Role of Inspection Strategies in Probabilistic Assessment of Reactor Components

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Outline

- **The role of inspections in probabilistic assessment (PA)**
- **Inspection strategy: Key Elements**
  - Sample size
  - Frequency of inspections
- **How to determine sample size and frequency?**
- **What is the effect of a chosen inspection strategy?**
  - In probabilistic terms

Motivation

- **Use of information provided by a probabilistic assessment**
  - PA investigates plausible degradation mechanisms affecting the component performance
  - PA determines suitable mechanistic models to predict the evolution of degradation over time
    - Onset of degradation, growth rate
  - PA leads to lifetime distribution of a component
    - Time to onset of degradation, or time to reach a degradation failure (or defective state)
- **How to (1) evaluate accuracy of these predictions, and (2) use them to guide the inspection/maintenance plans?**

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Role of Inspections

- **Collect data to characterize distributions of random variables involved with a PA**
- **Compliance demonstration**
  - Compliance with quality control targets of standards and codes
- **Diagnostic purposes**
  - Is the system in an acceptable state?
  - Detect the onset of degradation
  - Estimate the extent of degradation
  - Supporting role in ageing management

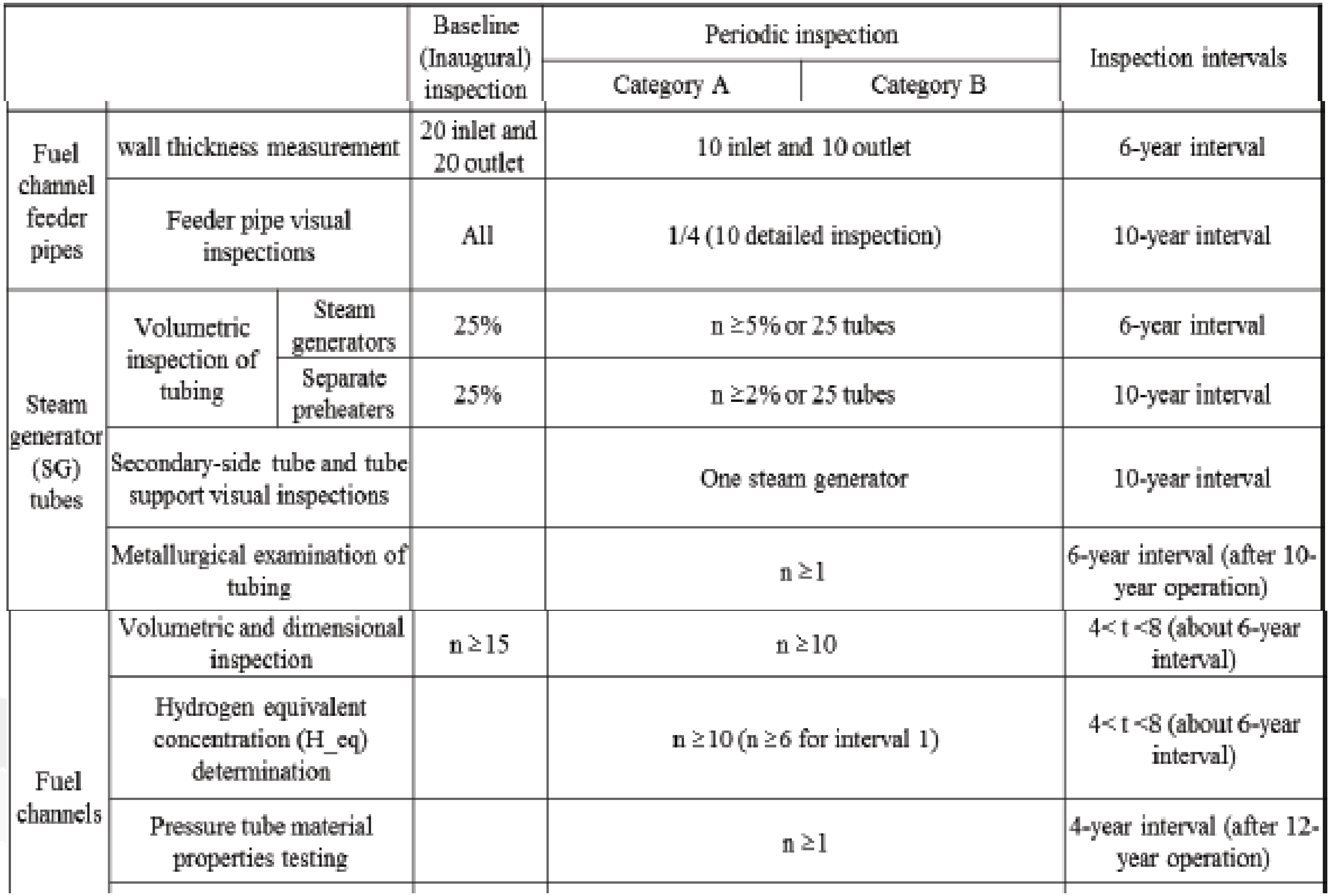
Objectives

- **Discussion of statistical approaches to determine the sample size and corresponding acceptance rules**
- **Present a model to evaluate the effect of an Inspection strategy in controlling the spread of degradation**

- Remark
  - Inspection and maintenance rules are well developed in PSA, and they are not discussed in this presentation

Inspection Guidelines: Examples

- CSA N 285.4 for periodic in-service inspection



			Baseline (Inaugural) inspection	Periodic inspection		Inspection intervals
				Category A	Category B	
Fuel channel feeder pipes	wall thickness measurement		20 inlet and 20 outlet	10 inlet and 10 outlet		6-year interval
