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The 1st International Electronic Conference on Metallurgy and Metals

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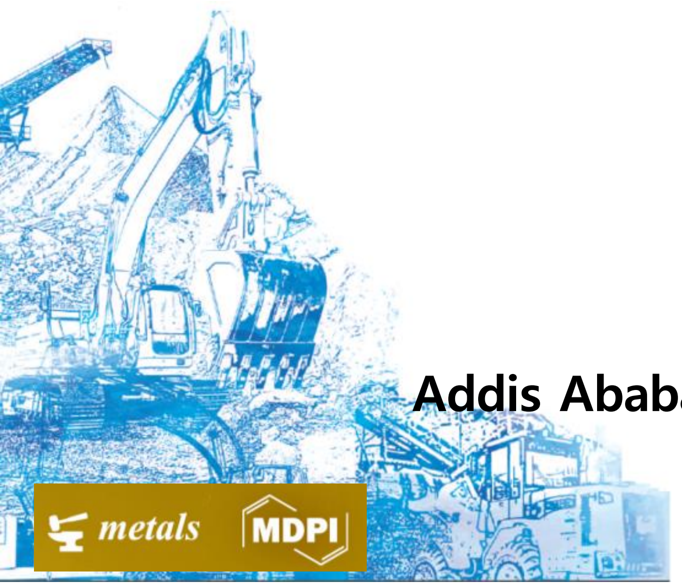
Reliability Design Of Mechanical Systems Such as Compressor Subjected To Repetitive Stresses



2021. 02. 25

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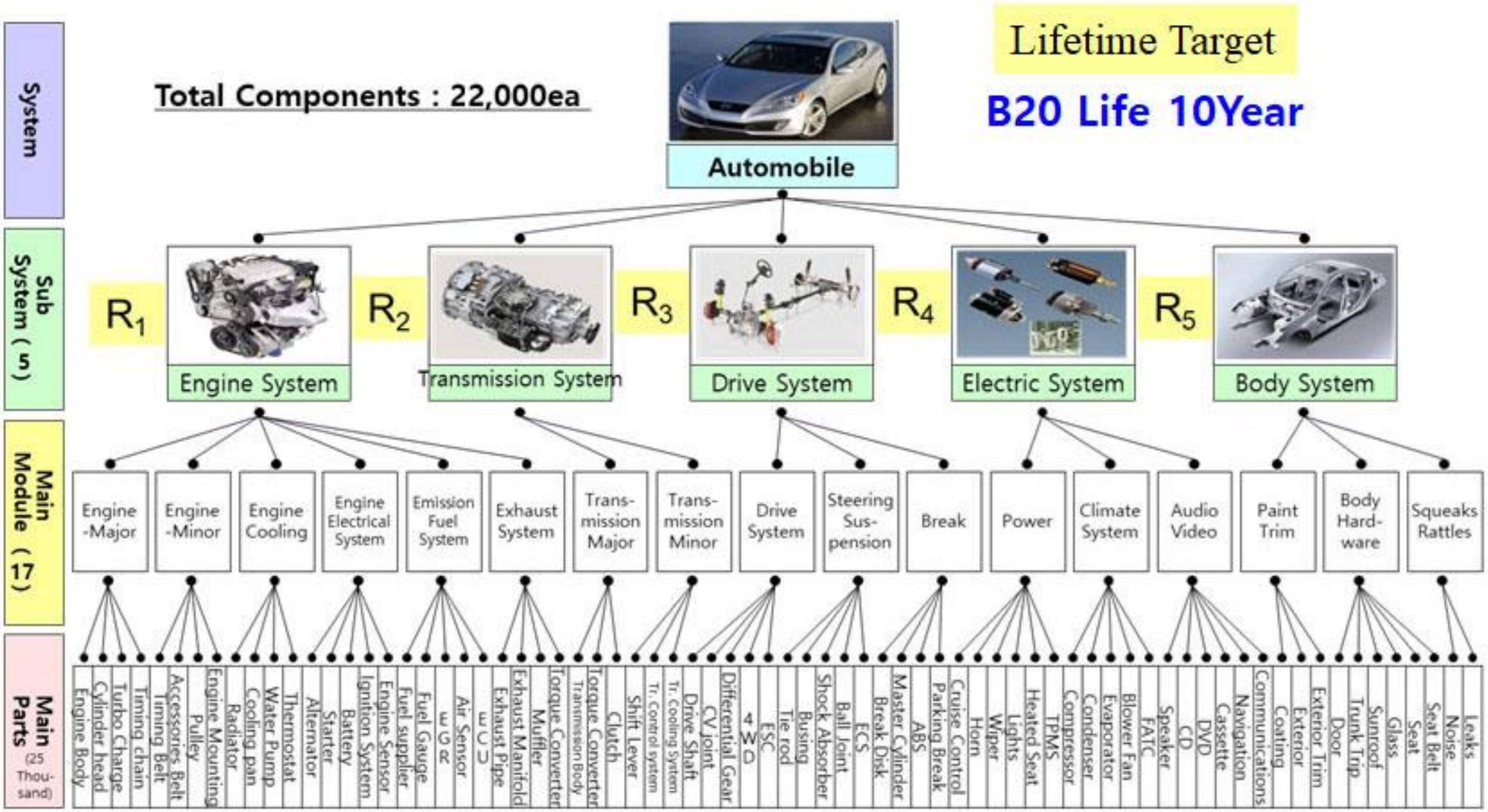
Introduction

