The 17th International Workshop on Nuclear Safety & Simulation Technology (IWNSST17)
January 21,2014, Kyoto University, Kyoto

Reliability Assessment for Detecting and Sizing Pipe Wall Thinning and its Application to Risk Management

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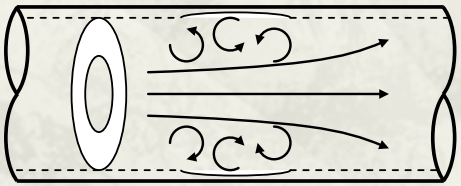
Talk of the scenario (Part I)

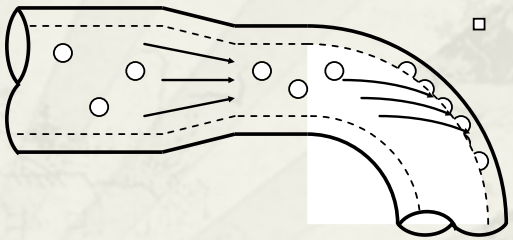
- **Pipe wall thinning management**
- E-MAT based NDE system
- Probability of detection (POD)
- Application to risk management

Pipe wall thinning management

Pipe wall thinning management in NPPs is aimed at providing a life management process ensuring replacement or repair prior to in-service failure. The main objective of pipe wall inspection is to:

- identify **the location of maximum thinning (Screening)**
- ascertain **the extent and depth of the thinning (Monitoring)**
- evaluate **the wear rate (Predicting)**

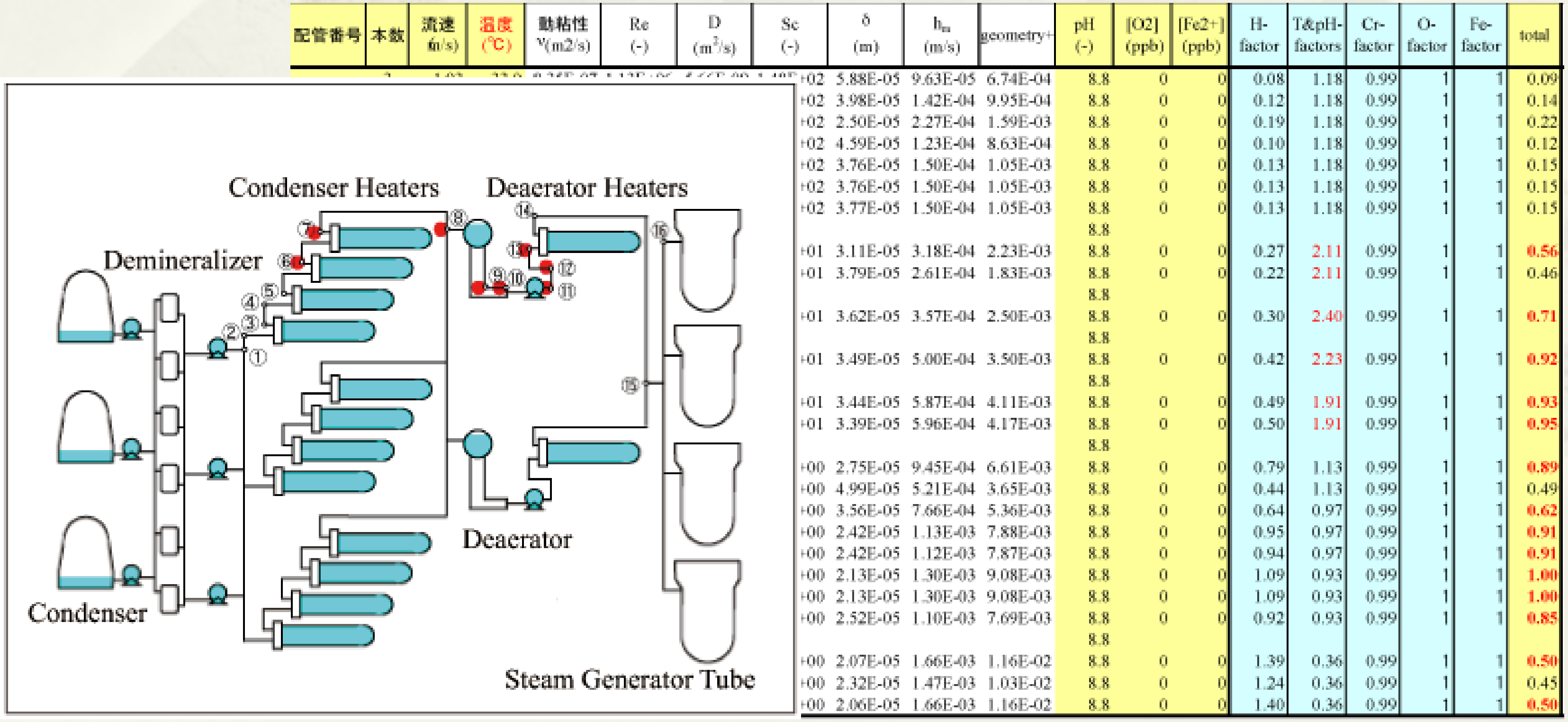




Flow-accelerated corrosion (FAC) and **liquid droplet impingement erosion** (LDI) are well-known damage mechanisms that commonly affect carbon steel piping. These occur on a piping internal wide range at an orifice, an elbow, and a reducer down stream.

Task for PWTM

Major tasks in PWTM include **the selecting and scheduling** components for inspection and the decision making for **repair or replacement** of the specific components of the piping system.



