



NUGENIA+ WP6.12

Justification of Risk Reduction through In-Service Inspection / REDUCE

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Introduction

- **Degradation is ongoing by for example fatigue, stress corrosion and erosion**
 - In-service inspection (ISI) is essential for continued safe operation of NPPs
 - ISI is performed by NDT-methods as UT, ET, PT or RT
- **Huge amount of welds and components in a plant**
 - Relevant processes are needed for determining necessary inspections
 - Risk-informed processes (RI-ISI) are developed for selection of sites
- **Assessment of the risk reduction achieved by the selected NDT method and interval differ between different risk-informed processes**
 - Improvements are needed and this project will develop guidelines
 - The risk reduction achieved by the chosen inspection strategy is dependent on the NDT-performance and the inspection interval, but also on the loading, degradation mechanism and material properties.
 - Probabilistic analysis based on models of the underlying degradation and failure mechanisms provide means to analyze and understand the effect on risk reduction from different choice of ISI in different situations.



Objectives

- **Effective In-Service Inspection (ISI) is essential for safe operation of NPPs considering degradation.**
 - Risk-informed processes (RI-ISI) are commonly used for selecting the sites for inspection.
 - This project has the purpose to study and develop guidelines for **assessment of the difference in risk reduction from alternative In-Service Inspection strategies (NDT-method and interval)** for **specific situations**.
- **The effect on risk reduction from changing inspection interval or improve NDT performance is investigated by structural reliability models (SRMs) for type cases.**
 - Different typical cases of degradation, loading, piping dimensions and materials are considered.
- **Recommendations have been developed on the work process and parameters important to consider when optimizing ISI**
 - The document will support the ENIQ framework document for Risk Informed In-Service Inspection (EUR21581EN), with details on the subject of assessment of risk reduction from alternative ISI strategies, in order to assure relevant risk reduction.



Partners



- **Project team, main responsible and deputies**
 - **Inspecta:** Jens Gunnars, Peter Dillström, Andrey Shipsha
 - **VTT:** Otso Cronvall, Ahti Oinonen, Qais Saifi
 - **CEA:** Pierre Calmon, Xavier Artusi, Steve Mahaut
 - **LEI:** Robertas Alzbutas, Gintautas Dundulis, Eugenijus Uspuras



Tasks

- **WP 1: Selection and development of a set of piping type cases – different geometries, loads and degradation (VTT)**
- **WP 2: Analysis of baseline risk reduction by ISI for type cases using best-estimate data (Inspecta)**
- **WP 3: Sensitivity evaluation of influence from key parameters on risk reduction (CEA)**
- **WP 4: Development of guidelines for assessment of the risk reduction from alternative ISI (LEI)**



WP1: Selection and development of a set of piping type cases

- **Computation matrix for 3 BWR and 3 PWR welds**
 - Butt-welds in pipes of different thicknesses ($t = 4 - 65$ mm), material data (austenitic stainless steel and ferritic steel)
 - Degradation mechanisms: SCC (6 case) and fatigue (1 case)
 - Defect data: orientation, distributions for initial defect sizes
 - Loading: normal operation, weld residual stresses, fatigue specific loading, upset events.
 - Inspection: interval, reliability (POD, from qualification data)
 - Leak rate detection capabilities
 - Consequence measure (CCDP)
- **Best estimate data are used for a baseline analysis**
 - Except for the SCC growth (upper bound)
- **14 baseline analyses**
 - 7 cases with no ISI, 7 cases with 5 year ISI interval

