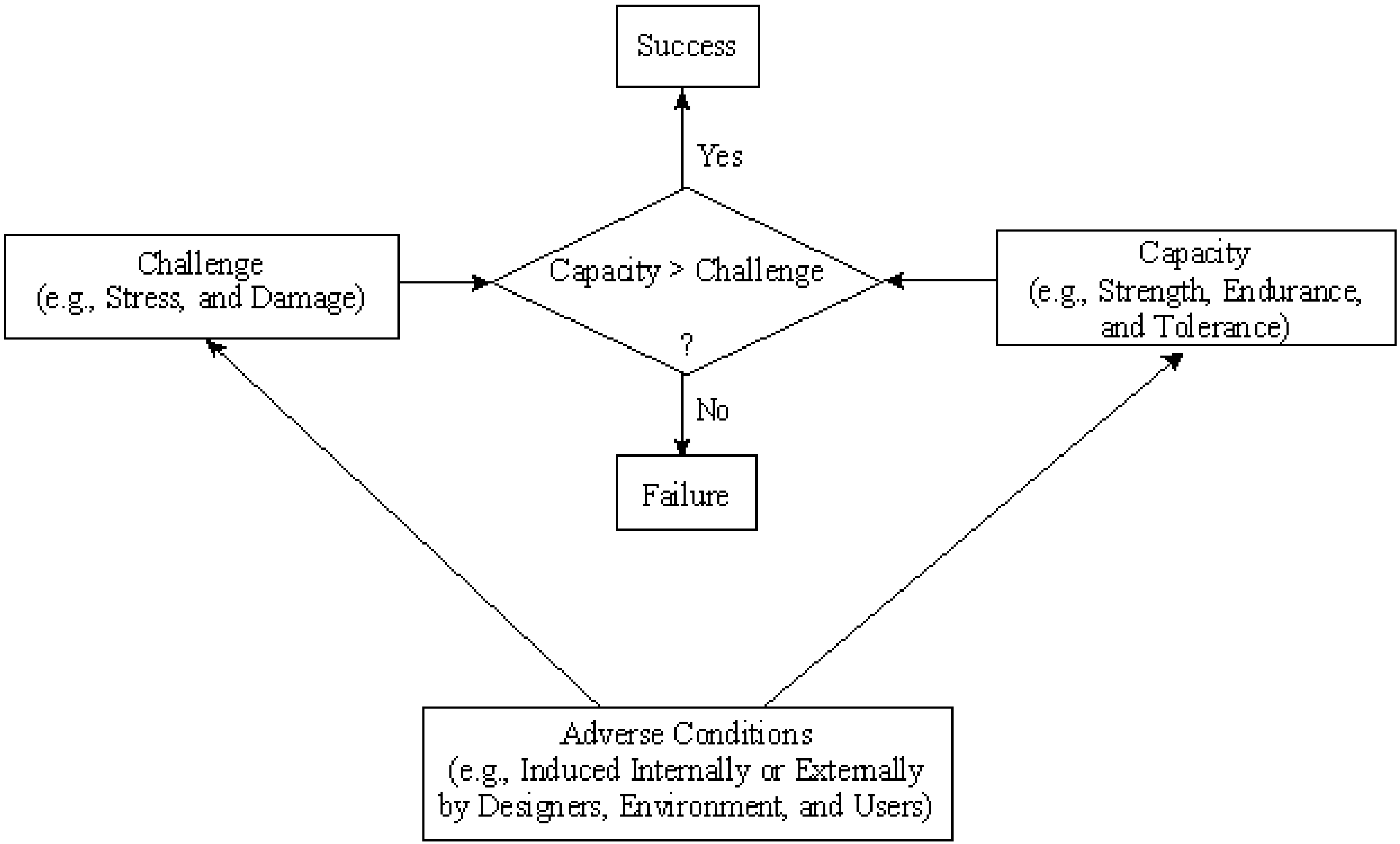
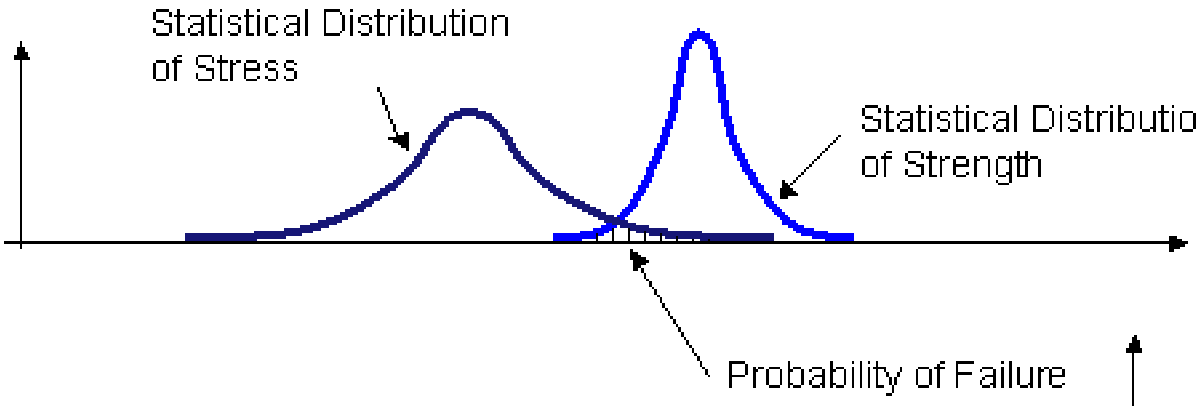
Engineering Approach to Reliability: Modeling and Probabilistic Assessment