	Feeder pipe visual inspections		All	1/4 (10 detailed inspection)		10-year interval
Steam generator (SG) tubes	Volumetric inspection of tubing	Steam generators	25%	$n \geq 5\%$ or 25 tubes		6-year interval
		Separate preheaters	25%	$n \geq 2\%$ or 25 tubes		10-year interval
	Secondary-side tube and tube support visual inspections			One steam generator		10-year interval
	Metallurgical examination of tubing			$n \geq 1$		6-year interval (after 10-year operation)
Fuel channels	Volumetric and dimensional inspection		$n \geq 15$	$n \geq 10$		$4 < t < 8$ (about 6-year interval)
	Hydrogen equivalent concentration (H_eq) determination			$n \geq 10$ ($n \geq 6$ for interval 1)		$4 < t < 8$ (about 6-year interval)
	Pressure tube material properties testing			$n \geq 1$		4-year interval (after 12-year operation)

Inspection for Ageing Management

- **Primary goals**
  - How widespread is degradation in the population of components?
    - Statistical hypothesis test
  - How quickly degraded components should be inspected/removed from the population?
    - Inspection sample size and frequency determines this.
    - At any given time, how many defective components are present in the population?
- **Probabilistic models are needed to answer these questions**

Statistical Sampling Plan

- **Developed in quality control to set up the acceptance sampling plan**
  - Ex: electronic items, material samples
  - ASTM Standards
  - Purpose: Demonstration of compliance with a quality standard
    - Ex: The % of defectives is less than some target value (1%)
    - Demonstrate this at a certain statistical confidence level
  - This can be used in degradation monitoring as well

Statistical Approaches

- **Precision of estimation criterion**
  - To estimate a parameter with a specified width of confidence interval
- **Hypothesis Testing Approach**
  - Hypothesis about the extend of % defective “*p*”
  - Determine the sample size to control the Type 1 (false negative) and Type 2 (false positive) errors
  - This is a standard approach to sample size determination in statistical literature
- **Bayesian Methods**
  - Commonly used in medical literature