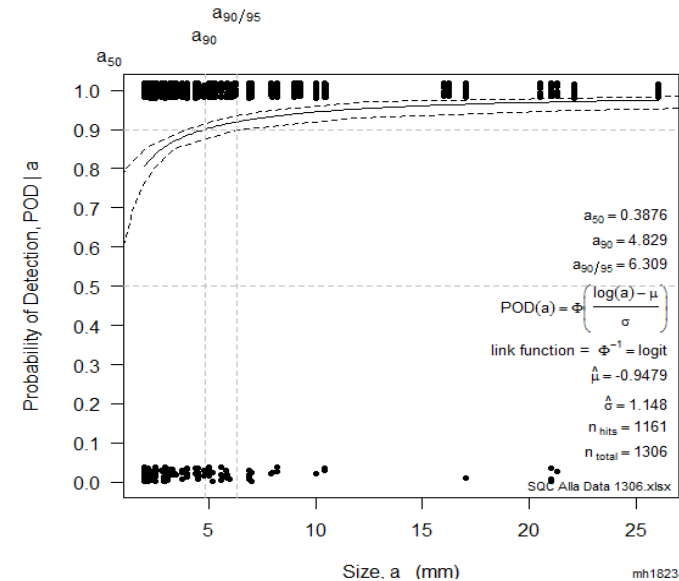


WP1: Example of input data

Inspection reliability (POD) and WRS

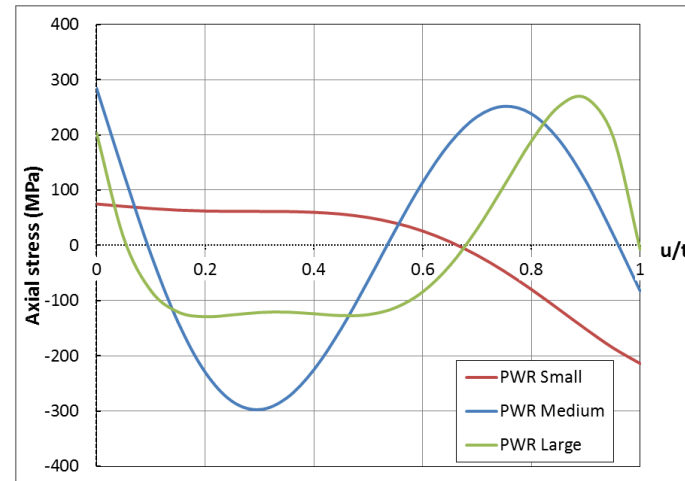
POD-curve for the baseline analyses

- Based on qualification data from a Swedish UT procedure
- From in total 1761 inspections (hit/miss data) for 161 different defects with depth 2-26 mm)



Best estimate weld residual stresses

- Based on advanced FE simulations, using best-estimate welding conditions. Published 2016
- For some cases these are validated against detailed experimental measurements



WP2: Analysis of baseline risk reduction by ISI for type cases

- **The risk reduction is determined for the type cases, to evaluate different NDT procedures and intervals.**
 - Structural reliability models (SRMs) to compute a baseline risk reduction, using realistic assumptions for influencing parameters.
 - The baseline result will also give a picture of the achievable level of risk reduction through in-service inspection.

