Strategic Look at Transformer On-line Monitoring

Business Case, Technology and Application

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Study Sponsored by SCE's Research Department

Today's Objectives

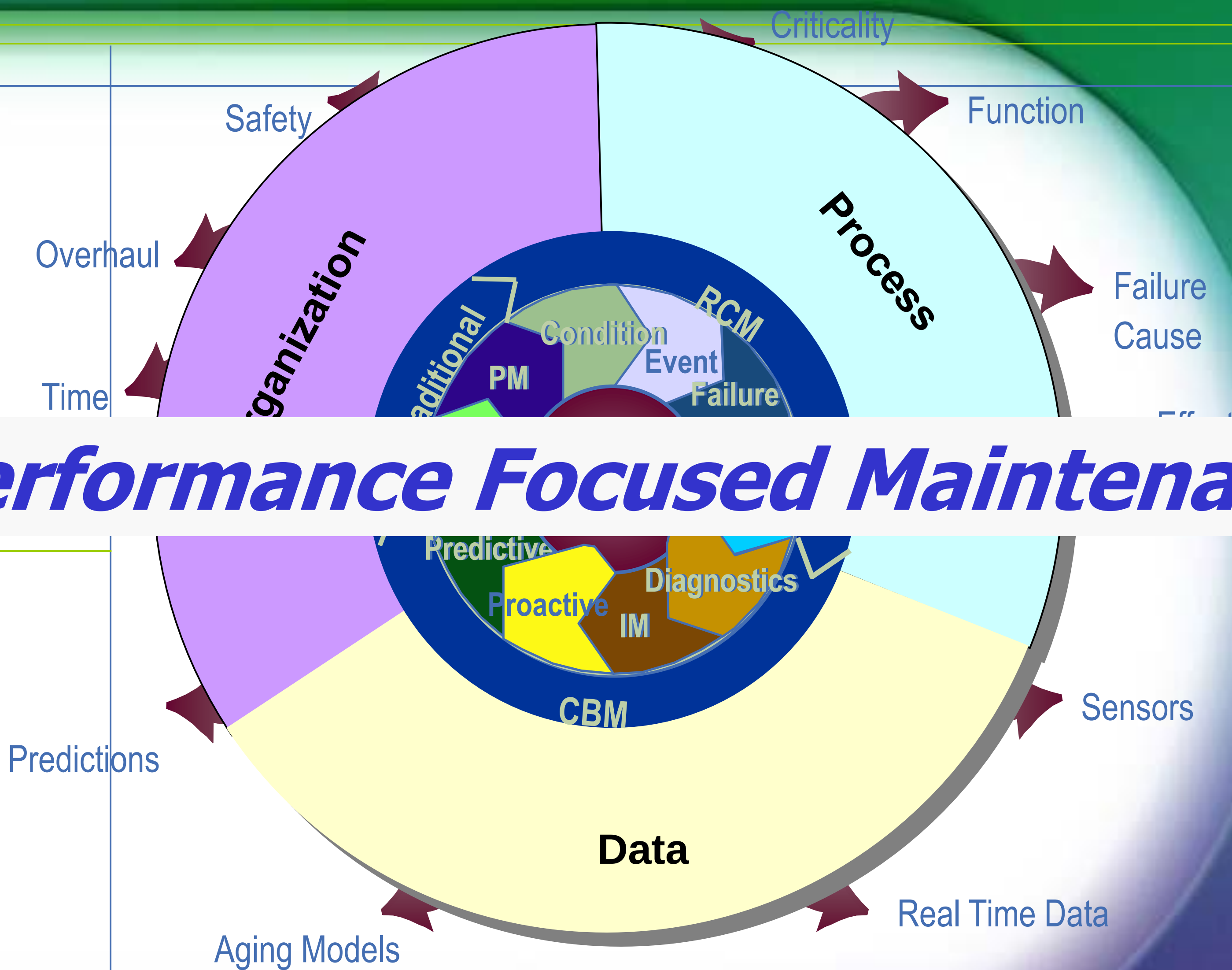
- Take a global view of transformer failure mechanisms
- Provide a "business approach" to transformer on-line monitoring
- Describe the technologies
- Discuss implementation experiences at SCE

Our Backgrounds

- Tony Johnson-Sr. Engineer
- MSEE – Montana State University
- 15 years utility experience
  - Substation Automation Engineering
  - Relay Test Technician Supervisor
  - Project Manager – Technology Development
  - Senior Engineer – Technology Integration
- Professional Activities
  - IEEE

- John Skog-Consultant
- MSEE – Washington State University
- 20 years utility experience Management and Operations of:
  - Substations
  - System Operations
  - Metering
  - System Protection
- Consulting 1978 to present with a focus on:
  - Maintenance Strategies
  - Technology Initiatives
- Professional Activities
  - Cigré
  - EPRI
  - Doble
  - IEEE

The Maintenance Evolution



Performance Focused Maintenance

What is Maintenance?

Maintenance includes … associated

with preserving or re… ns.

Typical maintenance a…

On-line Monitors

- Preventive Maintenance
- Condition Monitoring/Inspect… s
- Diagnostic Testing
- Integrated Monitoring
- Condition Directed Corrective and Renewal Tasks
- Predictive Activities
- Hidden Failure Finding
- Corrective Maintenance
- Pre-Emptive Replacement

Transformer Asset Management Issues

- Costly Asset
- Domestic Manufacturing is Limited
- Aging Fleet
- Difficult/Expensive to Remove from Service
- High Reliability is Expected
- Improvements are Difficult to Capitalize

On-line Monitoring Opportunities

In-service Transformers

- Improved reliability-reduction in catastrophic failures
- Extended operating life-longer return on initial capital investment
- Reduced risk
- An ability to overload the transformer without significant loss of life

New Power Transformers

- Reduced risk
- Capital Investment with rate base return

On-line Monitor Availability

- Bushing leakage current
- Moisture in oil
- Thermal
- Hydrogen
- Total combustible gas
- Multi-gas
- LTC
- Cooling System

Today's focus: Multi-gas Monitors

Making the Investment Decision

- Technical Basis-Realistic Impact
- Significant Reliability Improvement
- Long Term Cost Reductions
- Reduced Risk
- Operational Acceptance

Business Case Approach

What is a Business Case?

A structured proposal for business improvement that functions as a decision package for organizational decision-makers. A business case includes an analysis of business process performance and associated needs or problems, proposed alternative solutions, assumptions, constraints, and a risk-adjusted cost-benefit analysis.

Business Case Fatal Flaws

- Fatal Flaw One: Lack of flexibility
- Fatal Flaw Two: Theoretical, rather than practical
- Fatal Flaw Three: Information overload
- Fatal Flaw Four: No step-by-step implementation guides
- Fatal Flaw Five: Overlooked critical factors
- Fatal Flaw Six: Too complex

12 Elements of a Business Case

1. A brief, compelling, service-oriented problem statement
2. A mission statement or vision of the future that addresses the problem
3. A description of the specific objectives to be achieved
4. A description and rationale for your preferred approach
5. Economic analysis/ROI and a statement of the benefits that address the concerns of all relevant stakeholders
6. Measures for gauging improved performance or progress toward each objective
7. A statement of the likely risks of your initiative and how they will addressed
8. A basic plan of work with a timeline and key milestones
9. A project management plan and names and roles of key managers
10. Alternatives considered and how they would or would not work
11. Cost estimates and potential sources of funding
12. Opposing arguments and your responses to them

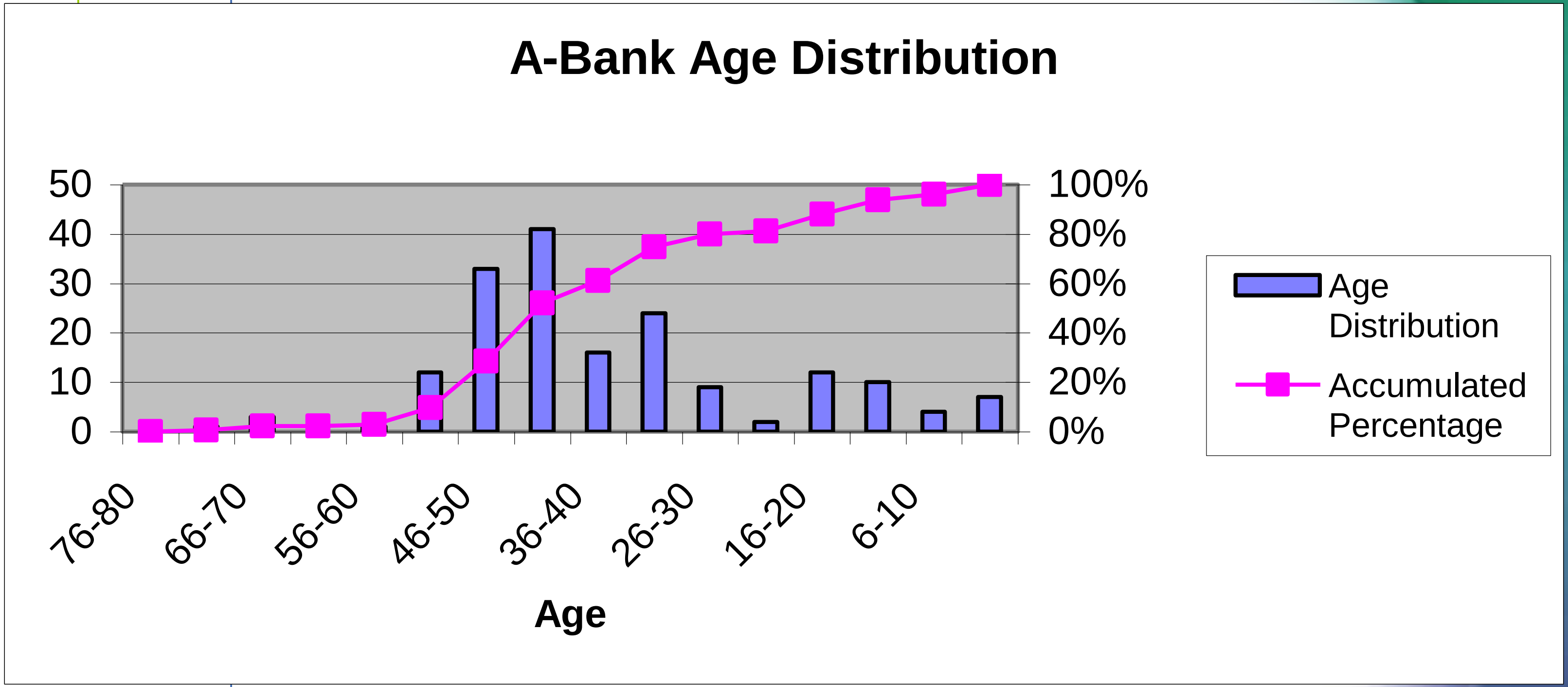
Specific Business Case Application

- "Large" Power Transformers
- 220 KV to 115 or 66KV
- 12 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

1. Problem Statement

- The “A-Bank” population is nearing their expected operating end-of-life. Continued operation will increase the risk of failure but delays major expenditures of capital.

