroad)

What we talked

- Hot topic within ISO/SC14 (space system) about
  - Safety, Debris mitigation, Reliability of small satellites
- Needs of small satellite top-level standard to define
  - What is small satellite? (small/micro/mini/nano/pico/femto/--)
  - Among the standards made for traditional satellites,
    - Standards to be adapted as it is
    - Standards to be tailored
    - Standards to be developed
  - Some actions will be taken toward ISO/SC14 plenary meeting at Tokyo in May 2014
- Discussion on working draft ver.3 of "Space systems - Design Qualification and Acceptance Tests of Small-scale Satellite and Units Seeking Low-cost and Fast-Delivery"
- Working draft and proceeding will be available from
  - http://cent.ele.kyutech.ac.jp/nets_web/nets_web.html
    - Or Google "nanosatellite environment"
- Give me your business card if you want to join the activity

Reliability Growth of Small-scale Satellites through Testing: Monte Carlo Simulation

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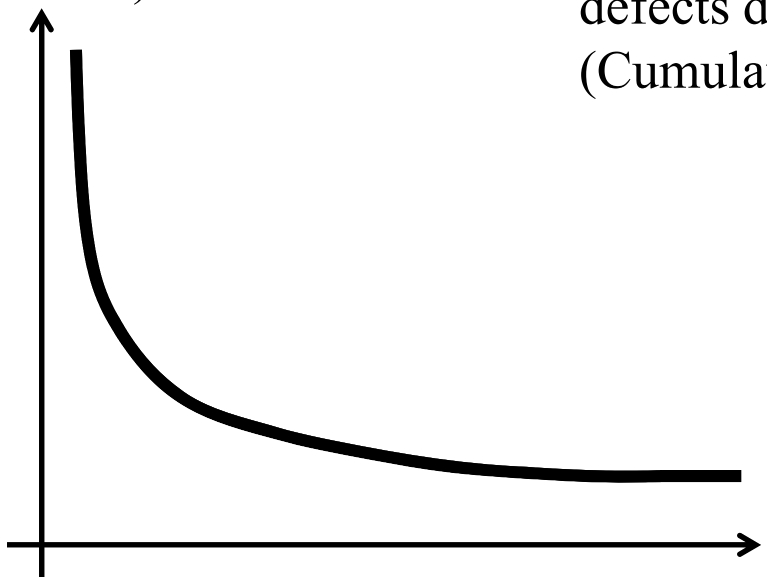
Basic Questions

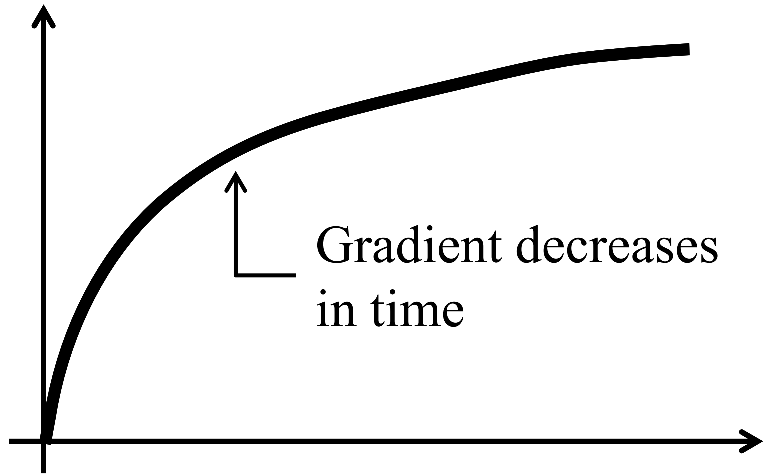
Why do we test?

How far should we do test?

Reliability Growth Due to Testing

- During the process of testing, defects are found. Modifications are made to design, manufacturing, material etc.
- As a result, the defect detection rate during the test decreases



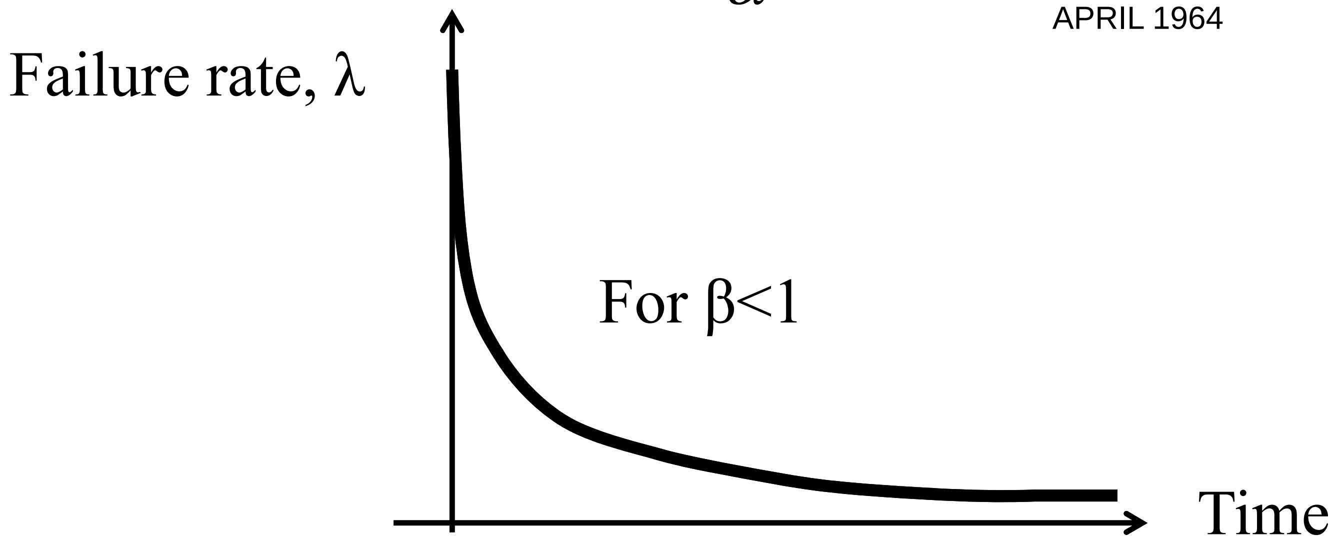


Reliability growth and Weibull distribution

- According to Duane, the fault rate has the following time dependence in the process of reliability growth