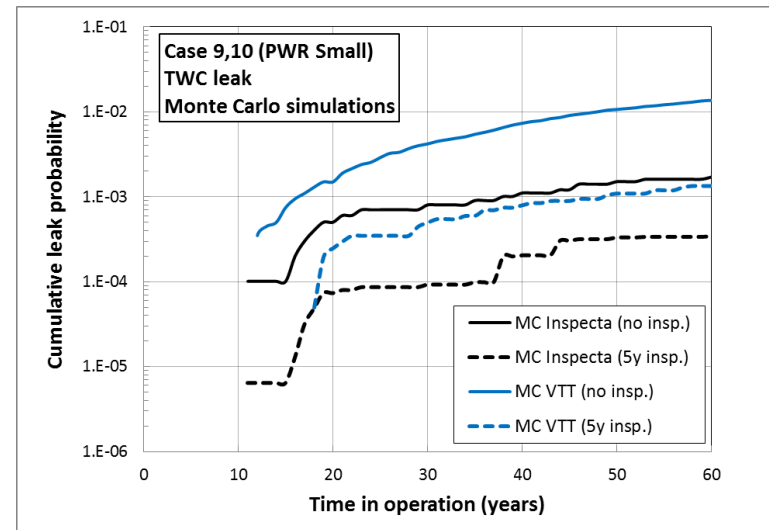
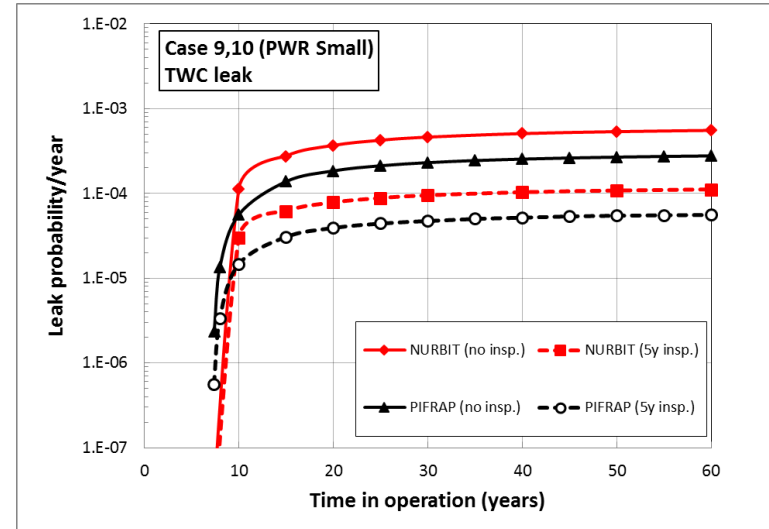
- **All baseline cases defined in WP1 were analyzed within WP2 using the PFM codes**
 - NURBIT (Inspecta)
 - VTTBESIT (VTT)
 - AutoPIFRAP (LEI)

- **In addition, complimentary calculations were performed by Inspecta and VTT using SRM models with a Monte Carlo simulation procedure.**



WP2: Example – baseline analysis results for case PWR-Small

- **Example:**
SCC at weld in 10.8 mm stainless steel pipe
- **In-service inspections results in lower probability of leak and rupture**
 - Risk reduction in the range 5-10 is achieved for a 5 years interval
- **Benchmarking / verification**
The *relative* risk reduction obtained from the different SRM models used are in good agreement –



WP3: Sensitivity evaluation of influence from key parameters on risk reduction

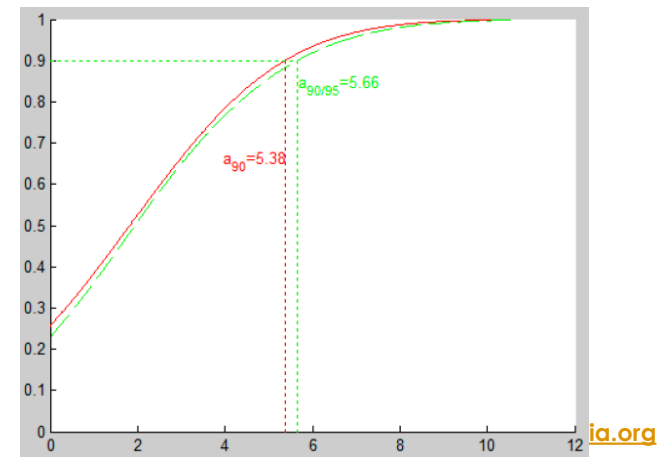
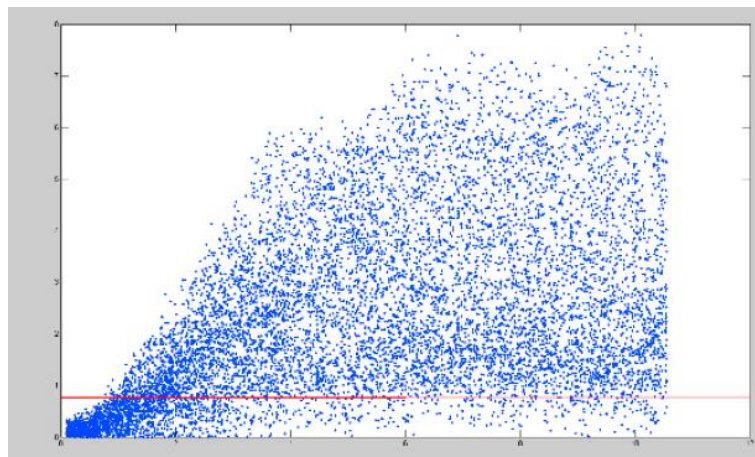
- Sensitivity analyses to evaluate the influence of foreseeable variations and uncertainties
- The selected parameters can be divided in two groups;
 - Related to uncertainty in crack size and growth rate, material properties, primary and secondary loads (WRS),
 - Related to an ISI program (POD of a NDT system, leak detection capability and ISI interval).

