Introduction to Maintainability

- The concept of maintainability encompasses:
  - An operational measure of effectiveness
  - A characteristic of design
  - An engineering specialty that supports design
  - A cost driver
  - A planned activity in each stage of product life-cycle

Introduction (cont)

- Maintainability - is the ability of an item to be maintained; this ability stems from the aggregate of all design features which promote serviceability.
- Maintenance - is a series of actions of appropriate character (content, timing, quality) to restore or retain an item in an operational state.
- Contrast:
  - Reliability is time to failure, probability of no failure
  - Maintainability is time to diagnose and repair a failure or time to prevent future failure

Maintainability is Inherently a Probabilistic Measure

- Detection, diagnosis, repair, check-out all involve uncertainty
- Human skill and learning are involved
  - Differences due to individuals
  - Differences due to experience
- Consider other definitions of maintainability:

  The probability that:
  - Item will be restored to operational status in T hours
  - Maintenance will not be required more than X times per time period
  - Maintenance cost will not exceed $Z per time period

Maintainability in the System Life-Cycle

- The Maintainability Plan is developed during conceptual design, reviewed internally and by customer, and includes:
  - Functions to be performed (p.391-393)
  - Standards/ Procedures/ models to be used
  - Schedule
  - Documents/ Reports
  - Organization, responsibilities, interfaces within your company and with customer, supplier

Maintainability in the System Life-Cycle

- The Systems Engineering Plan has a major section devoted to integration of the engineering specialties into the design process. The SE is responsible for assuring adequate participation, influence, visibility, etc. is granted to maintainability, and others.

Qualitative Maintainability Measures

- Especially important early in design when limited data exist
- Examples:
  - Skill level reduction
  - Ease of access
  - Simplicity of task
  - Identification, markings, coding
  - Standardization
  - Safety during maintenance
  - Clearly written, easy to follow instructions
  - Ease of fault isolation

Qualitative Maintainability Measures(cont)

- Some ways these get incorporated into design
  - Management emphasis
  - Experienced maintenance “chiefs” on each team
  - Checklists (see handout)
  - Degree to which quantitative measures/ models are sensitive to these

Quantitative Measures of Maintainability

- Maintenance Elapsed-Time Factors
  - Mean Corrective Maintenance Time $\overline{M}_{ct}$ (MTTR)
  - Mean Preventative Maintenance Time $\overline{M}_{pt}$
  - Median Corrective Maintenance Time $\tilde{M}_{ct}$
  - Median Preventative Maintenance Time $\tilde{M}_{pt}$
  - Mean Active Maintenance Time $\overline{M}$

Quantitative Measures of Maintainability

- Maintenance Labor-Hour Factors
  - Maintenance labor-hours per operating cycle
  - Maintenance labor-hours per cycle
  - Maintenance labor-hours per month
  - Maintenance labor-hours per maintenance action

- Maintenance Frequency Factors
  - Meantime between maintenance = MTBM
    - Unscheduled (corrective) and Scheduled (preventive)
  - Meantime between replacement = MTBR

Maintainability Function

- Definition: Let T = Repair Time Random Variable. The <u>Maintainability Function</u> M(t) is defined by M(t) = P(T≤t)
  - Example: Suppose T is exponential with repair rate λ.

    Mean time to repair:

$$MTTR = \frac{1}{\lambda}$$

$$M(t) = 1 - e^{-\lambda\ t} = 1 - e^{\frac{-t}{MTTR}}$$

Other Distributions Used

- Normal - Simple, remove and plug in.
- Lognormal - complex repair; multiplicative degradation model.
- Weibull - Variety of situations…most versatile. A generalization of the exponential, which has constant failure rate. Often used for “worst link”or “first of many flaws to produce a failure.”

Properties of Weibull Distribution

- Invented in 1951; tried to create $h(t) = at^b, t \leq 0$
- Set, $H(t) = (\lambda\ \mathrm{t})^{\beta}$, β controls shape of h(t), $\beta = 1$ is exponential
- Then, $h(t) = \frac{dH(t)}{dt} = \beta\ \lambda(\lambda\ \mathrm{t})^{\beta-1}$
- $F(t) = 1 - e^{-Ht} = 1 - e^{-(\lambda\,\mathrm{t})^{\beta}} = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}, \theta = \frac{1}{\lambda}$
- Adjoin a third “shift” parameter δ≥0, which shifts left endpoint of range of distribution:[δj+∞]. Require θ>δ≥0