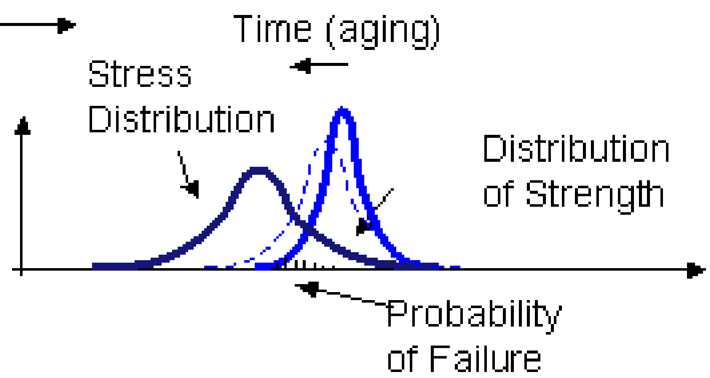
M. Modarres
Professor
Reliability Engineering
ENRE 607 Seminar
Spring 2006

FRAMEWORK FOR MODELING FAILURE



STRESS-STRENGTH MODEL





Examples:

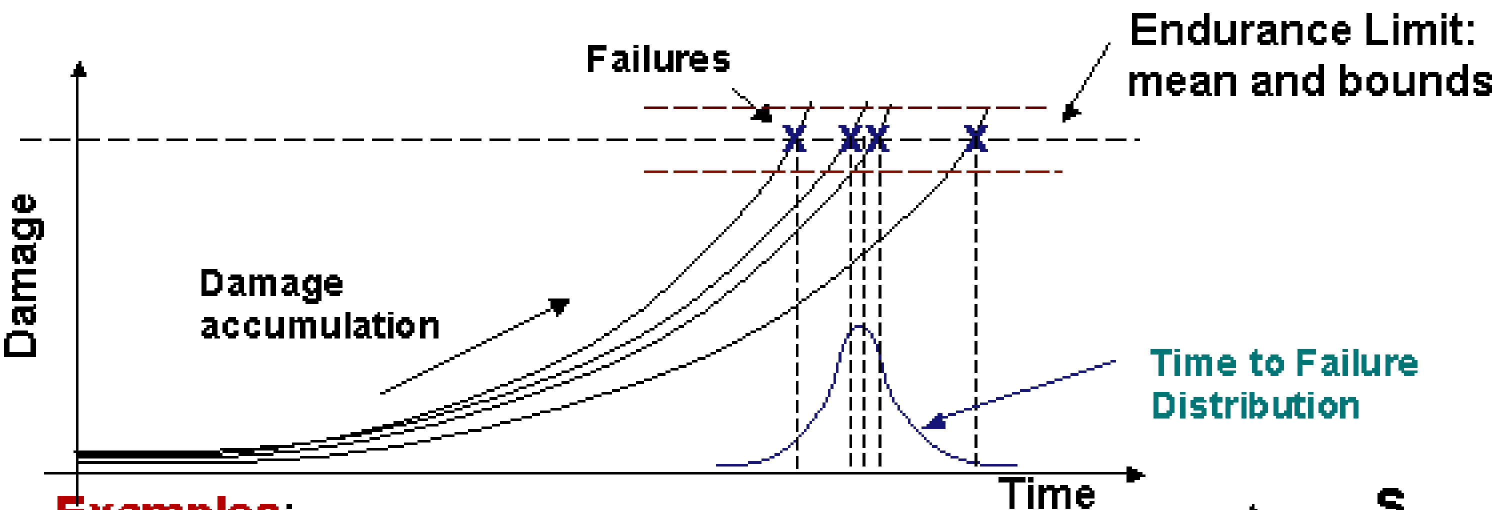
- Conditional containment failure probability under severe accident loads
- Seismic failure analysis of structures

Assumption: No permanent damage due to application of stress

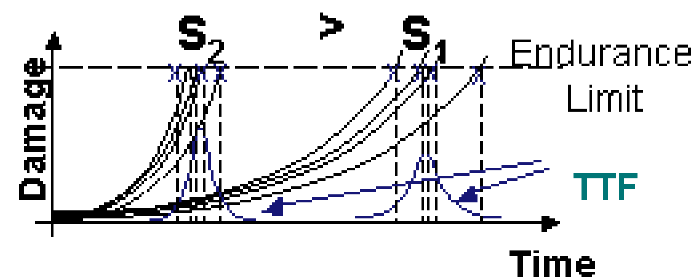
Implications

- Aging shifts the scale and shape parameters of stress and strength distributions

DAMAGE-ENDURANCE MODEL



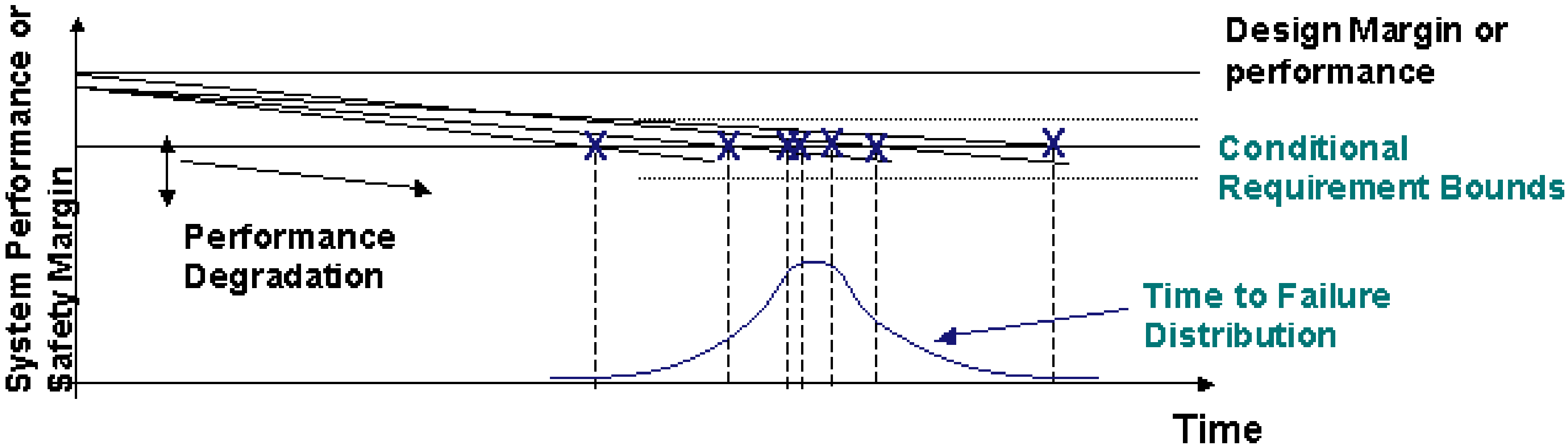
Examples:
- Fatigue corrosion cracking and growth in piping and components
- Vessel, piping and other structural corrosion
- Wear in key components, pump seals and bearing



