USACE Asset Management Risk and Reliability Workshop

Using CI Ratings as an Estimate of Failure Probability

Allen C. Estes

United States Military Academy

Agenda

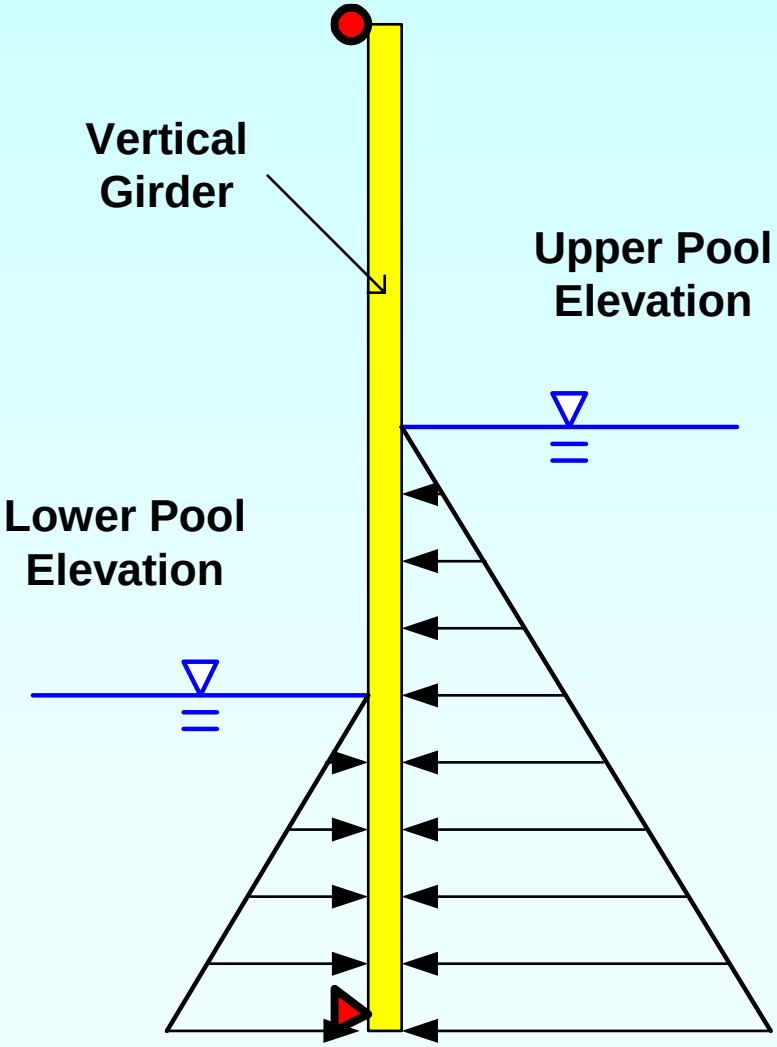
- Strength-based reliability
  - Miter gate example
- Serviceability-based reliability
  - Spillway gate system example
- Strengths and limitations

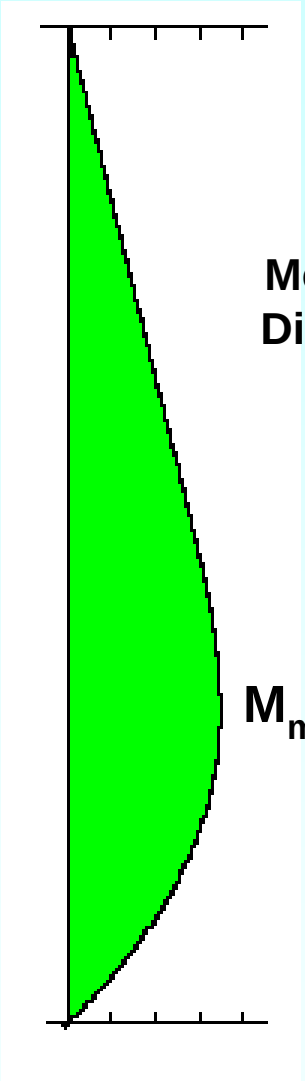
Reliability Methods

- Probabilistic Approach to Design and Analysis
- Corps of Engineers requires for major rehabilitation projects
- Used for life-cycle analysis
  - Probability of failure
  - Deterioration model
  - Hazard functions
- Reliability requires lots of data

Strength-Based Reliability
Miter Gate: Lock and Dam #12

Hydrostatic Forces on Vertical Girder





Reliability of Miter Gate on Lock 12

Actual Stress

$$\sigma_{actual} = M_{\max} y_{NA} k_s / I_{NA}$$

$$y_{NA} = \frac{\sum \bar{y} A}{\sum A}$$

$$I_{NA} = \sum (\overline{I_{NA}} + A\overline{d^2})$$

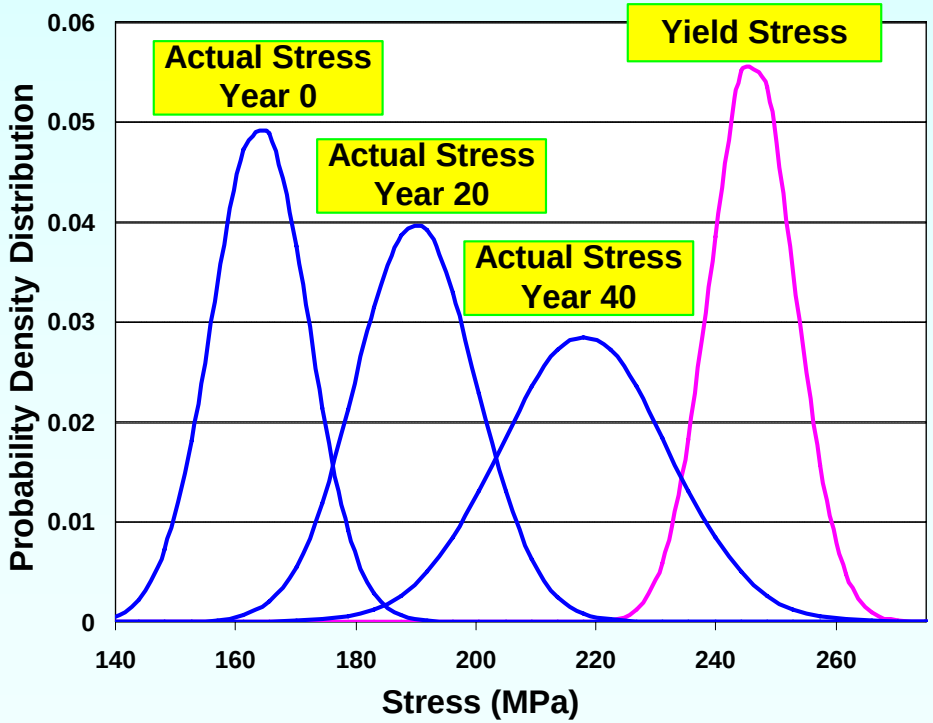
As time passes and corrosion ensues

Yield Stress

$$\sigma_y = N[34.8,\ 3.48]$$

Reliability

$$\Pr\left(\sigma_{actual} < \sigma_y\right)$$



Deterioration Model

Atmospheric Zone

$$\log C = \log 23.4 + 0.65 \log t + \varepsilon_c$$

Splash Zone

$$\log C = \log 148.5 + 0.903 \log t + \varepsilon_c$$

C = Thickness loss due to corrosion (micrometers)