$$\lambda(t) = \frac{\beta}{\alpha^{\beta}} t^{\beta-1}$$

J. T. DUANE, "LEARNING CURVE APPROACH TO RELIABILITY MONITORING", IEEE TRANSACTIONS ON AEROSPACE, APRIL 1964

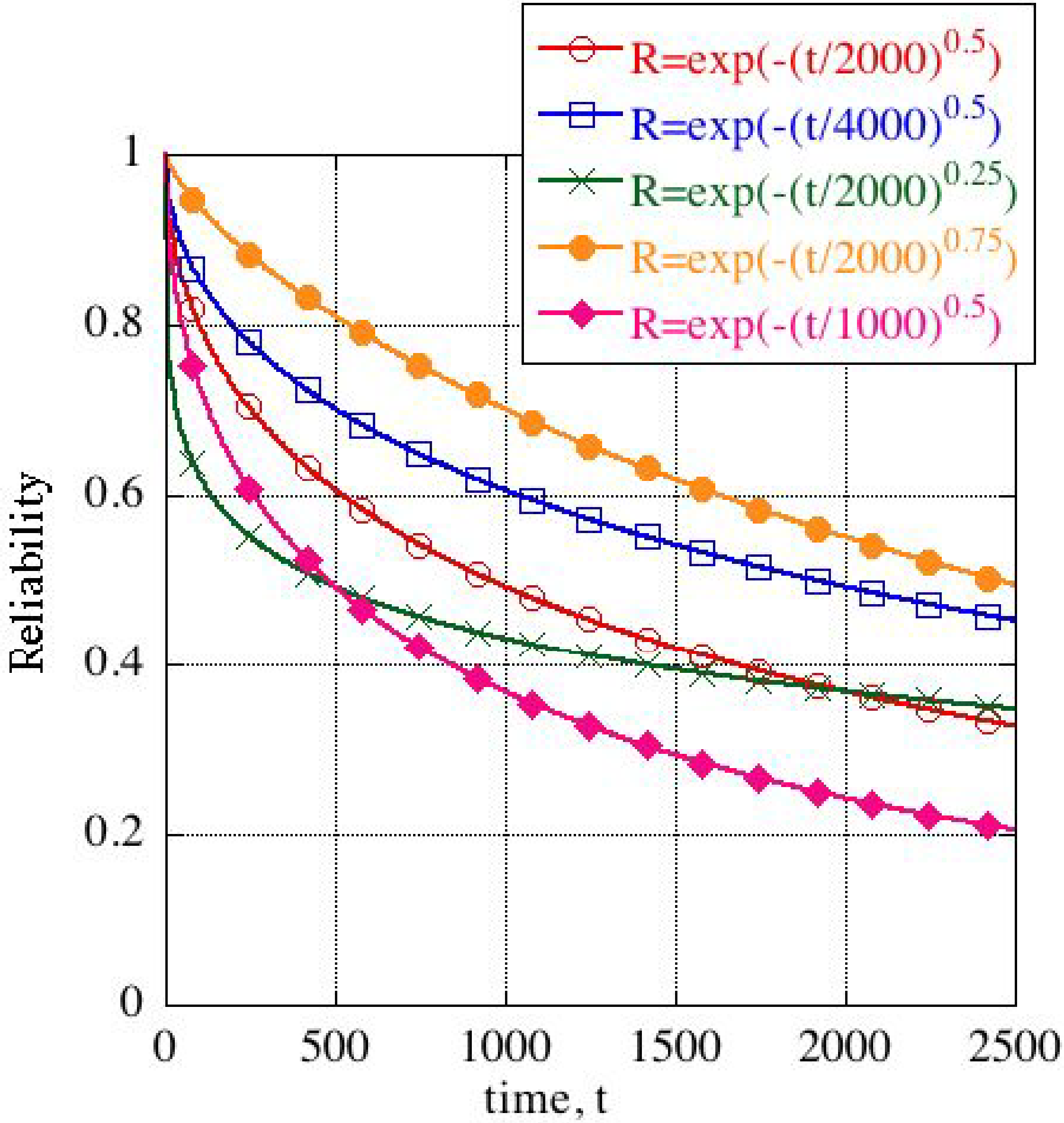


- Probability of no failure from time zero to time t is given by the following (Poisson process)

$$R(t) = \exp\left(-\int_0^t \lambda(t')\,dt' \right) = \exp\left(-\left(\frac{t}{\alpha} \right)^{\beta} \right)$$