Properties of Weibull Distribution(cont)

- Final Result

$$h(t) = \frac{\beta(t-\delta)^{(\beta-1)}}{(\theta-\delta)^{\beta}}$$

$$F(t) = 1 - e^{-\left(\frac{t-\delta}{\theta-\delta}\right)^{\beta}} \qquad \mathrm{R(t)} = \mathrm{e}^{-\left(\frac{\mathrm{t}-\delta}{\theta-\delta}\right)^{\beta}}$$

$$MTTR \ or \ MTBF = \delta + (\theta-\delta)\Gamma(1+\frac{1}{\beta})$$

$$\Gamma(t) = \int_{0}^{\infty} y^{t-1}e^{-y}dy \qquad \tilde{M} = \theta(\ln 2)^{\frac{1}{\beta}} + \delta$$

Howβ Controls Shape of h(t) For Weibull Distribution

This is a handout

Weibull Closure Property

- Recall for n exponential-life components with rates $\lambda_1, \lambda_2, ..., \lambda_n$ and a series system $\lambda_s = \sum_{i=1}^{n} \lambda_i$
- If a series system has:
  - n independent parts, each Weibull with the same β

    $$\theta_1 = \frac{1}{\lambda_1}, \theta_2 = \frac{1}{\lambda_2}, ..., \theta_n = \frac{1}{\lambda_n}$$

    The respective characteristic lives

Weibull Closure Property(cont)

- Then
  - System Lifetime Distribution is Weibull with shape parameter β
  - and,

$$\lambda_s = \left(\sum_{i=1}^{n} \lambda_i^{\beta} \right)^{\frac{1}{\beta}} \qquad \theta_s = \left(\sum_{i=1}^{n} \lambda_i^{\beta} \right)^{\frac{-1}{\beta}}$$

Example

- 5 Hoses in an Engine Cooling System have β=1.8, Respective θ1= 95, θ2= 110, θ3=130, θ4=130, θ5=150 months, then
-

$$O_s = \left(\frac{1}{95^{1.8}} + \frac{1}{110^{1.8}} + \frac{1}{130^{1.8}} + \frac{1}{150^{1.8}}\right)^{-\frac{1}{1.8}} = 48.6 \text{ months}$$

$$\tilde{R} = 48.6(\ln 2)^{\frac{1}{1.8}} = 39.6 \text{ months}$$

$$\text{MTBF} = 48.6\Gamma\left(1 + \frac{1}{1.8}\right) = 43.2$$

Properties of Lognormal Distribution

- Definition - X is lognormal with range space (0, + ∞), parameters μ and σ IFF Y= ln X, is normal with parameters μ and σ
  - Mode of X at $x = e^{\mu_y - \sigma_y^2}$
  - Median of X at $x = e^{u_y}$
  - Mean of X at $\mu_x = e^{\mu_y + \frac{1}{2}\sigma_y^2}$
  - Variation of X is $\sigma_x^2 = e^{2\mu_y + \sigma_y^2}\left(e^{\sigma_y^2} - 1\right)$

Properties of Lognormal Distribution (cont)

- Properties
- 1. If X_1 lognormal $\left(\mu_{y1},\sigma_{y1}^2\right)$, X_2 lognormal$\left(\mu_{y2},\sigma_{y2}^2\right)$ *and* X_1, X_2 independent; then $W = X_1 * X_2$ is lognormal with $\left(\mu_{y1}+\mu_{y2},\sigma_{y1}^2+\sigma_{y2}^2\right)$
- 2. If Xj, j=1,…,n are lognormal $\left(\mu_y,\sigma_y^2\right)$ and independent, then the geometric mean $\left(\prod_{j=1}^{n} x_j\right)^{\frac{1}{n}}$ is lognormal $\left(\mu_y,\frac{\sigma_y^2}{n}\right)$
  -

Example 1 pp.395-398

- Assumes normal
- Takes $\overline{X}$, s to be μ,σ. Is this ok ?
- What's wrong with equation 14.1 ?

