A Physics-of-Failure Approach for Common Cause Failures Subject to Age-Related

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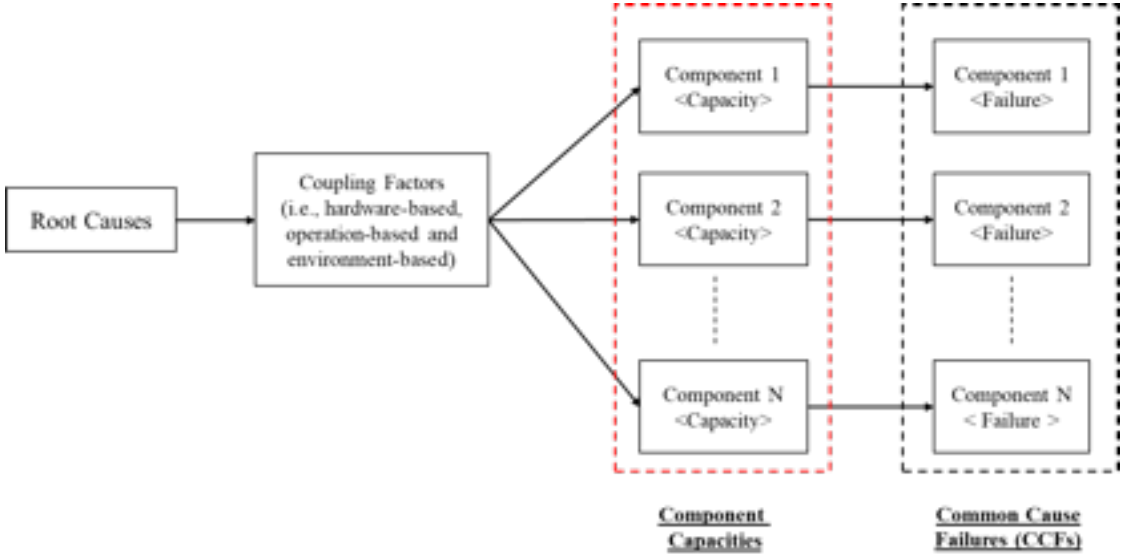
Background



- Sources: historical observations and expert judgment
- CCF Model: shock model and non-shock model