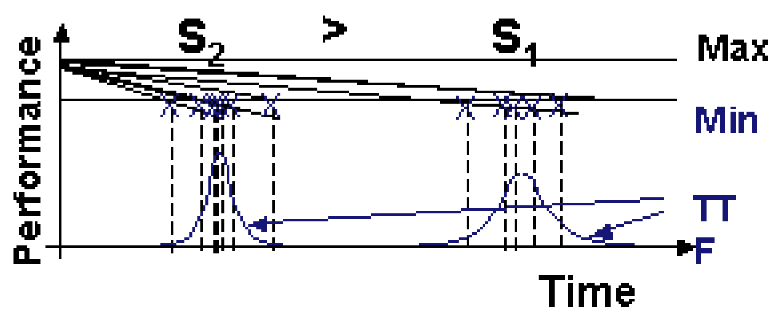
Assumption: Permanent damage occurs due to applied stresses and loads

Implication:
- Not used to model life of components and structures (favored by several industries)
- Engineering-based models of damage accumulation needed

PERFORMANCE-REQUIREMENT MODEL



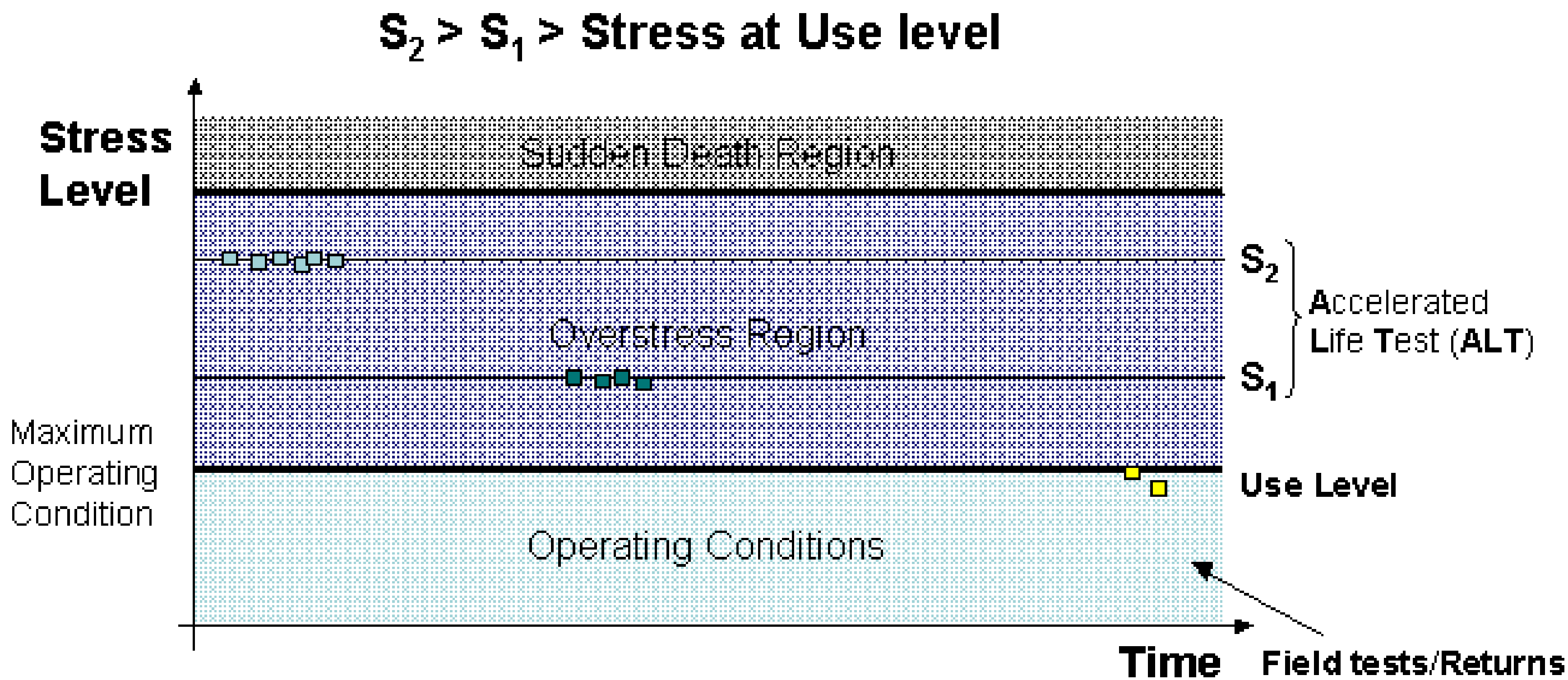
Examples:
- Degradation of safety margin
- System success criteria