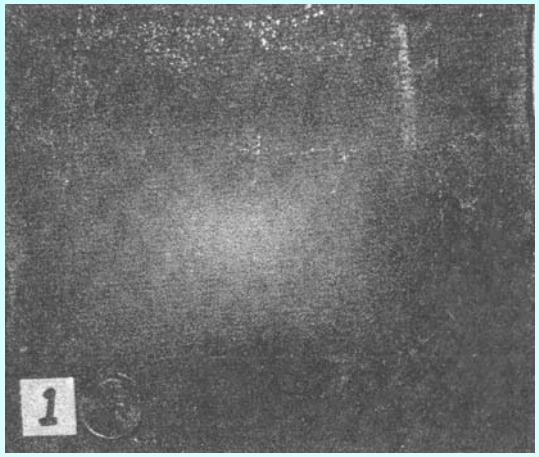
t = time (years)

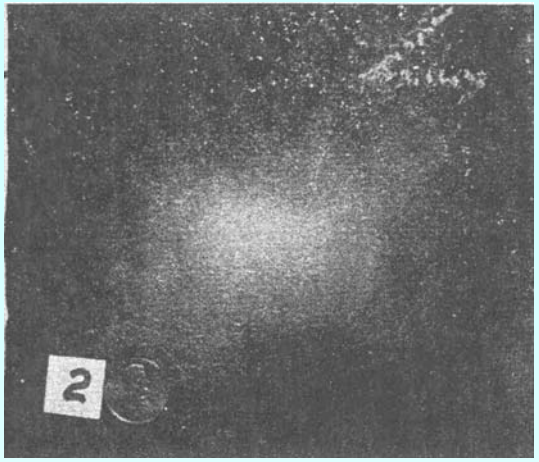
ε_c = uncertainty factor (mean = 0; Std. Deviation 0.099/0.219)

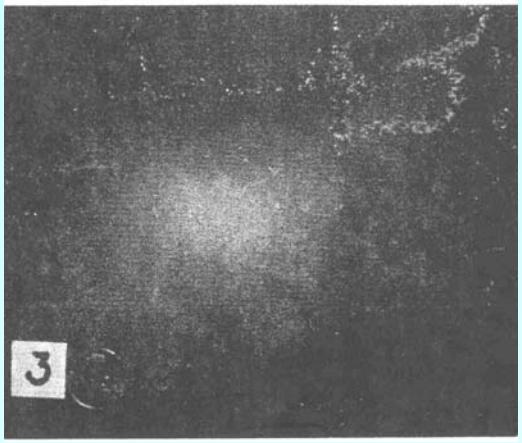
Condition Index Description: Corrosion

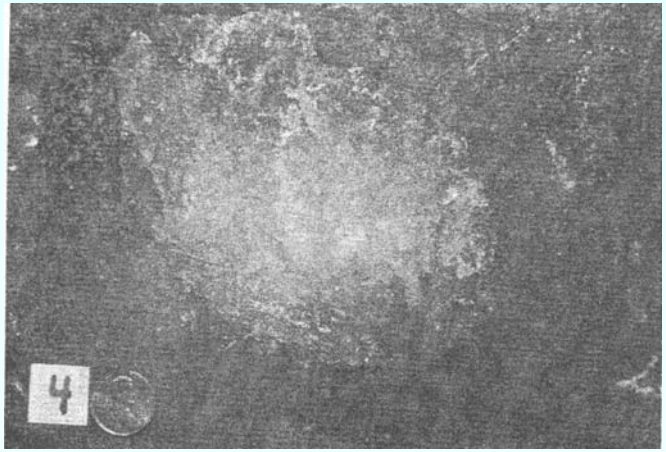
Level	Description
0	New
1	Minor surface scale
2	Moderate pitting
3	Severe pitting
4	Obvious thickness reduction
5	Holes due to thickness reduction

Condition State Guides

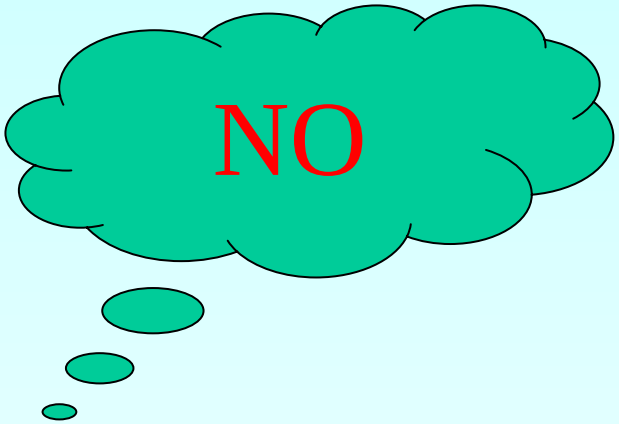








Can I use this to update reliability?



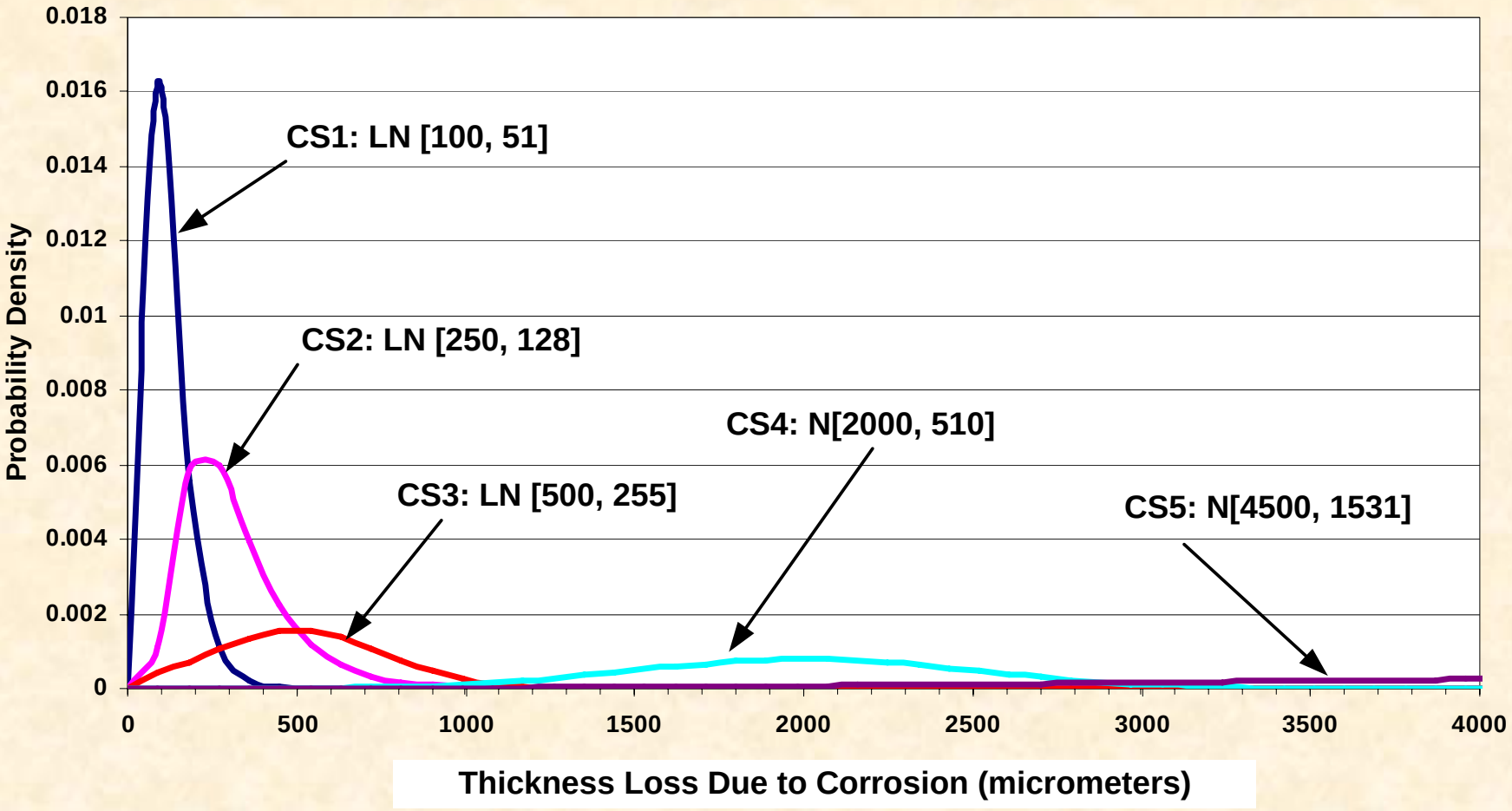
Well, what would it take?

