Today’s Agenda

• Evolution of Maintenance and Driving Theory
  – Traditional Bimodal Maintenance
  – Reliability Centered Maintenance
  – Condition Based Maintenance
  – Performance Focused

• Three Case Studies
  – Cables
  – SF$_6$ Breakers
  – Transformer On-line Monitoring
Overhaul

Time

Traditional

PM

CM

Asset

Maintenance Evolution – Traditional
Characteristics of Traditional Maintenance

- Conservative/Excessive
- Intrusive
- Belief
- More Maint.
- Increased
- Reliability
- Generalized
## Traditional Maintenance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic inspection servicing is necessary</td>
<td>Time is poor predictor of wear</td>
</tr>
<tr>
<td>Acknowledgement that full equipment operating life is only possible if worn parts are replaced.</td>
<td>Overhauls create more problems than they solve</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
</tr>
<tr>
<td></td>
<td>Manufacturers did not understand the operating environment</td>
</tr>
<tr>
<td></td>
<td>Reliability and availability were not being met</td>
</tr>
</tbody>
</table>
Overhaul
Safety
Function
Criticality
Failure Cause
Effects
Time
Overhaul
Asset
RCM
Condition
Event
Failure Finding
Run to Failure
Traditional
PM
CM
Maintenance Evolution – RCM
RCM

“A structured process that identifies the effects of failures and defines the appropriate maintenance path for managing their impacts. RCM identifies both the most technically and economic effective approach to maintenance.”
RCM History

- Airlines
  - 1965 MSG-1 (Maint. Steering Group)
  - 1970 MSG-2
  - Experience
    - DC 8
      - 339 Scheduled Removal Tasks
      - 7 Scheduled Removal Tasks
    - 747
      - 8 Scheduled Removal Tasks
RCM History (cont.)

- Airline Observations:
  - Maintenance needs to focus on systems that have significant impact on safety or economics.
  - Hard time overhaul policies were ineffective.
  - Management of maintenance was crucial.
RCM History (cont.)

• US Navy
  – 1978 Contracted United Airlines

• US Electric Utilities - 80’s
  – EPRI Sponsored Nuclear 1985-1987
  – Fossil Fuel Plants

• US Electric Utilities - 90’s
  – Substations 1990
  – T&D

• EDF and Others
  – Nuclear Plants
  – Transmission Substations
RCM Task Selection

"The RCM task selection approach used to ensure that only applicable and cost effective tasks are selected to address the causes of critical equipment failure modes"

RCM Task Categories

– Inspection-Condition Monitoring-Predictive Maintenance
– Periodic
  • Rework-Time Directed
  • Discard-Time Directed
– Failure Finding
– Run to Failure
Simplified Task Selection Logic

- **Preserved**
- **Simplified**

### Task Selection Logic

1. **Mode & Cause Selected**
   - Review Effects
   - **Is Condition Monitoring Effective?**
     - **Is a periodic task effective?**
       - **Is the Failure Evident?**
         - **Can the failure be tolerated?**
           - **Is a time directed task effective?**
             - **Is Condition Monitoring Effective?**
               - **No-Design Change**
               - **Corrective Maintenance**
               - **Run to failure**
               - **No-Periodic PM**
               - **No-Failure Finding Task**

2. **Hidden Failure Finding**
   - **Yes**
   - **Yes**
   - **No**
   - **No**
   - **Yes**
   - **Yes**
   - **No**
   - **No**

3. **Operational Consequences**
   - Task must cost less than the consequences

4. **Non-Operational Consequences**
   - Task must cost less than repair

5. **Run to failure**

- **Safety Consequences**
  - Task must reduce risk of failure

- **PDM**

- **PM**

- **Design Change**
Characteristics of Reliability Centered Maintenance

- Focused on Dominant Causes
- Preservation of Function
- Specialized Tasks
# Reliability Centered Maintenance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Functions</td>
<td>Viewed as difficult and not applicable to power industry</td>
</tr>
<tr>
<td>Equipment and application specific</td>
<td>99.999% (1 hour of outage per year) reliability is difficult to understand</td>
</tr>
<tr>
<td>Greater insight into failure process</td>
<td>Living program forgotten</td>
</tr>
<tr>
<td>Eliminated ineffective tasks</td>
<td>Did not set maintenance intervals</td>
</tr>
</tbody>
</table>
Maintenance Evolution – CBM

- Overhaul
- Safety
- Function
- Criticality
- Event
- Failure Finding
- Failure Cause
- Effects
- Sensors
- Time
- Predictions
- Aging Models
- Real Time Data
- Predictive
- Proactive
- CM
- PM
- Condition
- Run to Failure
- Diagnostics
- RCM
- CBM
- Traditional
- Asset
Condition Based Maintenance

“Condition Based Maintenance accentuates the value of RCM task selection logic and emphasizes that more intrusive replacement and overhaul tasks only need to take place when measurable wear or aging occurs.”