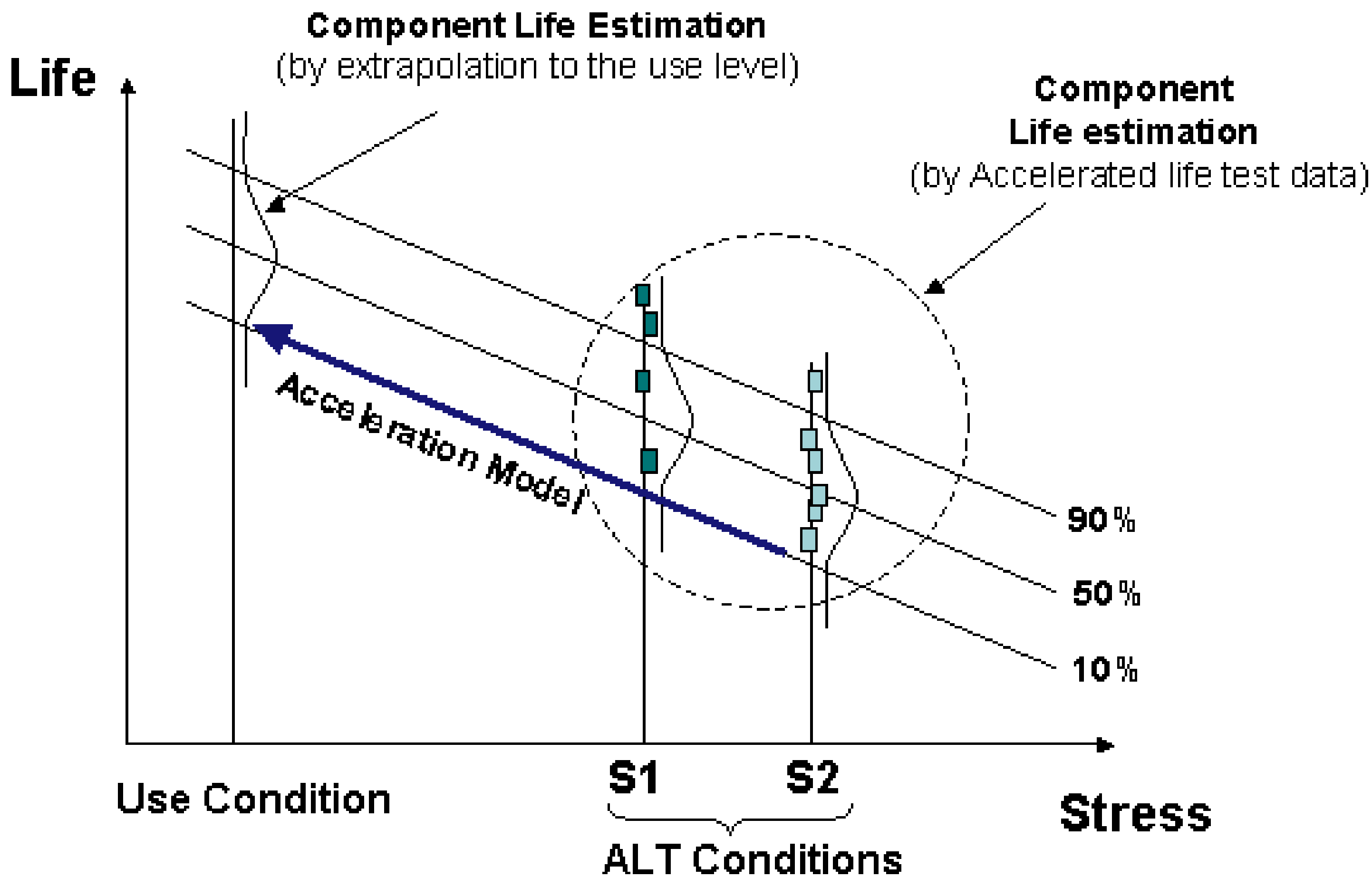
Assumption: Aging and operational changes lead to degradation of performance and safety margin

Implication:
- Overly conservation safety margins can be relieved
- Need advances in understanding of degradation and uncertainties