❒ Systems Engineering: Automobile

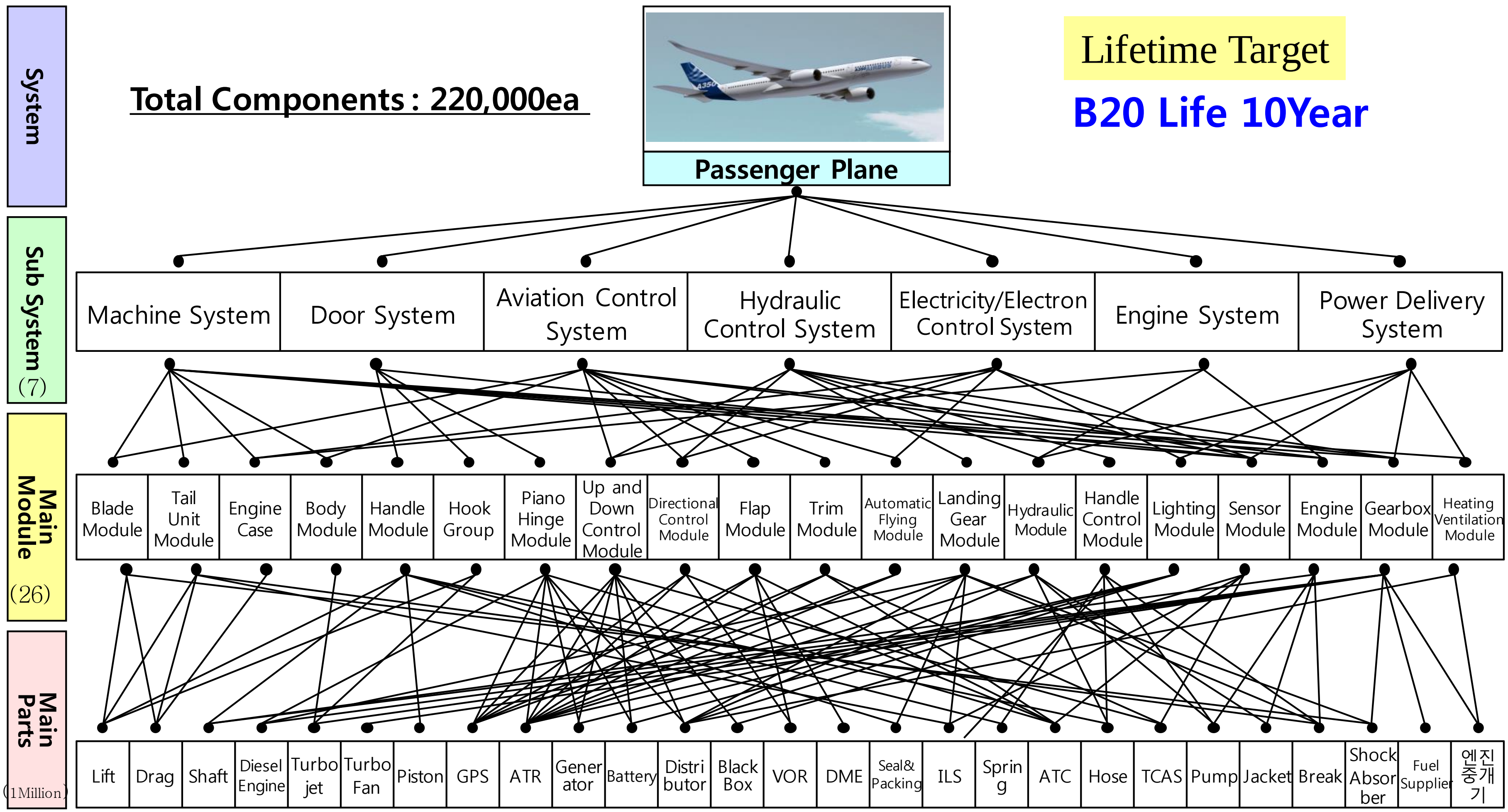


⇒ To improve performance or reducing cost, product will be designed yearly

⇒ By reliability testing, engineer should find the design flaws of product module

Introduction

❐ Systems Engineering: Airplane



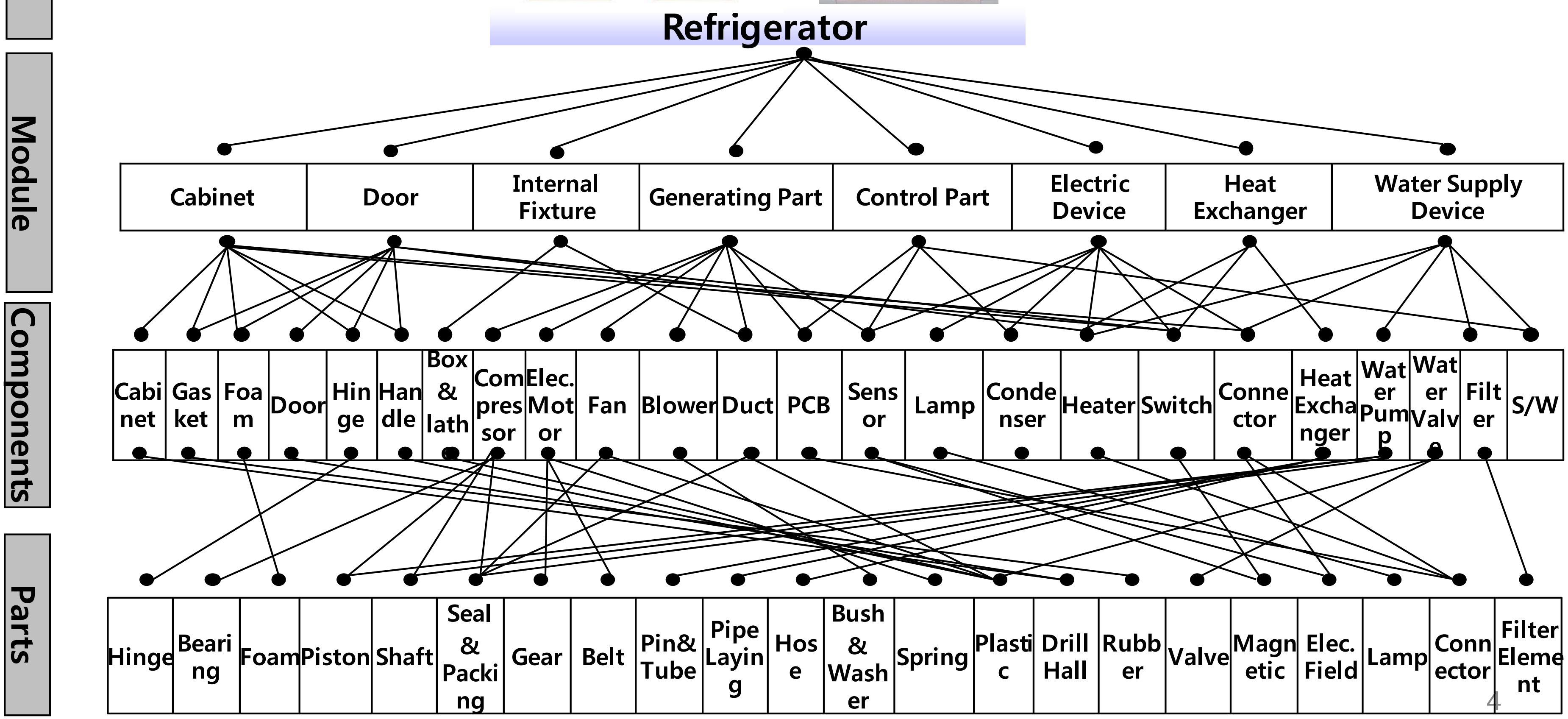
Introduction

❐ Systems Engineering: Refrigerator

Total Components : 2,200 pieces

Lifetime Target

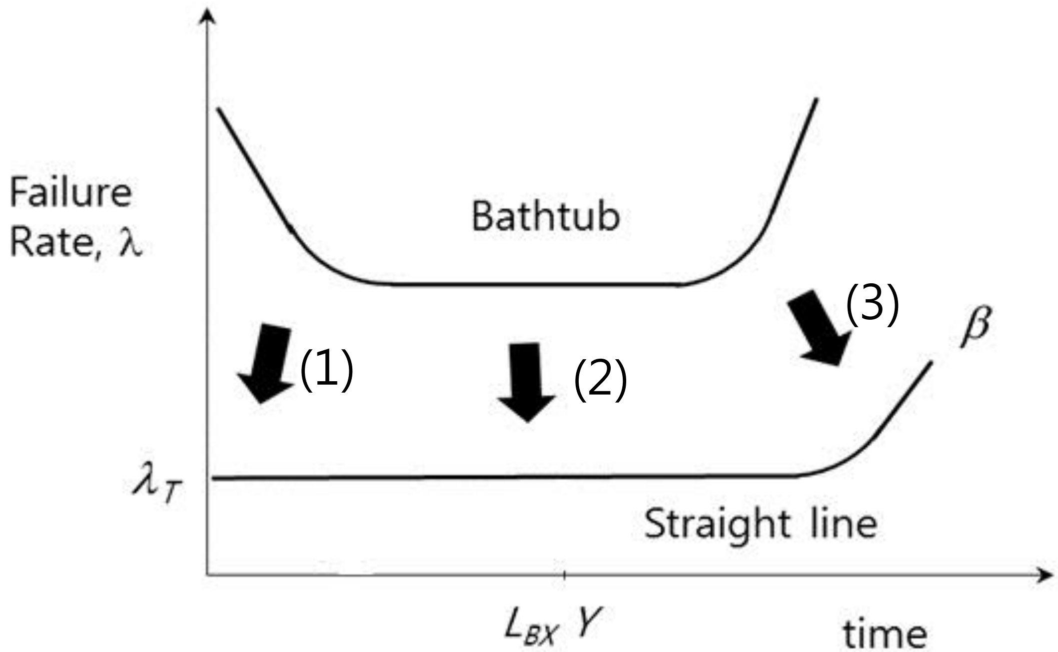
B20 Life 10Year



Introduction

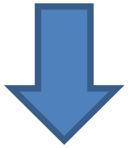
❒ Definition of Reliability

Ability of an item to perform a required function under stated environmental and operational conditions for a specified period of time