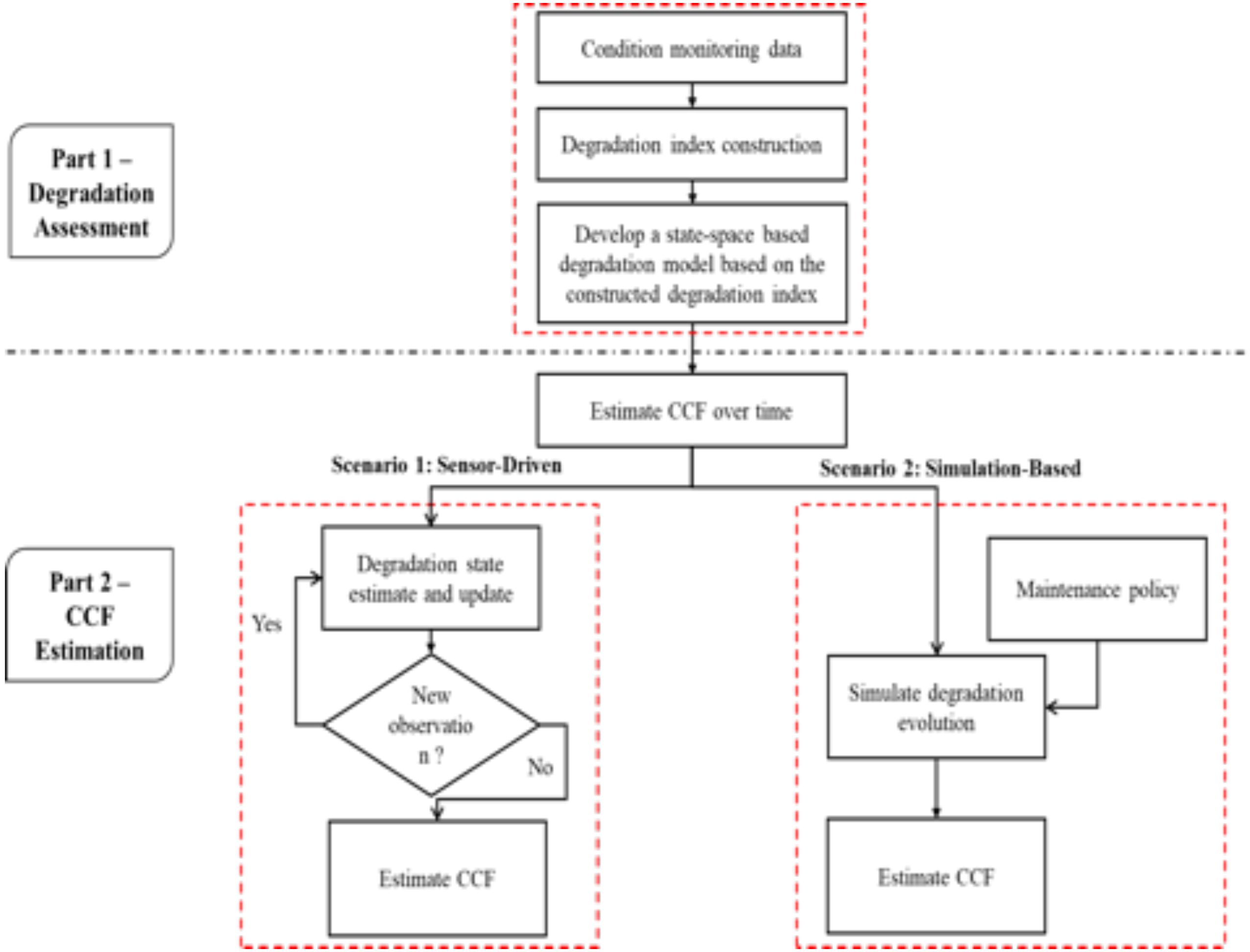
Limitations of the CCF models:

- Built from generic operational experience and not specific to components.
- Do not model asymmetrical components
- Difficulties in modeling dependencies among component groups
- Limited observed CCF events
- Do not model degraded components

Objectives

- Develop A CCF model for components under age-related degradation:
  - Using data related to degradation (i.e., sensor-based condition monitoring data).
  - Advance CCF models to assist the studies of internal events of MUPRA.
  - Extend the generic parametric models to component-specific and dynamic.
  - Assess maintenance impacts.