ACCELERATED LIFE TEST APPROACH



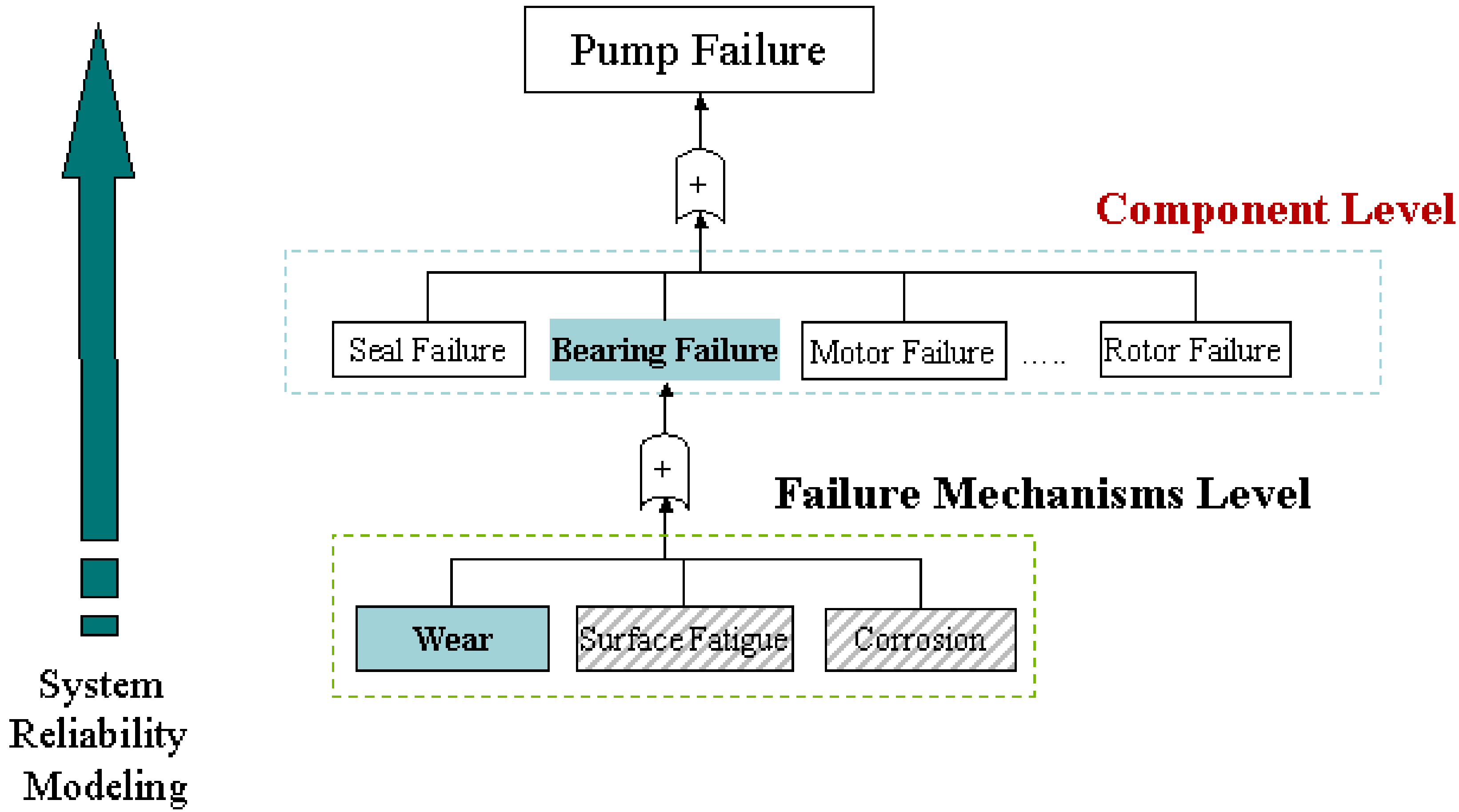
ALT MODELING



FAILURE MECHANISMS AND ACCELERATION STRESSES

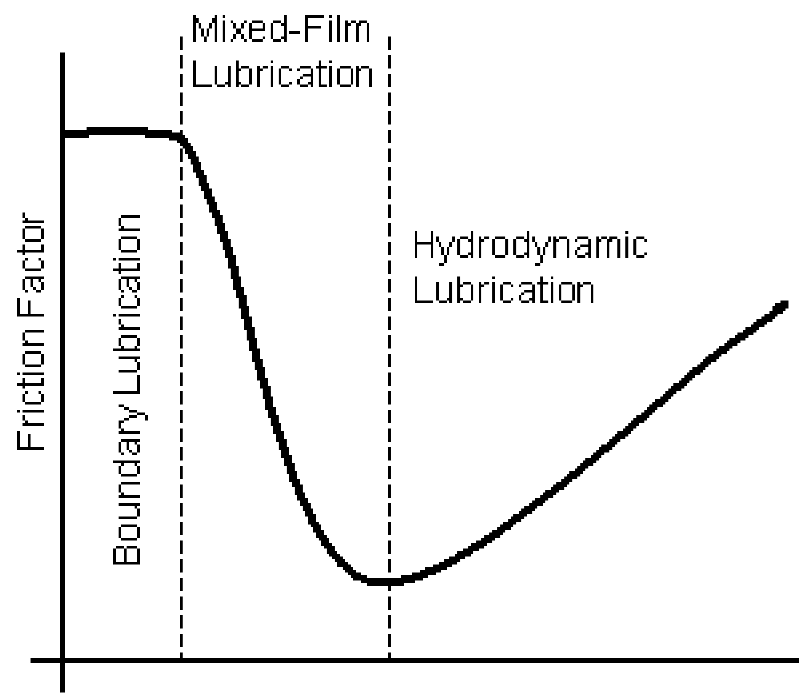
Wearout Failure Mechanisms	Acceleration Stresses
Fatigue crack initation	Mechanical stress/strain range, Cyclic temperature range, Frequency
Fatigue crack propagation	Mechanical stress range, Cyclic temperature range, Frequency
Creep	Mechanical stress, Temperature
Wear	Contact force, Relative sliding velocity
Diffusion	Temperature, Concentration gradient
Interdiffusion	Temperature
Corrosion	Temperature, Relative humidity
Electromigration	Current density, Temperature, Temperature gradient
Dendritic growth	Voltage differential
Radiation damage	Intensity of radiation
Surface charge spreading	Temperature
Slow trapping	Temperature
Stress corrosion	Mechanical stress, Temperature, Relative humidity

EXAMPLE: SYSTEM LIFE MODEL



JOURNAL BEARING LUBRICATION REGIMES

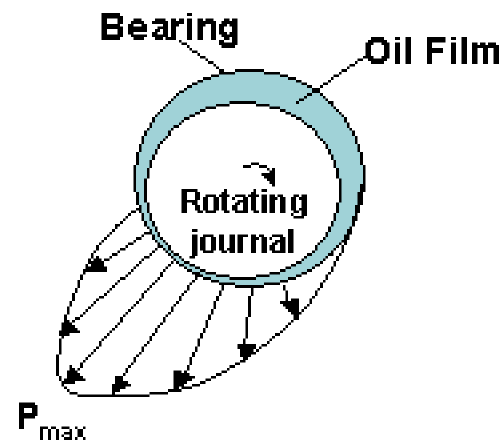
- Hydrodynamic lubrication is referred to as stable lubrication
- Mixed-film lubrication is unstable
- Suppose (most often is the case) bearings works in mixed-film and boundary regimes