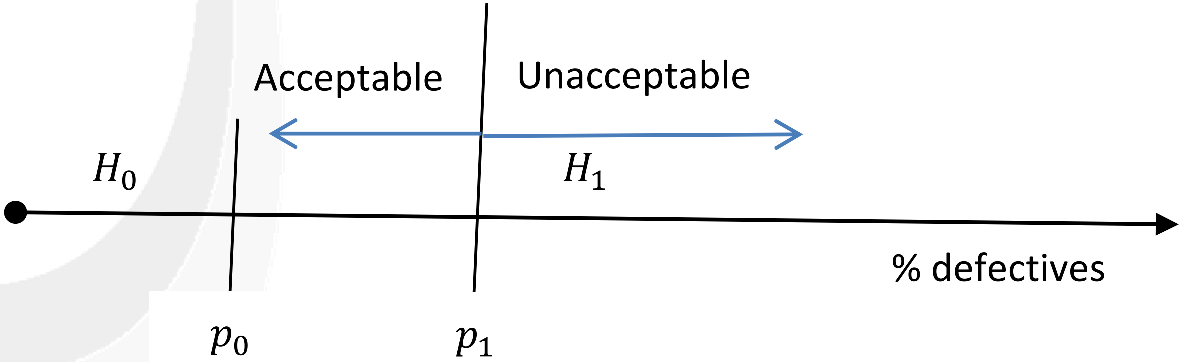
Applications

(1) Confidence Interval Approach

- **Estimate the defective fraction with a high confidence and a narrow error bound**
  - Estimate should be within $\pm\epsilon$ % of the true value of p
- **Example**
  - %defective p = 10%, error ϵ = 50% of p, confidence = 90%,
  - Sample size n = 97
- **This approach is impractical for detecting a small level of degradation with a small margin of error**

(2) Hypothesis Testing Approach

- **Test a statistical hypothesis regarding a certain percentage, "p", of defective components**
- **Null Hypothesis H$_0$: $p = p_0$**
- **Alternate Hypothesis H$_1$: $p = p_1 \quad (p_1 > p_0)$**
  - p_0: an acceptable value of p to meet the reliability goal
  - p_1: an unacceptable value of p



Statistical Errors

- **Hypothesis testing considers both Type 1 (α) and Type 2 (β) errors**
- **Type 1: Reject H_0 when it is true**
  - Judge that $p > p_0$ when in reality $p \leq p_0$
- **Type 2: Accept H_0 when it is false**
  - Judge that $p \leq p_0$ when in reality $p > p_0$
- **A careful calibration of this approach is necessary to limit the sample size to a small and manageable number**

Example

- **Objective**
  - The % defective in the population must be less than 10%, $\boldsymbol{p \leq 10\%}$
- **We treat $\mathbf{10\%}$ as an uppermost limit**
  - Select the alternate value, $\boldsymbol{p_1 = 10\%}$
  - Statistical Errors: $\boldsymbol{\alpha = 10\%, \beta = 10\%}$
  - For $\boldsymbol{p_0 = 0.04}$, sample size $\boldsymbol{n = 112}$
- **Second example**
  - Statistical Errors: $\boldsymbol{\alpha = 20\%, \beta = 30\%}$
  - For $\boldsymbol{p_0 = 0.04}$, sample size $\boldsymbol{n} = 29$
- **What is the meaning of all this?**

Interpretation

- **Take a sample $n =$112 and we find the number of defective components, $k \le 7$**
  - Conclusion: $\text{true}\, p \le 0.04$ with 90% confidence
  - There is less than 10% chance that a $p > 10\%$ can produce this outcome (type 2 error)
- **Take $n =$29 and if $k \le 2$**
  - $\text{true}\, p \le 0.04$ with 80% confidence
  - There is a less than 30% probability that $p > 10\%$
- **Sample size is inversely related to magnitudes of statistical errors**

Remarks

- **Hypothesis Testing is the standard statistical approach to sample size determination**
  - Used in environmental standards
- **The main drawback: a large sample size is required for high confidence and low Type 2 error**
  - Sample size is in hundred, unless higher statistical errors are tolerated
- **For some critical reactor components, these sample sizes may be impractical**
    - Bayesian methods are better suited to address this problem

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Inspection for Degradation Management