配管番号	本数	流速 (m/s)	温度 (°C)	動粘性 ν(m2/s)	Re (-)	D (m²/s)	Sc (-)	δ (m)	h_m (m/s)	geometry+	pH (-)	[O2] (ppb)	[Fe2+] (ppb)	H-factor	T&pH-factors	Cr-factor	O-factor	Fe-factor	total
							+02	5.88E-05	9.63E-05	6.74E-04	8.8	0	0	0.08	1.18	0.99	1	1	0.09
							+02	3.98E-05	1.42E-04	9.95E-04	8.8	0	0	0.12	1.18	0.99	1	1	0.14
							+02	2.50E-05	2.27E-04	1.59E-03	8.8	0	0	0.19	1.18	0.99	1	1	0.22
							+02	4.59E-05	1.23E-04	8.63E-04	8.8	0	0	0.10	1.18	0.99	1	1	0.12
							+02	3.76E-05	1.50E-04	1.05E-03	8.8	0	0	0.13	1.18	0.99	1	1	0.15
							+02	3.76E-05	1.50E-04	1.05E-03	8.8	0	0	0.13	1.18	0.99	1	1	0.15
							+02	3.77E-05	1.50E-04	1.05E-03	8.8	0	0	0.13	1.18	0.99	1	1	0.15
											8.8								
							+01	3.11E-05	3.18E-04	2.23E-03	8.8	0	0	0.27	2.11	0.99	1	1	0.56
							+01	3.79E-05	2.61E-04	1.83E-03	8.8	0	0	0.22	2.11	0.99	1	1	0.46
											8.8								
							+01	3.62E-05	3.57E-04	2.50E-03	8.8	0	0	0.30	2.40	0.99	1	1	0.71
											8.8								
							+01	3.49E-05	5.00E-04	3.50E-03	8.8	0	0	0.42	2.23	0.99	1	1	0.92
											8.8								
							+01	3.44E-05	5.87E-04	4.11E-03	8.8	0	0	0.49	1.91	0.99	1	1	0.93
							+01	3.39E-05	5.96E-04	4.17E-03	8.8	0	0	0.50	1.91	0.99	1	1	0.95
											8.8								
							+00	2.75E-05	9.45E-04	6.61E-03	8.8	0	0	0.79	1.13	0.99	1	1	0.89
							+00	4.99E-05	5.21E-04	3.65E-03	8.8	0	0	0.44	1.13	0.99	1	1	0.49
							+00	3.56E-05	7.66E-04	5.36E-03	8.8	0	0	0.64	0.97	0.99	1	1	0.62
							+00	2.42E-05	1.13E-03	7.88E-03	8.8	0	0	0.95	0.97	0.99	1	1	0.91
							+00	2.42E-05	1.12E-03	7.87E-03	8.8	0	0	0.94	0.97	0.99	1	1	0.91
							+00	2.13E-05	1.30E-03	9.08E-03	8.8	0	0	1.09	0.93	0.99	1	1	1.00
							+00	2.13E-05	1.30E-03	9.08E-03	8.8	0	0	1.09	0.93	0.99	1	1	1.00
							+00	2.52E-05	1.10E-03	7.69E-03	8.8	0	0	0.92	0.93	0.99	1	1	0.85
											8.8								
							+00	2.07E-05	1.66E-03	1.16E-02	8.8	0	0	1.39	0.36	0.99	1	1	0.50
							+00	2.32E-05	1.47E-03	1.03E-02	8.8	0	0	1.24	0.36	0.99	1	1	0.45
							+00	2.06E-05	1.66E-03	1.16E-02	8.8	0	0	1.40	0.36	0.99	1	1	0.50

by Dr. Shunsuke Uchida

JSME Codes for Nuclear Power Generation Facilities

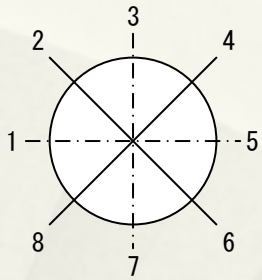
Rules on Pipe Wall Thinning Management for PWR plant

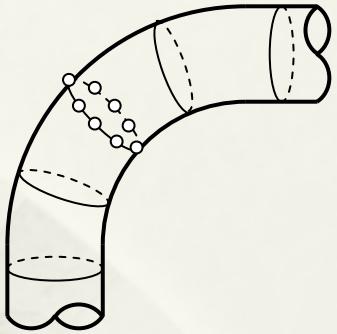
CA-2310 normal pitch

Standard thickness

$$t_m = t_{sr} + \frac{2}{3}(t_n - t_{sr})$$

t_n : minimum thickness
t_{sr} : requirement



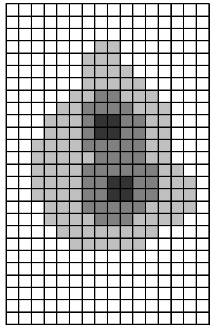


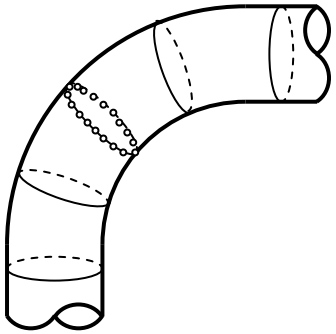
$t_{measure} > t_m$

Yes

No

CA-2320 Detailed survey





Measurement pitch with 20[mm]

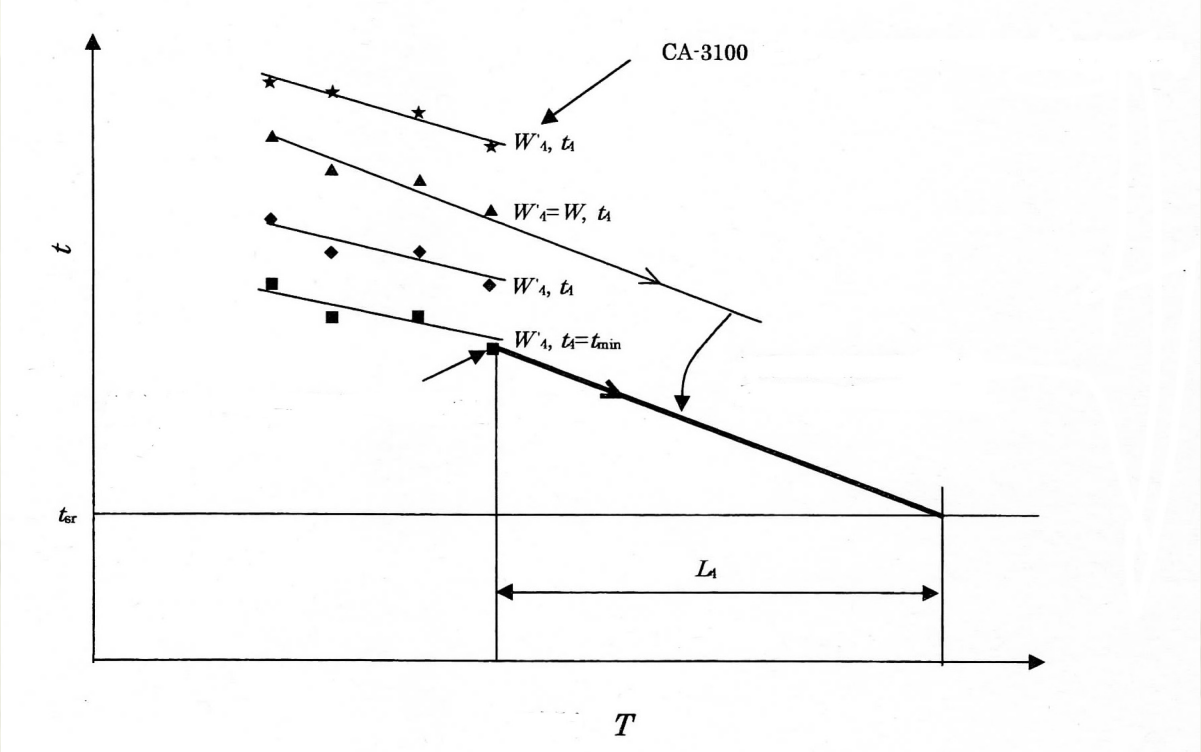
Thinning rate

Evaluation by CA-3000

Those have been performed by the conventional UT manually for the prescribed area of piping system.

Basic strategies

Analyses for **<u>predicting wear rates</u>** and **<u>periodical inspections</u>** for the pipe wall thickness play essential roles in PWTM.