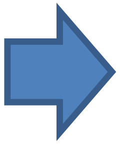
Bathtub Curve

design improvement



Straight Line

Product reliability: $\mathrm{R}(\mathrm{L_B}) = 1 - F(L_B) = e^{-\lambda \mathrm{L_B}} \simeq 1 - \lambda \mathrm{L_B}$



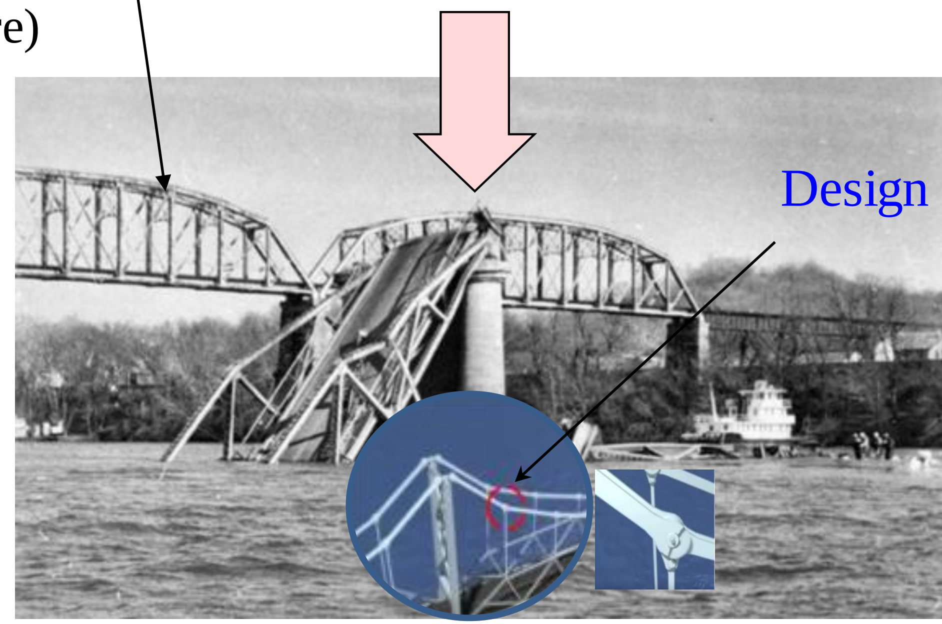
Reliability can be achieved without design failures

Failure Mechanics and Design

❒ Failure mechanics and product designs (material/shape)

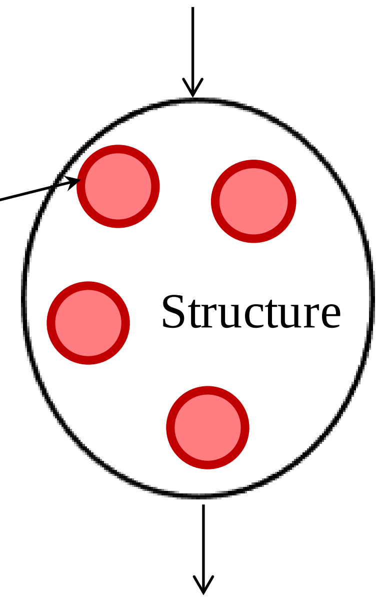
Bridge
(Structure)

Repetitive Load: **F = f (t)**



Design Flaws

Force: X



Fracture: Y

How to find the design flaws with rare probability (Poisson distribution)

→ Solution: Reliability testing under accelerated life testing

PARAMETRIC ACCELERATED LIFE TESTING

- **Solid–state diffusion of impurities (void/hole) in silicon**
  - **Electromigration-induced voiding / Build-up of chloride ions / Trapping of electrons or holes**

$$J = [aC(x-a)]\cdot \exp\left[-\frac{q}{kT}\left[w-\frac{1}{2}a\xi\right]\right]\cdot v$$

[Density / Area]·[Jump Probability]·[Jump Frequency]

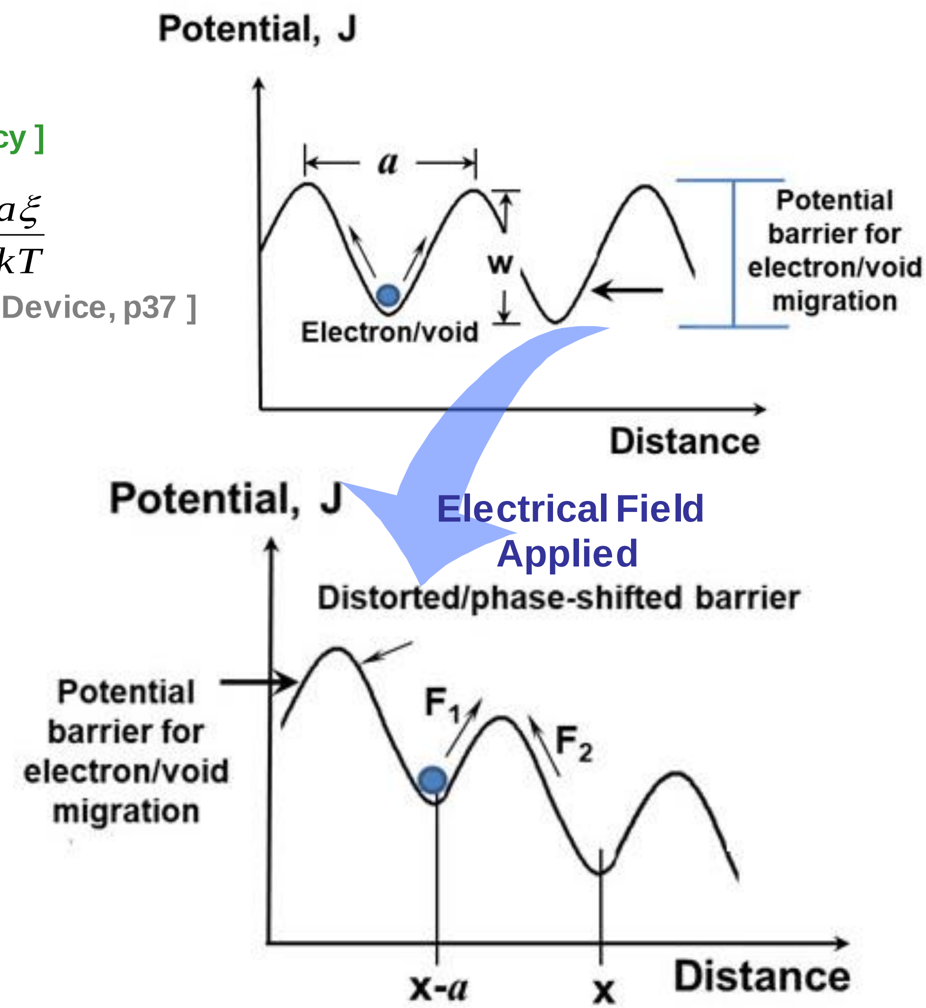
$$= -[a^2 v e^{-qw/kT}]\cosh\frac{qa\xi}{2kT}\frac{\partial C}{\partial x} + [2ave^{-qw/kT}]C\sinh\frac{qa\xi}{2kT}$$