Bearing Characteristic Number $= \frac{\mu V}{P}$

JOURNAL BEARING DESIGN ASPECTS

- There is a pressure distribution around the squeezed film
- In high pressures the viscosity of the lubricant increases exponentially with pressure

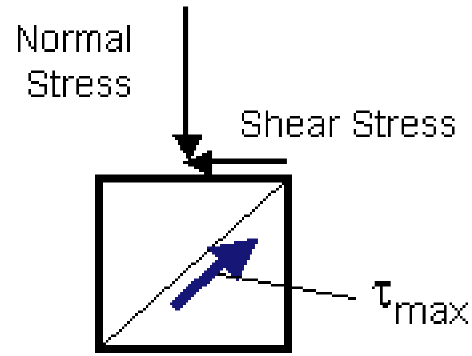


$$\mu = \mu_0 . e^{\alpha . p_{max}}$$

α : Pressure-Viscosity Coefficient

EMPIRICAL MODEL FOR ABRASIVE WEAR MECHANISM

- Employ the maximum shearing stress as the wear agent.



Material Elements at the Surface

$$L = C\left(\frac{\tau_{yp}}{\tau_{max}}\right)^n$$

where

L is the life as number of passes,

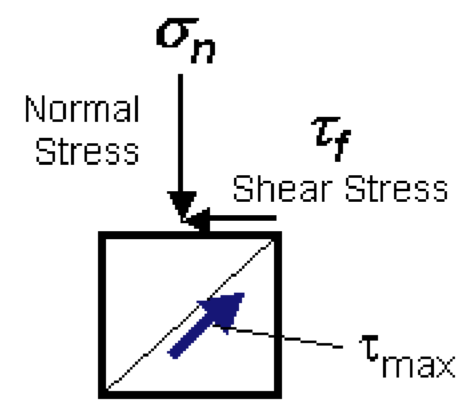
C, n is the constants to be determined from the test results,

τ_{yp} is the material shear yield point, and

τ_{max} is the maximum shear stress in the vicinity of the surface.

EMPIRICAL MODEL FOR ABRASIVE WEAR MECHANISM (cont)

$$\tau_{max} = ke\sqrt{\left(\frac{\sigma_n}{2}\right)^2 + \tau_f^{\,2}}$$

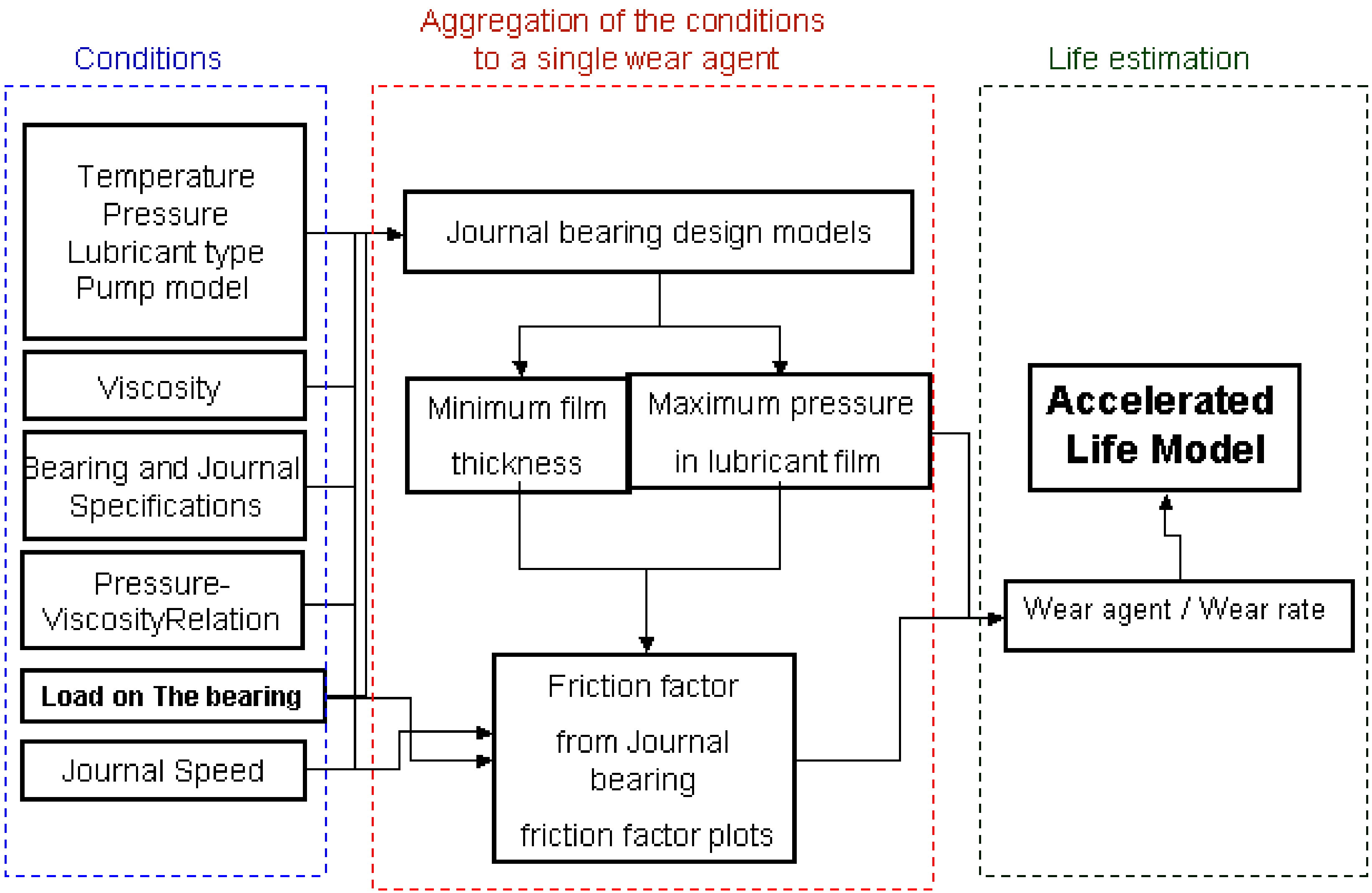


Material Elements at the Surface

where

- τ_{max} = Maximum shearing stress
- ke = Stress concentration factor
- $\sigma_n = P_0$ Normal stress on the surface
- $\tau_f = \mu P_0$ Friction generated shear stress
- μ = Friction Factor