- Sensitivity matrix of 10 parameters
 - Low/Baseline/High
 - Only 1 parameter is varied, others are at baseline level

BWR Small		Physical parameters							ISI program parameters		
Identification	Run no.	Flaw depth (FD)	Flaw length (FL)	Load level (LL) Pm/Pb+Pe	Flow stress (FS) (131+437)/2+284	Fracture toughness (JIC)	WRS	SCC law plateau	POD	Inspection interval	Leak detection limit (LDL)
S_BWR_base	1_1	1.0	10.66%	22.8/37.9		170.3	B	B	B	5 year	0.42 kg/s
S_BWR_FD_L	1_2	0.5	B	B	B	B	B	B	B	B	B
S_BWR_FD_H	1_3	3.0	B	B	B	B	B	B	B	B	B
S_BWR_FL_L	1_4	B	7.1%	B	B	B	B	B	B	B	B
S_BWR_FL_H	1_5	B	32.0%	B	B	B	B	B	B	B	B
S_BWR_LL_L	1_6	B	B	15.2/19.0	B	B	B	B	B	B	B
S_BWR_LL_H	1_7	B	B	45.6/113.7	B	B	B	B	B	B	B
S_BWR_FS_L	1_8	B	B	B	142	B	B	B	B	B	B
S_BWR_FS_H	1_9	B	B	B	426.0	B	B	B	B	B	B
S_BWR_JIC_L	1_10	B	B	B	B	56.8	B	B	B	B	B
S_BWR_JIC_H	1_11	B	B	B	B	340.6	B	B	B	B	B
S_BWR_WRS_L	1_12	B	B	B	B	B	Low	B	B	B	B
S_BWR_WRS_H	1_13	B	B	B	B	B	High	B	B	B	B
S_BWR_SCC_L	1_14	B	B	B	B	B	B	Low	B	B	B
S_BWR_SCC_H	1_15	B	B	B	B	B	B	High	B	B	B
S_BWR_POD_P	1_16	B	B	B	B	B	B	B	Poor	B	B
S_BWR_POD_A	1_17	B	B	B	B	B	B	B	Advanced	B	B
S_BWR_ISI_L	1_18	B	B	B	B	B	B	B	B	10	B
S_BWR_ISI_S	1_19	B	B	B	B	B	B	B	B	1	B
S_BWR_LDL_P	1_20	B	B	B	B	B	B	B	B	B	4.2
S_BWR_LDL_G	1_21	B	B	B	B	B	B	B	B	B	0.042