- Quantify the condition levels
- Segment-based inspection

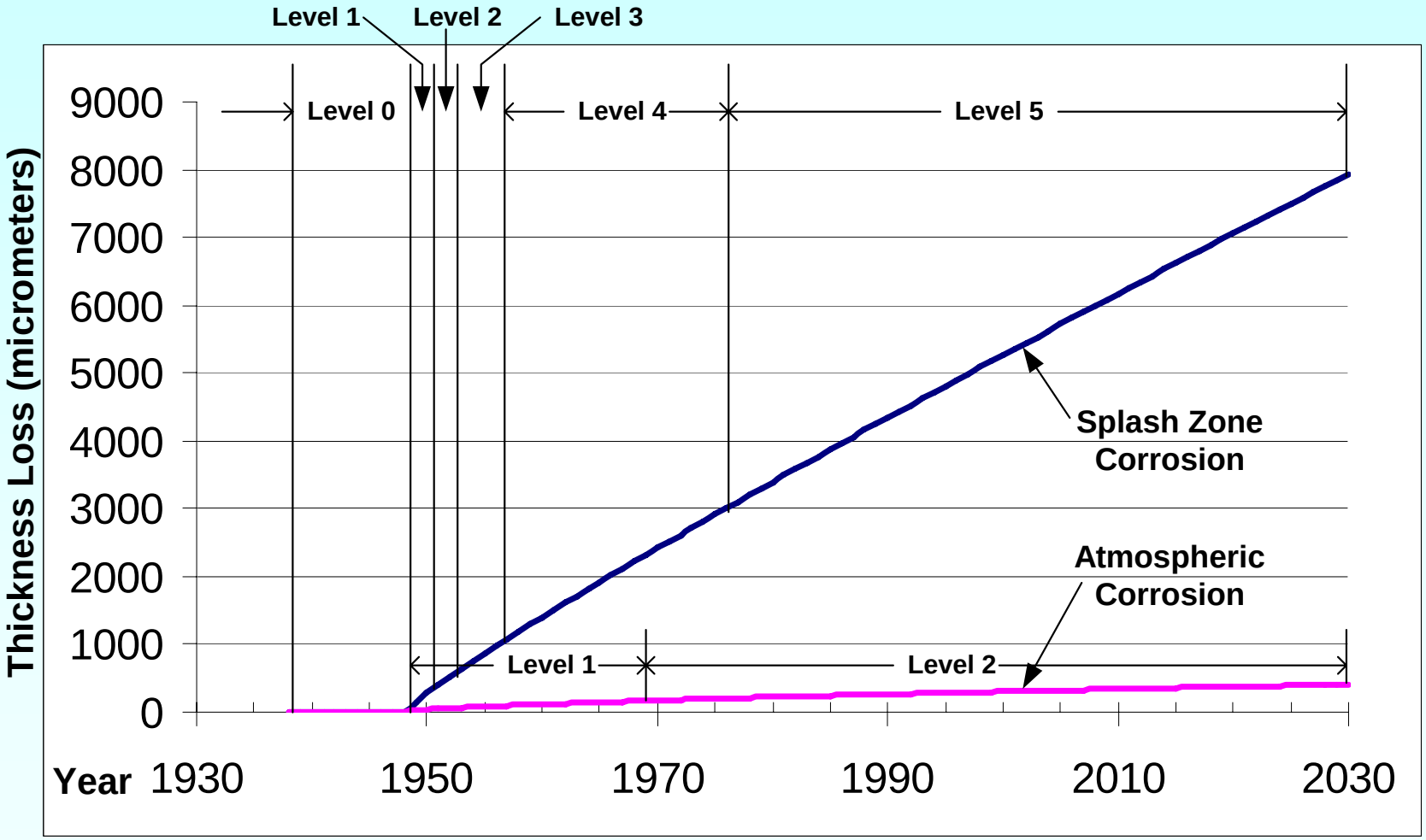
Corrosion Levels Quantified

Level	Description	Thickness Loss (μm)
0	New	0
1	Minor surface scale	0-200
2	Moderate pitting	0-500
3	Severe pitting	0-1000
4	Obvious thickness reduction	1000-3000
5	Holes due to thickness reduction	>3000