Age Distribution



Median Age

44 years

2. Mission or Vision Statement

- Installation of an on-line DGA system will allow SCE to extend and maximize the operating life of it's "A-Bank" fleet and at the same time reduce the risk of in-service failure.

3. Specific Program Objectives

- Reduce In-service failures to below 0.25% annually
- Provide relevant condition assessment data to key stakeholders
- Implement a strategic replacement program
  - **Rank the health of each transformer**
  - **Provide input to system planning**
- Streamline the data collection, accountability and response processes
- Develop a solid business rationale for applying on-line monitoring techniques to other equipment families

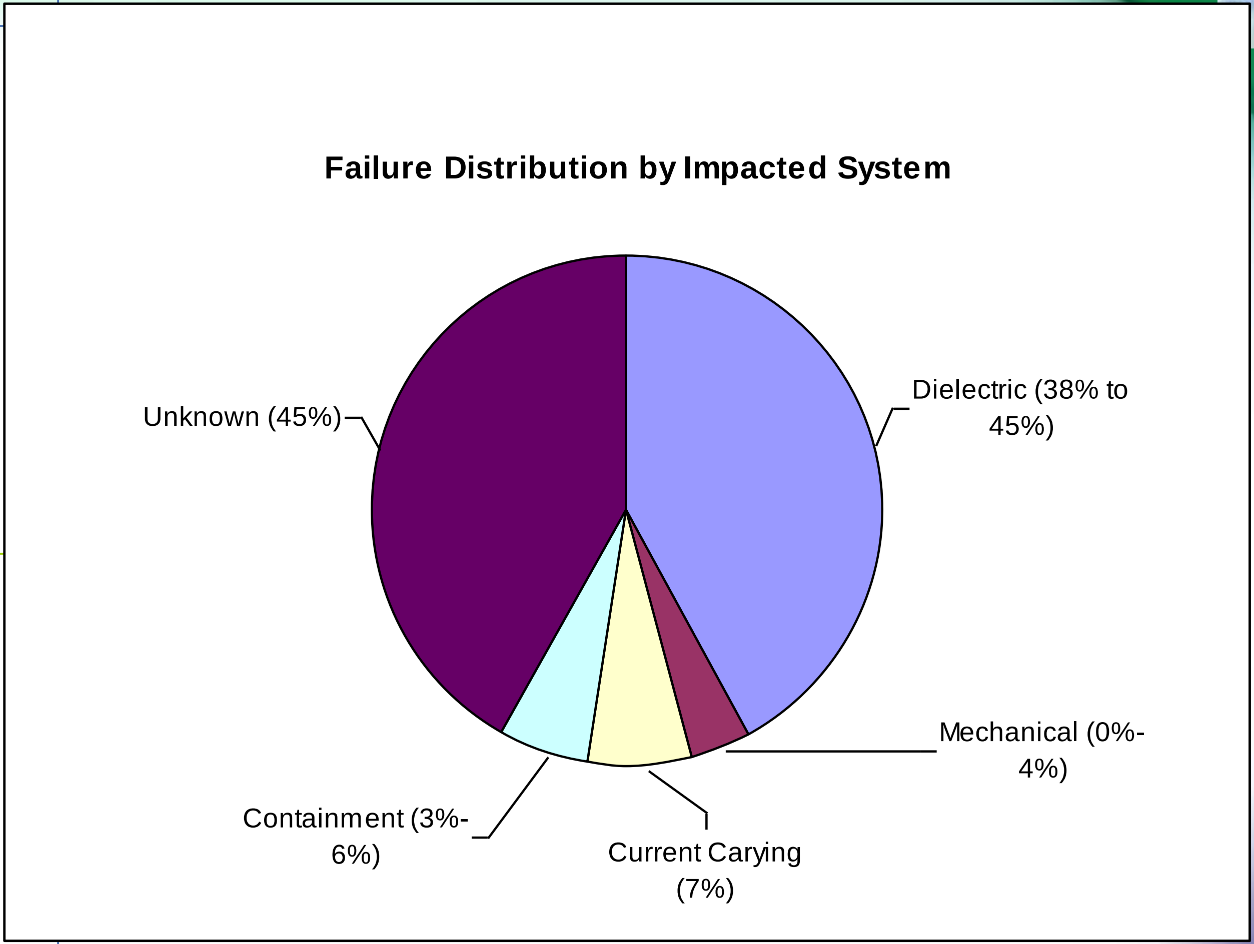
4. Rationale For The Preferred Approach

- Periodic DGA has been universally accepted as the single most effective condition assessment tool for power transformers
- Failure mechanisms can be fast
- Asset replacement costs exceed $1M/unit
- Delivery times for replacement units can exceed 1 year
- Back-to-back failures have occurred

How Do Transformers Fail?