Example 2

- Suppose n Components in series, each exponential with λI failure rate for component I; Let Mcti= time to repair system when ith component fails. Then $\overline{M}_{ct} = MTTR$ for system is estimated by (14.2)

$$\overline{M}_{ct} = \frac{\sum_{i=1}^{n} x_i M_{cti}}{\sum_{i=1}^{n} \lambda_i}$$

Repair time per failure

Repair time/unit time

System failure/unit time

- If there are n_i of type i in the system, then use:

$$\overline{M}_{ct} = \frac{\sum_{i=1}^{n} n_i \lambda_i M_{cti}}{\sum_{i=1}^{n} n_i \lambda_i}$$

Example 2 (cont)

i Assemblies	n_i . Components	λ_i *10^3hrs	M_{cti} (hr)	Repair Time per 10^3hr $n_i\lambda_i M_{cti}$
1	4	10	.1	4.0
2	6	5	.2	6.0
3	2	8	1.0	16.0
4	1	15	.8	7.5
5	5	12	.5	30.5
		161		63.5

$$\text{MTTR} = \frac{63.5}{161} = 0.394\ \textit{hours}$$

Mean Preventative Maintenance Time

- Includes
  - Inspection
  - Servicing, Cleaning
  - Replacements
  - Calibration
  - Overhaul

$$\overline{M}_{pt} = \frac{\sum_{i=1}^{n} (fpt_i)(M_{pti})}{\sum_{i=1}^{n} (fpt_i)}$$

Where fpti = frequency of the ith preventive maintenance action

Mpti = elapsed time for ith preventive maintenance action

Median (Active) Corrective Maintenance Time

- For sample of size n on Mct for one component

$$\tilde{M}_{ct} = e^{\left[\frac{\sum_{i=1}^{n} \ln M_{cti}}{n}\right]}$$

- For m classes of corrective maintenance on system, with respective failure rates λi

$$\tilde{M}_{ct} = e^{\left[\frac{\sum_{i=1}^{m} \lambda_i \ln M_{cti}}{\sum_{i=1}^{m} \lambda_i}\right]}$$

Note: It is possible to do the computations using log10 versus 10^x versus e^x

Median (Active) Preventative Maintenance Time

$$\tilde{M}_{pt} = e^{\left[\frac{\sum_{i=1}^{n} (fpt_i)\left(\ln M_{pti}\right)}{\sum_{i=1}^{n} fpt_i}\right]}$$

Mean (Active) Maintenance Time

$$\overline{M} = \frac{\lambda \overline{M}_{ct} + fpt \overline{M}_{pt}}{\lambda + fpt}$$

- λ = Overall Corrective Maintenance Rate

  $\sum \lambda_i$

- fpt = Preventive Maintenace Rate

  $\sum fpt_i$

Maximum(Active) Corrective Maintenance Time

$$M_{\max} = e^{\left[\frac{\sum_{i=1}^{n} \ln M_{cti}}{n} + Z_{\alpha}\sigma_y\right]}$$

Where;

$$\sigma_y = \sqrt{S_y^2} = \sqrt{\frac{\sum (\ln M_{cti})^2 - \frac{\left[\sum (\ln M_{cti})\right]^2}{n}}{n-1}}$$

Other Maintenance Elapsed-Time Measures

- Logistics delay time (LDT), waiting for
  - facility, equipment
  - Spare part
  - Tool
  - Transport
- Administrative delay time (ADT)
  - Organizational (people, paper, priorities, etc)
  - Non-physical

Other Maintenance Elapsed-Time Measures(cont)

- Maintenance Downtime (MDT)
  - MDT = $\overline{M}$+LDT+ADT
  - $$\overline{MDT} = \frac{\lambda_1 \overline{M} + \lambda_2 \overline{LDT} + \lambda_3 \overline{ADT}}{\lambda_1 + \lambda_2 + \lambda_3}$$
    - where λi= frequency of respective action/ delay

Maintenance Labor Hour Factors

- Together with skill levels and their day rates, these factors determine labor cost of maintenance and number in each skill level per maintenance facility
  - MLH/OH
  - MLH/cycle
  - MLH/month
  - MLH/MA

Maintenance Labor Hour Factors(cont)

- Any of above can be expressed as average over all subsystems
- Can apply to corrective, preventive, pr total active
- Can apply to total maintenance downtime
- Conceptually, want to select skill levels and maintenance difficulty to minimize maintenance costs

---

Maintenance Frequency Factors

- Meantime Between Maintenance (MTBM)

$$MTBM = \frac{1}{\frac{1}{MTBM_u} + \frac{1}{MTBM_s}}$$

  - $MTBM_u$ is approximately MTBF, the reliability factor, although in general $MTBF \le MTBM_u$

Maintenance Frequency Factors(cont)

- Meantime Between Replacement (MTBR)
  - A part, component, or a subsystem must be replaced by a spare part from inventory. Major link between maintenance actions and logistics support system