AGGREGATE OF CONDITIONS AS WEAR AGENT



BEARING LIFE MODELING OUTLINE

1. Introduce a wear agent to integrate the effect of viscosity degradation and other working conditions

$$\tau_{\max} = ke\sqrt{\left(\frac{\sigma_n}{2}\right)^2 + \tau_f^{\ 2}}$$

↓

2. Correlate the accelerated wear life of bearing with the wear agent

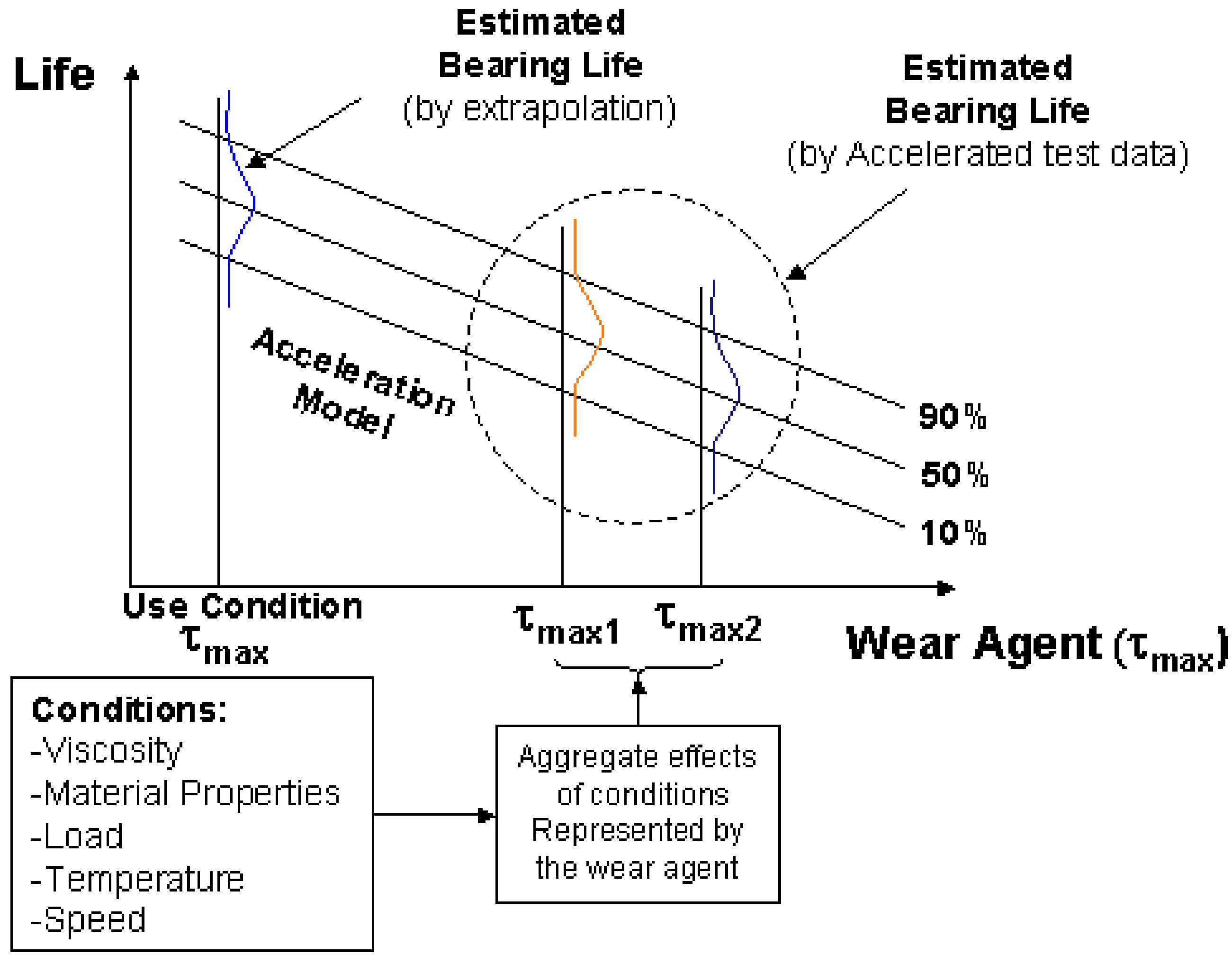
$$L = C\left[\frac{\tau_{yp}}{\tau_{\max}}\right]^n$$