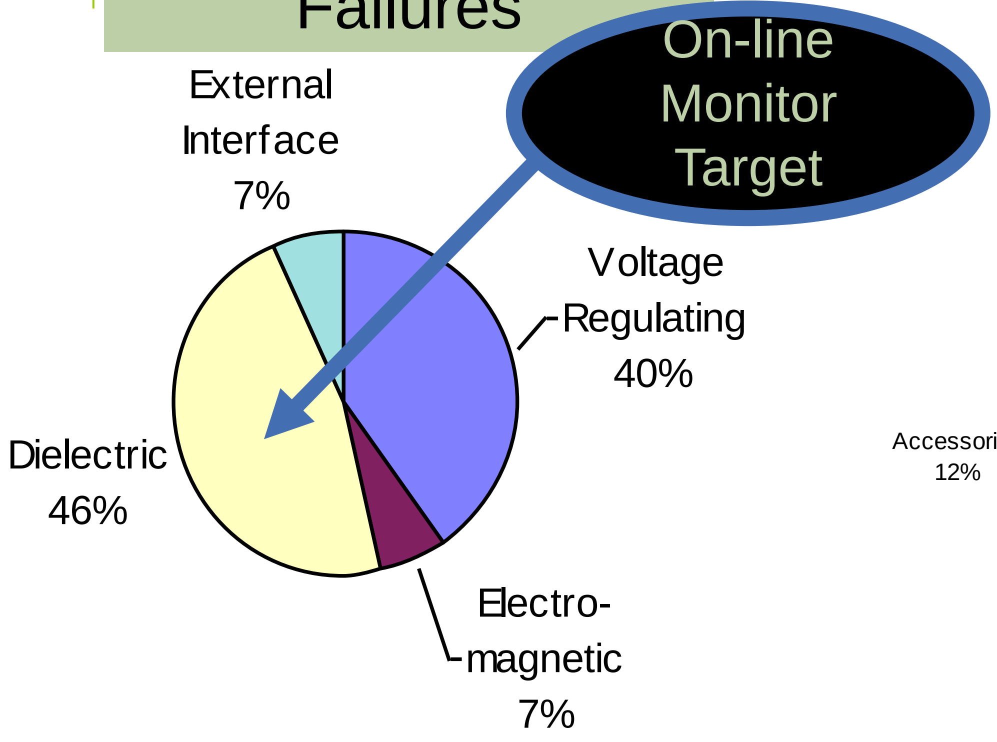
Building a failure model

Industry Reported Failure Distribution

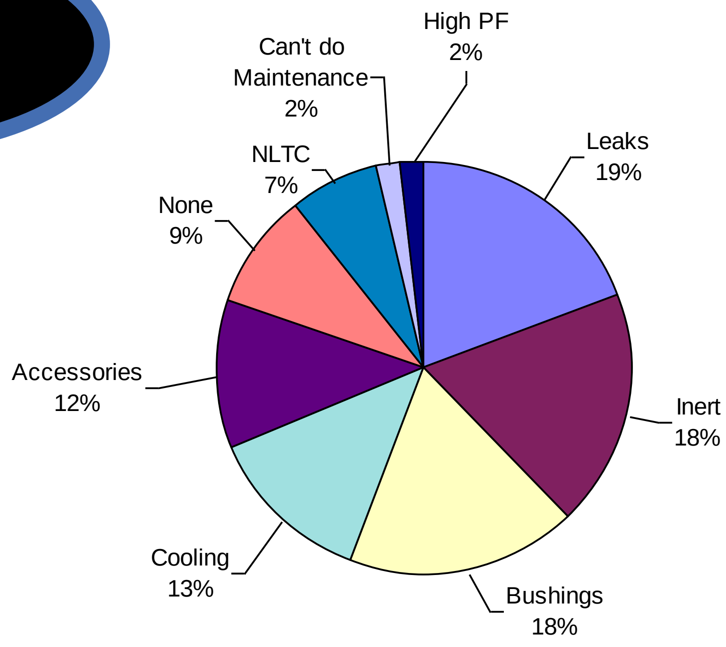


SCE Reported Failure and Trouble Distribution

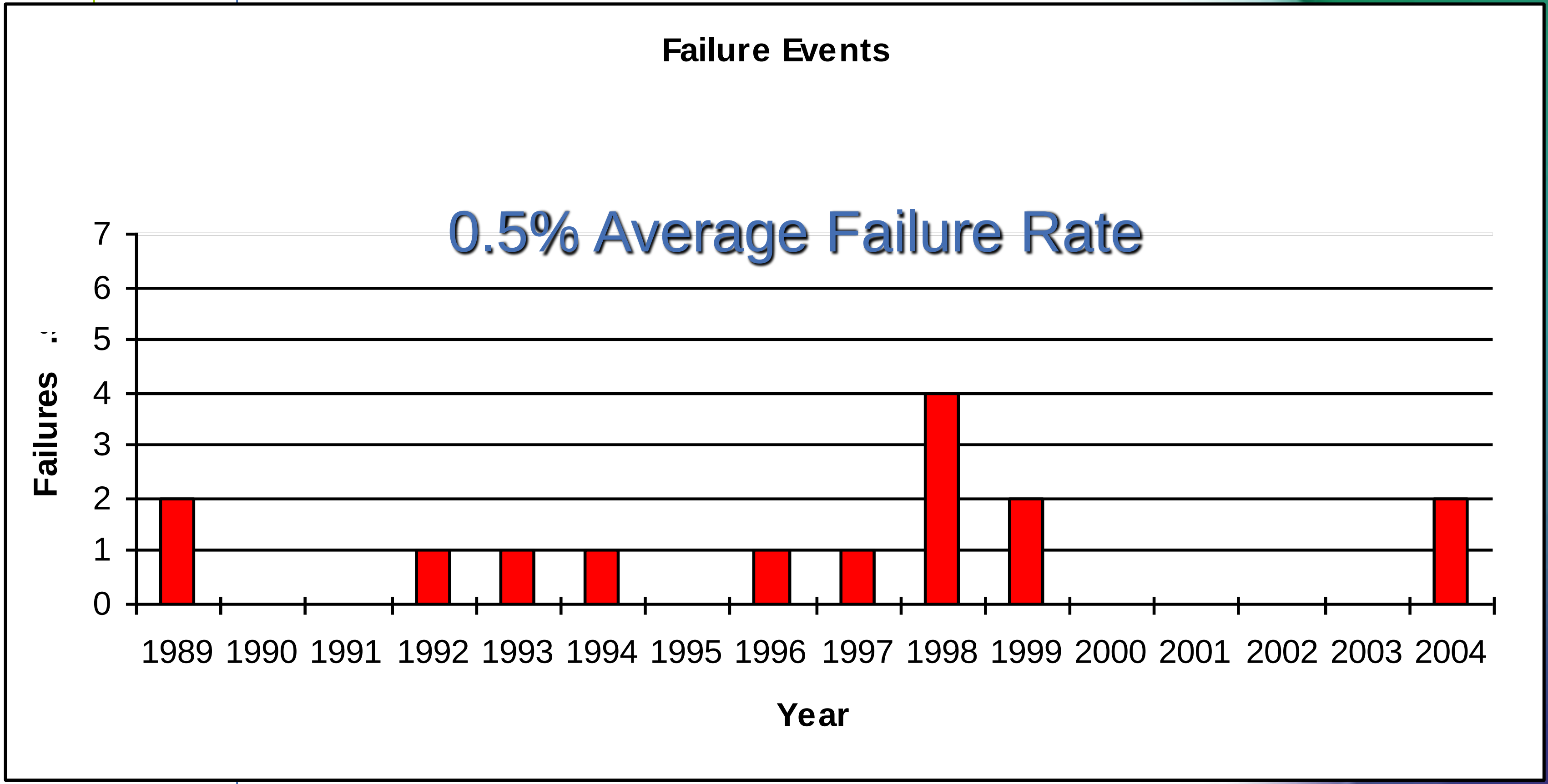
Failures



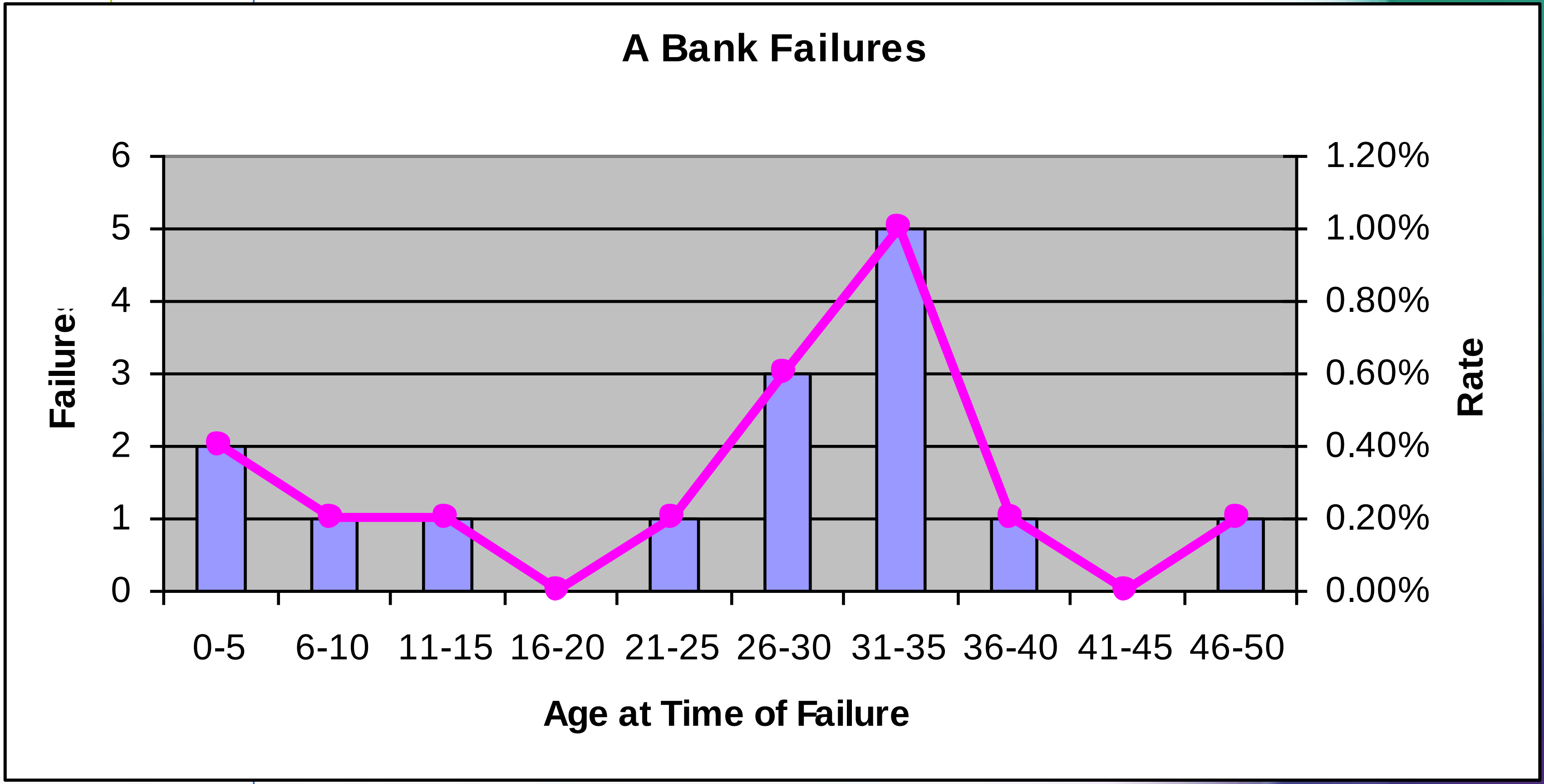
Problems



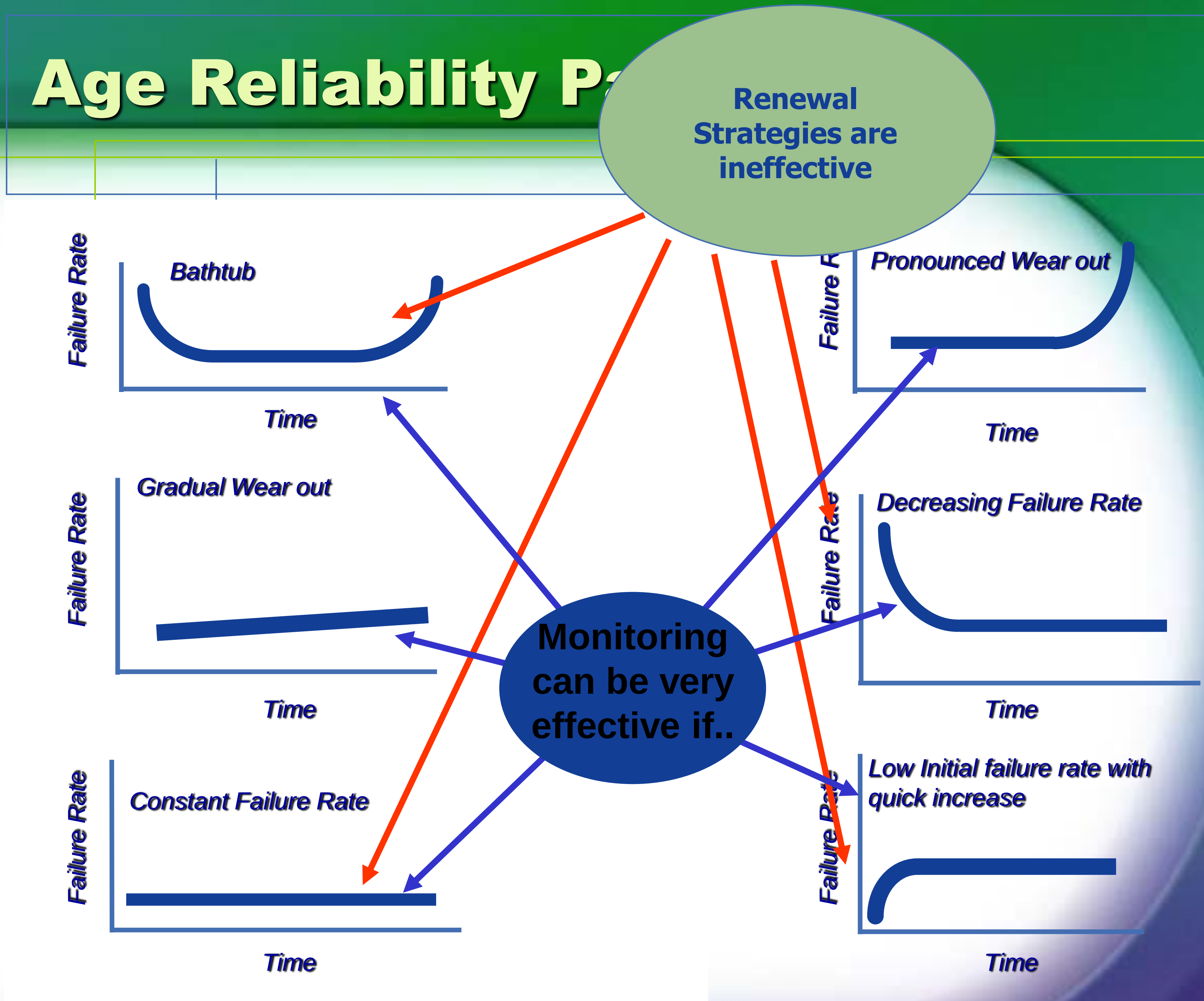
SCE Failure History (population = 188)