Weibull distribution

Weibull distribution

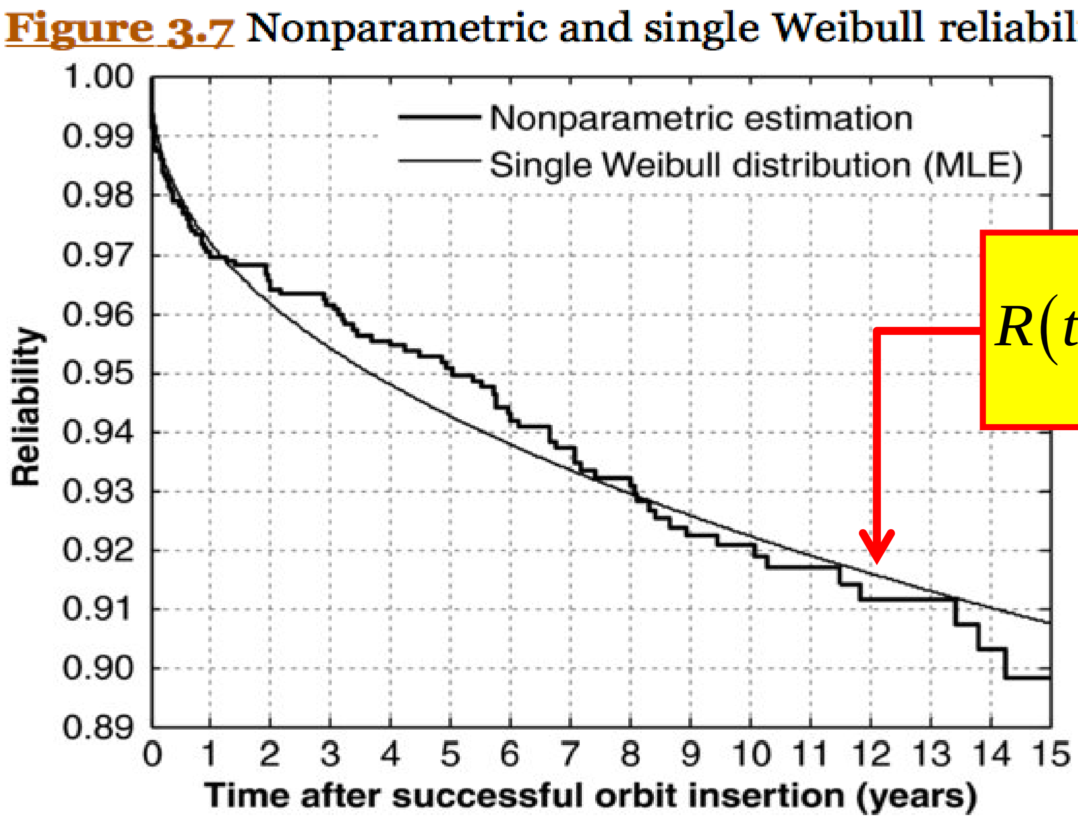


$$R(t) = \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$$

R(t): reliability
α: scale parameter
β: shape parameter

Reliability in orbit

- According to Saleh et al., reliability of satellite can be approximated by Weibull distribution



$$R(t) = \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$$

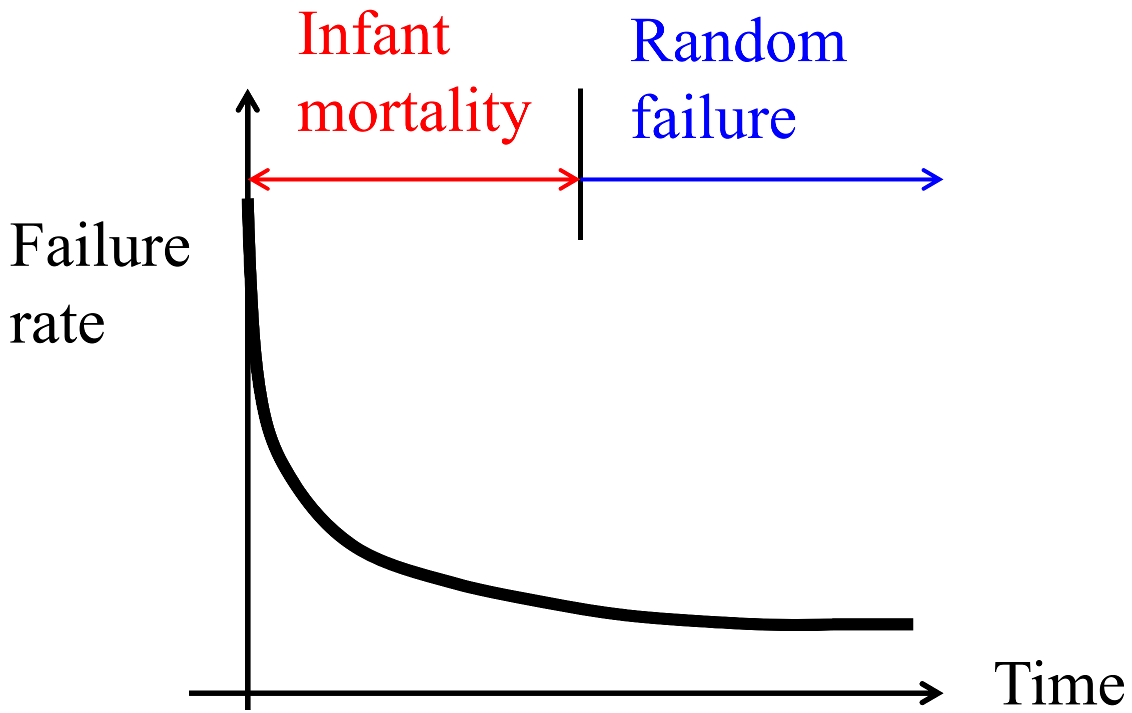
R(t): reliability
α: scale parameter
β: shape parameter

Saleh, J. H., and Caste J. F., Spacecraft Reliability and Multi-State Failures, Wiley, 2011

Operation in orbit can be regarded as continuation of testing without opportunity of modification.

Purpose of this study

- Failure of small-scale satellites governed by infant mortality
- Testing is not enough to improve the reliability up to a point where the random failure of individual subsystem/unit/parts dominates

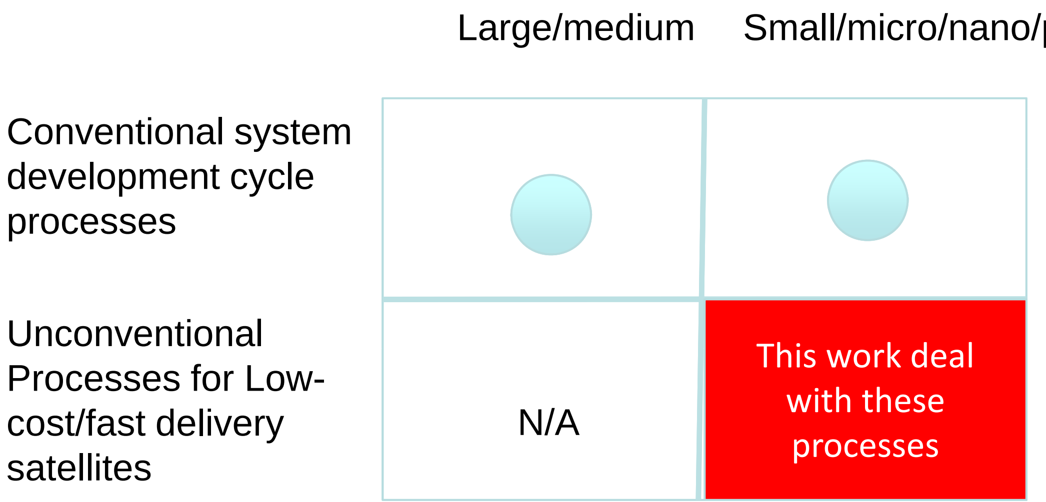


PURPOSE

- How is the reliability improved by testing?
- Testing strategy to optimize the schedule (i.e. cost) against the reliability

“Small-scale” satellite

- The small size of the satellite is a mere result of seeking the low-cost and fast delivery
- This work is applied to the satellites whose development methods are different from the conventional satellites where the reliability often precedes the cost and schedule
- Meaningless to limit the scope based on specific categories of satellite size such as micro-, nano- and pico-
  - Definitions are not yet agreed internationally
- A word of “small-scale” is used throughout this work