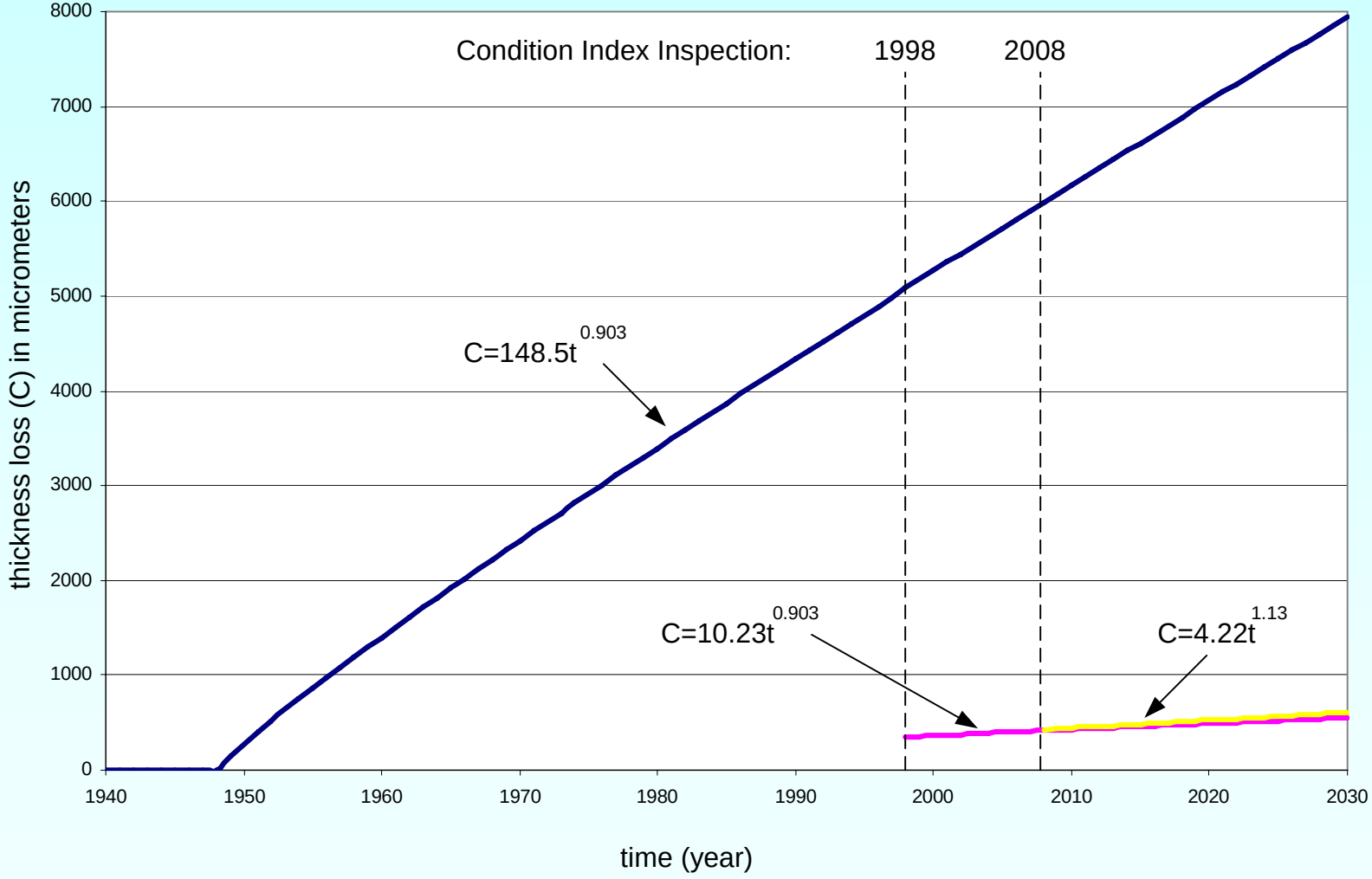
Corrosion Condition State Distributions



Projected Condition State Deterioration



Revised Splash Zone Corrosion Model



CI Limitations

- Not designed to accommodate reliability
- Based on subjective judgment of inspector
- Not enough information to quantify in probabilistic terms
- CI rating based on condition of the worst element
- Not conducted regularly -- no knowledge of condition state transition

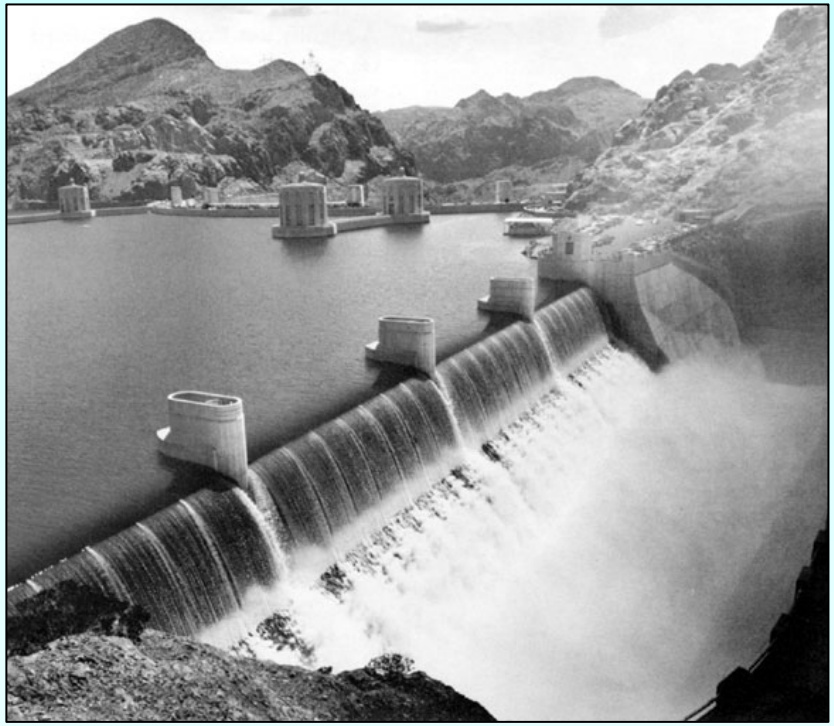
Strength-Based Conclusions

- Visual inspection information can be used to update reliability analyses
  - in some cases
  - with some modification
- Case studies show
  - Works well for external corrosion
  - Moderately well for internal corrosion
  - Poorly for fatigue
- Potential exists to use visual inspection data to update deterioration on many structures
- People who design visual inspections and the people who use the data need to talk
- The information is already there – we should use it