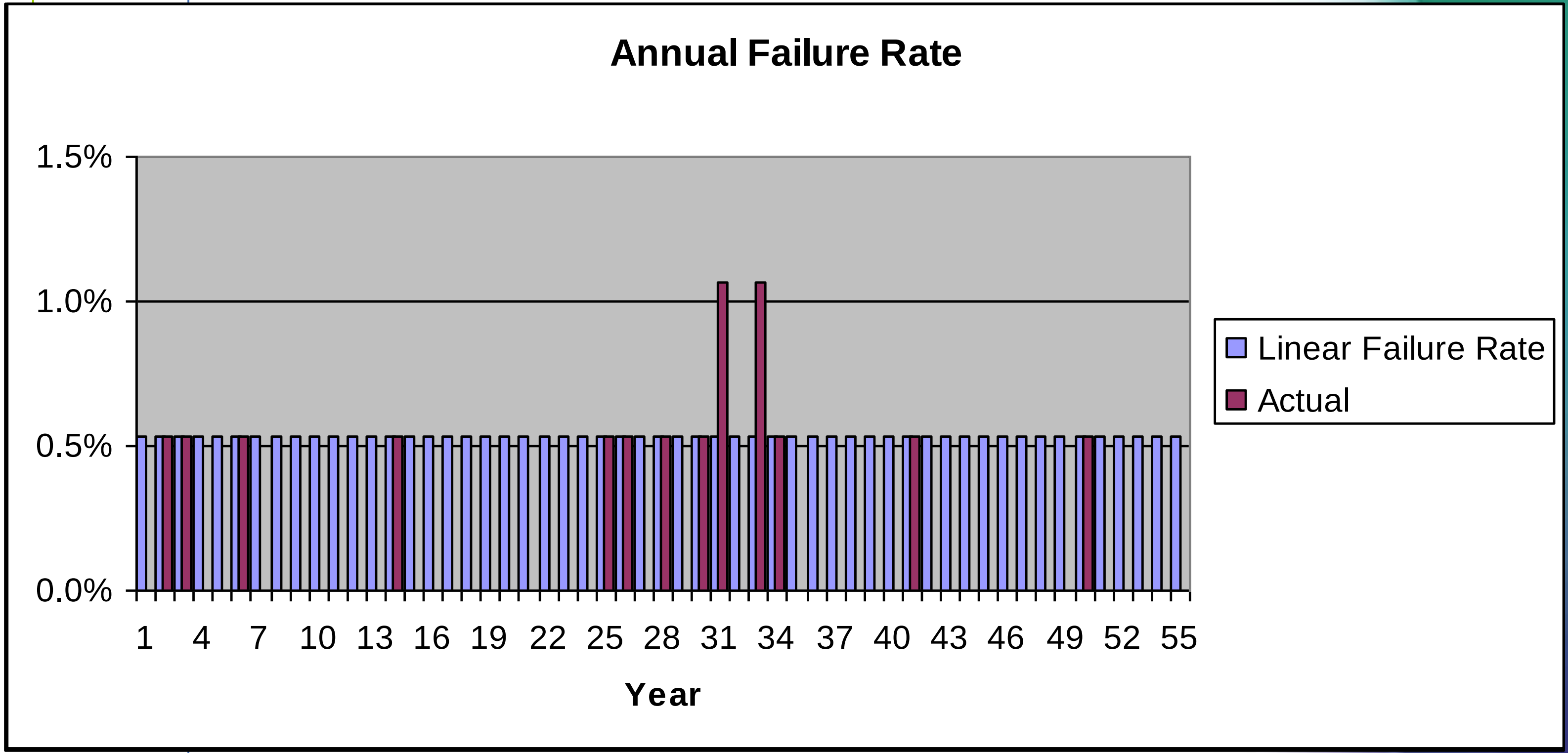
Failures as a Function of Age



Age Reliability Pa

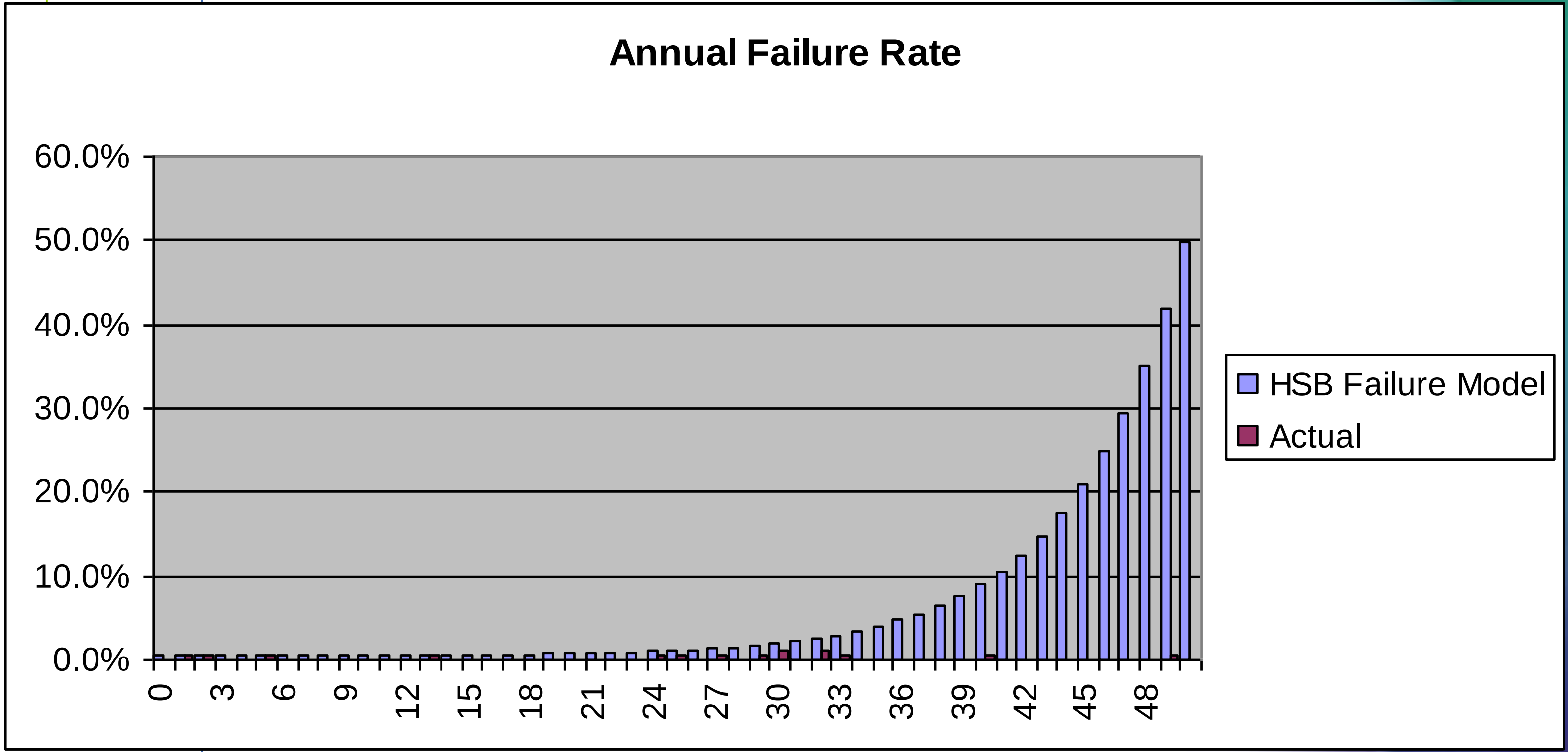


Linear Model



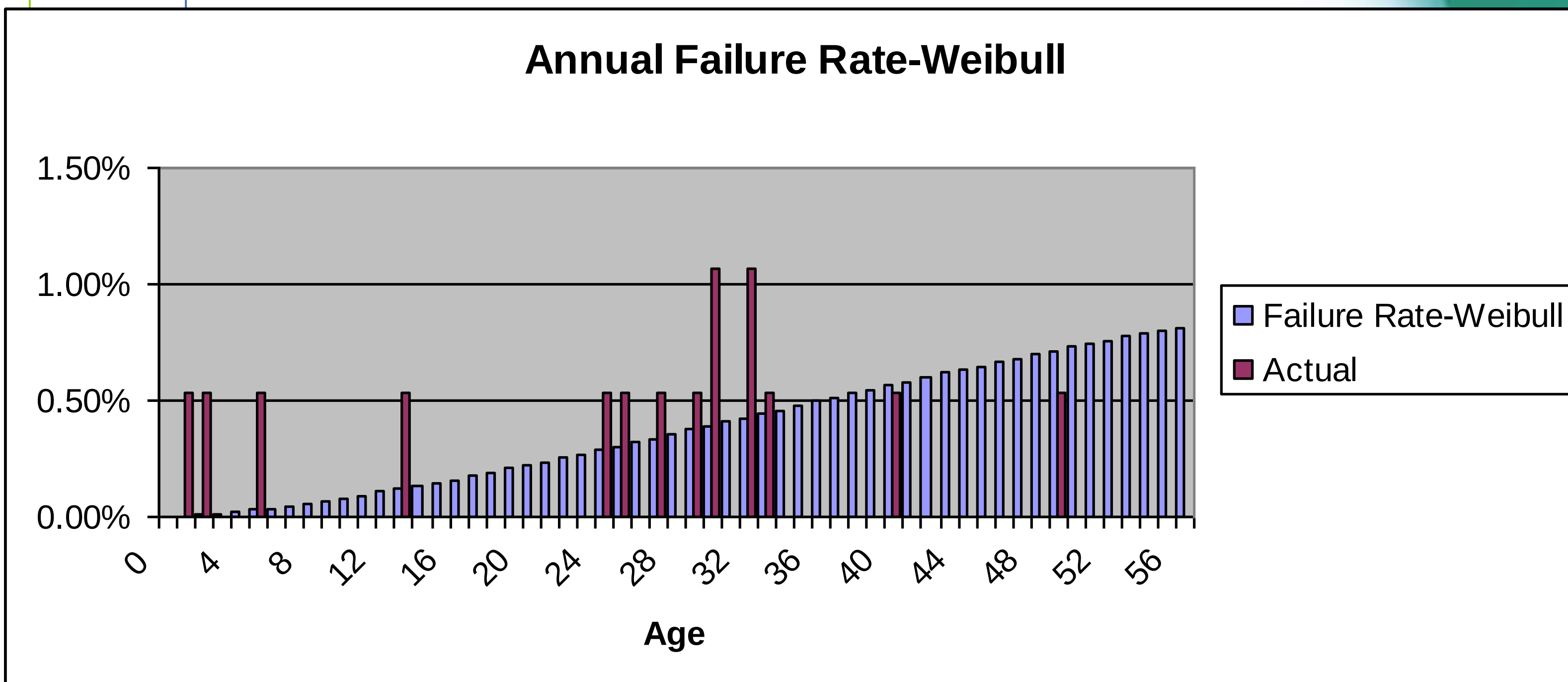
HSB Prediction Model

$$f(t) = A + \alpha e^{\beta t}$$

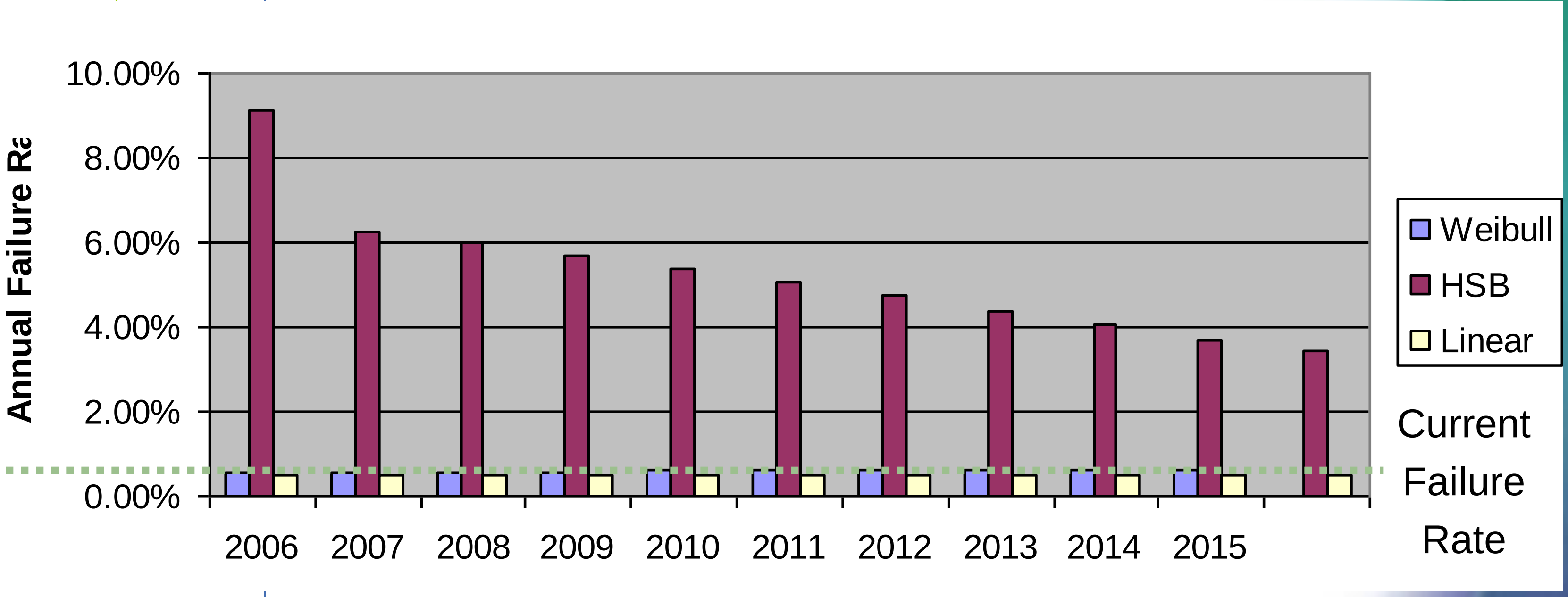


Weibull Model

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

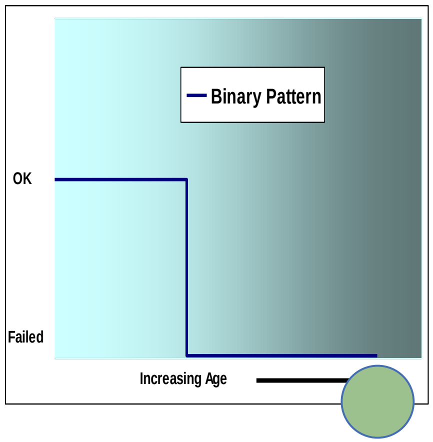


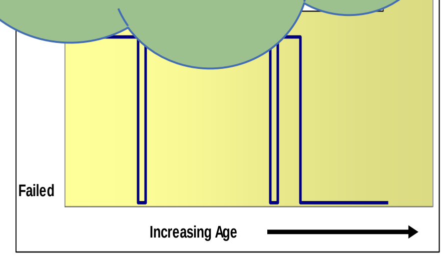
Model Comparison Applied to Existing Fleet

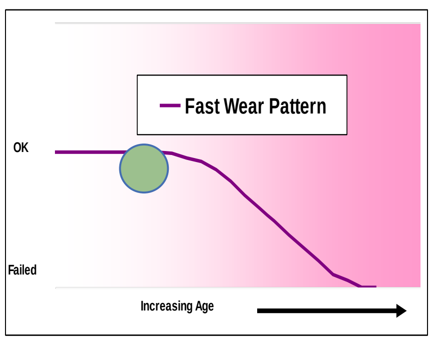


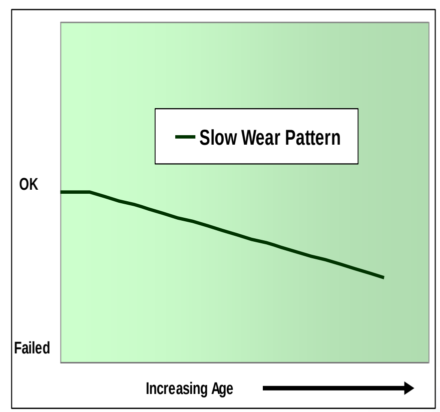
Failure Patterns