Follow-up inspections:

$$L_n = \frac{t_{min} - t_{sr}}{W_n} \times \frac{1}{8760} \quad \left(L_0 = \frac{t_{nom} - t_{sr}}{W_0} \times \frac{1}{8760} \right)$$

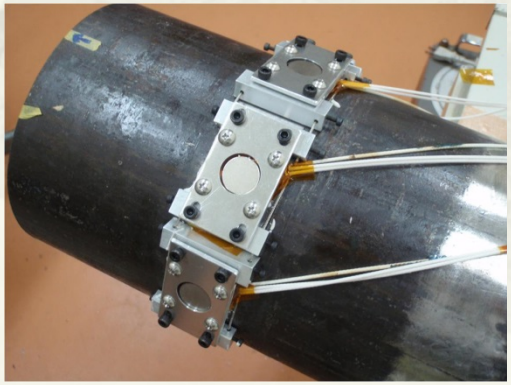
Talk of the scenario (Part II)

- ✓ Pipe wall thinning management
- ■ **E-MAT based NDE system**
- ◆ Probability of detection (POD)
- ◆ Application to risk management

Electromagnetic NDE

ENDE has advantages on …

- Remote capabilities (reproducing test signals,…)
- Rapid processing (non-contacting,…)
- Robustness in environments (high temperature, radiation,…)
- State monitoring (condition monitoring, continuous surveillance,..)



In the application of any NDT method, there exist so many uncertainties whether or not the inspection will result in the correct decision. Reliability assessment of NDT plays an essential role in the performance of the maintenance.

Critical issues for piping inspection

1. **Tedious tasks are required at each inspection**
   - Removing insulation from the piping area
   - Inaccessible locations for the in-situ inspection
   - Remarking grid points for measurements
2. **Need qualified human experts**
   - Lack of experts but increasing ageing plants

Pipe inspection using EMAT

Condition Monitoring using EMAT

Advantage using EMAT:

- Remote capabilities (reproducing exciting signal,…)
- Self-holding sensors (monitoring under sensor network,…)

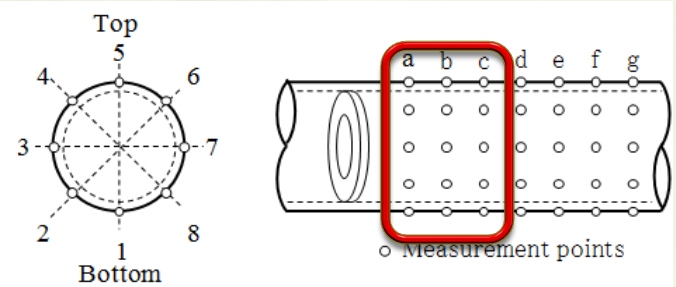
Needs to solve:

- Assure the same accuracy of thickness measurements by UT
- Require validity and feasibility studies for implementing on-line monitoring,…

Grand test at downstream of orifice

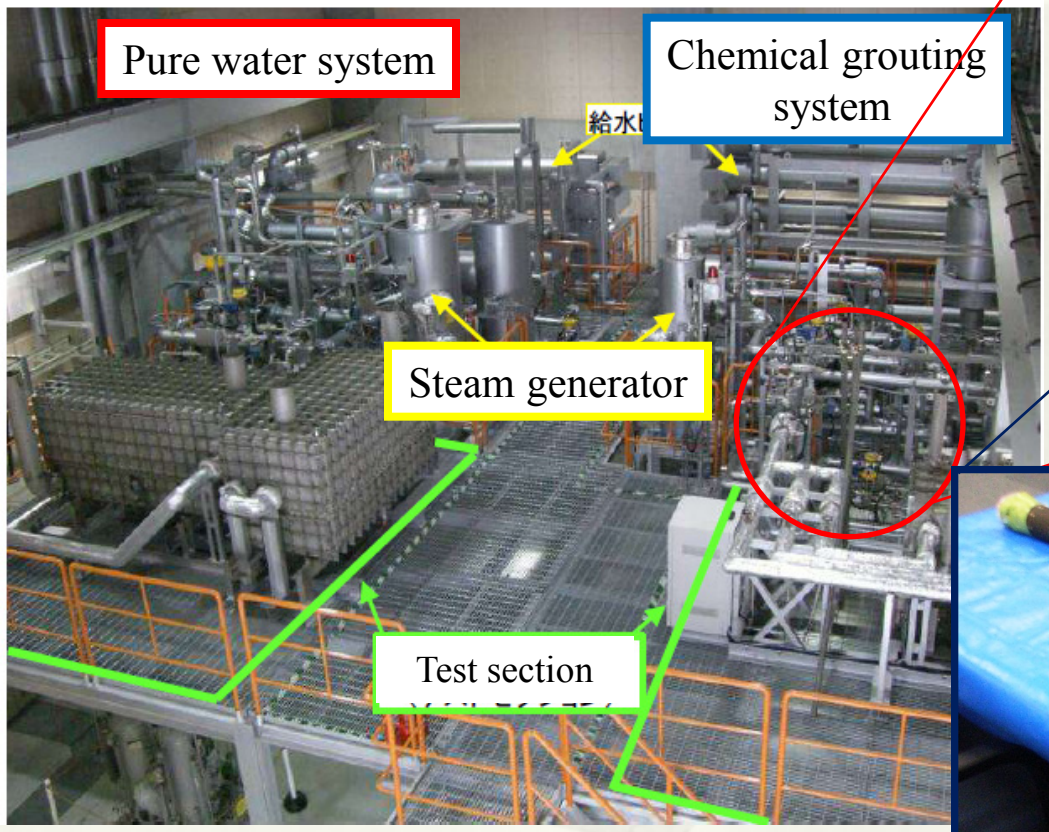
Compared with UT sizing results, maximum difference between UT and EMAT measurements became 0.28 [mm], average difference was 0.08 [mm], and median was 0.07 [mm].

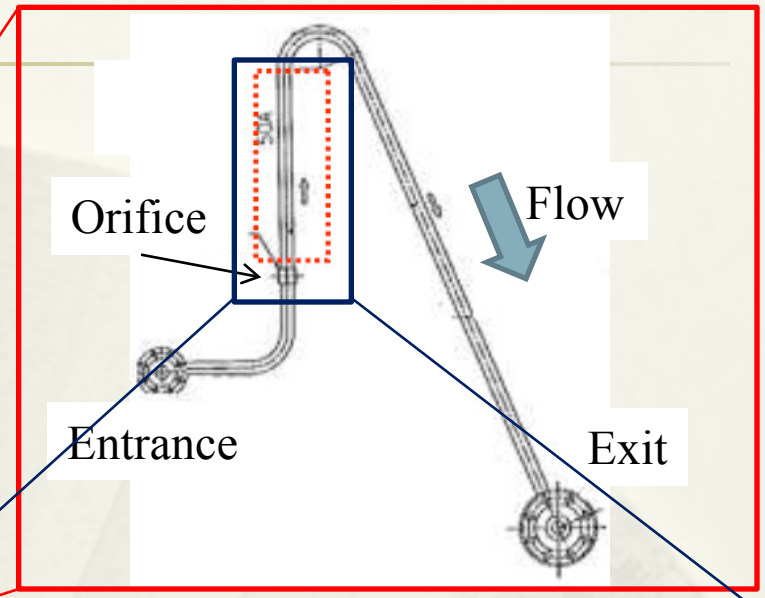
		1	2	3	4	5	6	7	8
a	EMAR	8.7	8.5	8.6	8.6	8.7	8.9	8.7	9.0
	UT	8.8	8.7	8.6	8.6	8.7	8.8	8.8	8.9
b	EMAR	8.5	8.6	8.7	8.8	8.5	8.7	8.6	8.8
	UT	8.6	8.7	8.5	8.8	8.7	8.5	8.7	8.8
c	EMAR	8.5	8.8	8.6	8.8	8.7	8.7	8.6	8.7
	UT	8.5	8.8	8.7	8.8	8.9	8.8	8.7	8.8
d	EMAR	11.0	10.9	10.8	11.1	10.9	10.8	10.7	10.9
	UT	11.0	11.0	10.9	11.0	10.7	10.9	10.9	11.1
e	EMAR	10.9	10.8	10.9	11.0	10.9	10.8	10.8	11.0
	UT	10.9	10.9	10.9	11.0	11.1	11.0	10.9	11.0
f	EMAR	10.4	10.8	11.0	11.0	11.3	11.1	10.7	11.1
	UT	10.7	10.9	11.0	11.1	11.4	11.0	10.9	11.0
g	EMAR	10.7	10.9	11.0	11.0	11.0	10.9	10.7	10.8
	UT	11.0	11.0	11.0	11.1	11.1	10.9	10.8	11.0