[A.Grove, Physics and Technology of Semiconductor Device, p37]

$$\cong \Phi(x,t,T)\sinh(a\xi)\exp\left(-\frac{Q}{kT}\right)$$

$$= B\sinh(a\xi)\exp\left(-\frac{Q}{kT}\right)$$

[ASM, Electronic Materials HDBK, V1, p888]



- **Chemical reaction dependent on speed**

$$K = K^{+} - K^{-} = a\frac{kT}{h}e^{-\frac{\Delta E-\alpha S}{kT}} - a\frac{kT}{h}e^{-\frac{\Delta E+\alpha S}{kT}} = 2\frac{kT}{h}e^{-\frac{\Delta E}{kT}}\cdot\sinh\left(\frac{\alpha S}{kT}\right)$$

$$= B\sinh(aS)\exp\left(-\frac{\Delta E}{kT}\right)$$

[鹽見, 故障物理入門, p79]

❐ Acceleration Factor (AF)

- **Junction energy in silicon**

$$J = [aC(x-a)]\cdot \exp\left[-\frac{q}{kT}\left[w-\frac{1}{2}a\xi\right]\right]\cdot v$$

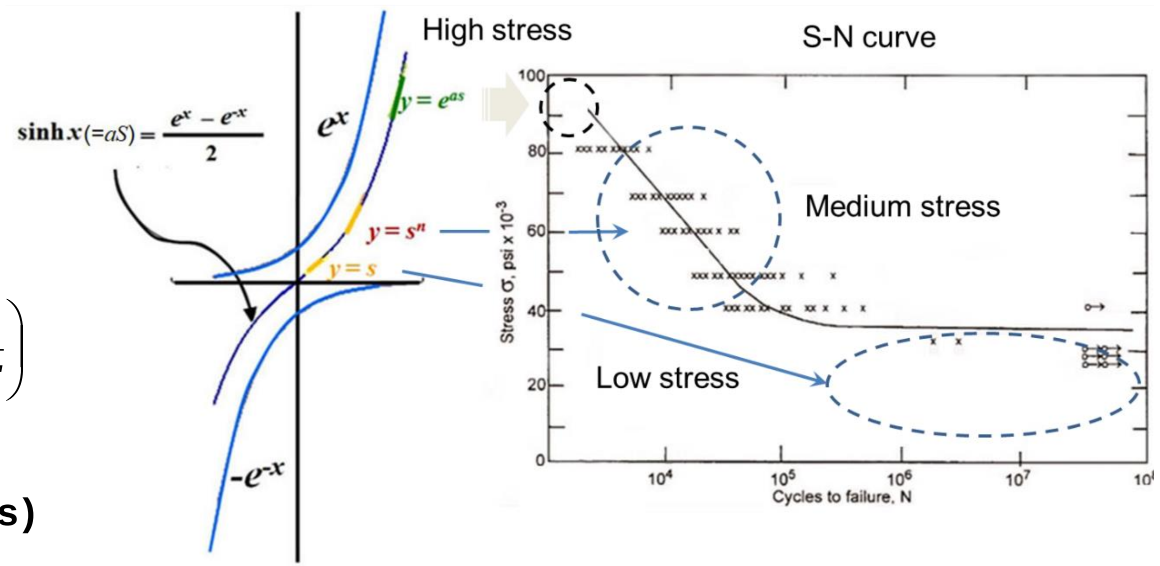
$$= B\sinh(a\xi)\exp\left(-\frac{Q}{kT}\right)$$

Inverse

General stress model

$$TF = B[\sinh(aS)]^{-1}\exp\left(\frac{Q}{kT}\right)$$

- **Low Effect,** $TF = C(S)^{-1}\exp\left(\frac{Q}{kT}\right)$
- **Medium Effect,** $TF = A(S)^{-n}\exp\left(\frac{Q}{kT}\right)$
- **High Effect,** $TF = D\exp(-aS)\exp\left(\frac{Q}{kT}\right)$



- **Acceleration Factor （Medium Stress)**

$$AF = \left(\frac{S}{S_o}\right)^n \exp\left[\frac{Q}{k}\left(\frac{1}{T_o}-\frac{1}{T}\right)\right]$$

PARAMETRIC ACCELERATED LIFE TESTING

❒ Power in Multi-port System (P= e(t)× f(t))

: Power might be defined as the product of effort and flow

System Units (or Parts)	Effort, *e(t)*	Flow, *f(t)*
Mechanical translation	Force component, *F(t)*	Velocity component, *V(t)*
Mechanical rotation	Torque component, $\tau(t)$	Angular velocity, $\omega(t)$
Compressor	Pressure difference, $\Delta P(t)$	Volume flow rate, *Q(t)*
Electric	Voltage, *V(t)*	Current, *i(t)*

$$TF = A(S)^{-n} \exp\left(\frac{Q}{kT}\right) = A(e)^{-\lambda} \exp\left(\frac{Q}{kT}\right)$$

$$AF = \left(\frac{S_1}{S_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] = \left(\frac{e_1}{e_0}\right)^\lambda \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right]$$

stress come from effort

PARAMETRIC ACCELERATED LIFE TESTING

➢ Sample Size Equation

If product follows Weibull distribution, reliability function is defined as:

$$R(t) = 1 - x = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad \Longleftrightarrow \quad L_{BX}^{\beta} = \left(\ln \frac{1}{1-x}\right) \cdot \eta^{\beta}$$

logarithm

Characteristic life η_α for the confidence level 100(1 - α):

$$\eta_\alpha^\beta = \frac{2r}{\chi_\alpha^2(2r+2)} \cdot \eta_{MLE}^\beta = \frac{2}{\chi_\alpha^2(2r+2)} \sum_{i=1}^{n} t_i^\beta$$

Testing data

where η_{MLE} from the Maximum Likelihood Estimation $\eta_{MLE}^\beta = \sum_{i=1}^{n} \frac{t_i^\beta}{r}$

Assessed BX Life:

$$L_{BX}^{\beta} = \frac{2}{\chi_\alpha^2(2r+2)} \cdot \left(\ln \frac{1}{1-x}\right) \cdot \sum_{i=1}^{n} t_i^\beta$$

PARAMETRIC ACCELERATED LIFE TESTING

➢ Sample Size Equation from approximation of BX life

BX life: $L_{BX}^{\beta} = \frac{2}{\chi_{\alpha}^{2}(2r+2)} \cdot \left(\ln \frac{1}{1-x} \right) \cdot \sum_{i=1}^{n} t_i^{\beta} \geq \frac{2}{\chi_{\alpha}^{2}(2r+2)} \cdot \left(\ln \frac{1}{1-x} \right) \cdot (n-r) \cdot h^{\beta}$

1) Chi-square Approx.:
For C.L.=60% and r < 4

2) Logarithmic Approx.:
Cumulative Failure x ≤ 20%

r	$\frac{\chi_{\alpha}^{2}(2r+2)}{2}$ (a)	$1-\alpha$
0	1	0.63
1	2	0.59
2	3	0.58
3	4	0.57