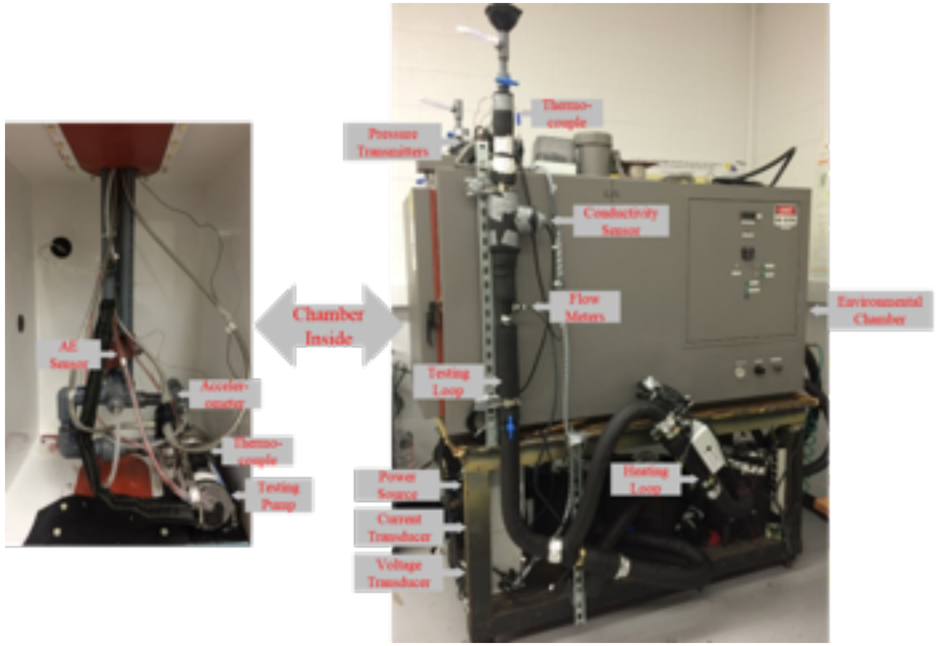
Approach



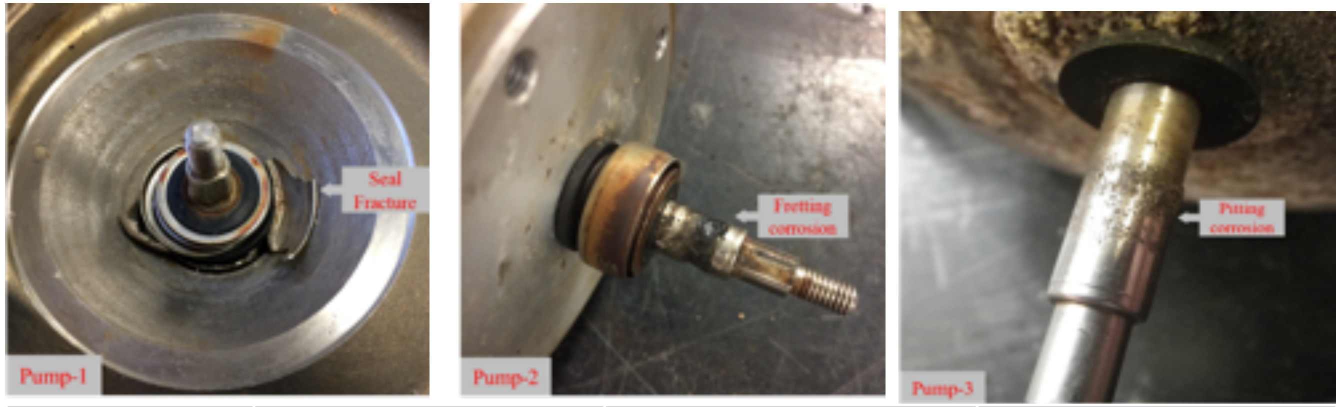
$$\beta_k = \frac{\sum_{j=1}^{N}\left\{I\left[2,\ \sum_{s=1}^{2} I\left(x_k^{(s,j)}, L_f\right)\right]\cdot \sum_{s=1}^{2} I\left(x_k^{(s,j)}, L_f\right)\right\}}{\sum_{j=1}^{N}\left\{I\left[1,\ \sum_{s=1}^{2} I\left(x_k^{(s,j)}, L_f\right)\right]\cdot \sum_{s=1}^{2} I\left(x_k^{(s,j)}, L_f\right)\right\}}$$
$$s = 1, 2; j = 1, \dots, N.$$