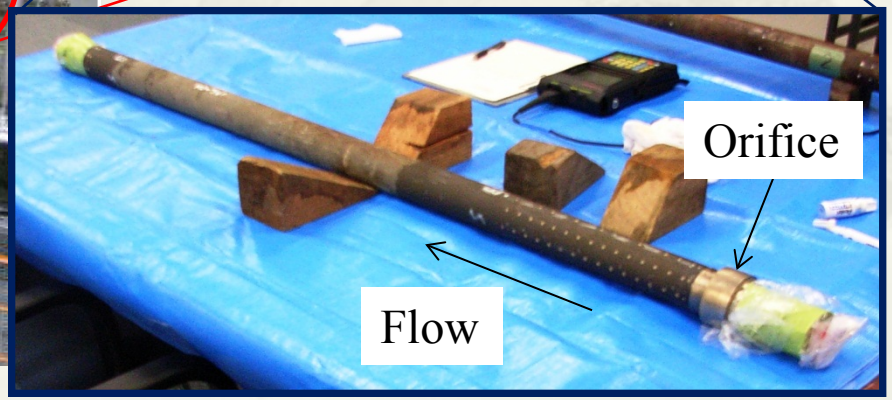


We gratefully acknowledge the Institute of Nuclear Safety System Inc (INSS) and the Fossil Power Engineering Center, KEPCO for their assistance in this experimental works.

FAC Specimen at laboratory facility

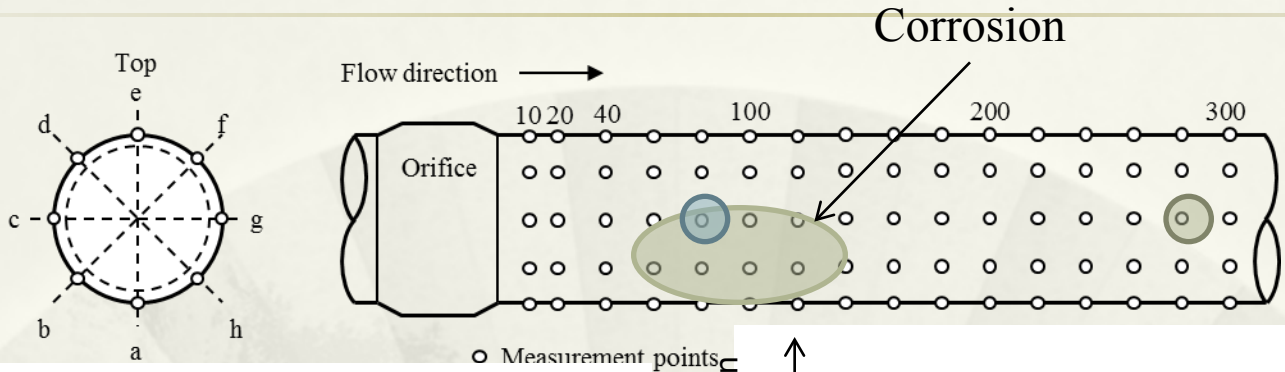


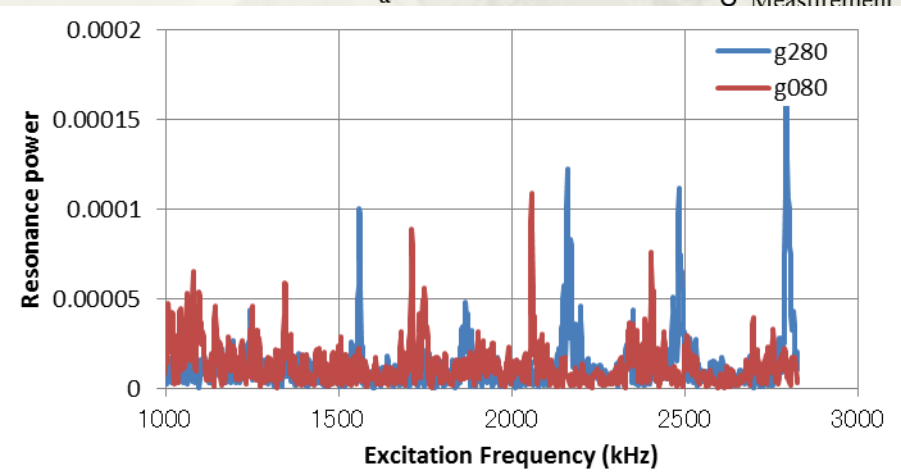


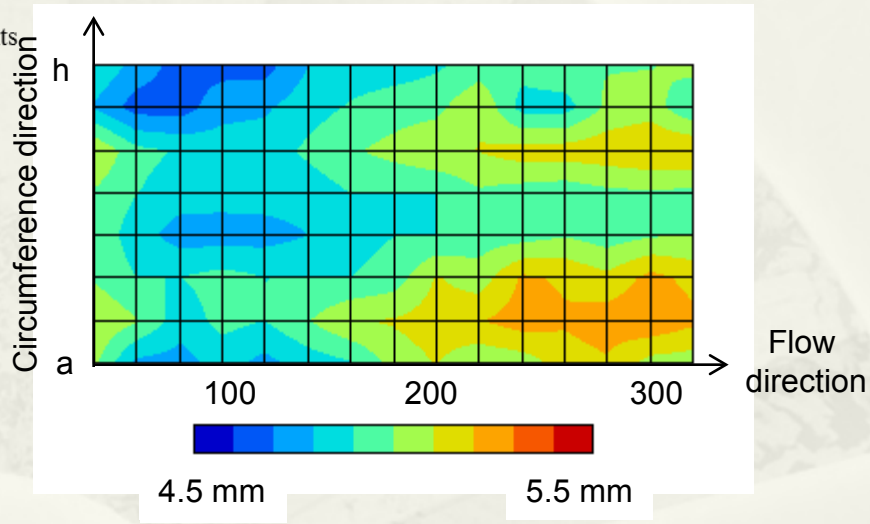


Acknowledgement: The authors also gratefully acknowledge Tokyo Electric Power Co. Inc. for their assistance in the experimental works.

