



## **Optimal Replacement of Underground Distribution Cables**

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# Aging Assets – What is the Problem?

- Asset “walls” in power delivery
- Risks of assets failing in groups at nearly the same time
- EPRI’s Aging Assets research develops least-cost strategies: methods, tools, data, and guidelines



# Issues That Make Aging Asset Management Challenging

- **Serious reliability and financial consequences**
- **Uncertainty about when an asset will fail**
- **Lack of data**
- **Diagnostic tests**



# Topics

- Objective, Decision Options, and Optimal Policies
- Condition Dynamics and State Definitions
- Failure Rates
- Expert Judgment
- Testing
- Data requirements

# Approach to Aging Equipment Replacement

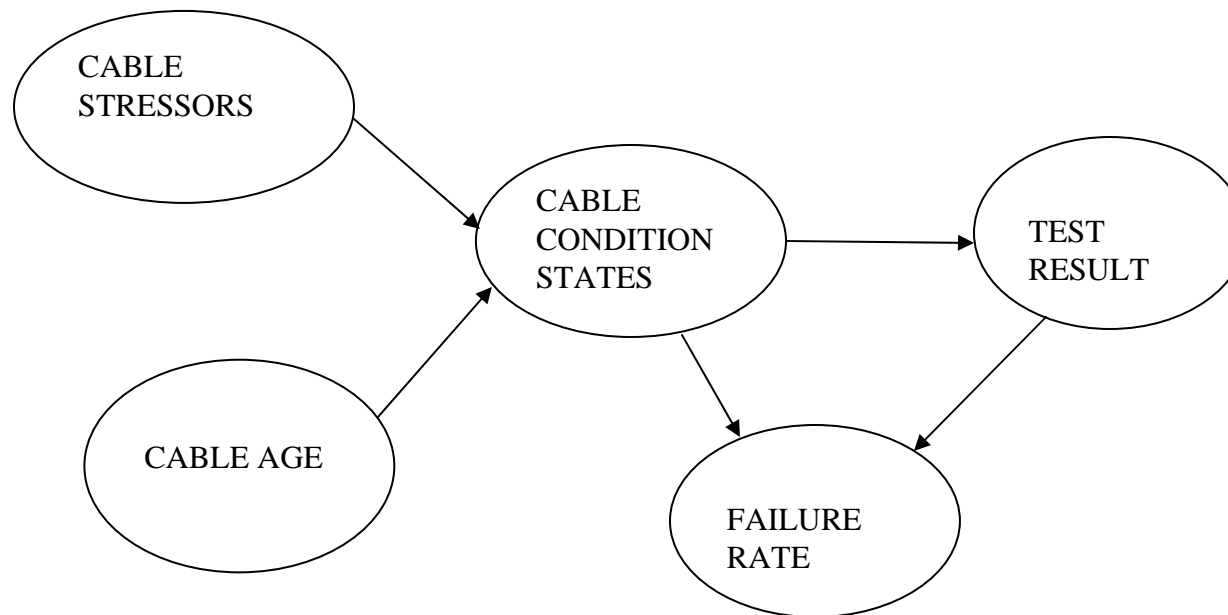
- Develops **conditioned-based policies**: decisions depend on equipment condition
- **Equipment failure models** forecast condition degradation and failure rates
- **Historical** equipment performance **data** and expert **judgment** calibrate equipment failure models
- Represents **diagnostic tests** of equipment condition
- Minimizes **lifecycle-cost** of equipment replacement and maintenance, including **failure costs**
- Determines **trade-off** between annual equipment budget and equipment reliability
- **Forecasts** annual equipment **budgets**

# Issues in Optimal Asset Replacement

- Representing **dynamics** of failure and replacement
- Projecting failure **rates** as equipment ages
- **Balancing** costs of **failure** with **replacement** options to come up with the least-cost equipment replacement policy



# How Equipment Condition Influences Failure Rates



Source: Guidebook for  
Intelligent Asset and Risk  
Management – Underground  
Cables 1010740

# Condition States and Failure Modes

## Cable Insulation Condition States (PILC and Extruded)

<b>Insulation Degradation Condition State</b>	<b>Description</b>
<b>None</b>	<b>Insulation good as new</b>
<b>Mild</b>	<b>Small water trees (&lt;10% of ins. thick.) or voids in the insulation</b>
<b>Moderate</b>	<b>Moderate water trees (lengths 10-30% of ins. thick.) or voids in the insulation</b>
<b>Severe</b>	<b>Severe water trees (&gt; 30% of ins. thick.), large voids (PD inc. &lt; 1.5 Vo)</b>