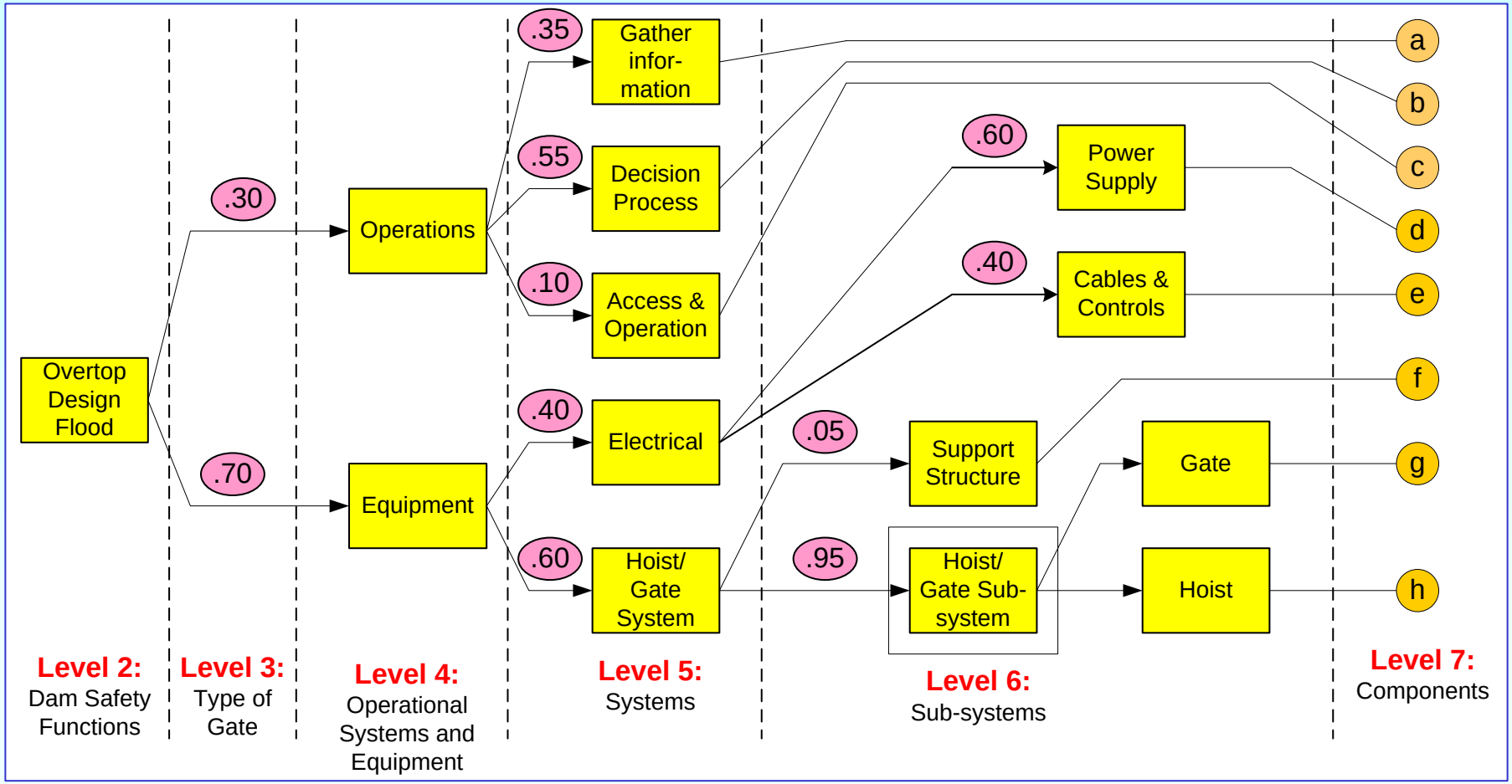
Serviceability-Based Reliability

- Serviceability issues typically drive repair and rehabilitation decisions
- Periodic inspection results are best measure of overall structural condition
  - The Corps has developed condition index rating systems for many structures
  - Condition index ratings are deterministic, have lots of variables, and are tough to quantify
  - AND, they currently have no data
- Can we use the condition index ratings to quantify the risk to a structure for purposes of repair and replacement?

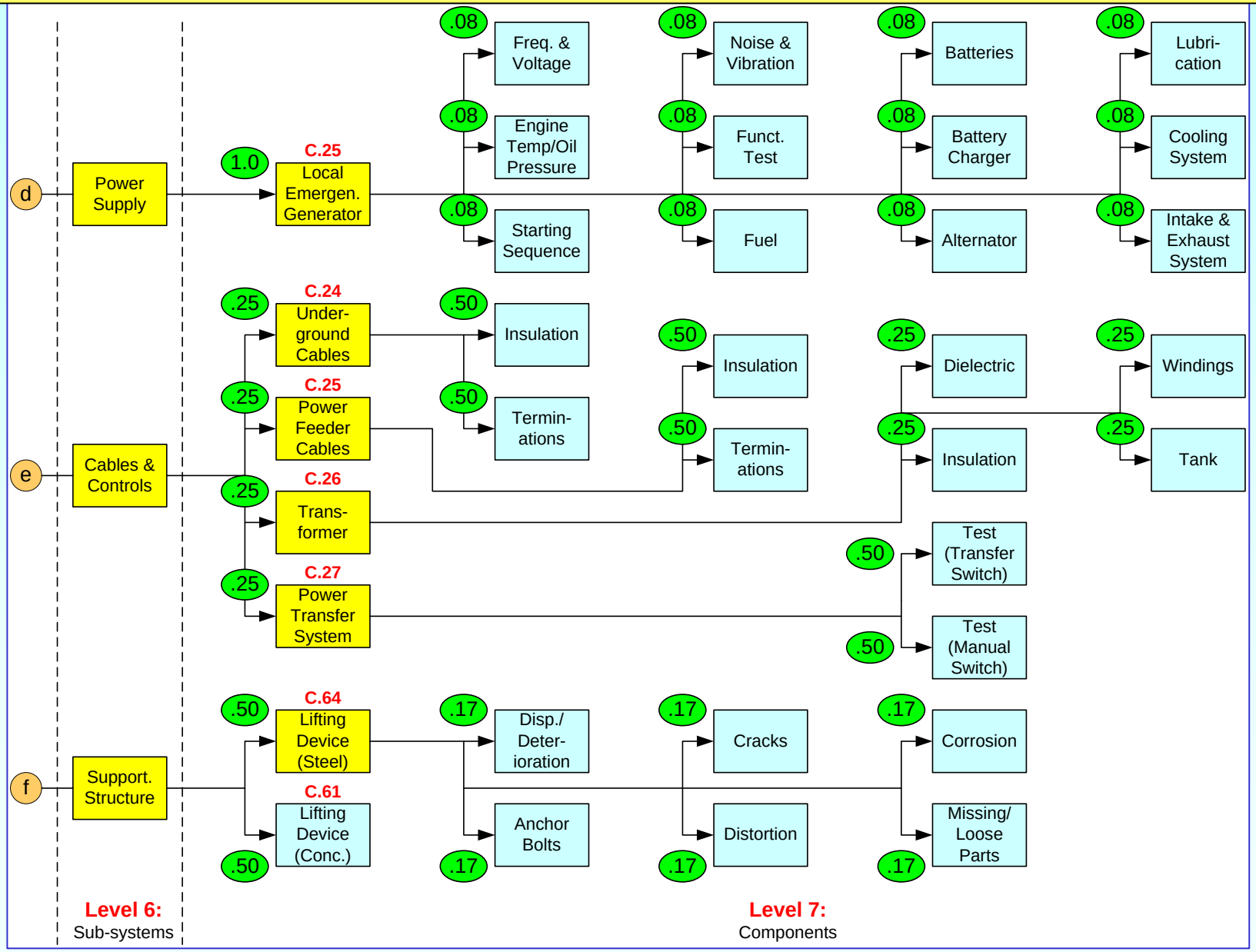
Spillway Gates on Dams



Great Falls Dam



Great Falls Dam



Typical Component Condition Table

Hoist Brake								
Function	To arrest motion of gate and hold gate in any position							
Excellent	Can arrest motion at any position, not seized							
Failed	Cannot arrest motion at any position, seizing of brake							
Indicator	0-9	10-24	25-39	40-54	55-69	70-84	85-100	Score
Can arrest motion at any position, not seized							x	
Limited slippage without impacting operation; no slip but vibration				x	x	x		
Limited slippage that impacts operation		x	x					
Continuous slippage, seizing of brake	x							

Serviceability: Condition Index

CI Value	Condition Description	Zone	Action
85-100	Excellent; no noticeable defects	1	Immediate Action not required
70-84	Very good: minor deterioration only		
55-69	Good: some deterioration or defects evident	2	Economic analysis of repair alternatives recommended
40-54	Fair: moderate deterioration; function still adequate		
25-39	Poor: serious deterioration; function inadequate	3	Detailed evaluation required to determine need for repair, rehabilitation or reconstruction
10-24	Very Poor: extensive deterioration, barely functional		
0-10	Failed: no longer functional		

General Approach

- Risk is product of Probability of Failure and Consequences
- Condition Index is the random variable
- Random variable assumptions
  - Normally distributed
  - Independent
- Probability of failure (repair/replacement action)