Measurement results by EMAT





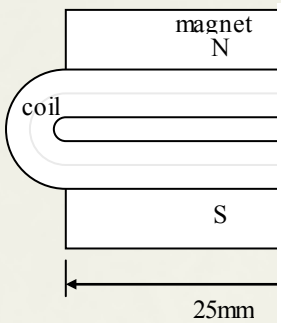


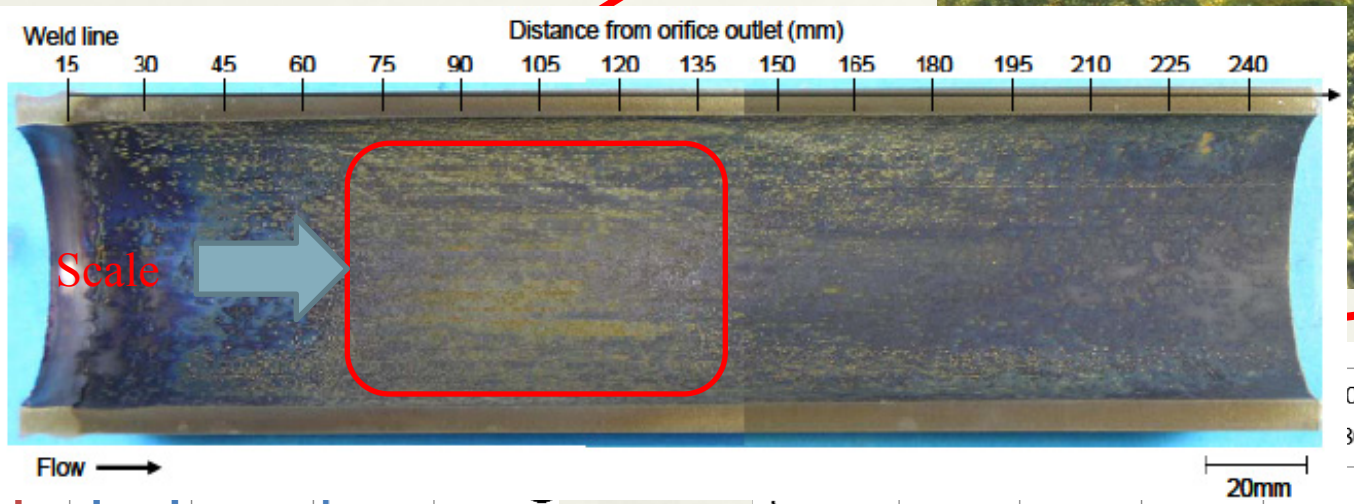
Measurements : Eight grid points (Circumferential), 10mm pitch (Axial)

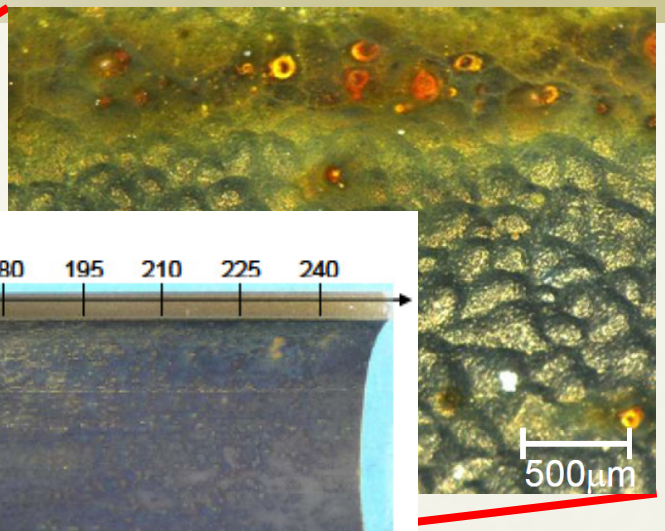
Detect wall thinning area at the downstream of orifice

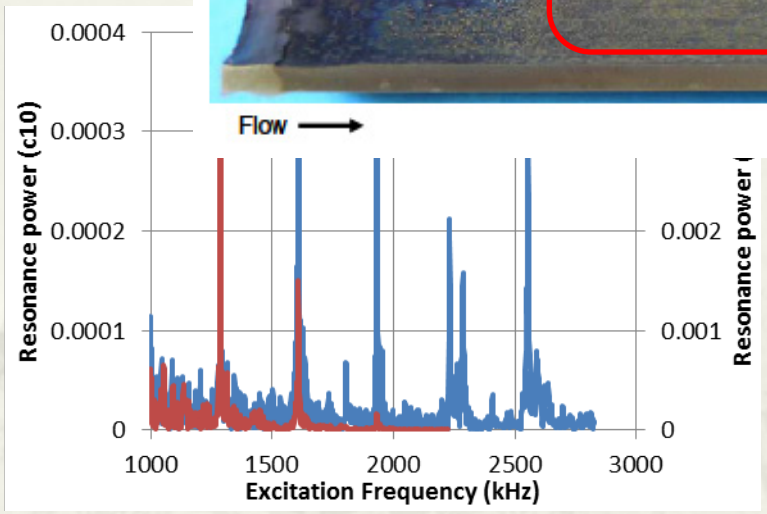
Extent of FAC : 20-60mm, Localization : g-a area

Effect of Real Scaly Profiles

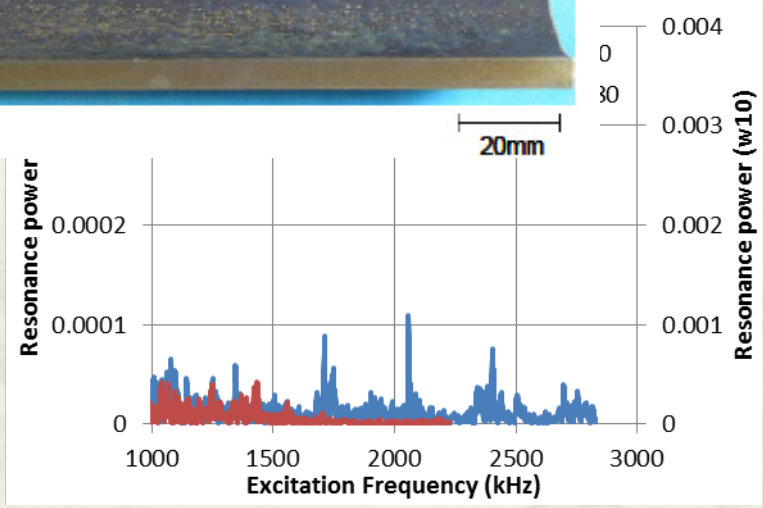








Without corrosion



With corrosion

- Signal strength is almost proportional to coil diameter and number of turns.
- Resolution of EMAT thickness measurement becomes worse due to the bad effect of scaly profiles.