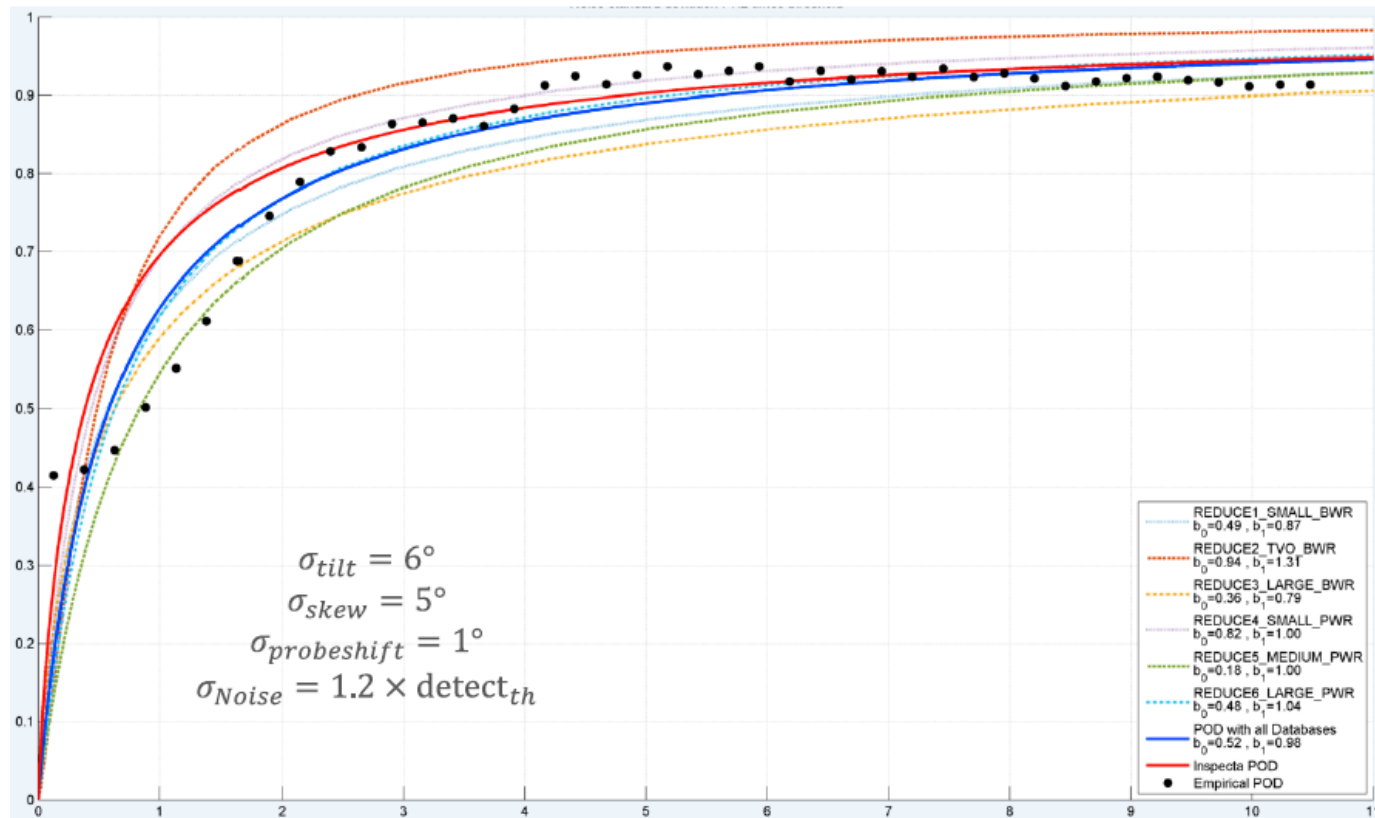
WP3-ii: Simulation of POD-curves

- **POD-curves are one of important input to the SRM analyses**
- **Simulation of POD-curves, based on UT modelling for different welds and geometries**
 - Provide a possibility to understand the importance of testing parameters for the POD-curve in specific cases
- **Example of parameters that was used in the POD simulations:**
 - The height (depth) and length of the defect
 - The frequency: Uniform distribution [2, 2.5 MHz],
 - The angular offset : Uniform distribution (interval dependent on pipe diameter)
 - The defect tilt: Normal distribution, from -30° to $+30^\circ$
 - The defect skew: Normal distribution, from -20° to $+20^\circ$



WP3-ii: Simulation of POD-curves

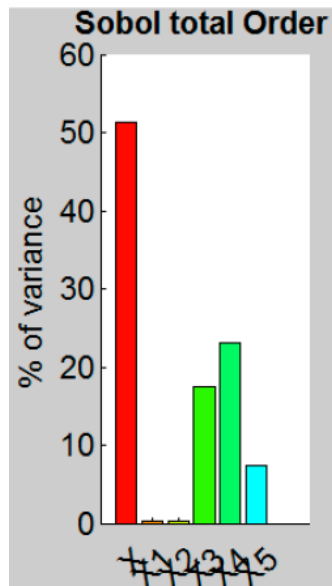
- Example - Simulated POD curves for specific weld geometries