At Time Step k

Experimental Setup & Failure Analysis

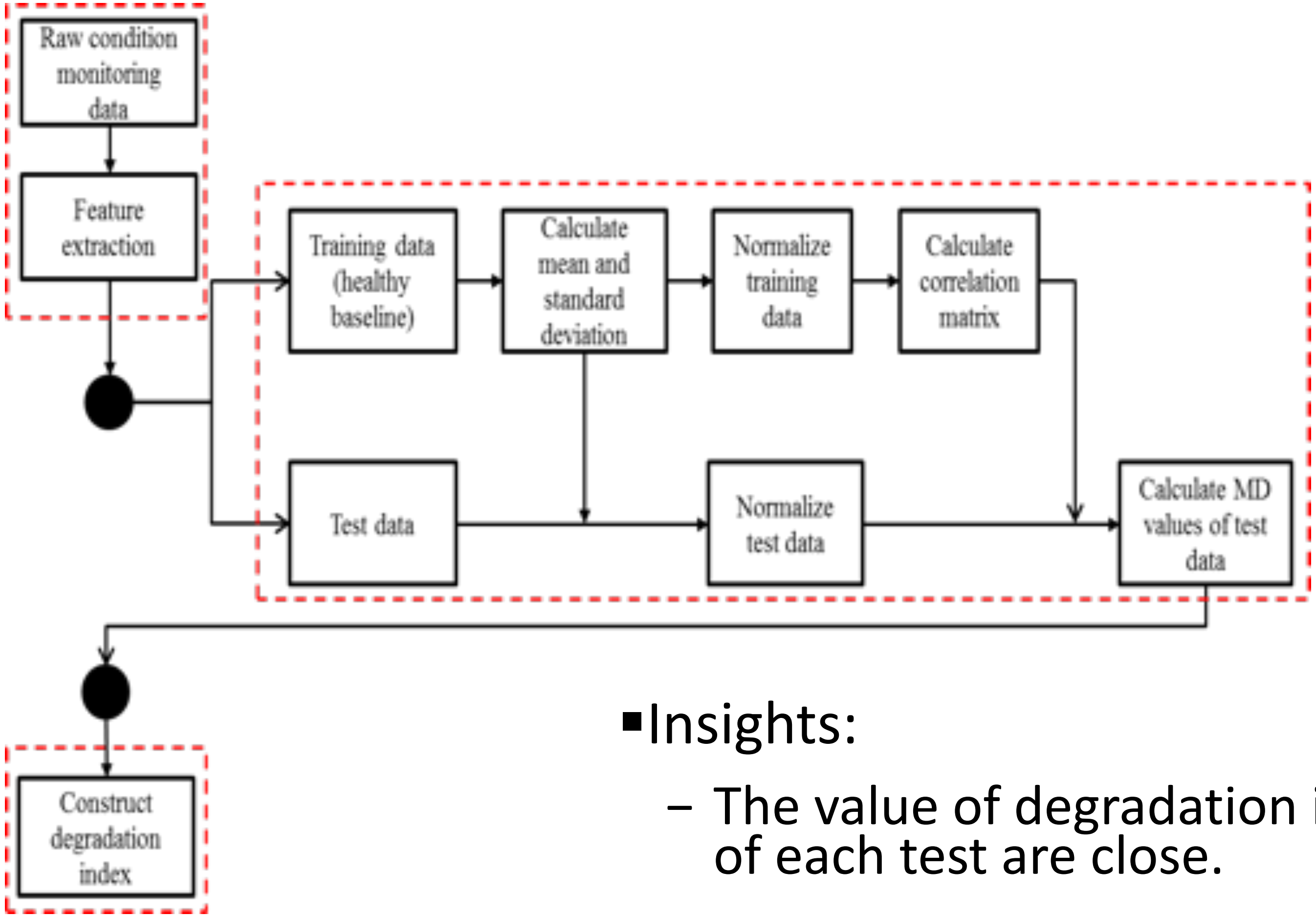


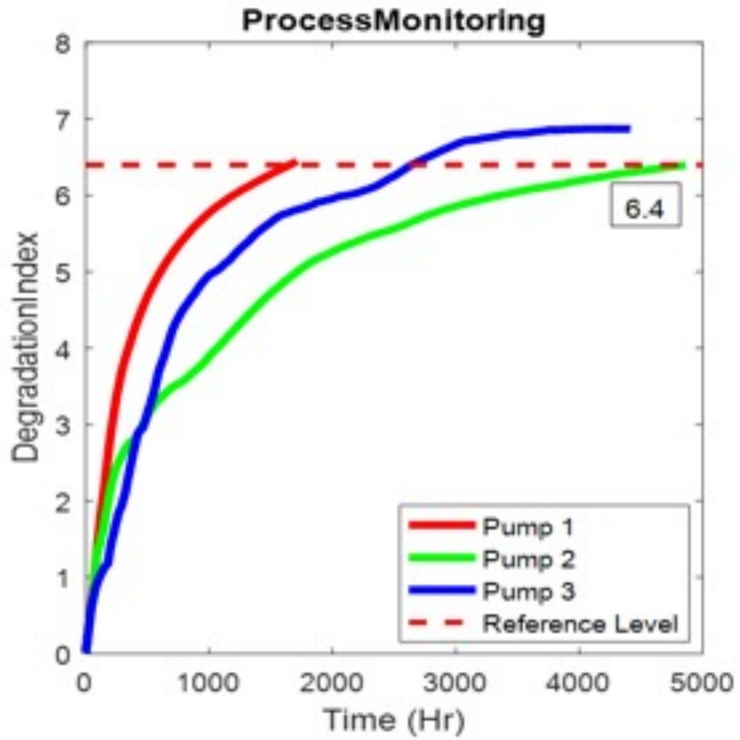
- Process Monitoring: flow Rate, differential pressure, electric current, and electric voltage
- Vibration Monitoring: three single-axis accelerometers
- AE Monitoring: three AE sensors located at suction, bearing and motor.



	Pump 1	Pump 2	Pump 3
Duration Until Failure	1954 hours	5103 hours	4654 hours
Failure Mode	Seal fracture	Shaft Corrosion	Leak
Failure Mechanism	Fatigue	Fretting corrosion	Pitting Corrosion
Failure Cause	Excessive fluid pressure on seal	Fretting corrosion in the contact surface	Pitting corrosion in the contact surface