“Condition Directed Tasks are initiated when deterioration has gone beyond a prescribed limit”
Characteristics of CBM

- Greater Reliance on Measurable Conditions
- Unobtrusive
- Aging Mechanism Understood
- Data Driven
# Condition Based Maintenance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased availability</td>
<td>Data systems were may not be adequate.</td>
</tr>
<tr>
<td>Reduced costs</td>
<td>Process management overlooked.</td>
</tr>
<tr>
<td>More frequent analysis of asset condition</td>
<td>No methodology for justifying increased monitoring</td>
</tr>
<tr>
<td></td>
<td>Increased back-office analysis</td>
</tr>
</tbody>
</table>
Maintenance Evolution – PFM
What is PFM?

**PFM** is a comprehensive maintenance strategy emphasizing the understanding of Failure Mechanisms, Measurement, Interval Optimization, Task Prioritization, Feedback and the use of Data. PFM recognizes the need for process control.

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*Mission critical goals and objectives are identified at the executive level. Bottom-up data collection ensures maintenance progress is effectively communicated to all levels of the organization and enterprise information requirements are satisfied.*
What Maintenance is Included in PFM?

**Maintenance** includes all activities associated with preserving or restoring critical functions. Typical maintenance activities include:

- Preventive Maintenance
- Condition Monitoring/Inspections
- Diagnostic Testing
- Integrated Monitoring
- Predictive Activities
- Hidden Failure Finding Tasks
- Condition Directed Corrective and Renewal Tasks
- Corrective Maintenance
- Pre-Emptive Replacement
PFM 12 Step Methodology

- Identify System Boundaries and Critical Functions
  Steps 1-2
- Perform Failure Mode and Effect Analysis (FMEA)
  Steps 3-5
- Aging Mechanisms
  Step 6
- Task Selection and Interval Optimization
  Step 7
- Measures, Metrics & KPIs
  Step 10
- Implementation Documentation
  Step 11-12

Reconciliation and Program Development
Step 8-9
Bridging Business Issues and Technical Requirements

Understanding:
The Aging Process
Failure Initiation Mechanisms
General Age Reliability Patterns

- **Bathtub Curve**: Pronounced Wear out
  - Initial failure rate is low, with a quick increase over time.

- **Gradual Wear out**: Low Initial failure rate followed by a gradual decrease.

- **Constant Failure Rate**: Failure rate remains constant over time.

**Renewal Strategies are Ineffective**
Task Interval Optimization - Weibull Age Modeling

\[ F(t) = 1 - e^{-\left[\frac{(t-t_0)}{\eta}\right]^\beta} \]

- \( t_0 \) = Guarantee Period
- \( \eta \) = Characteristic Life .. MTBF
- \( \beta \) = Shape factor

With Some Good Data, Failures Can be Predicted Mathematically
Failure Initiation Patterns

Some Failures Provide no Warning, Some Give Adequate Warning
Characteristics of PFM

- Optimization
- Life Cycle Approach to Data Management
- Focused Maintenance
- Process Measurement And Feedback
- Integrates Best Business and Technology Practices
## Performance Focused Maintenance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased availability and reliability</td>
<td>Requires quality data collection and storage processes</td>
</tr>
<tr>
<td>Reduced life-cycle costs</td>
<td>Must be understood and supported by the highest management levels</td>
</tr>
<tr>
<td>Data collection fundamental part of the process</td>
<td></td>
</tr>
<tr>
<td>Integrated business and technology approach to maintenance</td>
<td></td>
</tr>
</tbody>
</table>
Performance Focused Maintenance Case Studies (3)
Case I-15kV Distribution Cables

• Issues:
  – Aging population-(four insulation systems)
  – Inspection program that did not affect failure rates
  – Complicated and time consuming replacement ranking system
  – Ineffective condition assessment tasks
  – Poor asset data
  – 0.4% replacement rate

• Drivers
  – Performance Based Rates
  – High replacement costs

• Key Considerations
  – Design Improvements
  – Mostly in conduit
Equipment Group: Population by Age and Insulation Type