Some Failures Provide no Warning, Some Give Adequate Warning

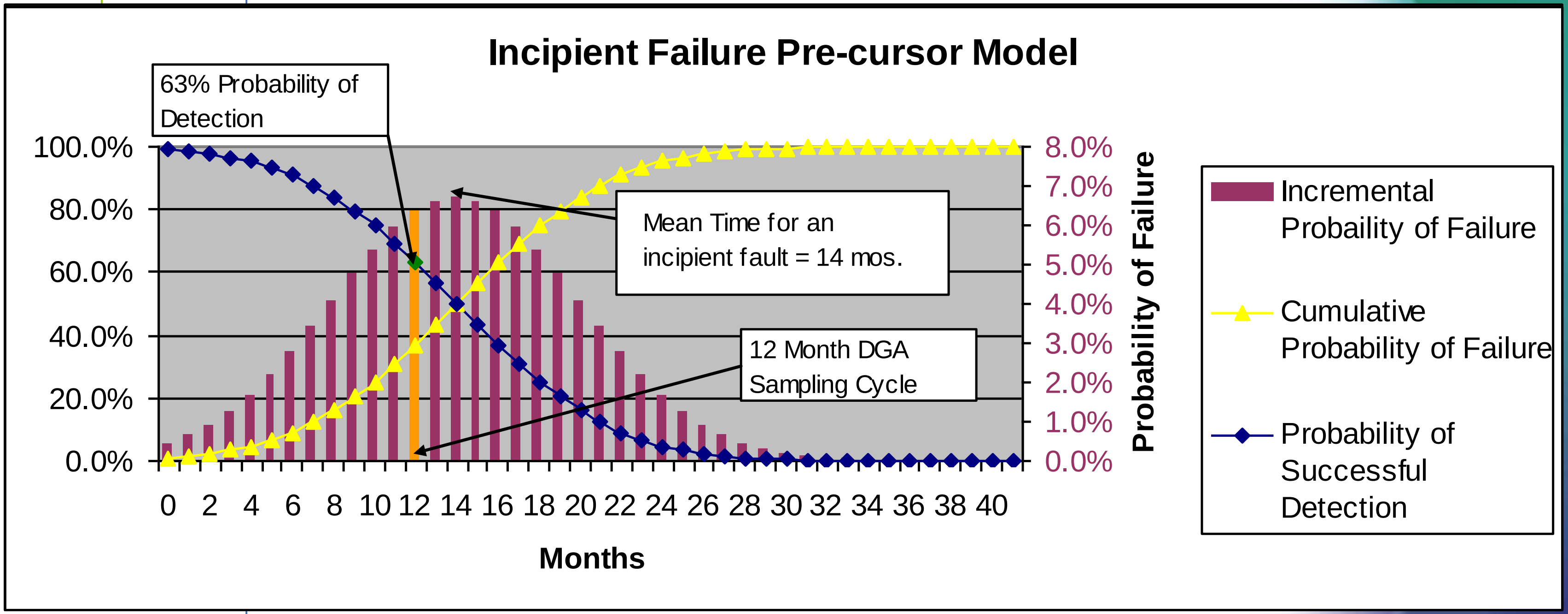








Incipient Failure Model



Risk Analysis-Criticality

probability

RISK BASED FAILURE CONSQUENCE MATRIX

Susceptibility	Risk based failure consequence class		

Susceptibility class	High Very susceptible to failure Asset age, non-redundancy, seashore	critical	vital	vital
	Medium Susceptible to failure under normal conditions, non-meshed grid	non-critical	critical	vital
	Low Susceptible to failures under severe conditions, meshed-grid, redundancy	non-critical	non-critical	critical