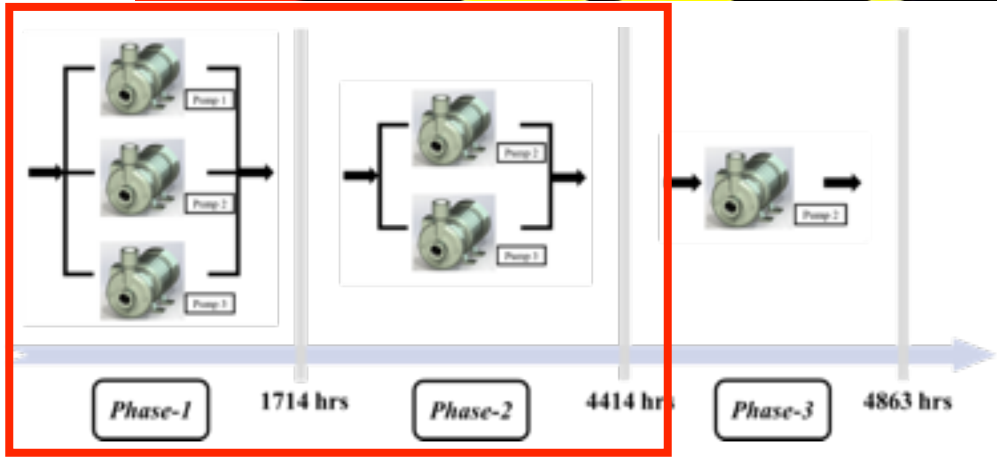
Degradation Assessment

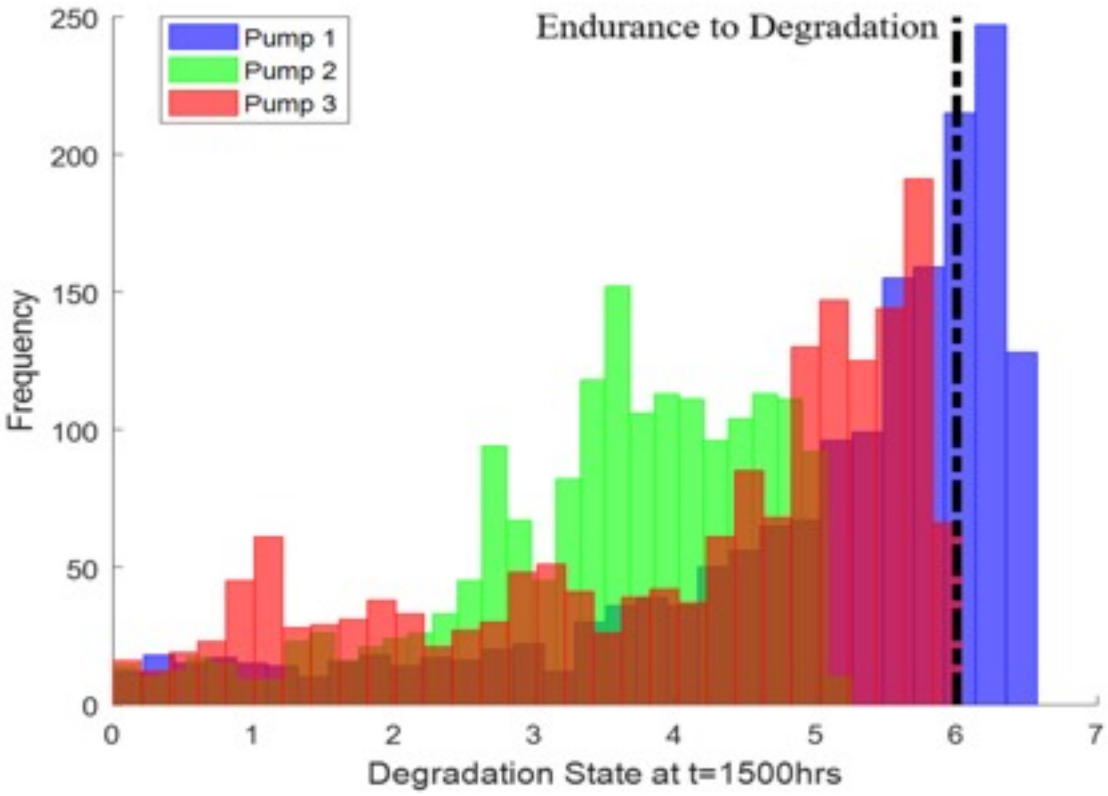




- Insights:
  - The value of degradation index by the end of each test are close.
  - All three types of failure mechanisms follow the same functional path.