See the discussion of small-scale satellite testing standard

Reliability growth simulation

- Assume satellite is made of N subsystem
- Tests are done in two steps (QT and AT)
- Each subsystem has the following latent defect rate

$$\lambda(t) = \frac{\beta_{DQ}}{\alpha_{DQ}^{\beta}} t^{\beta_{DQ}-1} + \lambda_r \qquad \text{QT}$$

$$\lambda(t) = \frac{\beta_{DA}}{\alpha_{DA}^{\beta}} t^{\beta_{DA}-1} + \frac{\beta_W}{\alpha_W^{\beta}} t^{\beta_W-1} + \lambda_r \qquad \text{AT}$$

- α_D, β_D : failure due to design
  - Q: during QT、A: during AT
- α_W, β_W: failure due to workmanship
- λ_r: random failure
- Probability of detecting a defect during the testing of time T

$$R(T) = \exp\left(-\int_0^T \lambda(t')\,dt' \right)$$

Reliability growth simulation

- Whether we find a defect or not is determined by a random number
- Once a defect is found, depending on whether it is due to design, workmanship or random failure, QT or AT are redone
- As the defect is corrected, we modify α and ß
  - We made α bigger after each modification
- Continue simulation until we finish AT without detecting defect
- Reliability after orbit insertion (probability of no failure) of subsystem i is given by the following

$$R_i(t) = \exp\left(-\int_0^t \lambda(t')\,dt' \right)$$

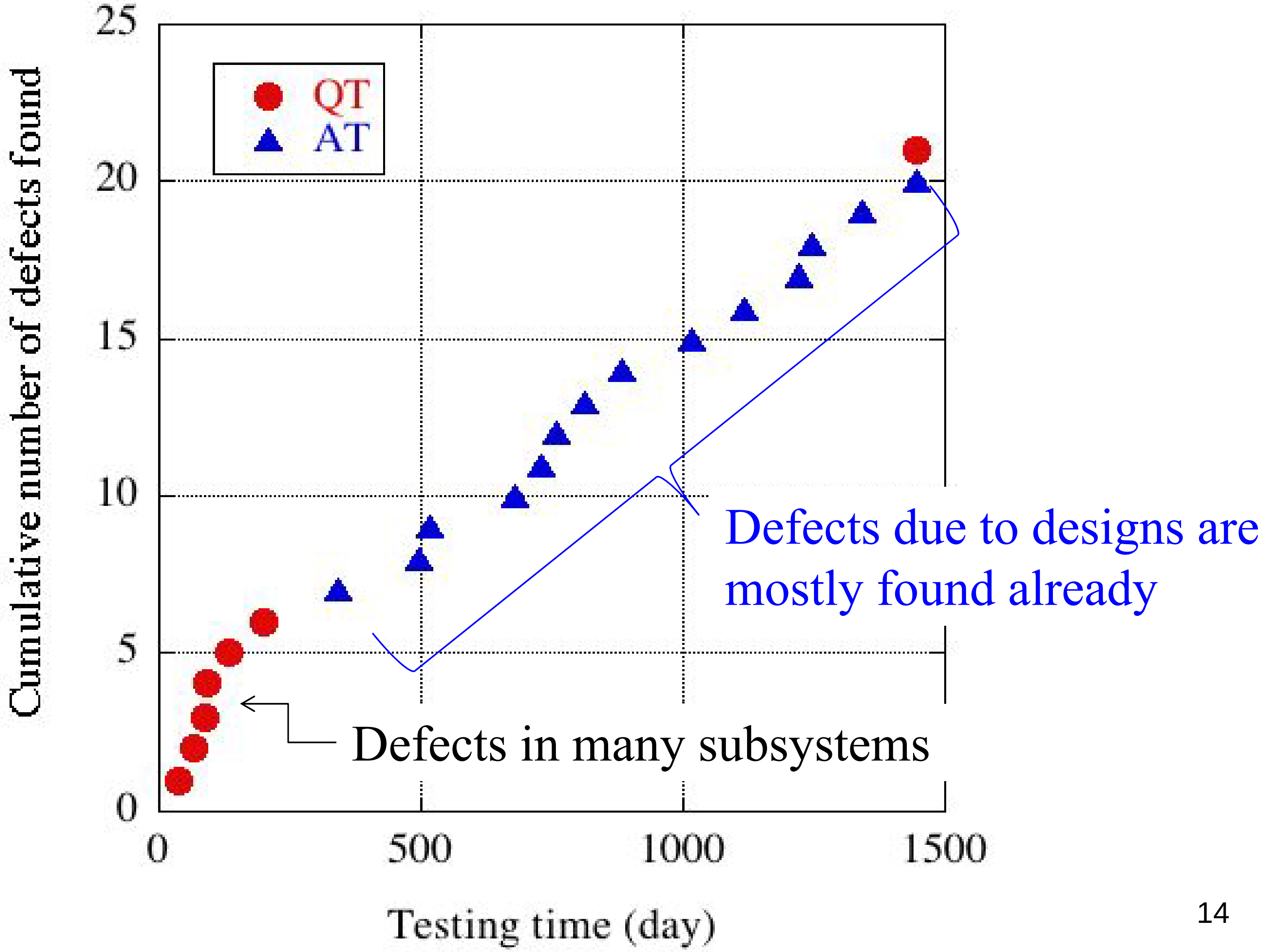
- But, λ(t) is already improved. It is given by

$$\lambda(t) = \frac{\beta_{DA}}{\alpha_{DA}^{\beta}}\left(t + t_{cD}\right)^{\beta_{DA}-1} + \frac{\beta_W}{\alpha_W^{\beta}}\left(t + t_{cW}\right)^{\beta_W-1} + \lambda_r$$