Talk of the Scenario (Part III)

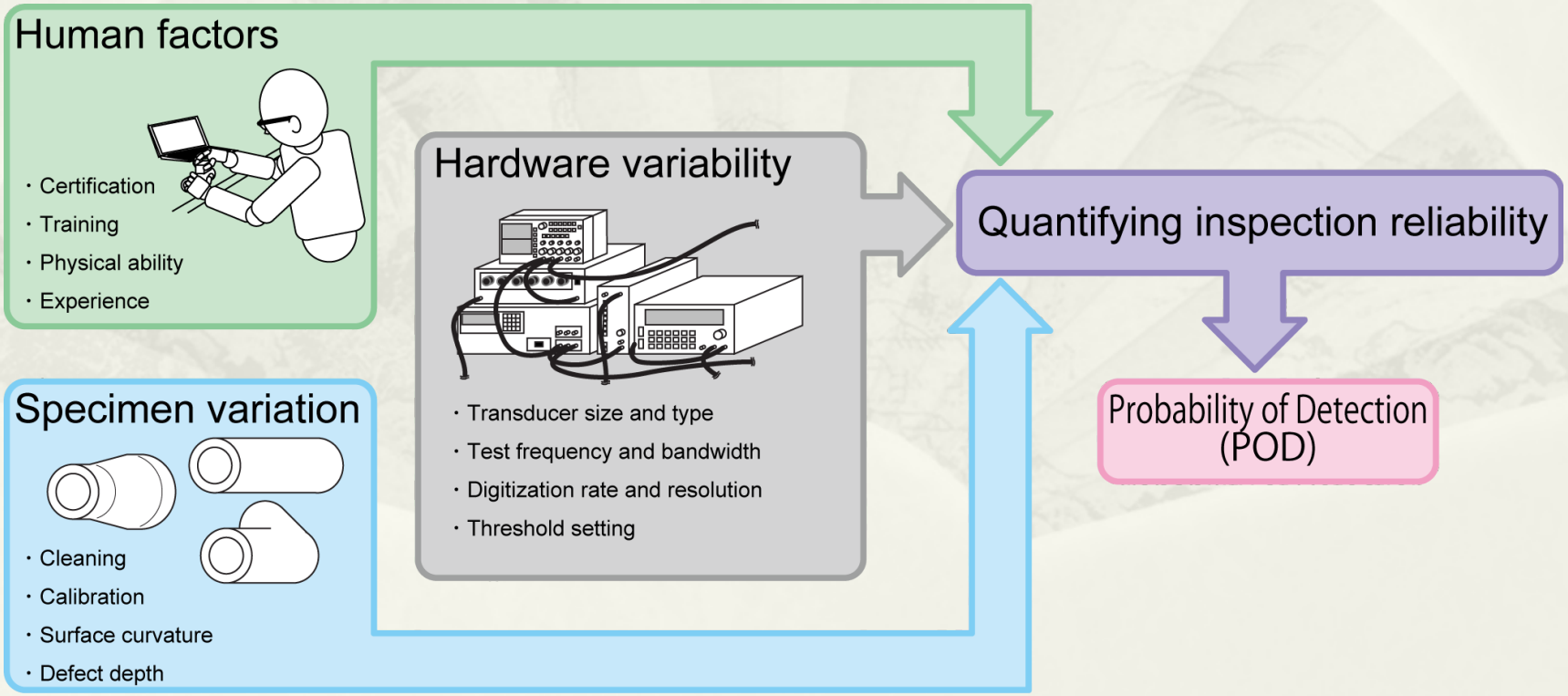
- ✓ Pipe wall thinning management
- ✓ E-MAT based NDE system
- ■ **Probability of detection (POD)**
- ◆ Application to risk management

Evolution of Structural Integrity

- Probabilistic approach has been establishing the lifetime service capability of large scale artifacts.
- The damage tolerance approach that leads to the safe-life service requires **qualification of inspection reliability.**
- The attempt at quantifying inspection reliability includes the development of a feasible **model using probability of detection (POD)**.
- This work has been performed in US Air force defense program involving NDI reliability that is known as MIL-HDBK-1823 since 1970s.

Reliability assessment using POD

POD provides the capability to develop a feasible inspection model used for quantifying inspection reliability for pipe wall management program.



Outline of POD

- Probability of Detection
  - A. P. Berenes, NDE Reliability Data Analysis, 1989
- Probability that acceptable wall thickness from the population would be detected
  - Given a defined inspection system
  - Given a population of experienced wall thinning
- Performance indices
  - Hit/Miss analysis, $\hat{a}$ vs. a - analysis
  - Confidence bound for quantifying NDT.

How to calculate POD

Signal Response Analysis by $\hat{a}$ vs. a

- Collect signal response set corresponding to many different inspections for piping system with variety of wall thinning

- Taking the logarithm of the signal response relation, we obtain the formula:

$$\log \hat{a} = \beta_0 + \beta_1 \log a + \delta \quad \delta \in \mathcal{N}(0, \sigma_\delta^2)$$

- Then the regression parameters β_0, β_1 and σ_δ^2 can be estimated from those data set.

POD model based on $\hat{a}$ vs. a

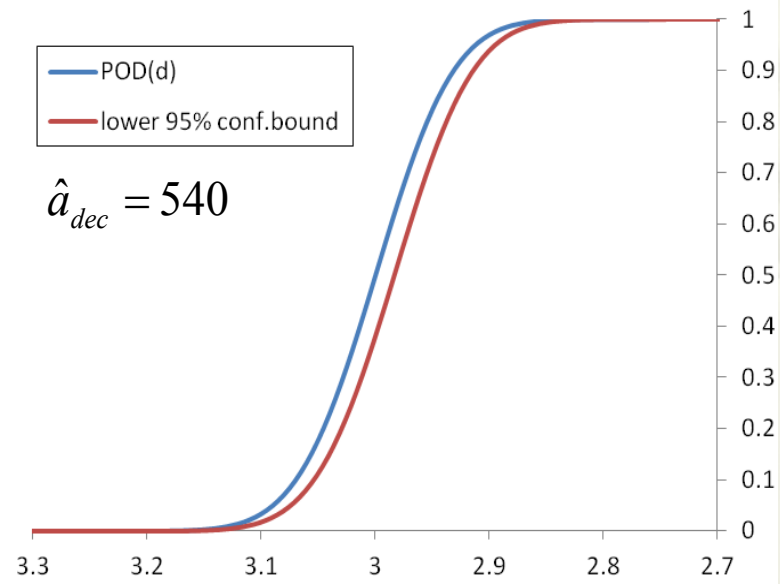
- Compute the maximum likelihood estimate $(\hat{\beta}_0, \hat{\beta}_1, \hat{\sigma}_\delta)$

- The POD function can be then calculated by:

$$\mathrm{POD}(a; \hat{a}_{\mathrm{dec}}) = P\left\{\log \hat{a} > \hat{a}_{\mathrm{dec}}\right\} = \Phi\left(\frac{\log a - \hat{\mu}}{\hat{\sigma}}\right)$$

where

$$\hat{\mu} = \frac{\log \hat{a}_{\mathrm{dec}} - \hat{\beta}_0}{\hat{\beta}_1}, \quad \hat{\sigma} = \frac{\hat{\sigma}_\delta}{\hat{\beta}_1}$$



Performance indices

- The "reliably" quantitative value for the applied inspection system can be detected by the inverse of POD(a) function:

$$a_{\mathrm{NDE}} = \mathrm{POD}^{-1}(\alpha) \quad (\text{e.g. } \alpha = 0.9)$$

- Traditionally, those have been designated as

$$a_{90}, \ a_{90/95}$$

those can be derived from the "confidence bound" of POD;

$$\mathrm{POD}_{\gamma}(a; \hat{a}_{\mathrm{dec}})$$

Confidence bound calculation

Step 1: Obtain the information matrix for the estimates of β_0, β_1, and σ_δ for the measurement model.