- **The concern is about limiting the extent of degradation in a large population of components**
  - The reactor core with 380-480 fuel channels and feeder outlet pipes
  - Steam Generator tubes in thousands
- **Inspection frequency determines how quickly the entire population can be inspected**
- Small sample size means a longer time horizon for completing the inspection
- A larger proportion of degraded components can be hidden in the population

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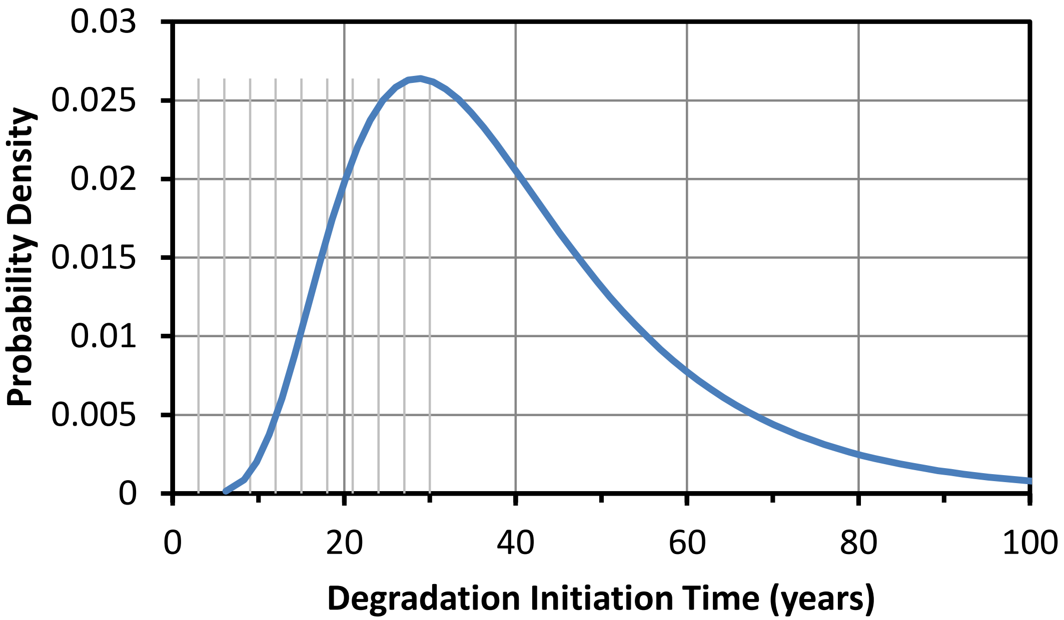
Lifetime Distribution

- **Lifetime is defined by the requirement of the probabilistic assessment**
  - Ex: the distribution of time to initiation of the degradation (i.e., degradation free lifetime) – a generic output
  - Ex: mean lifetime is 40 years (COV=0.4) , Weibull distribution



Probabilistic Approach

- **Suppose m inspections are planned in a time interval (t_1, t_2). The sample size is n per outage**
  - In any i^{th} outage, defectives are discovered and replaced from the inspected sample of n
    - Expected replacements are determined using the lifetime distribution
  - Defectives remaining in the population comes from
    1. the uninspected part of population,
    2. previously inspected and not replaced components
  - Different sub-populations of these defectives are tracked for all outage intervals
    - To compute the number of defectives remaining in the population in any given year