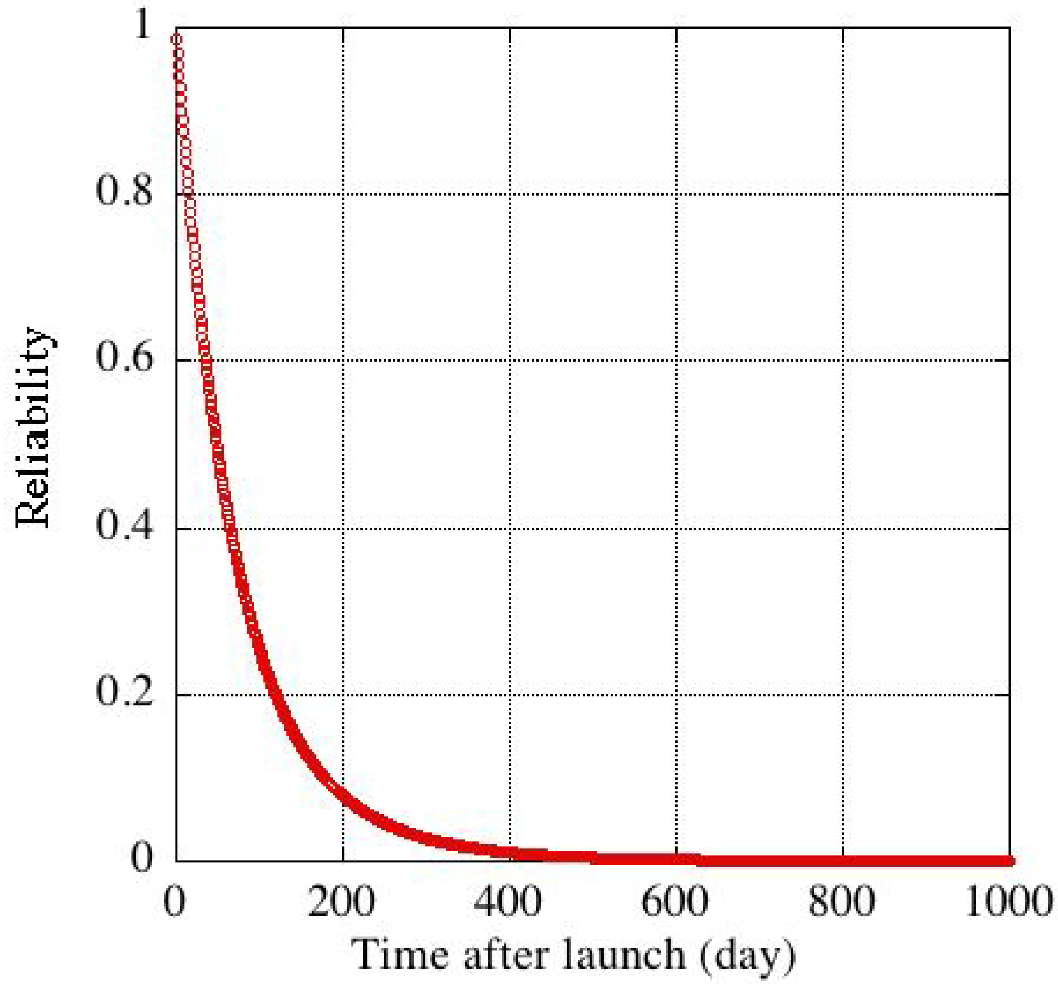
- t_{cD}, t_{cW}: The elapsed time since the last modification was made on the design or the workmanship
- The total reliability is $R(t) = R_1(t)\cdot R_2(t)\cdots R_{N-1}(t)\cdot R_N(t)$