Source: Guidebook for Intelligent Asset and Risk Management – Underground Cables 1010740

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# Occurrence Rates of Condition States

## INSULATION DEGRADATION STATES (PILC)

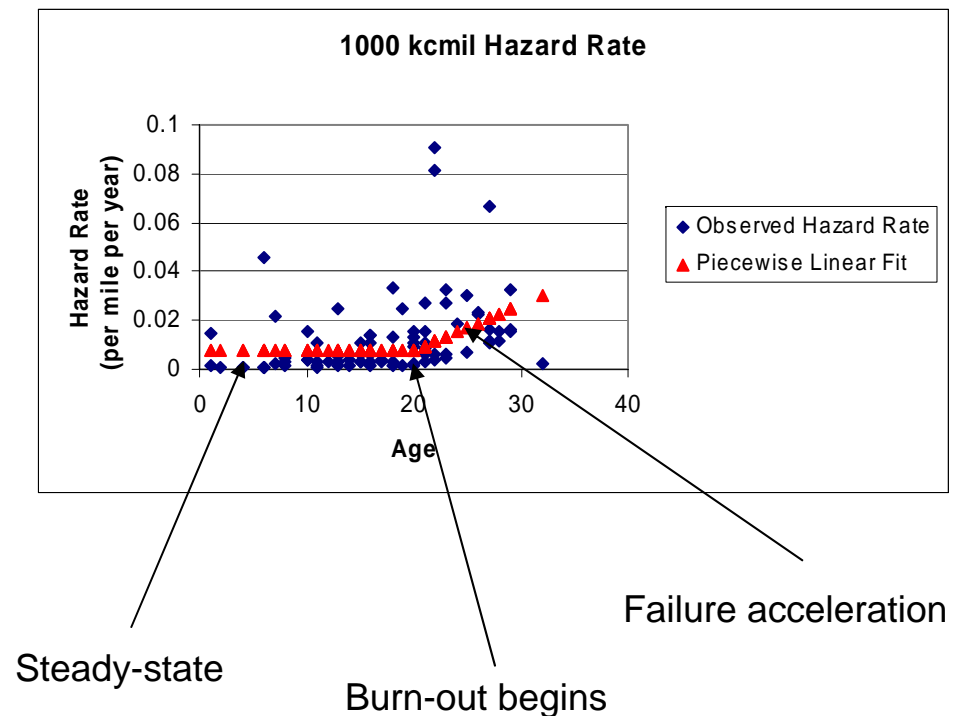
### Fraction of Cable in each Insulation Condition State

<b>Age</b>	<b>No Degradation</b>	<b>Mild Degradation</b>	<b>Mod Degradation</b>	<b>Severe Degradation</b>
<b>10</b>	95%	4%	1%	0%
<b>20</b>	75%	10%	10%	5%
<b>40</b>	60%	20%	10%	10%
<b>60</b>	50%	20%	20%	10%

# Estimating Failure Rates

Use statistical analysis of company-specific data

- Many companies have event data → observed Time To Failure
- Observations subject to random noise
- Fit a model that removes the noise



Source: EPRI Cable Testing Network Industry-Wide Database

# Expert judgment can fill the gaps left from statistical analysis

## IMPACT OF INSULATION CONDITION

<b>Insulation State</b>	<b>Steady state hazard</b>	<b>Onset of burnout</b>	<b>Doubling time</b>
	<b>Multiplier</b>		
<b>Mild Degradation</b>	1.0000	0.50	0.85
<b>Mod Degradation</b>	1.0000	0.35	0.60
<b>Severe Degradation</b>	1.0000	0.15	0.40

# Equipment Failure Modeling using EPRI PM Basis

- EPRI PM Basis Equipment Failure Model provides framework for expert elicitation of
  - degradation and failure mechanisms
  - time-to-failure estimates
- Can explore conditional effects of modifications to PM tasks and intervals
  - Increase in failure rate, and when it occurs
  - “Heads up” on the most likely failures
  - Compensating effects of modifying other PM activities

# Cable Failure Modeling Using EPRI PM Basis

What can fail?

How can it fail?

What influences degradation?