Consequence category	Social	Health & safety	No injury	Medical treatment	Physical & long term effects
		Public image & license	No impact	Negative PR Regulator discussions	Loss of clients Regulator effects
		Environment	No effect	Local effect	Possible hazard
	Technical		No effect	Lower reliability	Aging
	Economical		No damage	Damage 1 to 5 M	Damage > 5M
	Societal		Rural area	City (centre)	Heavy industries
	Consequence class		low	medium	high

consequence

Criticality Based Maintenance Response

risk

RISK/CONDITION BASED, ASSET DIRECTED, ACTIVITY MATRIX

failure consequence class	vital	continue maintenance concept	intensify measurements maintenance	investigate revision or replacement
	critical	consequences maintenance decrease	continue maintenance concept	investigate revision or replacement
	non-critical	do nothing? apply CM?	consequences maintenance decrease	continue maintenance concept
condition class	based upon FMECA directed condition measurements	good	medium	bad
		Condition 5 CM history < 1/year	Condition 3 CM history: < 3 /year	Condition 1 CM history: > 3 /year

performance

Winding Failure Risk & Criticality

Risked Base Consequence Matrix

Asset: Main Winding Insulation- Older "A Bank" Units

Susceptibility		Risk based failure consequence rating		
Susceptibility Ranking	**High** **Very susceptible to failure** **Asset Age, non-redundancy, environment**	Critical	**Vital**	Vital
	Medium Susceptible to failure under normal conditions	Non-Critical	Critical	Vital
	Low Susceptible to failure under severe conditions, redundancy	Non-Critical	Non-Critical	Critical

Consequence Category	Social	Health and Safety	**No Injury**	Medical Treatment	Physical and Long term effects
		Public Image	No Impact	**Negative PR Regulator Discussions**	Loss of Customers Regulatory effect
		Environment	**No Effect**	Local Effect	Possible Hazard
	Technical		No Effect	Lower Reliability	**Aging**
	Economic		No Damage	**Damage $1M to $5M**	Damage > $5M
	Societal		Rural Area	Urban	**Industrial**
	Consequence Rating		Low	Medium	High

Winding Failure Maintenance Response

Risked/Consequence Based, Asset Directed, Activity Matrix
Asset: Main Winding Insulation- Older "A Bank" Units

Failure Consequence Ranking	**Vital**	Continue current maintenance practice	Intensify maintenance and measurements	**Revise Maintenance Program or Replace Asset**
	Critical	Consequence control	Continue current maintenance practice	Intensify maintenance and measurements
	Non-Critical	Decrease PM or CM only	Consequence control	Continue current maintenance practice

Condition Rating	Based on Technical Analysis	Good	Medium	**Bad**
		Condition 5	Condition 3	**Condition 1**
		> 75% remaining life	40% to75% remaining life	**<40% remaining life**

5. Expected Benefits

- Positive ROI
- Fewer in-service failures
- Maximized utilization
- Reduced risk during emergency overload
- Planned replacement program

Financial and Risk Analysis

Decision Model Building Blocks

- **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**

On-line Monitor Selection

Input Parameters for On-line Monitoring Financial Analysis	units				Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
			Transformer Data					
Transformer System to be Analyzed			Transformer Main Insulation System					
			Transformer Data					
Current Age	years		39 Year(s)		39 Year(s)	39 Year(s)	39 Year(s)	39 Year(s)
Replacement Cost	$		$3,200,000		$3,200,000	$3,200,000	$3,200,000	$3,200,000
Estimated cost to repair transformer if failure was not catastrophic(% of replacement cost)	%		25%		25%	1%	5%	5%

Reliability Inputs:

			Reliability Data		Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
Reliability Model			Weibull		Weibull	Weibull	Linear	Linear
ɔability of transformer failure-Linear Failure Rate-No PM	%		0.53%		0.53%	0.50%	0.50%	0.20%
Random failures-HSB Model constant Parameter	%		0.5%		0.50%	0.00%	0.00%	0.00%
ɔability of transformer failure-HSB Model "A" Parameter	Constant		0.00007		0.00007	0.00007	0.00007	0.00007
ɔability of transformer failure-HSB Model-Time Constant	Constant		0.17619		0.17619	0.01762	0.01762	0.01762
Weibull Model-Characteristic Life-No PM	Eta		101		101.00	62.10	20.00	101.00
Weibull Model-Shape Factor-No PM	Beta		2.473		2.473	5.295	1.000	1.000
Mean Incipient Failure Time	Months		14 Month(s)		14	24	6	24
Standard Deviation for Incipient Failure	Months		6 Month(s)		6	6	2	2
					Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
Unplanned failure rate reduction with Normal PM	%		63.1%		63.06%	60.00%	80.00%	20.00%
Jnplanned failure rate reduction with On-line Monitoring	%		99.02%		99.02%	95.00%	90.00%	30.00%
ɔbability of major transformer failure being catastrophic	%		90.0%		90.00%	30.00%	50.00%	75.00%
ity that a catastrophic failure includes collateral damage	%		40%		40.00%	25.00%	20.00%	40.00%
Total Probability of Failure in Year 1	1		0.57%					
Total Probability of Failure in Year 2	2		0.60%					

Impacts:

	Failure Impacts				Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
Outage time due to catastrophic failure, with collateral damage	days		10 Day(s)		10 Day(s)	1 Day(s)	10 Day(s)	10 Day(s)
Outage time due to catastrophic failure, without collateral damage	days		5 Day(s)		5 Day(s)	1 Day(s)	1 Day(s)	1 Day(s)
Outage time due to non-catastrophic failure, unplanned transformer repair	days		1 Day(s)		1 Day(s)	0 Day(s)	0 Day(s)	0 Day(s)
Estimated collateral damage cost to other equipment	$		$500,000		$500,000	$5,000	$0	$0
Estimated environmental cleanup cost with collateral damage	$		$500,000		$500,000	$0	$100,000	$0
Estimated environmental cleanup cost without collateral damage	$		$50,000		$50,000	$0	$10,000	$0
Estimated customer claims cost	$		$100,000		$100,000	$100,000	$100,000	$100,000
Estimated PR and damage control (cleanup) costs	$		$50,000		$50,000	$50,000	$50,000	$50,000
PUC Penalty for Power Interruption	$		$0		$0	$0	$0	$0
	Insurance							
Include insurance reimbursement?	**Yes/No**		No		No	No	No	No
Baseline insurance deductible	$		$4,000,000		$4,000,000	$4,000,000	$4,000,000	$4,000,000
Additional insurance deductible (when baseline is exceeded)	%		0%		0%	0%	0%	0%
	Generation and Power Contracts							
Price of replacement power	$/MWh		$28.00		$28.00	$28.00	$28.00	$28.00
Variable costs associated with production of power (dispatch cost)	$/MWh		$12.00		$12.00	$12.00	$12.00	$12.00
Net marginal cost of replacement power (lost margin)	$/MWh		$16.00					
Purchase power required as a result of failure	MW		0 MW		0	0	0	0

Maintenance and Repair:

	Repair				**Transformer Main Insulation System**	**Bushing**	**LTC**	**Electro-Magnetic**
Outage time required for a planned repair	days		10 Day(s)		10 Day(s)	0 Day(s)	10 Day(s)	10 Day(s)
Extra days of useful life added by proactively "nursing" a transformer to repair	days		90 Day(s)		90 Day(s)	0 Day(s)	0 Day(s)	0 Day(s)
	Current Maintenance Program							
PM Program	Name		DGA		DGA	PF Test	Internal Inspect	SFRA
Current PM Interval	Months		12 Month(s)		12 Month(s)	48 Month(s)	48 Month(s)	48 Month(s)
Cost Per PM Task (include all overheads)	$		$250		$250	$1,000	$2,000	$1,000
Current average annual PM Cost	$/Year		$250		$2,000	$250	$500	$500
Expected decrease in annual PM costs due to On-line Monitoring	$		$0		$0	$500	$0	$0
Current PM System Capital Cost	$		$5,000		$5,000	$5,000	$5,000	$5,000

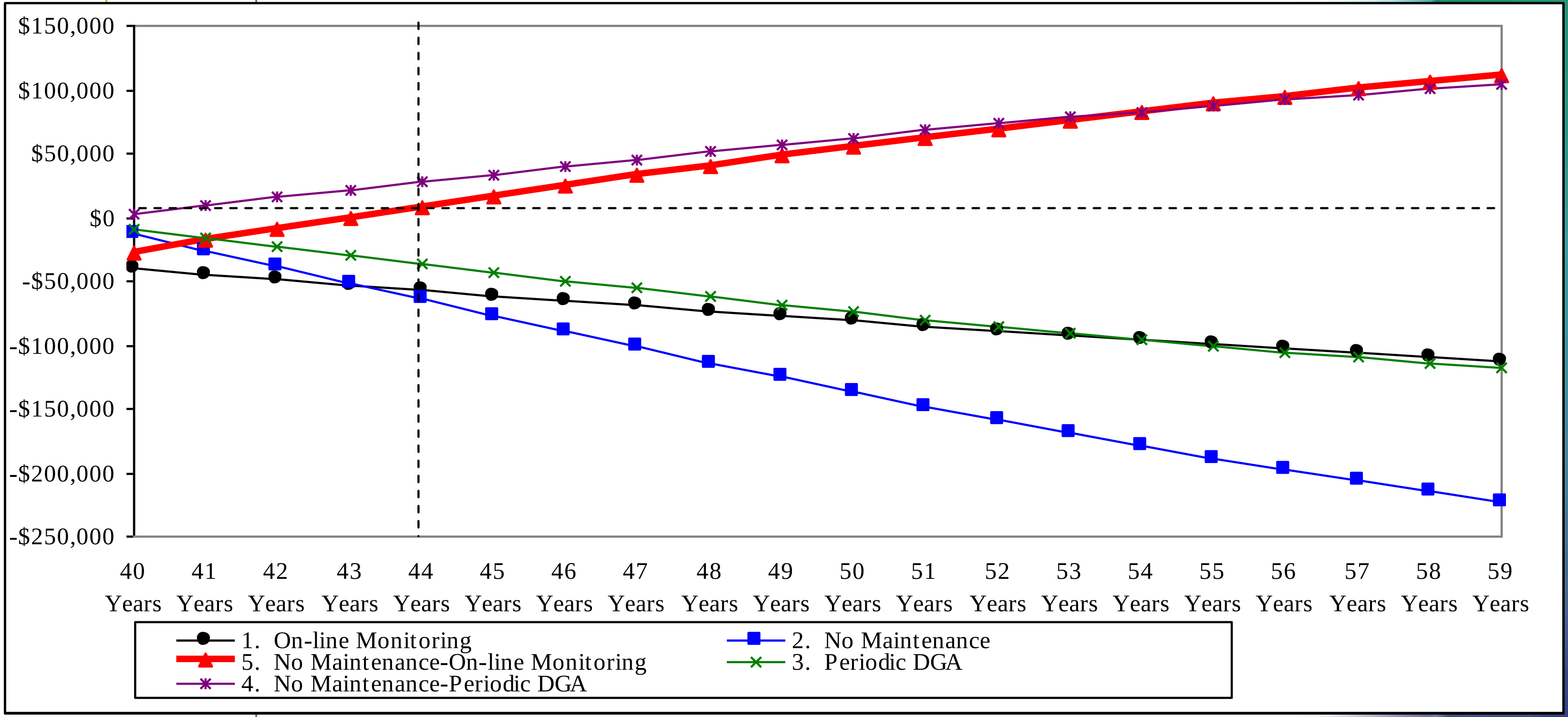
Financial:

	Financial				Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
Cost Rate-Debt	%		7.5%					
Cost Rate-Equity	%		10.0%					
Percent of Financing-Debt	%		50.0%					
Percent of Financing-Equity	%		50.0%					
NPV discount rate	%		8.75%					
Weighted Average Cost of Capital (WACC)	%		8.75%					
Estimated IRR (Guess used to initialize the calculation)	%		35.0%					
Federal Tax Rate	%		35.0%					
Inflation Rate	%		3.0%					
Book Depreciation Life	Years		10 Year(s)					
Tax Depreciation Life	Years		5 Year(s)					
Capital Closed to Plant	Year		Year 1					
Regulated Investment	(Yes/No)		Yes					

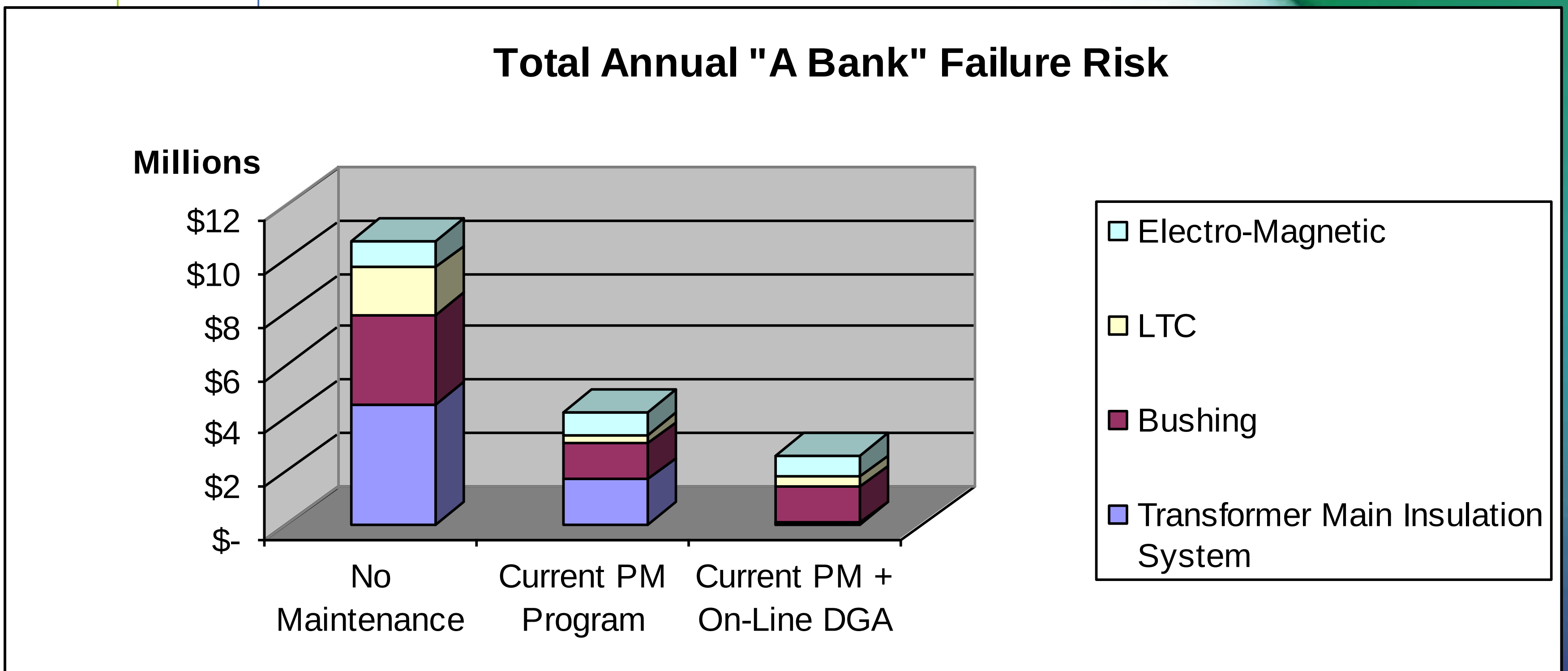
Cost:

			Monitoring Hardware		Transformer Main Insulation System	Bushing	LTC	Electro-Magnetic
Monitoring System Capital Cost	$		$30,000		$30,000	$25,000	$15,000	$15,000
Monitoring System Installation fees	$		$4,000		$4,000	$3,000	$6,000	$4,000
Monitoring System Operational Costs	$/yr		$3,000		$3,000	$3,000	$3,000	$3,000
Outsoure Monitoring	(Yes/No)		No					
Monitoring System Service Fees	$/yr		$0		$1,500	$1,500	$1,500	$1,500
Monitoring Systems Required			1		1	1	1	1

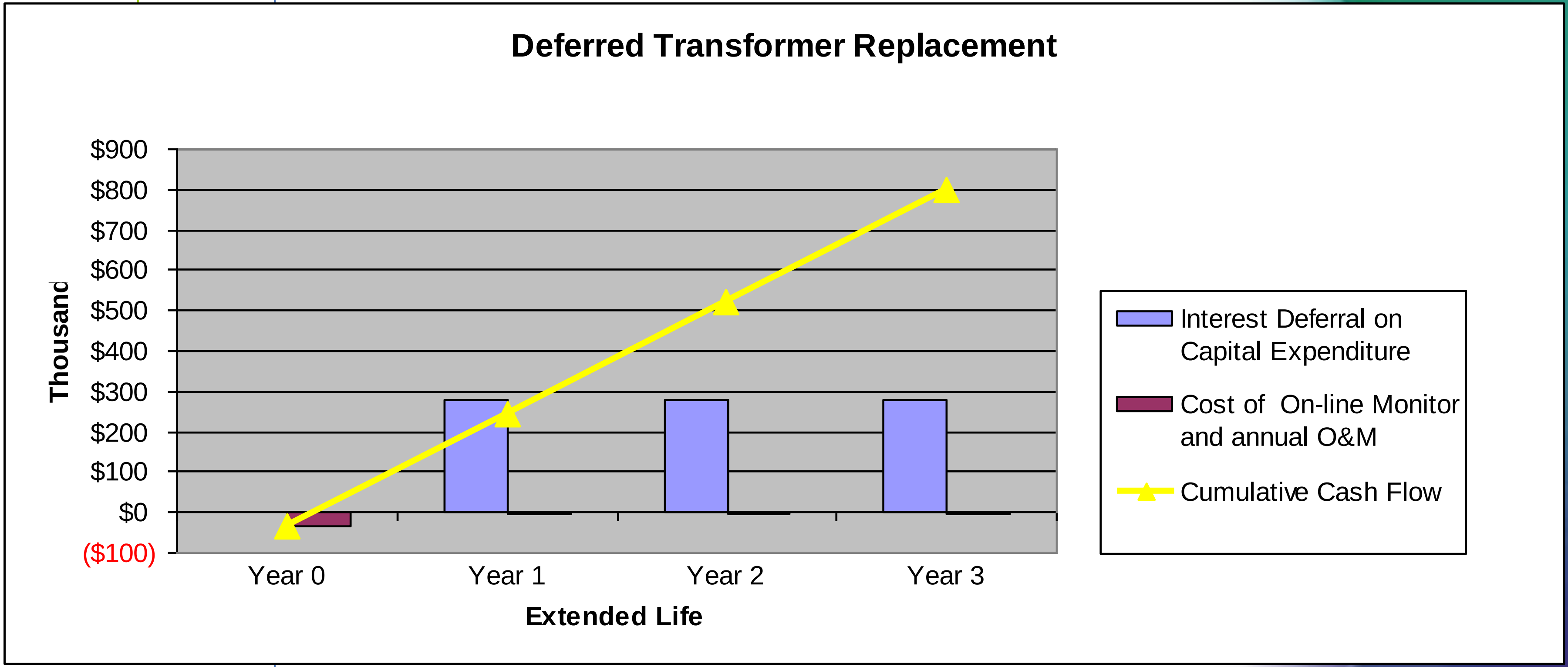
Cumulative Cash Flow



Transformer Fleet Risk Exposure Profiles



Extended Life



6. Performance and Progress Measures

- Budgetary acceptance
- Technology selection
- Communication strategy
- Data storage architecture
- Response and accountability plan
- Equipment installation
- Key performance indicators (KPI)

7. Risks And Ways To Address Them

- Technology obsolescence
- Through-faults and lightning
- High installation cost
- Sensor failure/calibration error
- Communication failure
- Response latency

Technology Obsolescence

- DGA has a 30+ yr. record
- Improvements are expected but won't significantly reduce risk
- Hardware can be redeployed

Through-faults and Lightning

- Design/genetic root
- A different solution set reduces impact but may only slow down the failure mechanism
- Odds of detecting an incipient fault are still improved

High Installation Cost

- Delay installation at high cost sites
- Implement a lower cost communication solution

Sensor Failure/Calibration Error Communication Failure

- Perform periodic DGA sample
- Self Diagnostics
- Monitor Communication Link
- Subscribe to monitoring service

Response Latency

- On-line monitoring response times are still better than other condition assessment approaches.