$* \frac{\chi_{\alpha}^{2}(2r+2)}{2}$ **=(r + 1)**

$L_{BX}^{\beta} = \frac{1}{(r+1)} \cdot x \cdot n \cdot h^{\beta}$

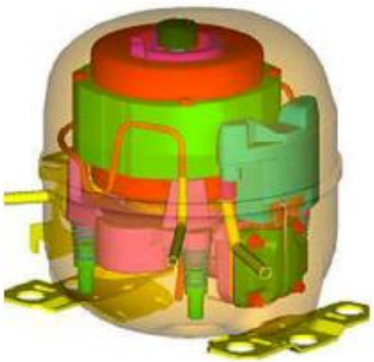
Rearrange

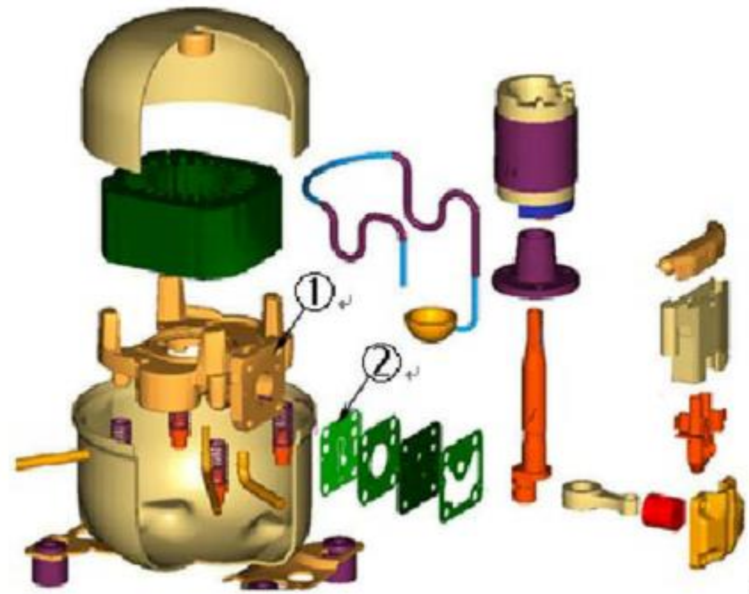
Sample Size Equation: $n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}}{AF \cdot h_a} \right)^{\beta} + r$

Case Study: Domestic Compressor

- **Refrigerator and redesigned compressor**

Refrigerator





Compressor System

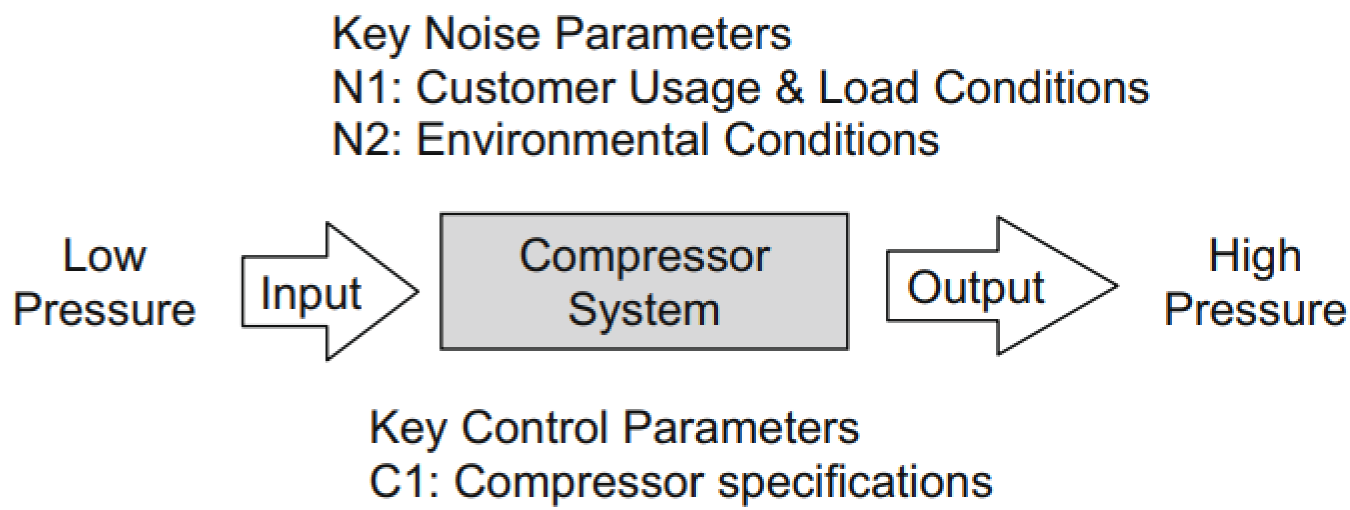
There are design faults in compressor, but we don't know which parts are

⇒ Compressor lifetime depends on the design faults of parts

⇒ To finding them, it require new reliability methodology

Case Study: Domestic Compressor

➢ **Parametric design schematics**



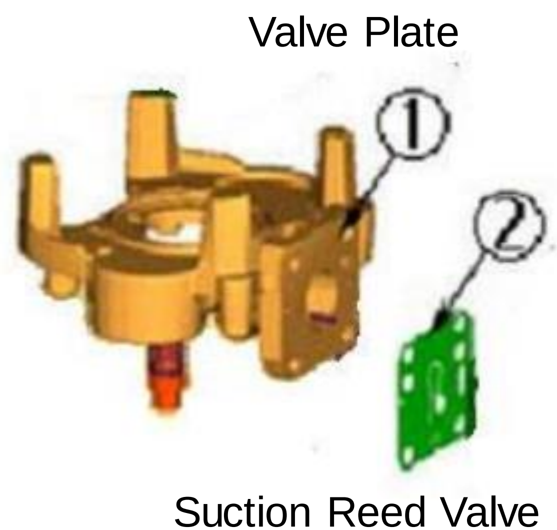
⇒ Reliability methodology: 1) failure analysis for returned product

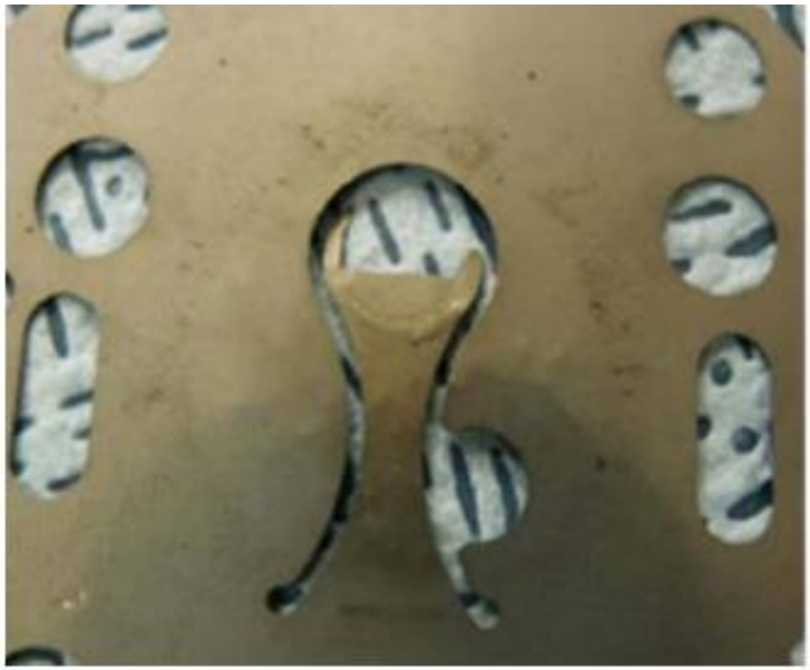
⇒ 2) Parametric ALT and its design modification