How to detect degradation

Quantify failure rate

Failure Location	Degradation Mechanism	Degradation Influence	Discovery Methods	Time Code
Cable - conductor	Mechanical stress (bending)	Too small a bending radius	None	R
Cable - insulation	Tracking	Manufacturing defects	Partial discharge	W30_40
Cable - insulation	Tracking	Lightning	Partial discharge	R
Cable - insulation	Tracking	Water ingress	Power or dissipation factor, partial discharge	R
Cable - insulation	Mechanical stress	Improper pulling technique - depends on degree	Partial discharge	W20_30
Cable - insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (e.g.)	Partial discharge	R
Cable - insulation	Material degradation	Normal life (i.e. remaining dry)	Partial discharge	UW60_80
Cable - insulation	Loss of oil, drying of paper	Oil migration - effect of elevation changes, thermal cycling, joint	Partial discharge	R
Cable - insulation	Thermal aging	External temperature, load factor	Partial discharge	UW80
Cable - lead sheath (jacketed and uni-jacketed)	Corrosion	Ground water contact, chemistry	Power factor, partial discharge	UW60
Cable - lead sheath (jacketed and uni-jacketed)	Corrosion	Insufficient cathodic protection	Power factor, partial discharge	W2_5
Cable - outer jacket, if present	Damaged	Digging, foreign material or protrusions in the duct	None	R
Splices	Tracking	Installation error (e.g. paper creasing or tearing due to	Partial discharge	R
Splices	Tracking	Improper sweating	Partial discharge	R
Splices - transition to extruded cable	Tracking	Installation error (e.g. wrong connector leads to oil migration	Partial discharge, infra-red	R
Splices - transition to extruded cable	Overheating	Poor connection or crimp	Partial discharge, infra-red	R
Terminations - lead	Tracking	Manufacturing defect	Partial discharge, infra-red	R
Terminations - lead	Tracking	Surface contamination and	Partial discharge, infra-red	R

# Testing and the Value of Information

- Failure likelihood is a critical uncertainty
- Tests can provide some information about failure likelihood, but tests are not perfect
- Whether or not to test is a decision
- Tests have value if outcome leads to a different decision
- Test should be used only if value exceeds cost of the test



# Diagnostic Tests

- Represent test protocols, not individual tests
- Represent test outcomes as indicators of actual condition
- Represent test accuracy as probability that test outcome matches actual condition

## Description of Insulation Degradation Test Protocol

Withstand or diagnostic test
PD test measures local degradation (tracking, etc)
Damage caused by PD depends on location of PD
Different types of test voltages (DC, 60 Hz, VLF, DAC)
Standards available for some tests (include criteria to assess cable condition)
Bulk degradation measured by tan delta or power factor (extent of WT damage)