WP3-ii: Simulation of POD-curves

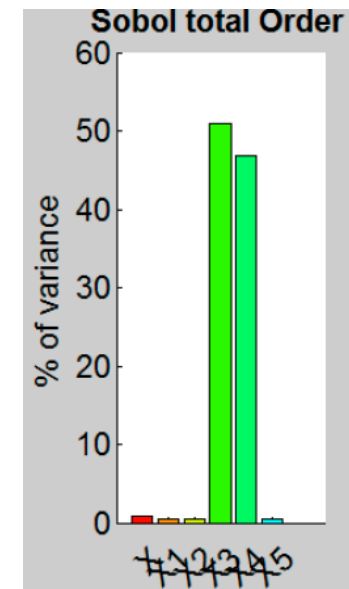
Results from sensitivity analysis for POD

For better understanding of the relative influence of the different parameters in UT procedures, sensitivity analysis were performed



**Small defects
0-5 mm**

**Larger defects
> 5 mm**



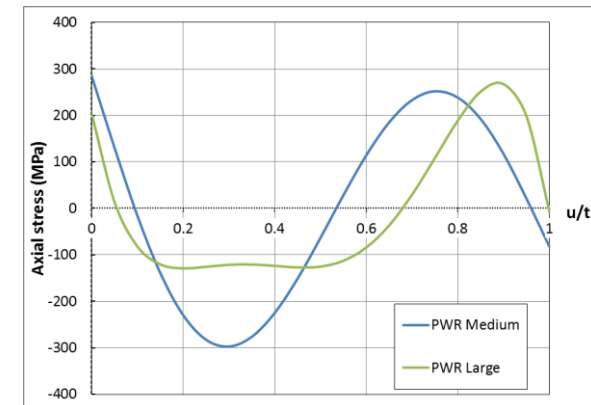
- Tilt and skew are very important parameters for the POD.
- The defect height (depth) has large influence on POD for small defects, but height has little influence on POD for large defects.

Analysis results – Main influencing factors

Middle and thick walled pipes

■ For SCC degradation:

- For welds in middle and thick walled pipes, all considered SRM codes demonstrate very low probabilities
- Crack arrest is in principle predicted well before unacceptable crack sizes
- Weld residual stresses is the most important parameter. Validation of the best-estimate WRS will contribute to risk reduction.
- No additional risk reduction is possible for these welds through ISI and advanced NDT



■ For fatigue degradation

- In contrast to SCC, in-service inspections will contribute to risk reduction
- Important uncertainties include loading and ISI related parameters (interval, POD)

Analysis results – thin-walled pipes: Influence of uncertainties in loads & degradation

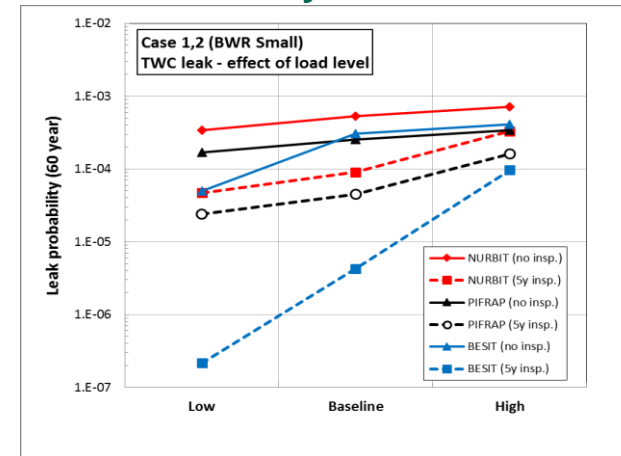
- SCC degradation in thin walled pipes
- Uncertainty in primary loads and WRS has a strong influence on predicted probabilities