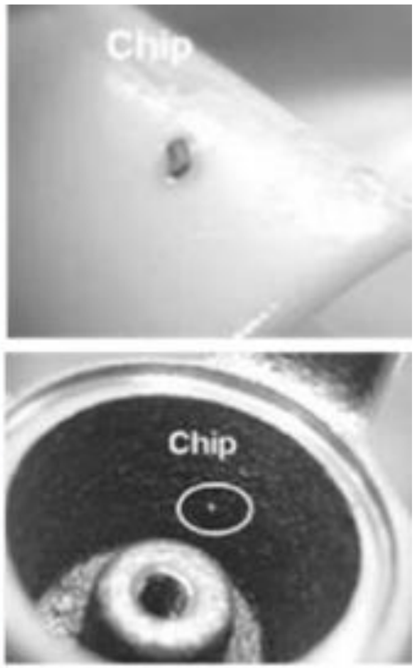
⇒ 3) Finally, checking if the lifetime target is achieved

Case Study: Domestic Compressor

- **Damaged products in field**







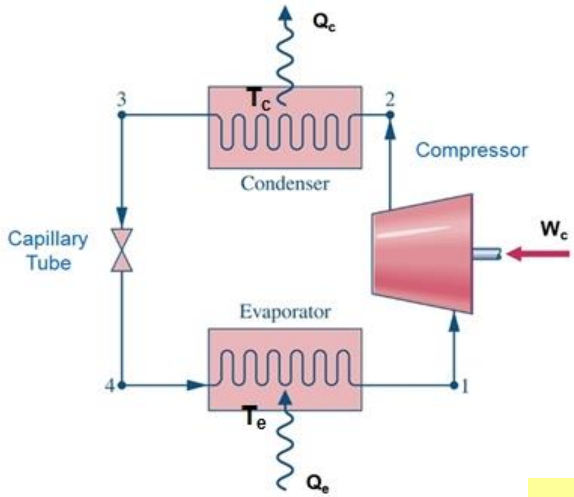
There were a lot of cracks on compressor part

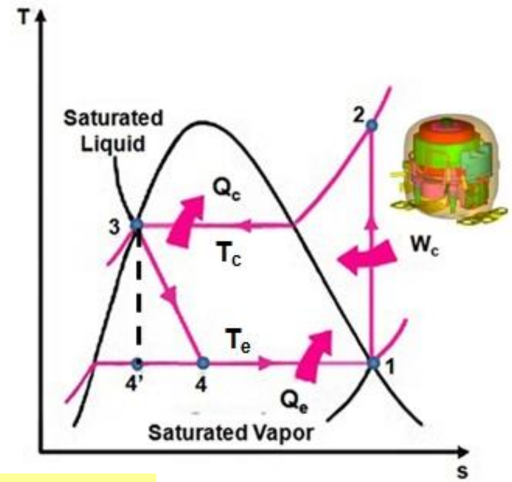
⇒ It came from fragile structure (design flaws)

⇒ By reproducing by parametric ALT, we can correct them

Case Study: Domestic Compressor

➢ Load Analysis for Accelerated Testing





Determine

Conservation of mass in capillary

$$\dot{m} = \dot{m}_{cap} \Rightarrow \dot{m}$$

Energy balance in the condenser

$$Q_c = \dot{m}(h_2 - h_3) = (T_c - T_o)/R_c \Rightarrow T_e$$

Energy balance in the evaporator

$$Q_e = \dot{m}(h_1 - h_4) = (T_i - T_e)/R_e \Rightarrow T_c$$

Time to Failure

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) = A(\Delta P)^{-\lambda} \exp\left(\frac{E_a}{kT}\right)$$

where

$$\Delta P = P_{dis} - P_{suc} \cong P_c - P_e$$ and

$$P_e = f(T_e) \text{ or } P_c = f(T_c)$$

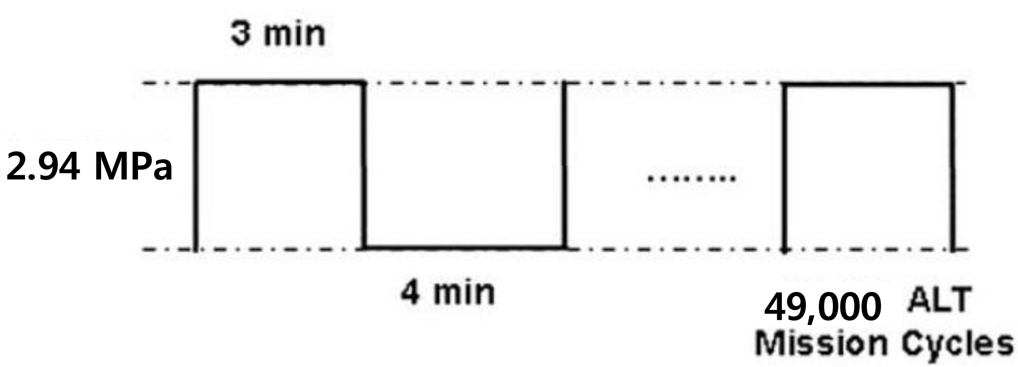
Case Study: Domestic Compressor

➢ Accelerated Factor

$$AF = \left(\frac{S_1}{S_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] = \left(\frac{\Delta P_1}{\Delta P_0}\right)^\lambda \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right]$$

System Conditions		Worst Case	ALT	AF (λ=2)
Pressure (MPa)	High-side	1.27	2.94	**5.36** ①
	Low-side	0.0	0.0	
	ΔP	1.27	2.94	
Temperature (°C)	Dome	90	120	**1.37** ②
Total *AF* (=(①×②))				**7.32**

➢ By applying duty cycle F on compressor



⇒ Search out the design failure

Case Study: Domestic Compressor

➢ Calculation of the mission cycle, h_a

Lifetime target of domestic compressor: **B_1 life 10 years**

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}^*}{AF \cdot h_a} \right)^{\beta} + r$$

(1) x = 0.01 (B1 life)

(2) r = 0 (No Failure)

(3) AF = 7.32

Total sample size of domestic compressor: n=100

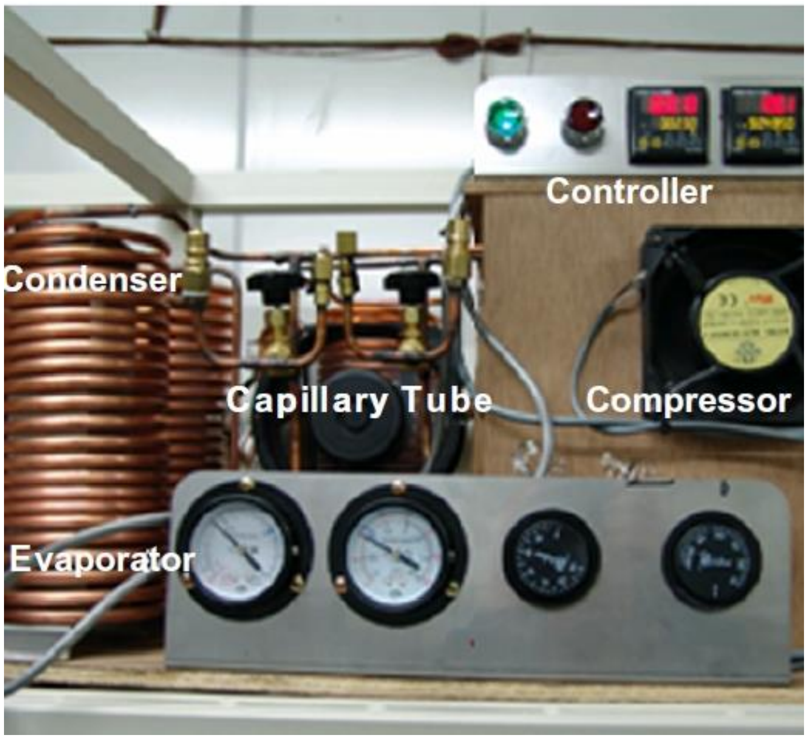
Compressor Lifetime: 98 cycles/day×365day/year×10 years = 357,6700 cycles