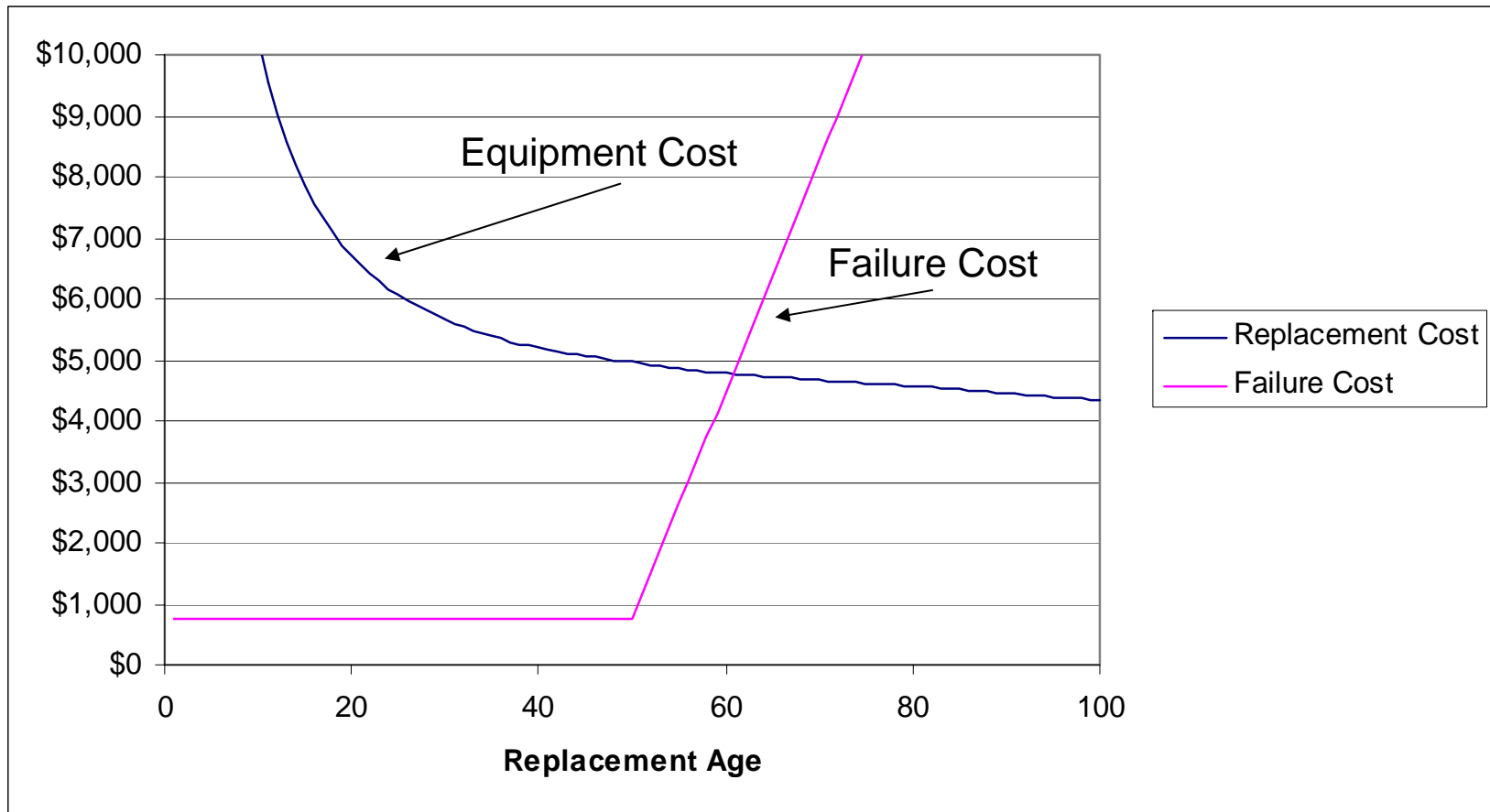
## INSULATION DEGRADATION TEST

Actual Condition	Test Protocol Outcome			
	"No Degrade"	"Mild Degrade"	"Mod Degrade"	"Severe Degrade"
No Degrade	0.80	0.10	0.05	0.05
Mild Degrade	0.20	0.40	0.30	0.10
Mod Degrade	0.15	0.30	0.35	0.20
Severe Degrade	0.05	0.10	0.15	0.70

Source: Guidebook for Intelligent Asset and Risk Management – Underground Cables 1010740