Results for Sensor-Driven Scenario

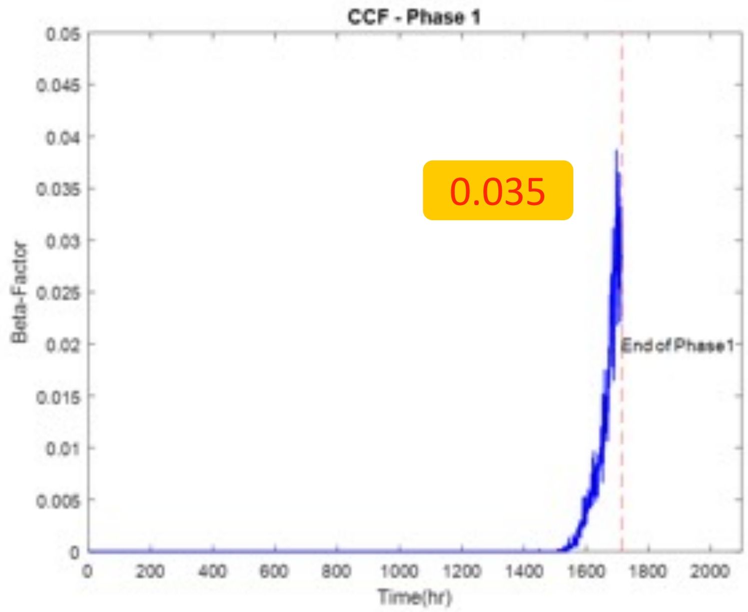


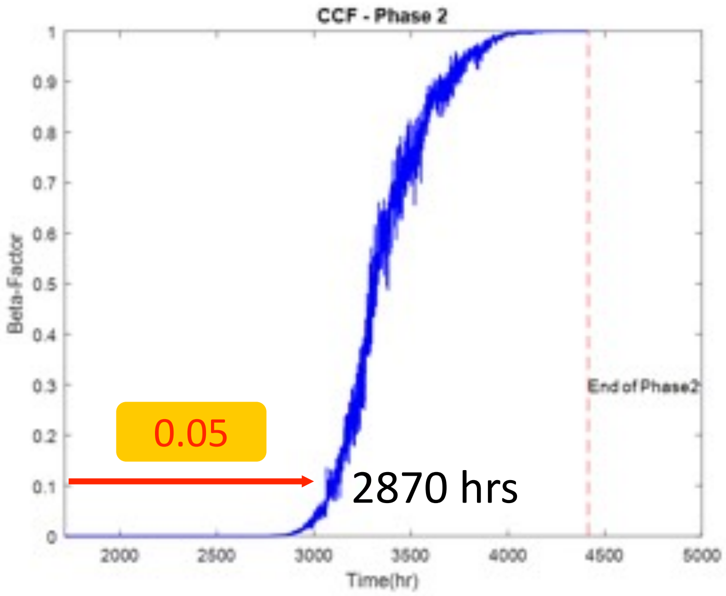


CCF at 1500 hours estimated based on the fractions of concurrent exceedance of failure threshold

Results for Sensor-Driven Scenario

- With newly acquired sensor monitoring data at each time instant, the degradation state of each pump would be estimated and utilized to update the CCF estimate.





- Phase-1: low β-factor and independent failure dominant.
  - Phase-2: β-factor approaches one since pump degrades without mitigating actions.
  - Allow one to determine the time that is required to implement mitigating actions. (β-factor=0.05 at 2870 hours)

Simulation-Based Scenario

Assumed An Inspection
Interval of 720 hours

- A condition-based maintenance policy
  - Subject to periodical Inspection that is perfect
  - Failure can only be detected at the time of inspection
  - The maintenance is imperfect due to degree of repair
  - Effectiveness is modeled by the Beta Distribution (α, γ).

Results for Illustrative Example

Mean	0.025
5% Quantile	0
Median	0.008
95% Quantile	0.084

- The evolution of β-factor shows a periodical increasing trend.
  - Mostly β-factor is close to zero and its distribution is highly skewed
  - Treating CCF using mean β-factor is not sufficient

Results for Sensitivity Analysis

27 Maintenance Polices

- β-factor ranges from 0.01 to 0.16
- With longer inspection intervals, the β-factor monotonically increases
- Better maintenance quality is associated with low β-factor. Poor maintenance quality with larger β-factor
- A small degradation in maintenance quality would lead to significant increase of β-factor
- Even under the perfect maintenance, it is still possible to underestimate plant risk

Conclusions

- Demonstrate the significance of CCF using a component-specific study
- Demonstrate the dynamic characteristics of CCF
- The age-related degradation and maintenance could significantly affect CCF
- Treating CCF with generic CCF parameters potentially underestimate plant risk if components degradation accumulates
- Treating CCF with generic CCF parameter potentially overestimates plant risk if maintenance effectively removes degradations
- The proposed approach estimates more component-specific CCF parameters
- Application of this approach to cases where little or no operational data are available such