Step 2: Calculate the inversion of information matrix

Step 3: Calculate the variance-covariance matrix of the estimates μ and σ for the POD.

Step 4: Obtain the information matrix for the POD

Step 5: Obtain the lower confidence bound:

$$\mathrm{POD}_\gamma(a; \hat{a}_{\mathrm{dec}}) = \Phi(\hat{z} - h)$$

where

$$\hat{z} = \frac{\log(a) - \hat{\mu}}{\hat{\sigma}} \qquad h = \sqrt{\frac{\gamma}{nk_0}\left\{1 + \frac{(k_0\hat{z} + k_1)^2}{(k_0k_2 - k_1^2)}\right\}}$$

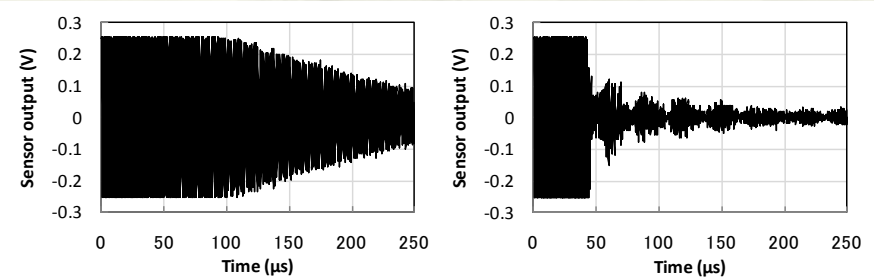
POD evaluation for EMAT

The evaluation can be performed with the following three primary components:

- Standardization of thickness measurements
- Experimental equipments and setting environmental condition
- Data acquisition method

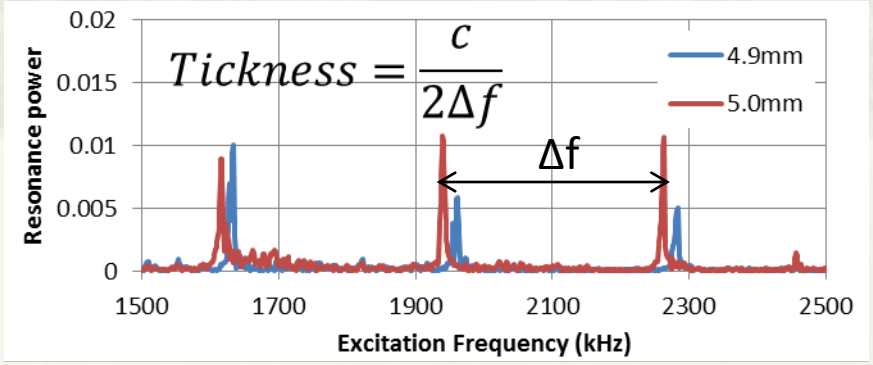
Standardization of measurement

Electromagnetic resonance method (EMAR) provides high resolution of wall thickness measurements from seeking a sequence of peak spectrums of detecting signals corresponding to sweeping frequencies of exciting test signals.

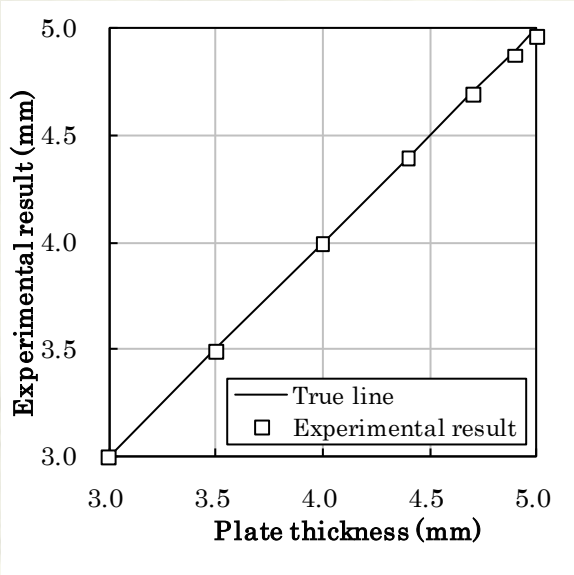


resonance

no resonance



Thickness measurement



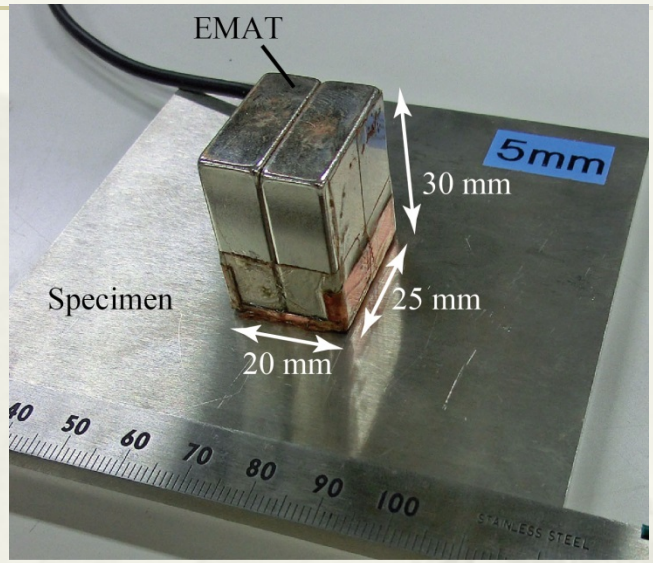
Resolution of resonance method

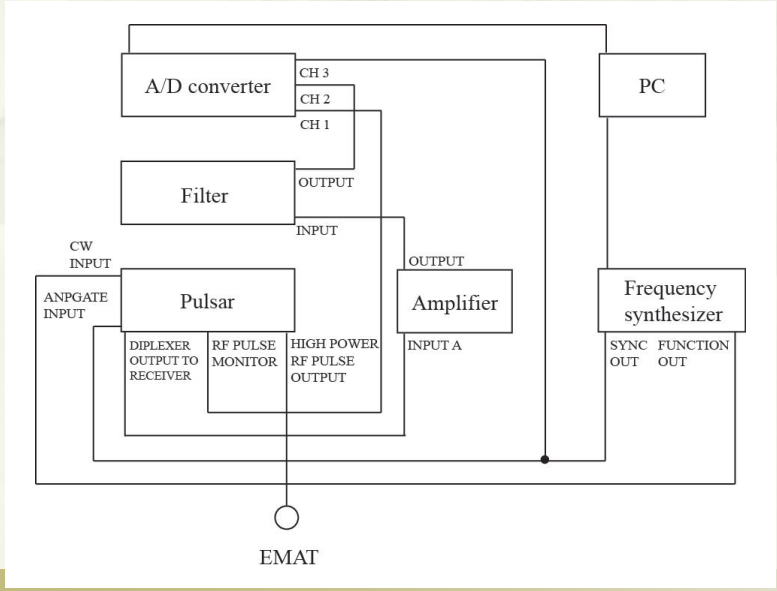
24

Experimental equipment

The EMAT has one circular coil and two magnets.