- For high load levels it is necessary with short intervals to achieve desired risk reduction
- Use of measures to mitigate WRS can result in substantial risk reduction

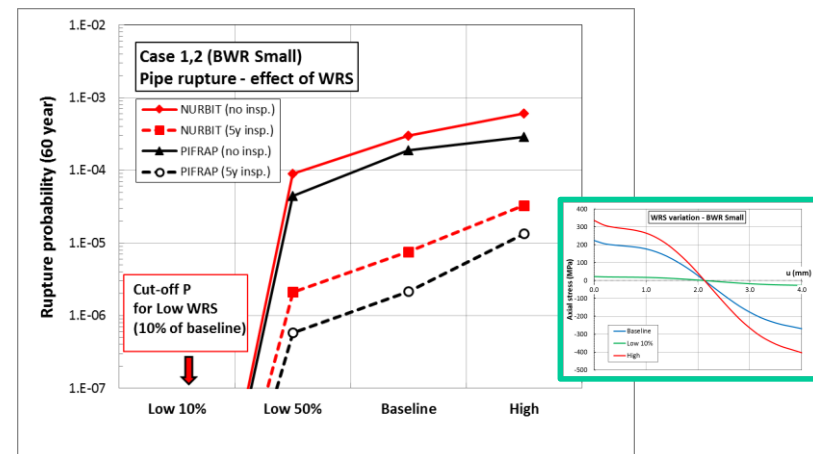
SCC growth rate

- Upper bound data is used as baseline case due to lack of best-estimate data
- Improved modelling of SCC would be valuable

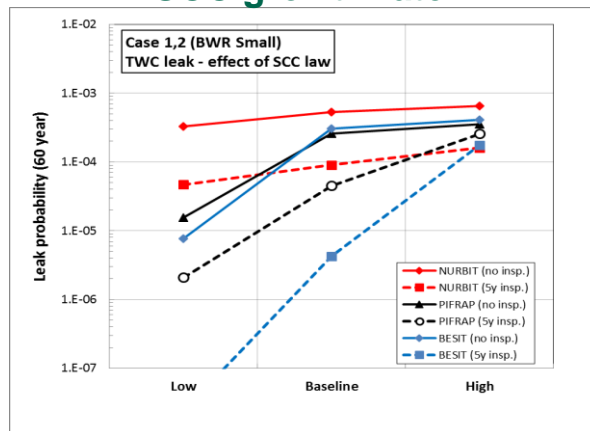
Primary loads



Weld Residual Stresses



SCC growth rate



Analysis results – thin-walled pipes: Influencing parameters related to ISI strategy

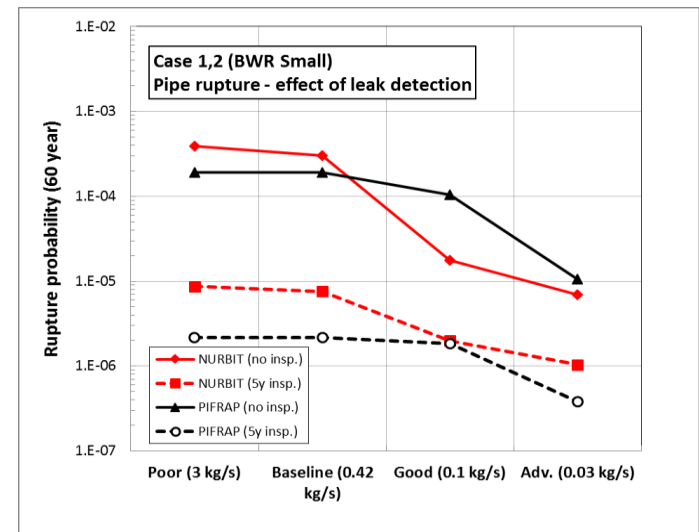
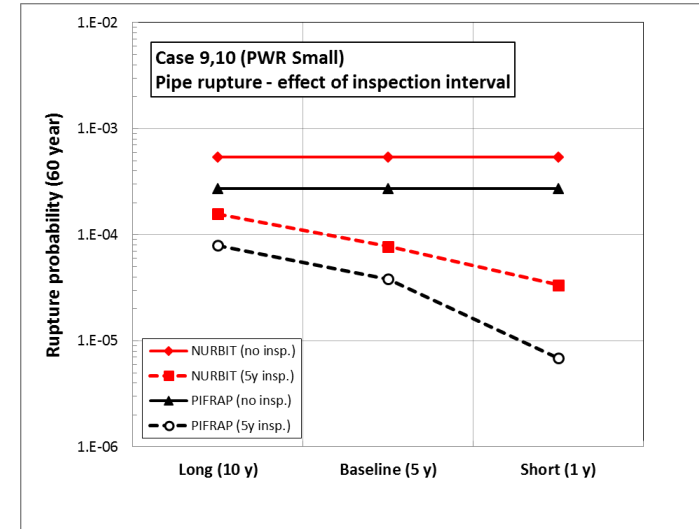
- **SCC degradation in thin walled pipes**