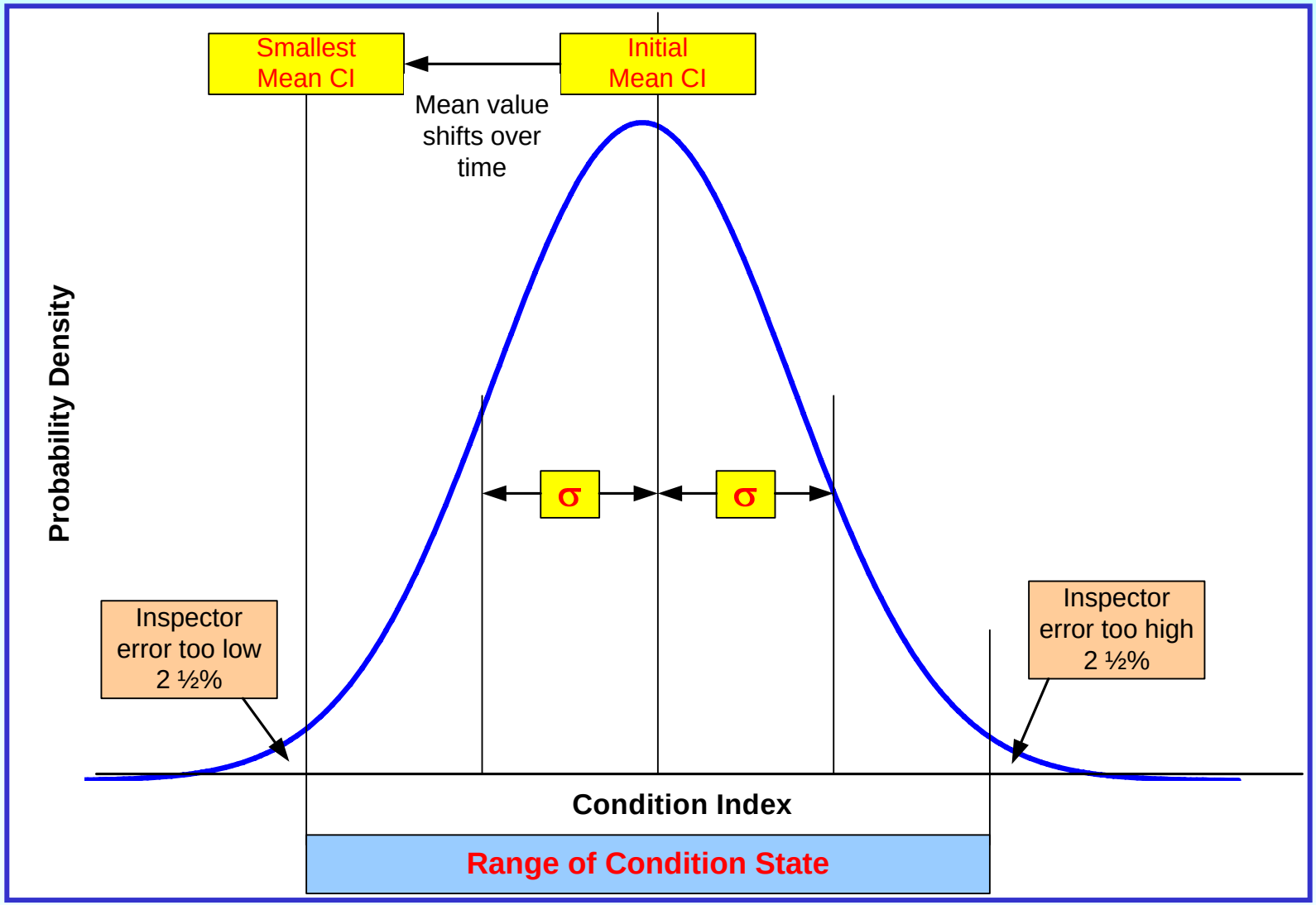
$$P_f = P(CI_{actual} < CI_{failure})$$

- Structural systems are a function of
  - Component condition
  - Component importance

General Assumptions

- Initially enter a condition state at the mean value
- Inspector correctly identifies condition 95% of the time
- Inspector error is equally distributed between high and low
- Failure is defined as mean CI = 25; σ = 12.75
  - 0 – 40 is failure range in description
  - 88 % of failures occur in that range; 10 % in 40 – 50 range
  - Values will improve with a database established
- Linear transition through condition states based on expected life of structure
- If expected life is exceeded, mean CI remains at lowest value in the condition state