Example

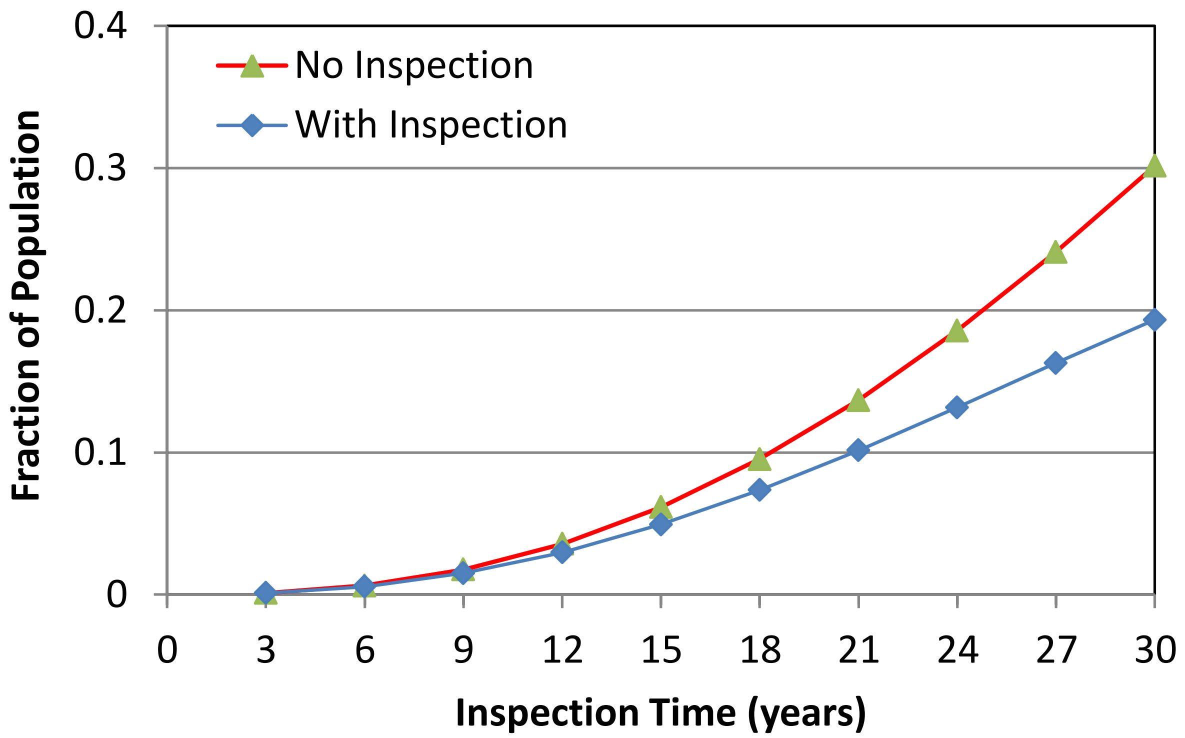
- **Component population = 480**
- **Sample size 48 component per outage**
- **In 10 outages (30 years), the core will be fully inspected**
- **Degraded components found during inspection are replaced**
  - Replaced components are free from this degradation
  - Components not replaced after inspection are still susceptible to degradation

Results: No inspection

- **Without an inspection program, the cumulative number of defectives grows over time**
  - A case of widespread degradation in late life
    - Flow accelerated corrosion in pipes

Results: With Inspection

- **Defective population is reduced over time**
  - Sample size 48 per outage, 10 inspection in 30 years
  - Initial inspections are not useful in removing defectives
    - Sample size is not large enough to control late life degradation