- **ISI program**

- The ISI interval has large influence on risk reduction for thin pipes, when short enough
 - For SCC and thin walled pipes, additional risk reduction is obtained by improved POD of the NDT system

- **Leak detection**

- Leak detection provides a substantial contribution to risk reduction.
 - *In a case of no ISI the risk reduction can be large by good leak detection*
 - *Combined ISI and leak detection reduce the risk further*



WP4: Development of guidelines for assessment of risk reduction from ISI

Contents

- Main steps of the RI-ISI process
- General description of process for assessment of alternative ISI strategies
- Definition of risk reduction measures
- Information gathering and QA
- Assessment of risk reduction by SRMs
- Use of results for type cases
- Discussion on consideration of influence from key parameters on the risk reduction
- Selection among options and implementation



Dissemination

- Press releases will be written
- The conference “Probabilistic Safety Assessment and Management” in October 2016, Korea
- Nordic Symposium on Nuclear Technology 2016 (Kärnteknik 2016), in Stockholm, 15 – 16 November 2016
- 2017 QNDE international conference (Quantitative Non Destructive Evaluation Review of Progress) in July 2017 USA
- ASME 2017 PVP Conference, July 16-20, 2017, USA
- 7th EAW 2017 (European-American Workshop on Reliability of NDE) Sept. 2017 Germany
- The results will be used in courses on ISI



General impact of the project



■ Safety improvement

- Improved assessment in overall perspective of the effectiveness of in-service inspections (ISI) to reduce risk

■ Knowledge

- New knowledge has been developed
- The project will increase understanding and insights of important factors among ISI responsible and NDT specialists

■ Economy

- More efficient use of resources for safety improvement



Conclusions

- **SRM provide means to analyze the efficiency of different strategies for risk reduction**
 - Risk reduction must be assessed regarding uncertainty in loads and degradation for specific situations, as well as effect of ISI program (intervals, POD of NDT systems, and leak detection capabilities)
 - Simulation of POD-curves is powerful for analyzing influencing parameters of the NDT-system for different testing cases
- **The importance of influencing parameters has to be considered in the total perspective.**
 - For example, for a thin-walled pipe, ISI with shorter interval can result in large risk reduction
 - For example, SCC in thick walled stainless steel is controlled by WRS, and ISI do not contribute to risk reduction in this case
- **A structured and practical process for assessment of the risk reduction from different ISI programs is important**



Next steps

- **It is recommended to focus further development to the following areas;**
 - Assessment of several fatigue situations (both low-cycle and high-cycle fatigue)
 - Weld residual stress validation and investigation of uncertainty sources (due to high importance for thick welds)
 - Practical use of POD simulation to address differences in response to defects from specific degradation mechanisms (SCC and fatigue)
 - Application to a pilot piping system

- **It is suggested that a proposal is developed within the framework of H2020, NUGENIA or similar**