<table>
<thead>
<tr>
<th>Type of Insulation</th>
<th>Expected Service Life</th>
<th>Circuit Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>PILC</td>
<td>45 - 50 years</td>
<td>4,900</td>
</tr>
<tr>
<td>HMW-PE</td>
<td>15-20 years</td>
<td>1,500</td>
</tr>
<tr>
<td>XLPE</td>
<td>25-30 years</td>
<td>30,200</td>
</tr>
<tr>
<td>TR-XLPE</td>
<td>45 years +</td>
<td>2,400</td>
</tr>
</tbody>
</table>

Identify System Boundaries and Critical Functions
Steps 1-2
FMEA: Cables

Perform Failure Mode and Affect Analysis (FMEA) Steps 3-5

Dominant Failure modes are “Failure to Insulate and Failure to provide a ground plane”

Effects:
- Public Safety, Local, System, Remote, Customer

Functions:
- Provide Rated Insulation
- Conduct To Rated Ampacity
- Contain Oil PILC Only
- Provide Ground Plane

Modes:
- Failure to Insulate
- Failure To Conduct

Causes:
- Corrosion
- Water ingress
- Thermal Stress
- Manufacturer Defect
- Treeing
- Corrosion

Aging Mechanism:
- Time Random
- Time Random
- Overload Event
- Over Voltage Event
- Time Infant Mortality
- Time Environment

* Varies with each type of cable
Tree Examples - Failure to Insulate

#2 AWG HMW vintage cable which failed in Ridgecrest. Water treeing more than 50% through the insulation.

#2 AWG XLPE cable from Fullerton. Water treeing more than 40% through the insulation.

Resultant Strategy:
Pre-emptive Replacement

Cable Insulation Failure Model

Cable Unreliability

Years after installation

Unreliability

10% Limit

0 0.2 0.4 0.6 0.8 1

yr(s) 10 yr(s) 20 yr(s) 30 yr(s) 40 yr(s) 50 yr(s) 60 yr(s)

PILC
HMW
XLPE
TR-XLPE
Pre-emptive Replacement Strategy – Age Limit
(10% failure)
Case II – SF₆ Breaker Maintenance

• Issues:
  – Extension of Oil Breaker Maintenance Philosophy
  – Declining Reliability
  – Increasing Maintenance Costs
  – Increased Availability Required
  – No CMMS
  – Maintenance Behind Schedule
10 Year Results

- Effective Knowledge Transfer
- Improve Data Collection
- Extended Maintenance Intervals (double) with Defendable Basis
- Additional PM Triggers-Age Exploration
- Reduction in Rework Activities-Improved PM Effectiveness
- Increased Availability
- Improved Reliability
- Elimination of PM Backlog
SF₆ PFM Implementation Results

SF₆ Breakers
(69% of the total population)

10 Year Analysis Period

More than 10,000 Inspections and Maintenance Tasks
Improved Maintenance Plan Resulted in a Decreased Failure Rate

- **RCM Implementation**
- **Stability**

**SF6 Circuit Breakers**
Type of Problems Detected During Maintenance Activities

- Decreasing Failure Rate
- Decreasing Number of Inspections
- Catch-up Period

No problems found
Minor Problems Detected
Major Problems Detected
Major Failures (% / Installed)
SF6 Circuit Breakers Measured
Minor Failures (% / Installed)
Improved Effectiveness

SF6 CIRCUIT BREAKERS
FINDINGS DURING REVISIONS - RESOLUTION OF MINOR FAILURES

100%
80%
60%
40%
20%
0%


Resolved during works
Resolved in short term
Schedule for next inspection

Improved Maint. Techniques

Improvement in Maintenance Effectiveness
Case III-Application of On-Line Monitors

• Issues:
  – Aging Asset Population
  – Recent Cascading Failure
  – Push to Install New Monitoring Technology
  – Poor Experience with Hydrogen Monitors
  – Increased Insurance Rates
Fleet Characteristics

- “Large” Power Transformers
- 220 KV to 115 or 66KV
- 120 to 280 MVA
- Single and Three Phase
- Average Age = 39 Years
- Max Age = 76 Years
- Replacement Costs $3M to $4M (on the pad)
- Population = 188
Failure History (population = 188)

![Failure Events Chart]

Year: 1989 to 2004

- 1998: Maximum failures
- Minimum failures in other years
Age Distribution

A-Bank Age Distribution

Median Age
44 years
Failures as a Function of Age

A Bank Failures

Age at Time of Failure

Rate

Failure
Industry Reported Failure Distribution

Failure Distribution by Impacted System

- Unknown (45%)
- Dielectric (38% to 45%)
- Containment (3% - 6%)
- Current Carrying (7%)
- Mechanical (0% - 4%)
Utility Reported Failure and Trouble Distribution

Failures:
- Dielectric: 46%
- Voltage Regulating: 40%
- Electro-magnetic: 7%
- External Interface: 7%

Problems:
- Inert: 18%
- Bushings: 18%
- Cooling: 13%
- Accessories: 12%
- None: 9%
- NLTC: 7%
- Can't do Maintenance: 2%
- High PF: 2%
- Leaks: 19%

On-line Monitor Target: 7%
Age Reliability Patterns-Failure Probability

Monitoring can be very effective if...