For detail, read the paper

Simulation result example



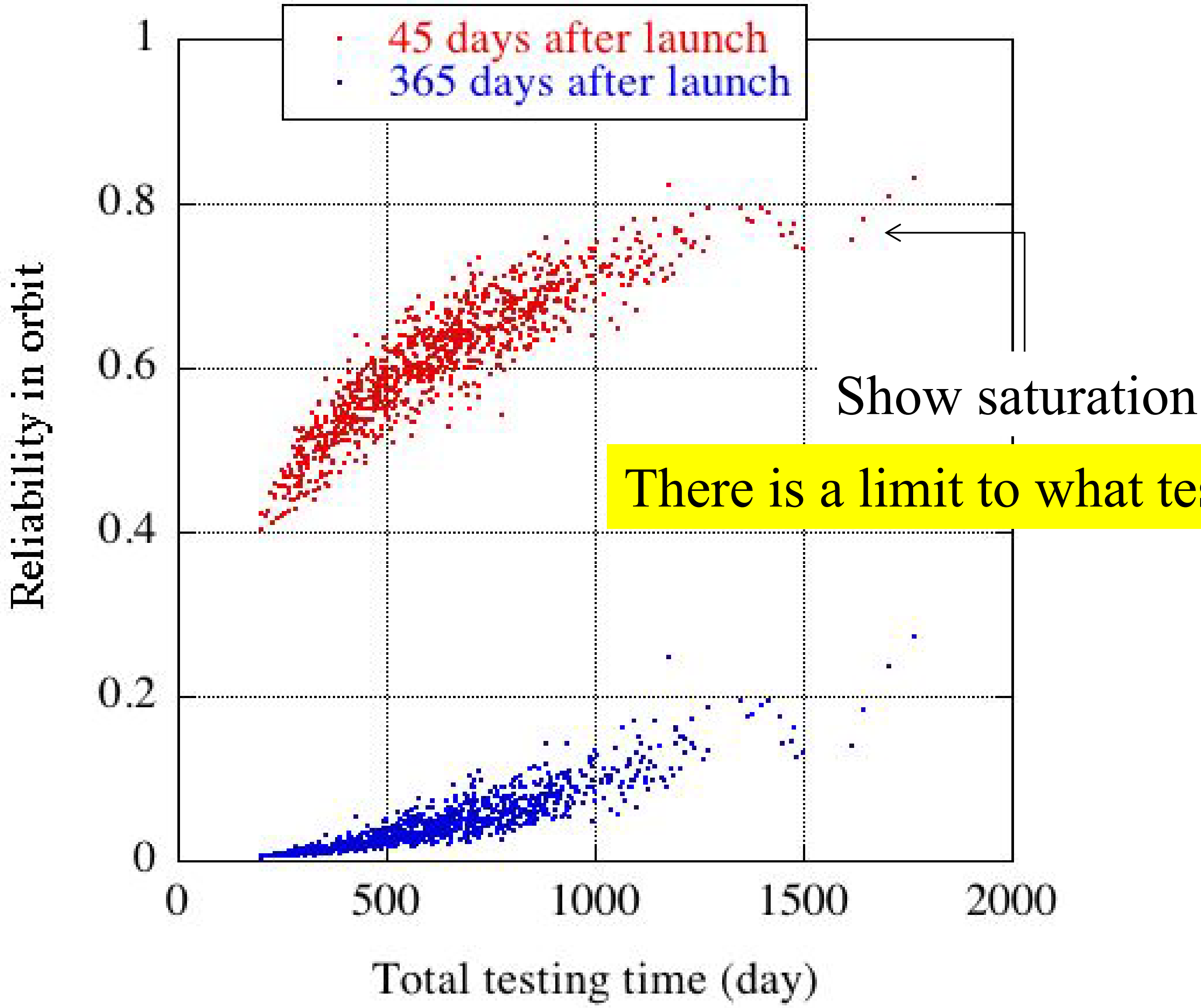
Simulation result example



Reliability after launch follows Weibull distribution

Simulation result example

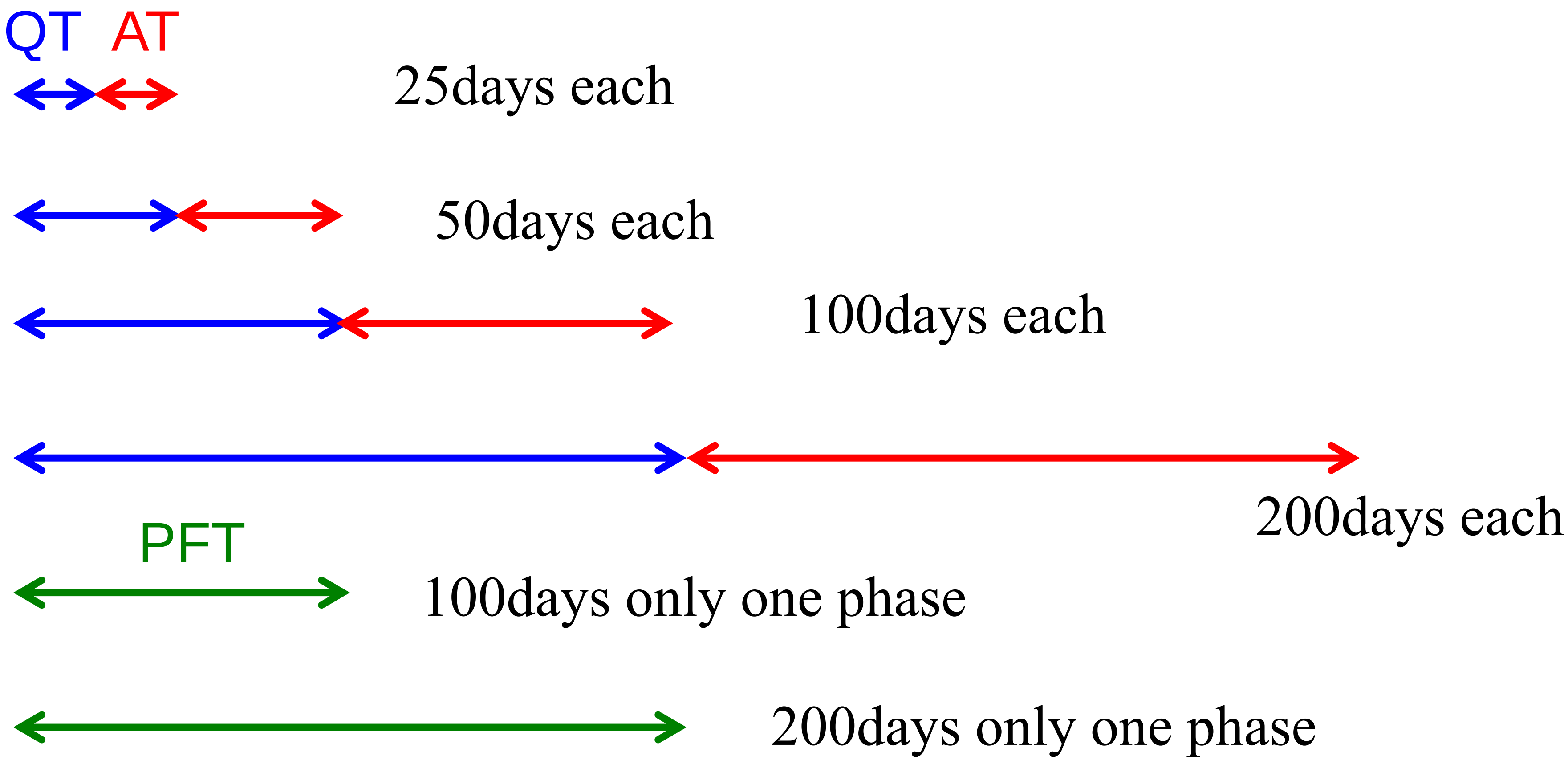
Results of 1,000 runs with different random numbers



There is a limit to what test can do!!

Simulation cases

6 cases with different unit test time, t_0



Compare the reliability at 45 days after launch

Unit test time

- Unit test time corresponds to how extensively we test
  – Example: Number of thermal cycles