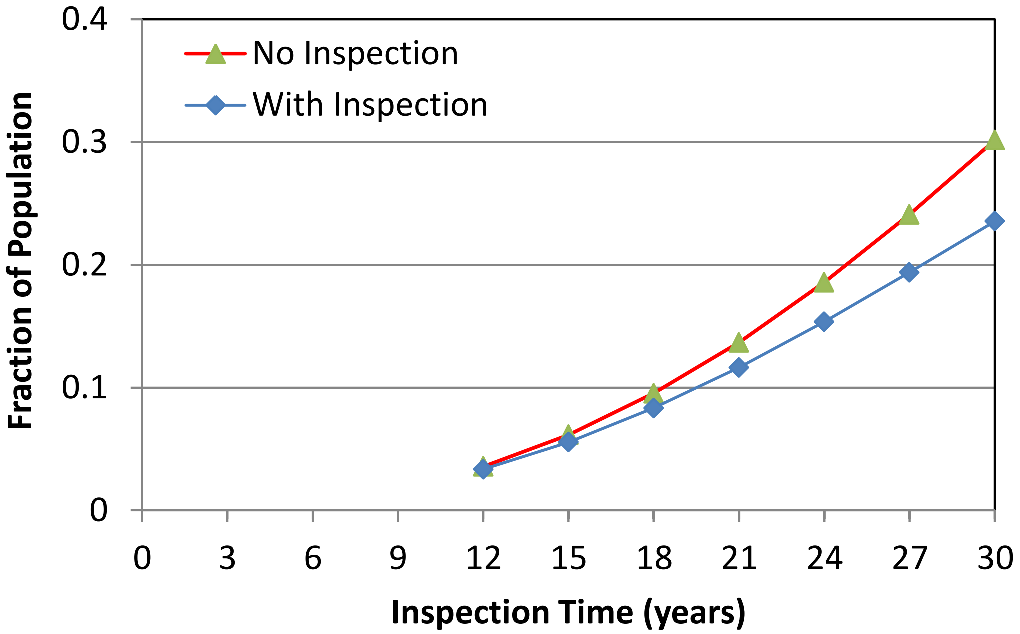


Results: Delayed Start

- **Inspection program starts at 12 years**
  - Sample size is increased to 68 to cover the population
  - More effective in reducing the defectives
    - Late life inspections are more useful

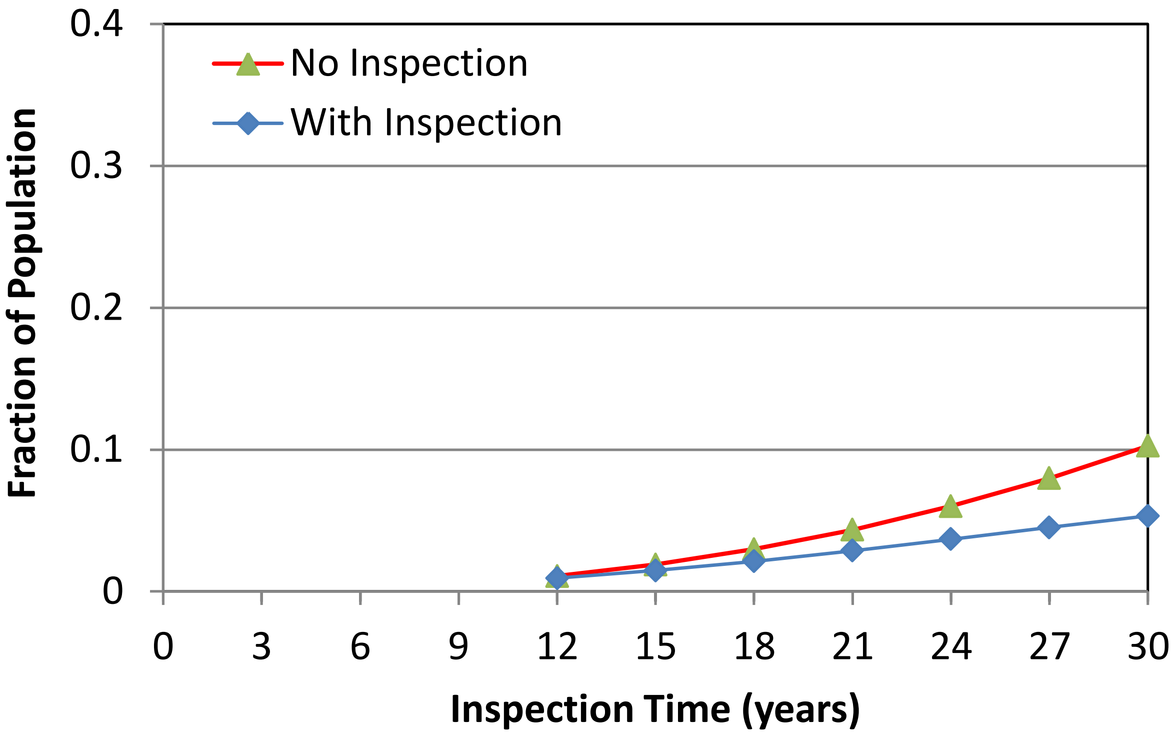
Partial Inspection

- **Inspection program starts at 12 years**
  - Sample size is fixed at 30 (for practical reasons)
    - It means 56% population will not be inspected at all
  - The effectiveness of the plan is reduced