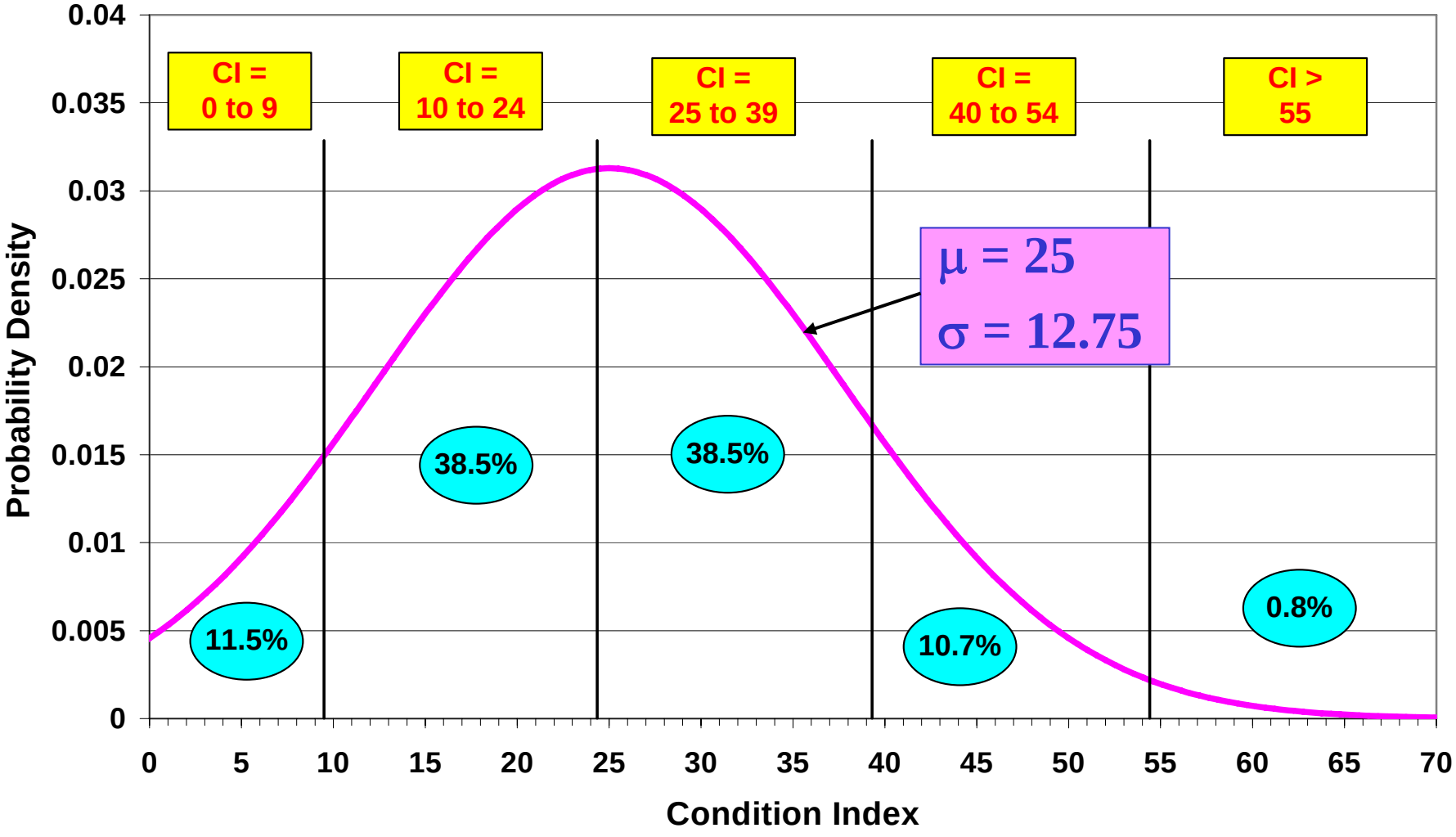
Condition Index Assumptions



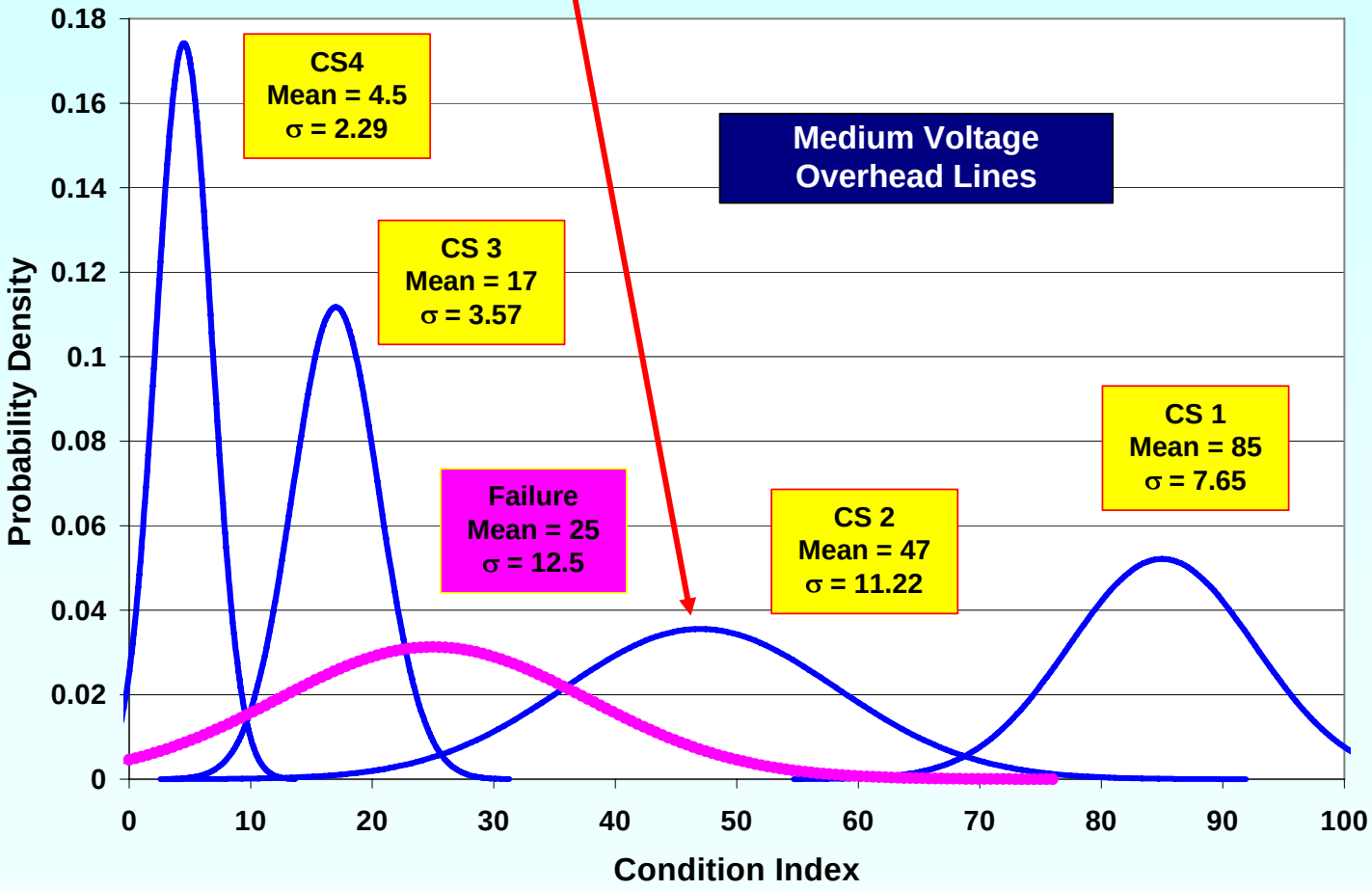
Serviceability: Condition Index

CI Value	Condition Description	Zone	Action
85-100	Excellent; no noticeable defects	1	Immediate Action not required
70-84	Very good: minor deterioration only		
55-69	Good: some deterioration or defects evident	2	Economic analysis of repair alternatives recommended
40-54	Fair: moderate deterioration; function still adequate		
25-39	Poor: serious deterioration; function inadequate	3	Detailed evaluation required to determine need for repair, rehabilitation or reconstruction
10-24	Very Poor: extensive deterioration, barely functional		
0-10	Failed: no longer functional		