↓

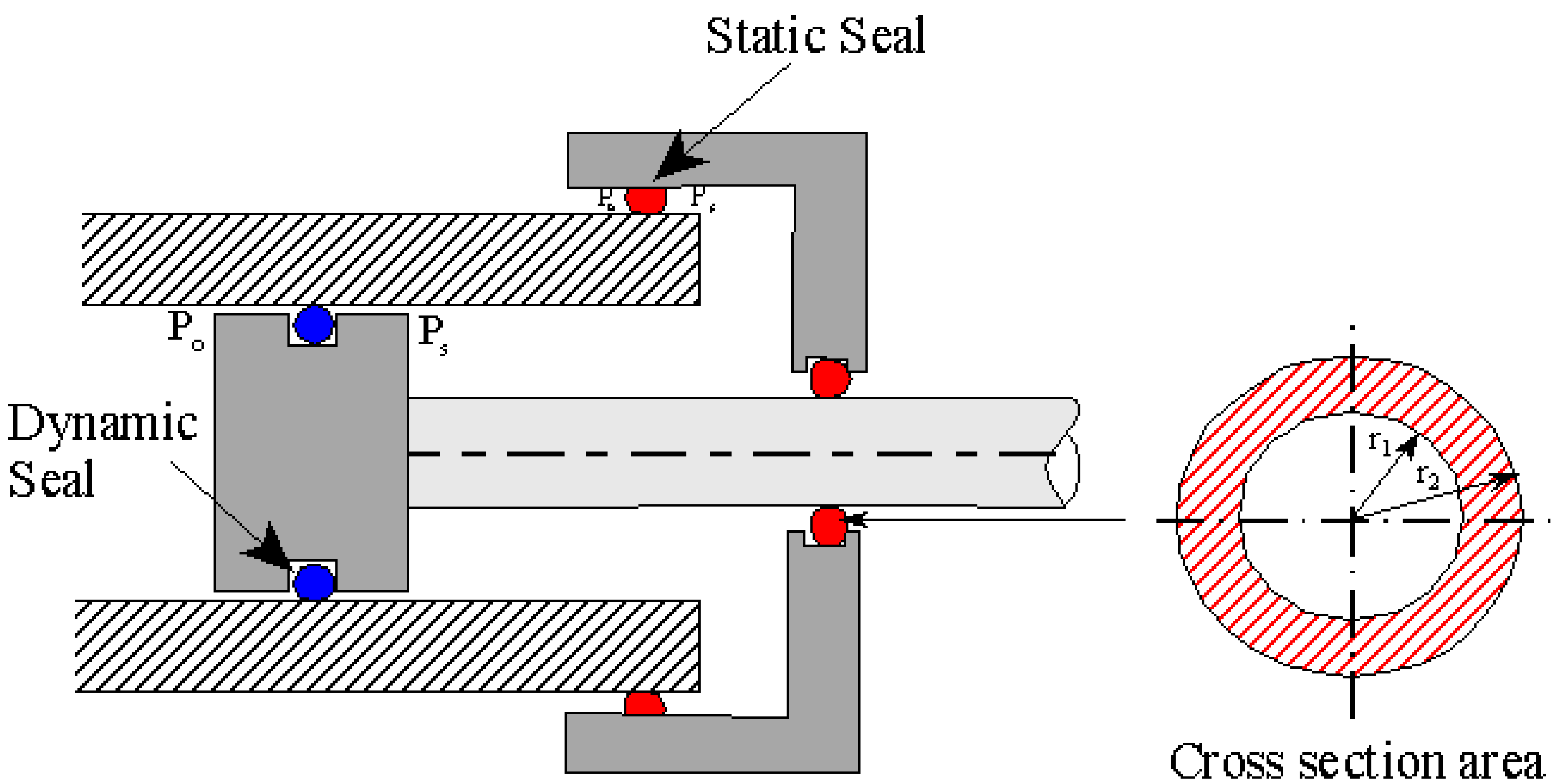
3. Use accelerated life tests to find model parameters

Life test data analysis to find C, n

BEARING ACCELERATED LIFE TEST OUTLINE



SEAL MODEL



SEAL MODEL

Failure Criterion $Q_a > Q_f$

where

Q_a is the actual leakage rate (vol./time),

and

Q_f is the allowable leakage rate.

$$R = Pr\,(Q_a > Q_f)$$

SEAL MODEL (cont)

$$Q_a = \left[\frac{\pi\left(P_s^2 - P_o^2\right)}{24\nu_a P_o}\right]\frac{r_2 - r_1}{r_2 - r_1} H \qquad \left(in^3/min\right)$$

where

P_s is the system pressure,

P_o is the atmospheric pressure (or downstream pressure) [psi],

ν_a is the absolute fluid viscosity [lb-min/in^2],

r_1 is the inside radius of seal [in],

r_2 is the outside radius of seal [in], and

H is the leak parameter.

SEAL MODEL (cont)

For Flat Seals And Gaskets

$$Q_a = \frac{2\pi r_1 \left(P_s^2 - P_o^2\right)}{24 \nu_a L P_o} H$$

where

r_1 = radius, and

L = contact length.

SEAL MODEL (cont)

$$H = \beta \frac{S}{M} \alpha^{1/3}$$

where

- β is constant,
- S is the contact stress, (psi) = F/A,
- F is the force compressing deal (lbs),
- A is the area of seal in contact (in^2),
- M is Meyer's Hardness (psi) in material constant,
- α is the wear coefficient (flow in^3/partical removed)^2

SEAL MODEL (cont)

Agents of Failure are: stress S, "flow" in in3/min that affects α, temperature that affects $\nu_a \propto 1/T_s$, where T_s is the system temperature

$$Q_a \propto \frac{P_s^2 \cdot S \cdot (Q_a)^{1/\beta}}{\frac{1}{T_s}}$$

$$Q_a^{2/\beta} = k \cdot P_s^2 \cdot S \cdot T$$

since $L \propto Q_a$, (i.e., the leak rate) therefore,

$$L = k' \cdot P_s^3 \cdot S^{1.5} \cdot T^{1.5}$$

Conclusions

- New Directions in Reliability Engineering is Focusing on Modeling Mechanical Systems using Probabilistic Engineering of Failure Concepts
- Broad Opportunities Exists in Modeling Mechanical Parts, Components, Systems and Structures for Accurate Estimates of Reliability