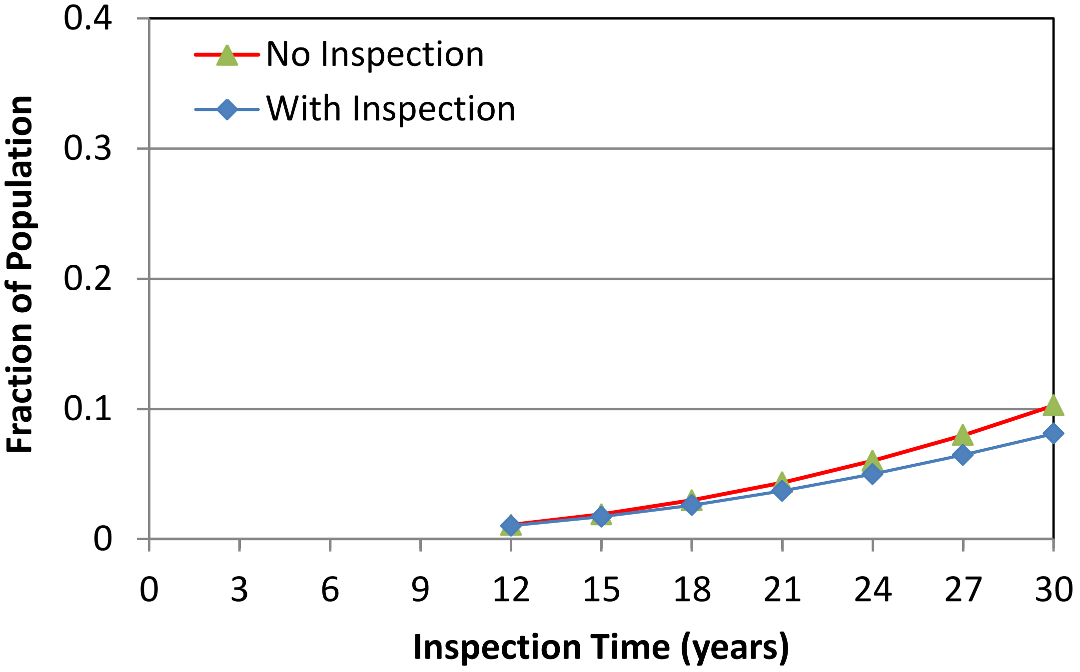
Example - 2

- **Case of low incidence of degradation**
  - Mean lifetime 65 years (COV=0.4)
  - Full core inspection starting year 12
    - Sample size = 68 per inspection outage



Example 2 – Partial Inspection

- **Inspection of 30 components starting year 12**
  - It means 210 components inspected in 7 outages
  - The effectiveness of this program is quite limited



Remarks

- **An inspection strategy needs to recognize its impact over the entire service life of the population**
    - Arbitrary selection of sample size and frequency may not be useful at all
- **Effectiveness of inspection strategy depends on the nature of degradation mechanism**
    - Use of an “uncalibrated” sample size may be meaningless from a reliability view point

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Summary

- **Inspection rules must be complementary to the probabilistic assessment**
  - demonstrate that the spread of degradation is below a safety/reliability threshold
- **Inspection/maintenance strategies play a key role in the success of a degradation management program**
  - Information provided by probabilistic assessment must be used to guide the inspections

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Summary

- **Statistical hypothesis test can be used to determine the inspection sample size**
  - Sample can be quite large if high confidence results (80% - 90%) are sought
  - To reduce the sample size, there should be a tolerance for higher statistical errors (25 – 40%)
  - This is a challenging aspect of verifying the prediction of a probabilistic assessment

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Summary

- **Degradation management**
  - Inspection program should be in tune with the lifetime distribution obtained from the assessment
  - The remaining defectives in the population depend on sample size and inspection frequency
  - Small sample size and long inspection cycles are not effective
  - The efficiency of inspection depends on the rate of spread of degradation with time.
    - Rapid degradation can be contained by aggressive inspections
    - Rare form degradation require more inspection efforts