- Bathtub failure rate pattern
  - Pronounced Wear out
- Gradual Wear out
  - Decreasing Failure Rate
- Constant Failure Rate
  - Low Initial failure rate with quick increase
Typical Reliability Predictive Models

Annual Failure Rate
- Linear Failure Rate
- Actual

Annual Failure Rate
- HSB Failure Model
- Actual

Annual Failure Rate - Weibull
- Failure Rate - Weibull
- Actual

Age
- Annual Failure Rate - Weibull
Model Comparison Applied to Existing Fleet

Weibull
HSB
Linear

Current Failure Rate

Annual Failure Rate

<table>
<thead>
<tr>
<th>Year</th>
<th>Weibull</th>
<th>HSB</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>6</td>
<td></td>
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<tr>
<td>2008</td>
<td></td>
<td>4</td>
<td></td>
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<td>2009</td>
<td></td>
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<td></td>
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<tr>
<td>2010</td>
<td></td>
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<td>2011</td>
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<tr>
<td>2014</td>
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<tr>
<td>2015</td>
<td></td>
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</tbody>
</table>
Failure Mechanisms

- **Binary Pattern**
  - Increasing Age
  - OK → Failed

- **Intermittent Failure Pattern**
  - Increasing Age
  - OK → Failed

- **Fast Wear Pattern**
  - Increasing Age
  - OK → Failed

- **Slow Wear Pattern**
  - Increasing Age
  - OK → Failed
Incipient Failure Model

- Mean Time for an incipient fault = 14 mos.
- 63% Probability of Detection
- 12 Month DGA Sampling Cycle
- 63% Probability of Detection

- Incremental Probability of Failure
- Cumulative Probability of Failure
- Probability of Successful Detection
On-line Monitoring Decision Model

- Failure Model
- Direct Costs
  - Transformer
  - Collateral Damage
  - Fines
- Indirect Costs
  - Commissions and Ratepayers
  - Insurance
  - Stress on other units
  - Supply impacts
- True Risk Reduction
- Fleet Replacement Impacts
Cumulative Cash Flow for Multi-Gas Monitors

1. On-line Monitoring
2. No Maintenance
3. Periodic DGA
4. No Maintenance-Periodic DGA
5. No Maintenance-On-line Monitoring
Transformer Fleet Risk Exposure Profiles

Total Annual "A Bank" Failure Risk

Millions

- No Maintenance
- Current PM Program
- Current PM + On-Line DGA

Electro-Magnetic
LTC
Bushing
Transformer Main Insulation System
Extended Useful Life

Deferred Transformer Replacement

<table>
<thead>
<tr>
<th>Year 0</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$200</td>
<td>$400</td>
<td>$600</td>
</tr>
<tr>
<td>$100</td>
<td>$300</td>
<td>$500</td>
<td>$700</td>
</tr>
<tr>
<td>$200</td>
<td>$400</td>
<td>$600</td>
<td>$800</td>
</tr>
<tr>
<td>$300</td>
<td>$500</td>
<td>$700</td>
<td>$900</td>
</tr>
</tbody>
</table>

Thousand

Extended Life

- Interest Deferral on Capital Expenditure
- Cost of On-line Monitor and annual O&M
- Cumulative Cash Flow
Conclusions from PFM Approach:

Substantial benefit can be obtained from installation of multi-gas monitors across a large fleet of power transformers

- Improved transformer reliability
- Reduced failure impacts
- Realization of full transformer useful life
- Identification of units in urgent need of repair/replacement.
- Substantial reduction in overall transformer operating risks
Future Trends in Maintenance

• Sharing of Failure and Trouble data
  – Mode and Cause Level
  – Demographics
    • Application
    • Type
  – Population
    • Age models vs. Failure Rate

• Full Asset Utilization

• Risk Reduction

• Key Performance Indicators
  – Asset Family
  – Maintenance Process
  – Life Cycle Costs
Open Discussion and Questions:

Need More Information?

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