⇒ Specification(h_a): if there is no problem in 49,000 cycles,

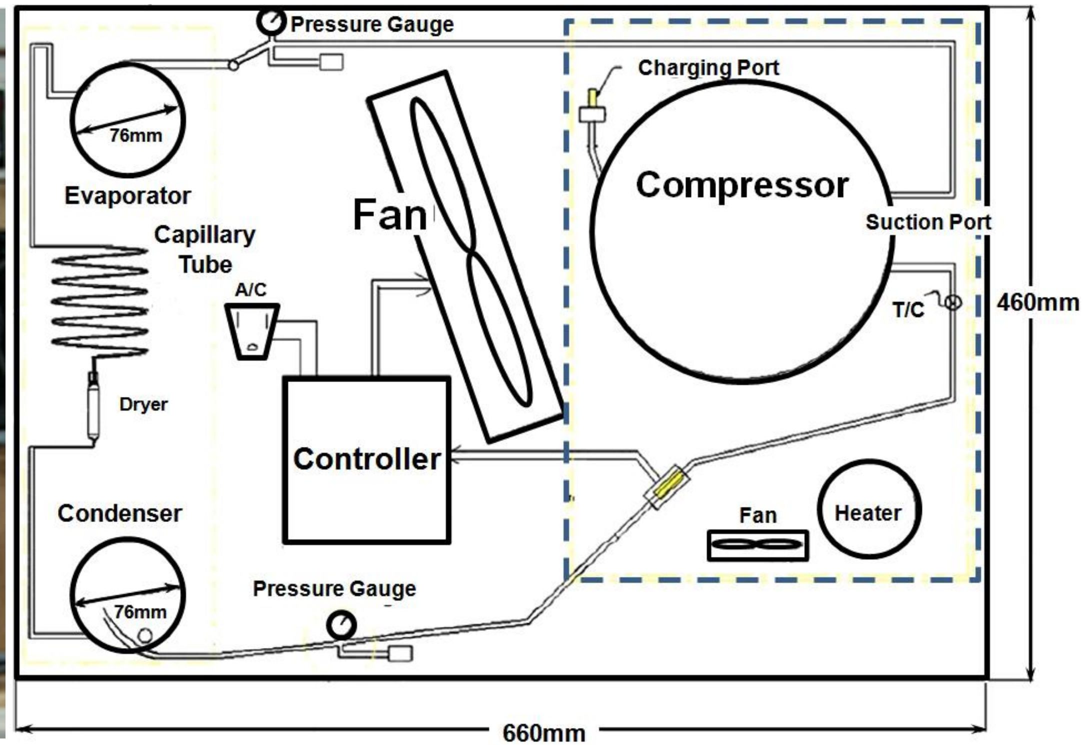
⇒ We can guarantee compressor lifetime target: B1 life 10 years