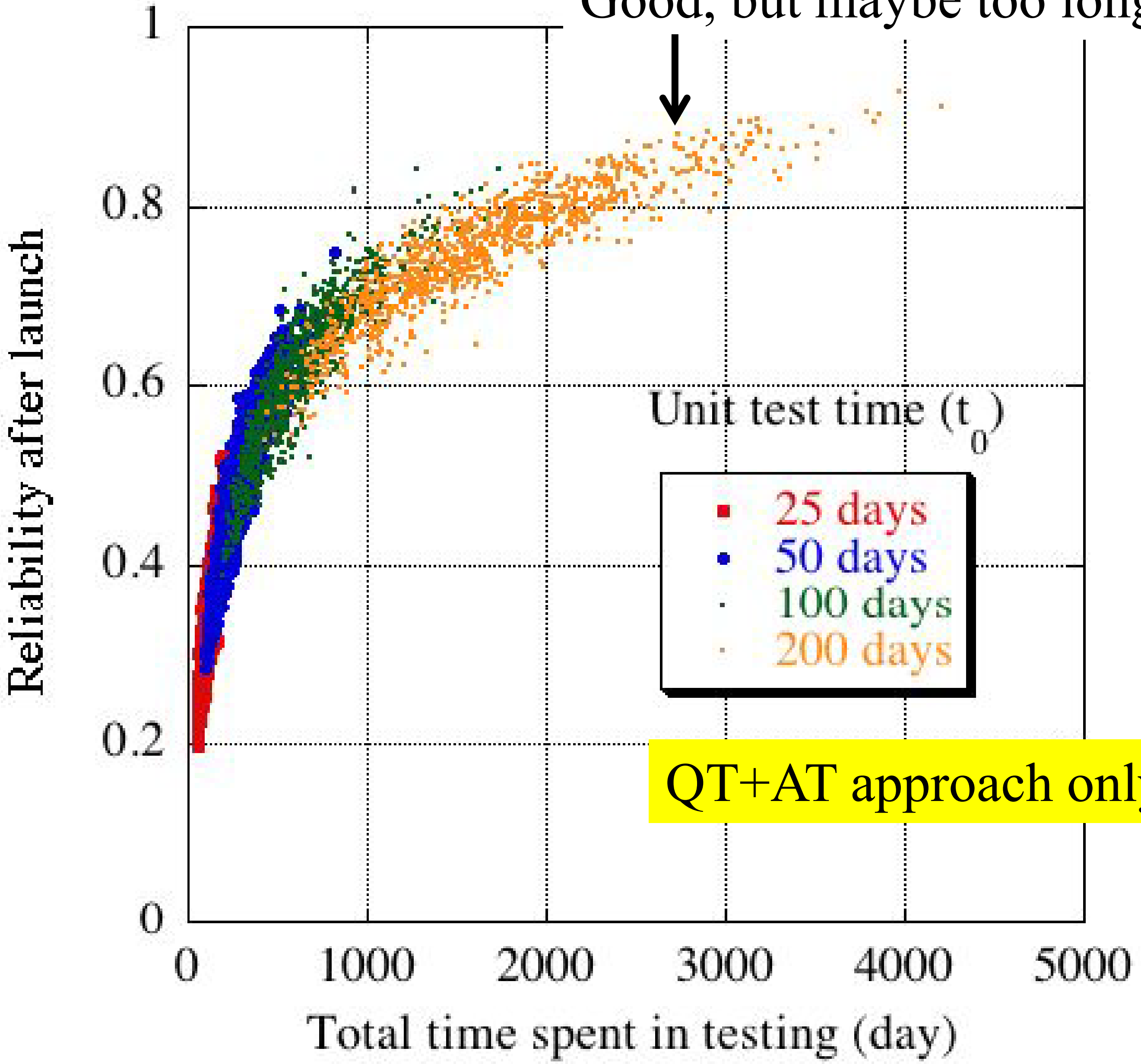
- Short test time
  – Many cycles of finding and repairing defect
  – Risk of overlooking the defects

vs

- Long test time
  – High rate of defects detection
  – Expensive

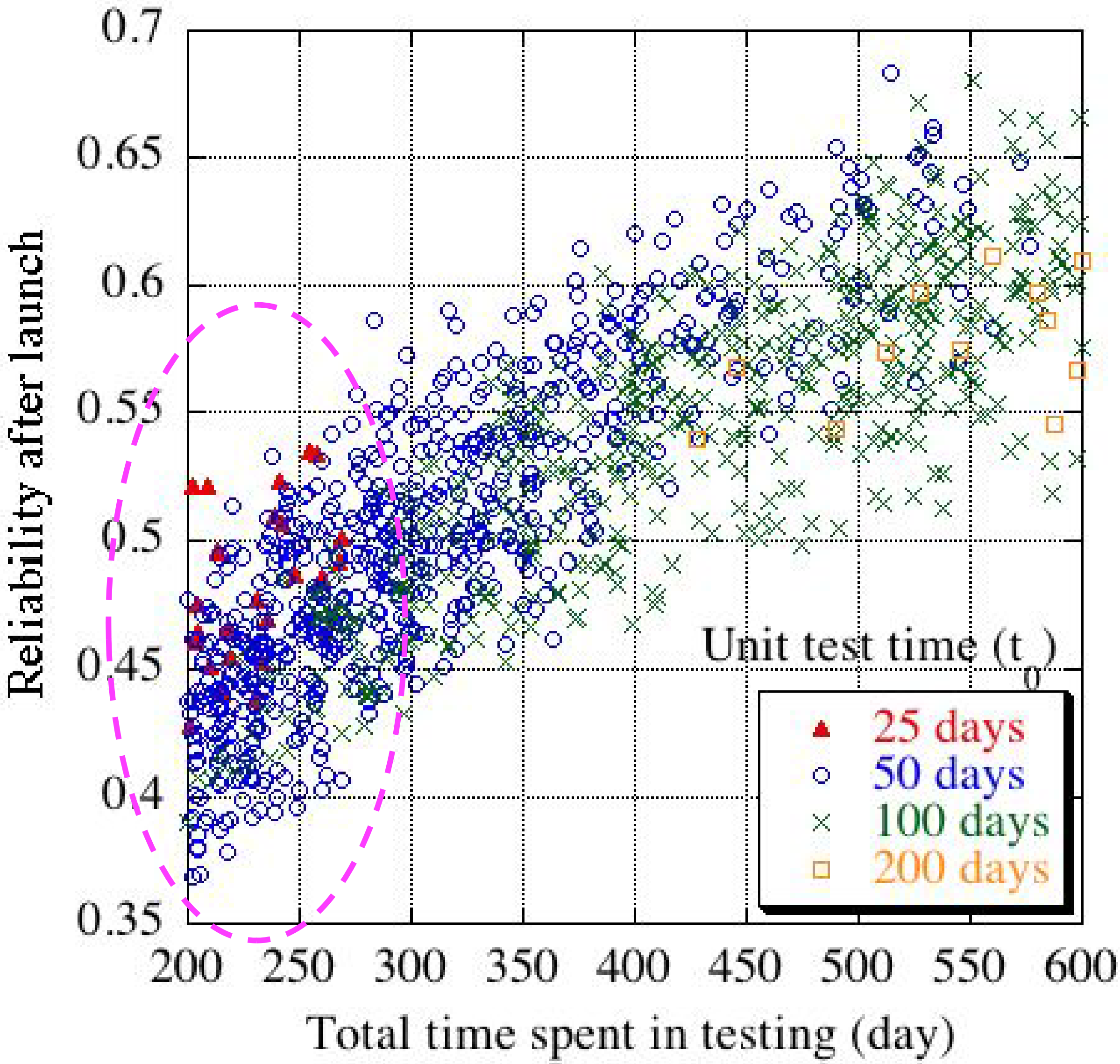
Simulation results

Good, but maybe too long (expensive)