Risks addressed by the SCE Business Case

- Is On-line Monitoring Technically Effective?
- Is On-line Monitoring Economically Effective?
- Does On-line Monitoring Effectively Reduce the Risk of Failure?
- Can SCE Adequately Manage the Data?

8. Timeline (Optimistic)

- Month 1&2-Business case development
- Month 3-Technology assessment and selection
- Month 3-5 Budgetary development and acceptance
- Month 6&7 Planning
- Month 8&9-Station Design
- Month 10 - Installation
- Month 8&10-IT integration and testing
- Month 11&12-Operationalization

9. Project Management

- Technology Selection
- Installation
- Communications
- IT integration
- Operations/Process Control

10. Alternatives

- Increased Sampling Frequency
- Equipment Retirement
- Run-to-failure

11. Cost Estimates

$30K	Project Management
$25-35K	Hardware
$2-5K	Communication
$1-15K	Installation
$10K	IT Integration
$5K	Annual O&M

12. Opposing Arguments

- Periodic DGA has served the utility very well
- Failure rates are currently quite low
- Current design is fault tolerant
- Industry acceptance

Business Case Conclusions:

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

SCE Application and Experience

Baseline Monitoring

- **Transformer Loading**
  - Amps
  - Watts
  - VARs
- **Low side Voltage**
- **Main Tank Temperature**
- **LTC Tank Temperature**

Fault Gases

Gases	Indication
Hydrogen	Partial Discharge, Heating, Arcing
Methane, Ethane, Ethylene	“Hot Metal” gases
Acetylene	Arcing
Carbon Oxides	Cellulose Insulation Degradation

The Technologies (greater depth)

- Hydrogen (or Single Reading Devices)
- Multi-gas single
- Multi-gas dual

Single Reading Devices

- **Single reading devices**
  - Several units are on the market
    - The reading is based primarily on Hydrogen.
    - Lower cost than Multi-gas units
    - Can not be used for remote diagnostics, primarily used as an indicator to take a manual DGA sample.

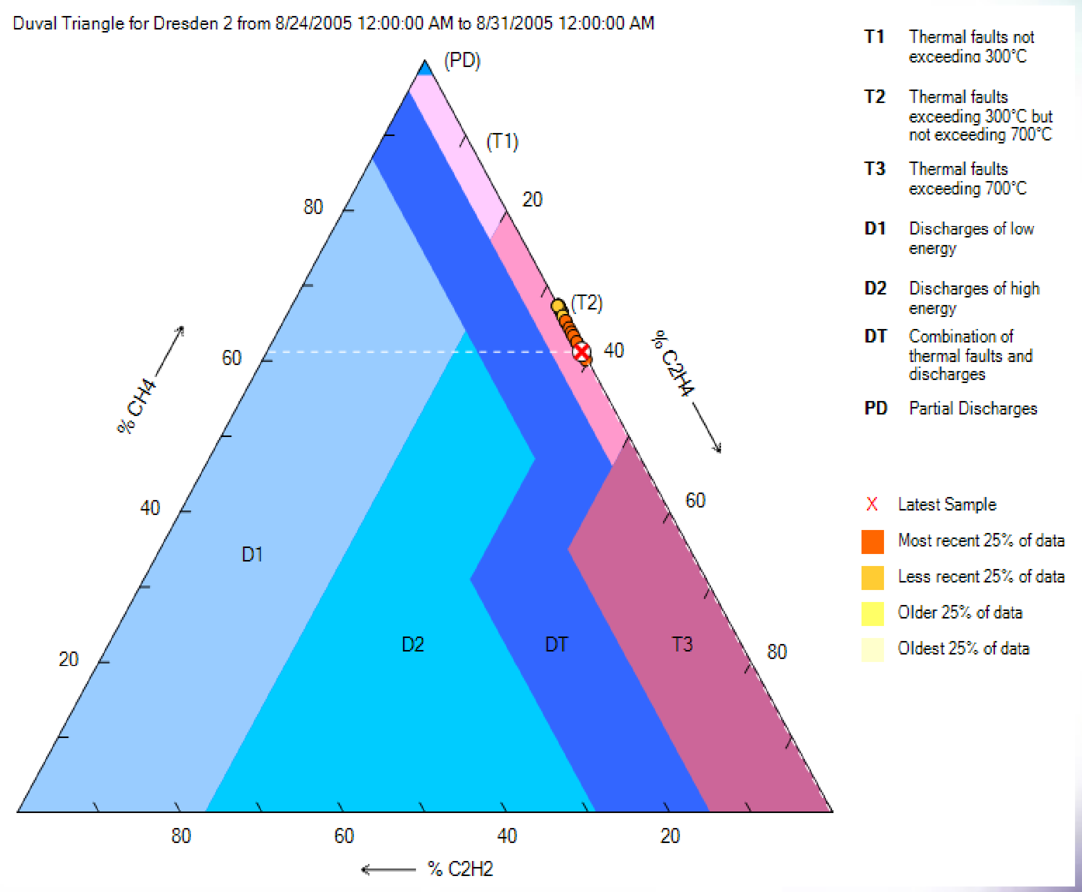
Multi-Gas Single Tank Application

- This application installs an on-line multi-gas unit on the transformer main tank.
- This application is on what the study was based.

Multi-Gas Dual Tank Application

- **This application installs an on-line multi-gas unit on both the main tank and the LTC.**
  - This would also give an indication of an issue with the LTC.
  - Business case did not include an evaluation of this option.
  - Standards for interpretation need to be developed.

Industry Case Studies (Omitted)



SCE Strategy

- Enhance Existing Annual Program Where Beneficial
- Provided Detail Action Requirements Upon Transition to Next Higher Level of Alert
- Utilize Existing Communication and Notification Platforms Where Available
- Provide Action Requirements for the Operations Department

Installation

Installation: Top valve

Installation: Bottom Valve

Installation: Side View

Installation: Communications

- Each Transformer bank will have a fiber optic patch panel.
- Individual units will be connected via fiber to the patch panel.

Communication Challenges

- “The last 1000 feet”
- Use of SCADA
- Security
- Other issues

Communication

- From Transformer Bank to Station Control Room: SCE Standard is Fiber Optic Communication
- Data will be collected by SCE's Energy Management System and Stored in our Historian

Data Management

- Data is Worthless
- Information is needed
- Data Historian has tools available to convert the data into INFORMATION.

Application Experience

- **In the past SCE has used several On-Line DGA units to monitor banks at risk.**
  - This has required SCE to establish a person responsible to "call" into the unit, collect and analyze the data.
  - This process is not sustainable as the technology becomes more wide spread

Application Experience Cont.

- **Pilot at Viejo Substation Collected All Bank On-Line Data into the EMS Historian.**
  - This provided the platform to convert the data to information.

Annual DGA Program

- **SCE has a well defined Annual DGA program that provides significant value.**
  - Pre-defined criteria levels
  - Pre-defined actions at each level
  - Program was developed and maintained by SCE's in-house experts

Annual DGA Action Condition: Normal

Condition: Normal

- Action – No additional action required.
- Example Comment – “Continue Normal Test Schedule”

Annual DGA Action Condition: Caution

Condition: Caution

- Action – Re-test in an indicated interval
- Example Comment – “Sample in 3 months”
- Contact appropriate Maintenance Manager for area regarding transformer condition.
- Identify rate of change for the identified gasses, if the positive rate of change is less than 20% for 2 test cycles then the condition code will return to Normal.
- For Second test of Caution, Warning, and Critical classifications a 6 part test should be included, unless one has been performed in the last year.

Annual DGA Action Condition: Warning

- **Condition: Warning**
  - Action – Re-test in an indicated interval
  - Example Comment – “Sample within 30 days”
  - Contact Technical Specialist for further actions required.
  - Contact appropriate Maintenance Manager for area regarding transformer condition.
  - Develop Action plan for continued transformer testing and operation.
  - Identify rate of change for the identified gasses, if the positive rate of change is less than 20% for a total of 4 test cycles, then the condition code will return to Caution.
  - For Second test of Caution, Warning, and Critical classifications a 6 part test should be included, unless one has been performed in the last year.

Annual DGA Action Condition: Critical

- **Condition: Critical**
  - Action – Re-test in an indicated interval
  - Example Comment – “Sample within 7 days”
  - Contact Technical Specialist for further actions required.
  - Develop Action plan for continued transformer testing and operation.
  - Evaluate need for additional on-line monitoring equipment.
  - Contact appropriate Maintenance Manager for area regarding transformer condition.
  - Identify rate of change for the identified gasses, if the positive rate of change is less than 20% for a total of 8 test cycles, then the condition code will return to Warning.
- **If on-line DGA equipment is installed and the values of the gas reach the critical state, the bank should be cleared or at least load decreased, and SC&M notified for immediate action.**

DGA Program Revision
Due to On-Line DGA Monitoring

- **Condition: Normal**
  - No Annual DGA Required
- **Condition: Caution**
  - DGA Required upon transition into state.
- **Condition: Warning**
  - DGA Required upon transition into state.
  - Develop action plan to identify and correct cause of gas generation

DGA Program Revision
Due to On-Line DGA Monitoring

Condition: Critical

- On Transition in State:
  - DGA sample required to confirm
  - De-energize bank until confirmation is available
  - Develop action plan for bank
- For Continued Operations
  - Revise analog set points for operations to clear alarm but, maintain sensitivity to further issues that may arise
  - Clearly identify any operating restrictions on bank until repair/replacement is available.

SCE Program Update

- Technical Review Council approved on-line monitoring for all new projects (500kV and 220kV)
- Once funding is identified, retrofit program will be identified and implemented

SCE Standard Approach to Monitoring

- **Continue Monitoring:**
  - Amps
  - Watts
  - VARs
  - Volt
  - Temp (Main and LTC)
- **Main Tank 8 Gas On-line Monitoring**
- **LTC 8 Gas On-line Monitoring (when available)**

Conclusions:

- On-line DGA is both technically and economically effective for larger/critical units
- On-line DGA can be applied to smaller units
- Increased sampling frequency is justified on other units
- Other failure modes must not be neglected

More Information

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