Case Study: Domestic Compressor

➢ **Equipments used in accelerated life testing**



Testing Zig



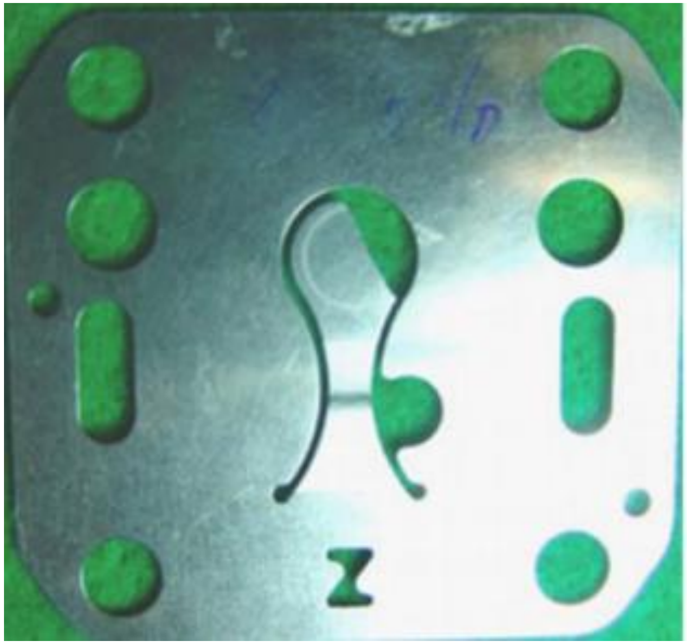
Schematic Diagram

$\Rightarrow$ We can proceed the parametric ALT with equipment

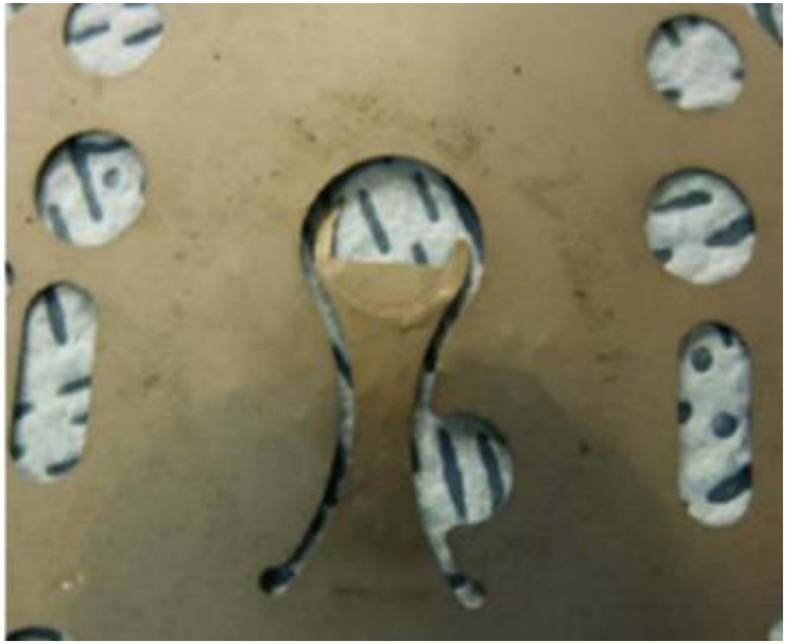
Case Study: Domestic Compressor

➢ Results of 1st ALT

: Compressor locked due to the fractured suction reed valve at 10,500 cycles



Field



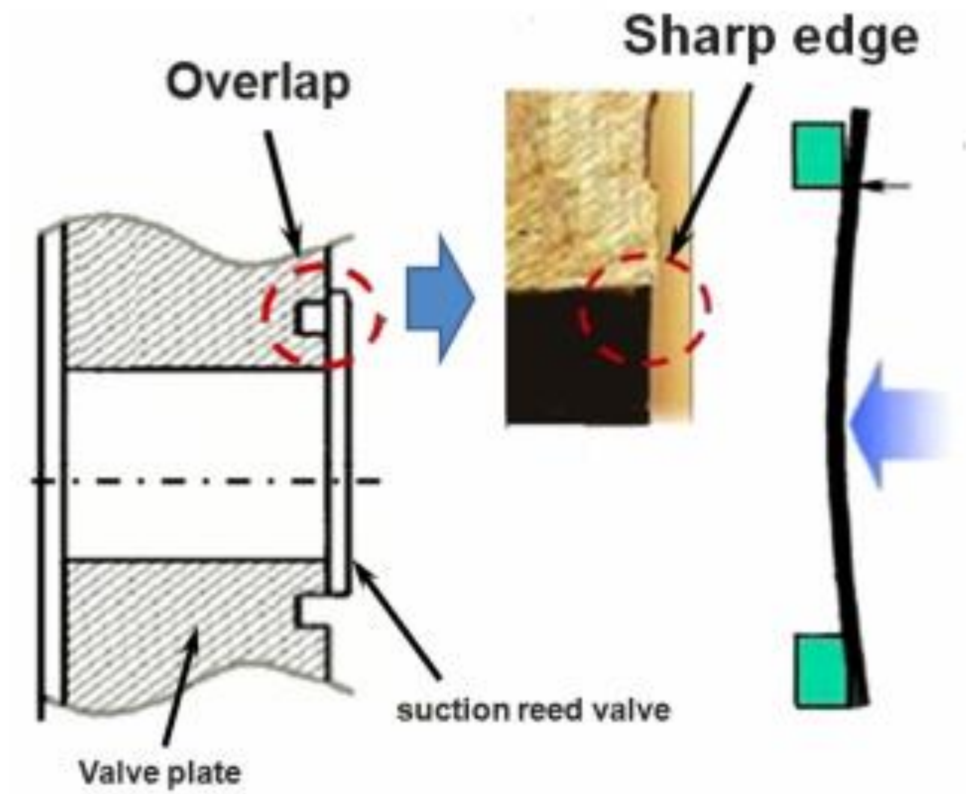
1st ALT

By parametric ALT, we could reproduce the compressor failure in field

Case Study: Domestic Compressor

➢ Results of 1st ALT

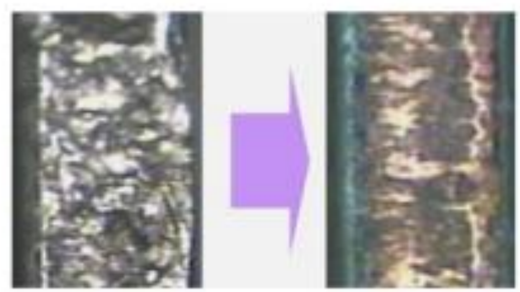
Fractured suction reed valve



Root causes: **a) Overlapped suction reed valve b) valve plate with sharp edge**

Case Study: Domestic Compressor

➢ Redesigned valve plate and suction reed valve

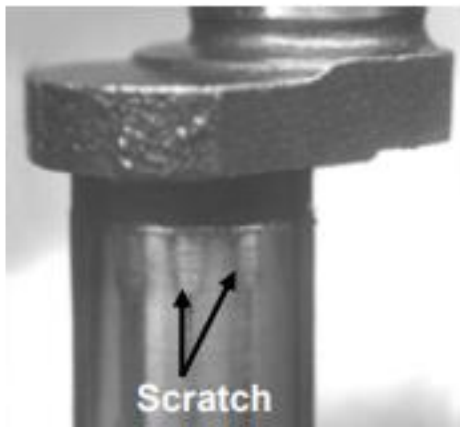
Valve plate	Suction reed valve
	 Section A–A' 
C1: Trepan:0.73 mm →1.25 mm C2: Ball peening and brush process	C3: 0.178t → 0.203t (SANDVIK 20C thickness) C4: Tumbling process time: 4 h → 14 h

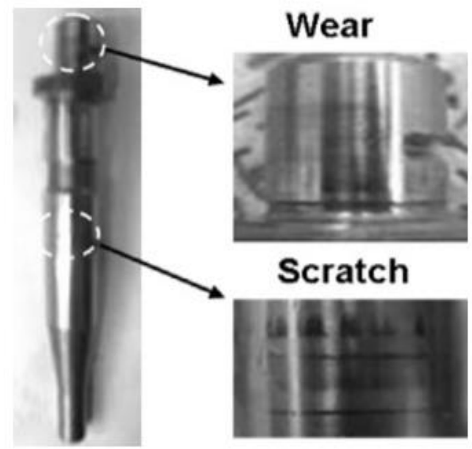
Case Study: Domestic Compressor

- **Results of 2nd ALT**

: Compressor locked at 17,000 cycles .

Root cause
: Crankshaft material





Redesigned crankshaft

Old Design		New Design
FCD500 + No Heat Treatment	→	FCD500 + Heat Treatment

By parametric ALT, we can modify the problematic crankshaft in compressor

Case Study: Domestic Compressor

➢ Summary of Parametric ALT Results

Parametric ALT	1st ALT	2nd ALT	3rd ALT
	Initial Design	Second Design	Last Design
In 49,000 cycles, there are no problems in the compressor	10,500 cycles: 1/100 locking	17,000 Cycles: 3/100 locking	49,000 cycles: 100/100 OK
Structure			-
Action plans	C1: Trepan size: 0.73 mm→1.25 mm C2: Adding ball peening and brush process C3: SANDVIK 20C: 0.178t→0.203t C4: Extending tumbling: 4 h→14 h	C5: FCD500 + No Heat Treatment → FCD500 + Heat Treatment on the crank shaft	-

➢ Because there is no problem to 49,000 cycles,

➢ Compressor achieves the lifetime target – B1 life 10 years

Conclusion

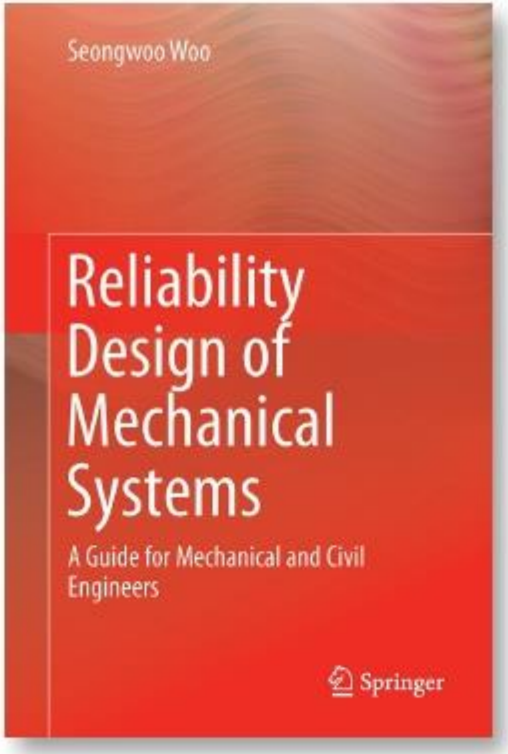
S. Woo

Reliability Design of Mechanical Systems

A Guide for Mechanical and Civil Engineers

Springer

- **It enables mechanical and civil engineers to find the designs flaws and achieve the targeted product reliability. It also suggests a variety of case studies on the mechanical system. Presents Taguchi method's alternative experimental Methodology. Describes new parametric ALT methods for reliability quantitative test specifications (RQ).**



1st ed. 2017, XII, 310 p. 249 illus., 132 illus. in color.

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