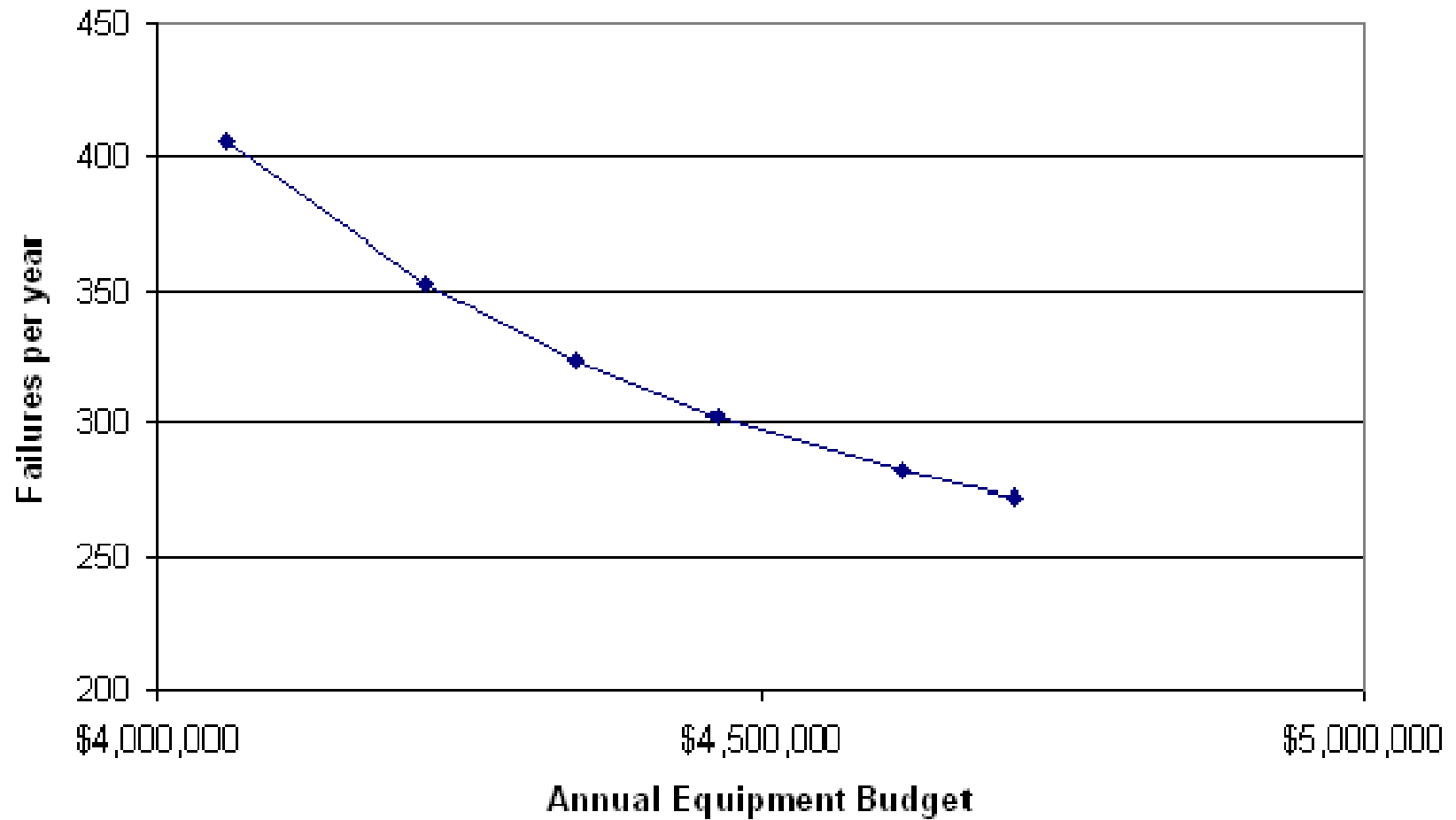
# Optimal Replacement Age

- Balance cost of failure with cost of early replacement



See: Asset Population Management and Testing – Methodology Extensions, EPRI Report 1011665. 2005

# The Cost vs. Reliability Trade-off



# Example Policy with Testing

## OPTIMAL CABLE STRATEGY WITH TESTING

Age	Failures		
	0	1	2
0	No Action		
5	No Action	No Action	
10	No Action	No Action	No Action
15	No Action	No Action	No Action
20	Test	Rejuvenate	Rejuvenate
25	Test	Replace	Replace
30	Replace	Replace	Replace
35	Replace	Replace	Replace
40	Replace	Replace	Replace

## COMPARISON TABLE

Cost per period without Testing

Cost per period with Testing

Value per period of Testing

## STRATEGY CONTINGENT ON TEST OUTCOME

Shaded cells indicate change in policy due to test

Age	Failures	Test Outcome			
		No Degrade	Mild Degrade	Mod Degrade	Severe Degrade
20	0	No Action	Rejuvenate	Rejuvenate	Rejuvenate
25	0	No Action	Replace	Replace	Replace

# Summary Data Requirements

- Cost per cable segment for the following: replacement, rejuvenation, failure, testing, and operation
- Hazard rates as functions of age, prior failures, and condition
  - Basic hazard rate estimates as a function age developed from utility-specific or industry-wide data
  - Adjustments, using either statistical analysis or expert judgment for past failures, degraded conditions, and environmental or operating stressors
- Effect of rejuvenation on the state (effective age adjustment)
- Probability distributions of condition as a function of age
- Testing protocols and their accuracy

# Conclusions

- **Optimal Equipment Replacement**
  - Represent equipment **condition**; **model** its evolution
  - Estimate **hazard** functions, other relevant parameters
  - **Optimize**
- **Tests** can provide useful information when **condition** is not observable
  - Whether or not to test is a **decision**
  - **Value** of testing depends on the **actions** taken as a result
- EPRI's **aging assets analysis** tools can handle many specific **issues** that arise in planning **replacement** policies

# Typical Questions Addressed with EPRI's Aging Assets Management Tools

- What is the **optimal replacement strategy** for a given asset?
- How will the asset population **evolve** over time with this strategy?
- What are the **cash flows** associated with the optimal policy?
- What is the economic **value** of a **testing** program?
- How **sensitive** are the results to assumptions about failure **rates** or **costs**?
- How **sensitive** are the results to test **accuracy**?

**For more information**

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