Quantification of Failure



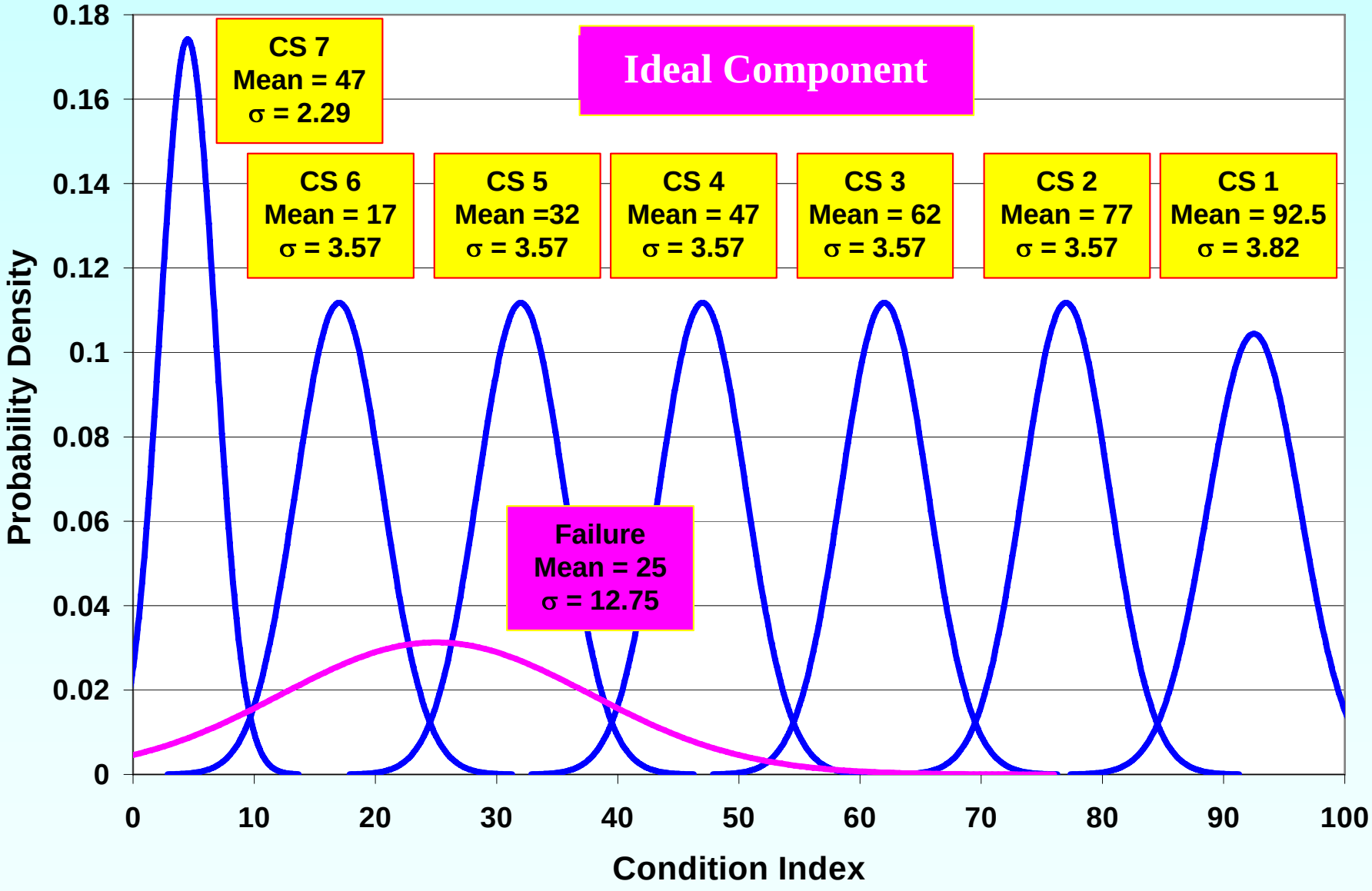
Medium Voltage Overhead Wires									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1						x	x	85	7.65
2			x	x	x			47	11.22
3		x						17	3.57
4	x							4.5	2.29



Ideal Component

Ideal Component									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1							x	92.5	3.82
2						x		77	3.57
3					x			62	3.57
4				x				47	3.57
5			x					32	3.57
6		x						17	3.57
7	x							4.5	2.29

Ideal Component



System Condition Index

Mean Value (Chouinard *et.al.* 2003) Eqn [4.5]

$$CI_{Structure} = \sum_{j=1}^{n} I_j CI_j = I_A CI_A + I_B CI_B$$

Standard Deviation

$$\sigma_{CI_{Structure}} = \sqrt{\sum_{j=1}^{n} I_j^2 \sigma_j^2} = \sqrt{I_A^2 \sigma_A^2 + I_B^2 \sigma_B^2}$$

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Power Supply			86.25	2.07	4.74	
Local or Emergency Generators	7d	1.00	86.25	2.07	4.74	C.25
Frequency and Voltage	7d.1	0.08	85.00	7.65	4.03	
Engine Temperature / Oil Pressure	7d.2	0.08	85.00	7.65	4.03	
Starting Sequence	7d.3	0.08	85.00	7.65	4.03	
Noise and Vibratiion	7d.4	0.08	85.00	7.65	4.03	
Functional Test	7d.5	0.08	92.50	3.83	5.07	
Fuel	7d.6	0.08	92.50	3.83	5.07	
Batteries	7d.7	0.08	85.00	7.65	4.03	
Battery Charger	7d.8	0.08	85.00	7.65	4.03	
Alternator	7d.9	0.08	85.00	7.65	4.03	
Lubrication	7d.10	0.08	85.00	7.65	4.03	
Cooling System	7d.11	0.08	85.00	7.65	4.03	
Intake and Exhaust System	7d.12	0.08	85.00	7.65	4.03	
Cables and Controls	7e		87.94	2.57	4.84	
Underground and Encased Cables	7e.1	0.25	85.00	5.41	4.33	C.24
Insulation	7e.1.1	0.50	85.00	7.65	4.03	
Terminators	7e.1.2	0.50	85.00	7.65	4.03	
Power Feeder Cables	7e.2	0.25	85.00	5.41	4.33	C.25
Insulation	7e.2.1	0.50	85.00	7.65	4.03	
Terminators	7e.2.2	0.50	85.00	7.65	4.03	
Transformer	7e.3	0.25	89.25	5.69	4.60	C.26
Dielectric	7e.3.1	0.00	N/A	N/A	N/A	
Insulation	7e.3.2	0.50	85.00	7.65	4.03	
Windings	7e.3.3	0.55	85.00	7.65	4.03	
Tank	7e.3.4	0.00	N/A	N/A	N/A	
Power Source Transfer System	7e.4	0.25	92.50	3.83	5.07	C.27
Test (Transfer Switch)	7e.4.1	0.00	N/A	N/A	N/A	
Test (Manual Transfer Device)	7e.4.2	1.00	92.50	3.83	5.07	
Supporting Structure	6e		92.50	2.07	5.22	
Lifting Device Structure (Steel)	7f.1	0.50	92.50	1.56	5.25	C.64
Displacement / Deterioration	7f.1.1	0.17	92.50	3.83	5.07	
Anchor Bolts	7f.1.2	0.17	92.50	3.83	5.07	
Cracks	7f.1.3	0.17	92.50	3.83	5.07	
Distortion	7f.1.4	0.17	92.50	3.83	5.07	
Corrosion	7f.1.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7f.1.6	0.17	92.50	3.83	5.07	
Lifting Device Structure (Concrete)	7f.2	0.50	92.50	3.83	5.07	C.61

Derived from a Combination of Inspected Items

Directly Measured by Inspection

Conclusions: Strengths

- Based on the assumptions, a risk-based approach is possible
- Structure is described in visible hierarchical format; easy to include/exclude variables
- Inspector is only required to choose the condition state
- Range and inspector uncertainty is quantified
- Linear transition accounts for effects of aging
- Normal, independent assumptions make computations easy
- Methodology can be applied to any structure
- Any relevant variable can be included
- Wrong assumptions are corrected as data becomes available
- System CIs provide effective means of comparison between entire structures

Conclusions: Limitations

- Not based on any real data; assumptions have not been verified
- System CI proposal is controversial; violates rules of traditional reliability
- Linear transition across condition states needs further analysis
- Not a replacement for a traditional reliability analysis
- Need a red flag provision for component CI scores lower than CI = 40

Recommendations

- Apply methodology to a single class of structures to
  - develop procedural modifications
  - verify assumptions
  - time dependence on real structure
  - compare with cost-benefit from traditional reliability
- Investigate for other types of structures (i.e., bridges, buildings)
- Corps of Engineers needs to commit to CI inspections
  - Mandatory for all USACE districts
  - Centralized consolidation of data
  - Publish deterioration rates

USACE Asset Manageme Risk and Reliab Wo op

Us in Esti e Pro ability

Questions?

Allen C. Estes

United States Military Academy