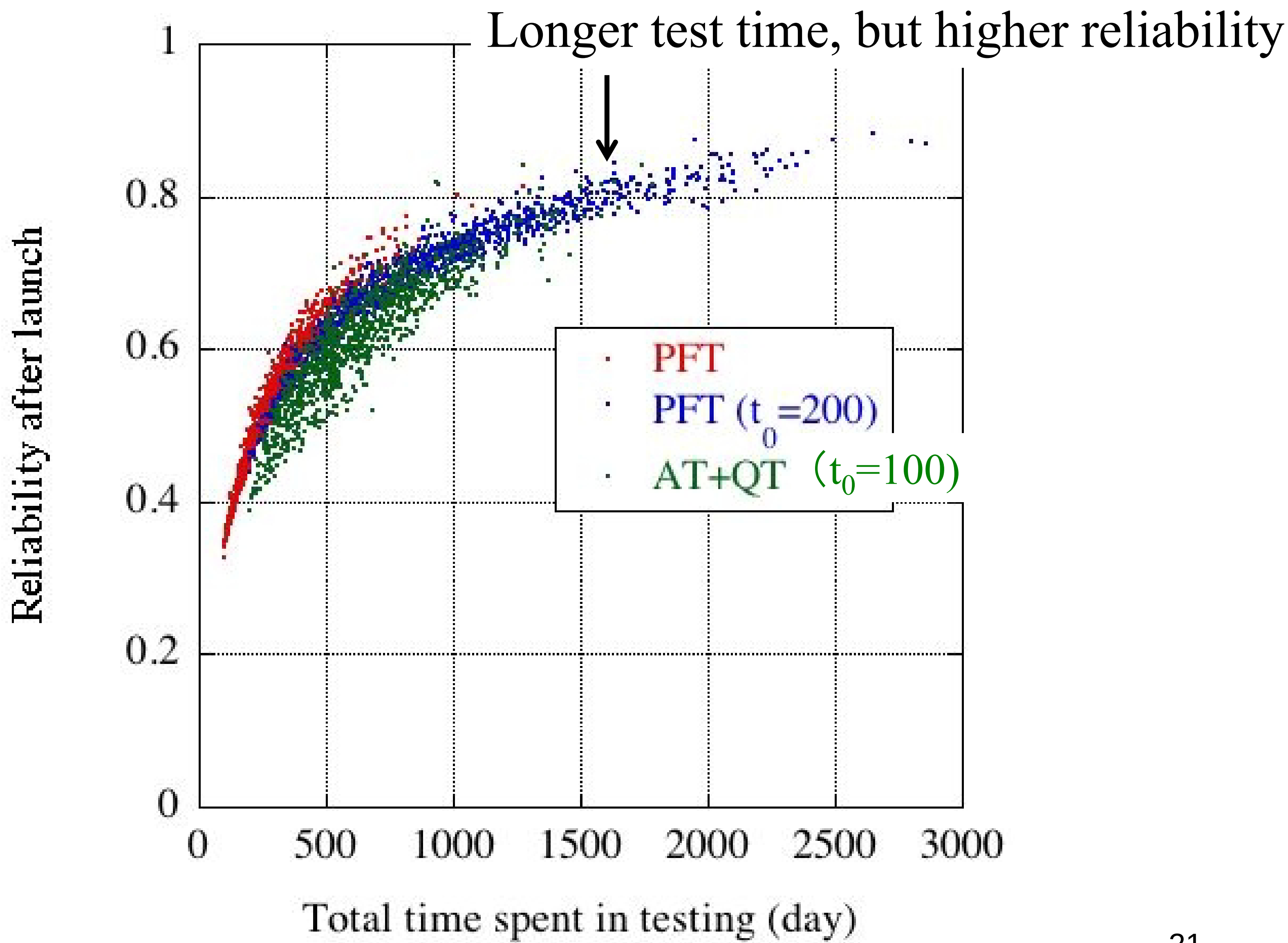
QT+AT approach only

Simulation results



Shorter unit test time gives the higher reliability at the same total test time

Simulation results

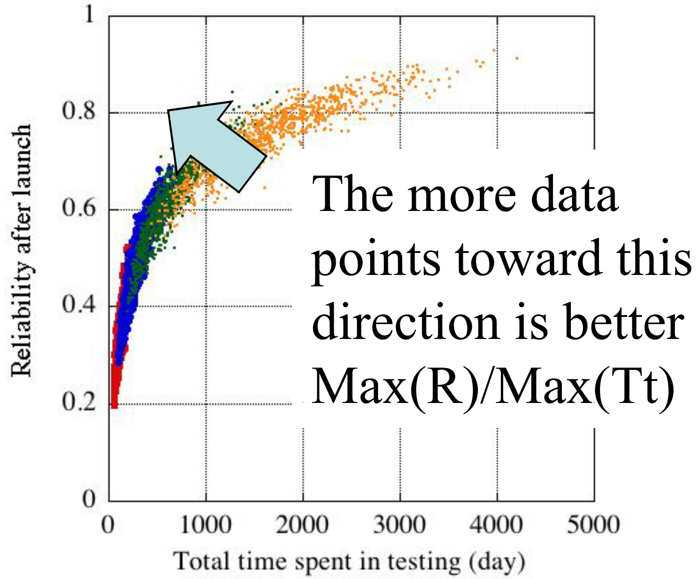


Simulation results

Strategy	Unit test time	Average R	*Average R/ Average Tt*	Max(R)/Max(T_t)
AT+QT	25	0.32	**0.00304**	**0.00221**
AT+QT	50	0.46	0.00179	0.00095
PFT	100	0.55	0.00162	0.00064
AT+QT	100	0.61	0.00096	0.00054
PFT	200	0.70	0.00073	0.00021
AT+QT	200	0.75	0.00045	0.00024

R: Reliability at 45 days after launch
T_t: Total testing time

Although the average R is the smallest, the shortest unit time has the most effective testing strategy



Conclusion

- Monte Carlo simulation of reliability growth of small-scale satellite via testing
- Repeating short cycles of testing is effective to achieve relative high reliability with less testing time
  - If we can accept the relatively low reliability

- Future works
  - Realistic numbers of α and β
  - Include cost associated with fixing each defect
  - and many mores