- The coil is 20 turns of two layers, and its diameter is 5 mm. The wire diameter of the coil is 0.05 mm.
- The magnets are rectangular neodymium magnets, and are combined each other with the opposite magnetic poles. The coil is attached at the bottom of the magnets.





The measurement system of the EMAT is composed of the following equipment:

- Pulsar-receiver system (RITEC, RPR-4000)
- Frequency synthesizer (NF, WF-1945B)
- Filter (Tektronix, FV-628B)
- A/D converter (Tektronix, TDS2024B)
- PC

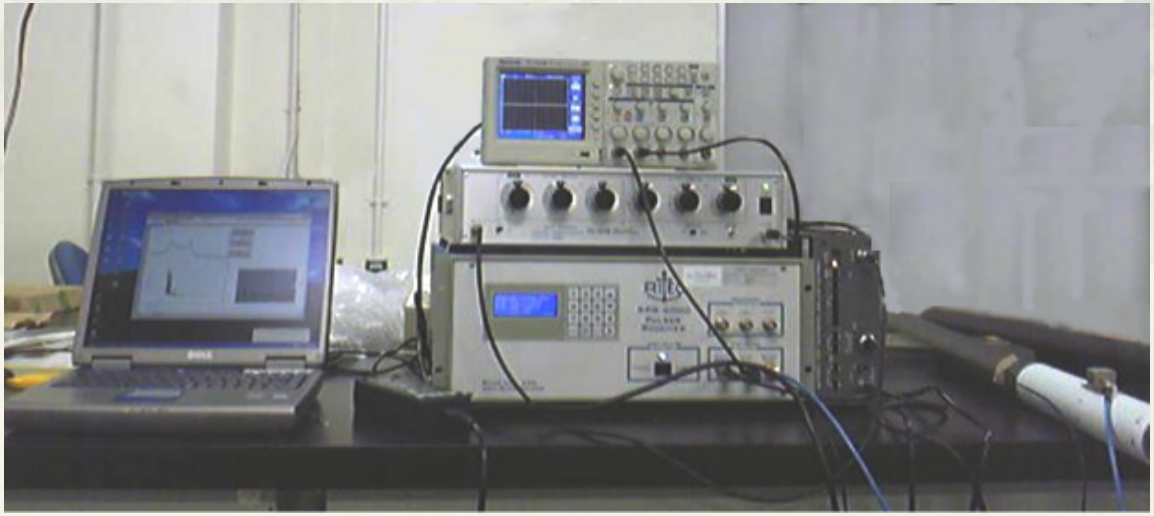
Data acquisition method

Measurement settings are as follows:

- Frequency interval: 50 kHz.
- Range of sweep frequency: 2 to 4 MHz.
- Excitation voltage: 200 V.
- Excitation interval: 100 us.
- Calibration of sound velocity: 3240 m/s.

Specimens are three carbon steel plates as substitutes for pipes.

- Thicknesses: 3.0, 4.0, and 5.0 mm

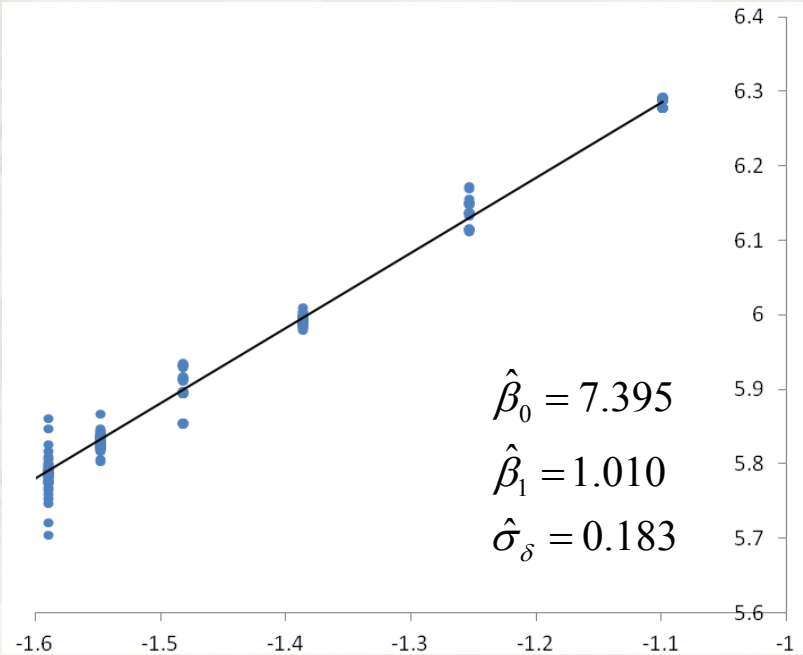


Test categories of inspection capabilities

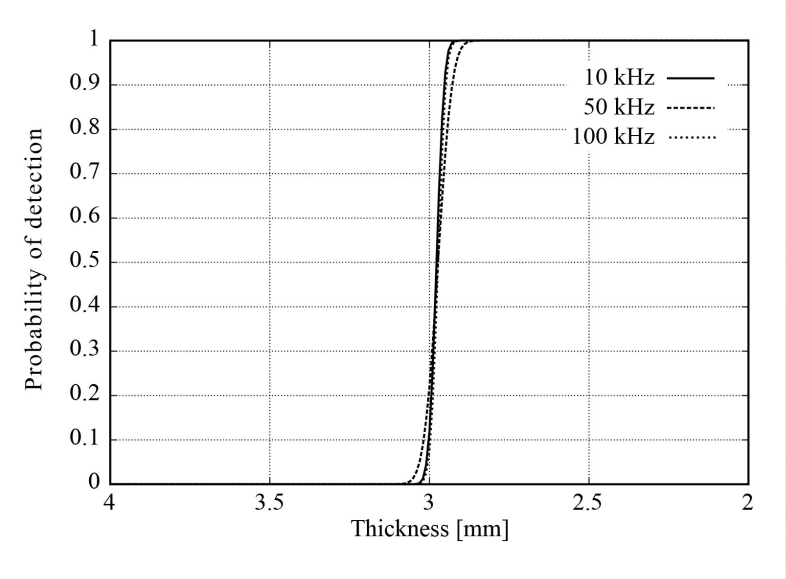
Categories	Test No.	Specification
Geometries	-	downstream of orifice
	-	elbow
	-	reducer
Control Parameters	Case 1	sweep frequency interval
	Case 2	excitation voltage
	Case 3	excitation time interval
Design Parameters	Case 4	magnetic material
	Case 5	turns and layers of coil

Signal response analysis

$$\log \hat{a} = \beta_0 + \beta_1 \log a + \delta \quad \delta \in \mathcal{N}(0, \sigma_\delta^2)$$



Case 1: Sweep frequency interval

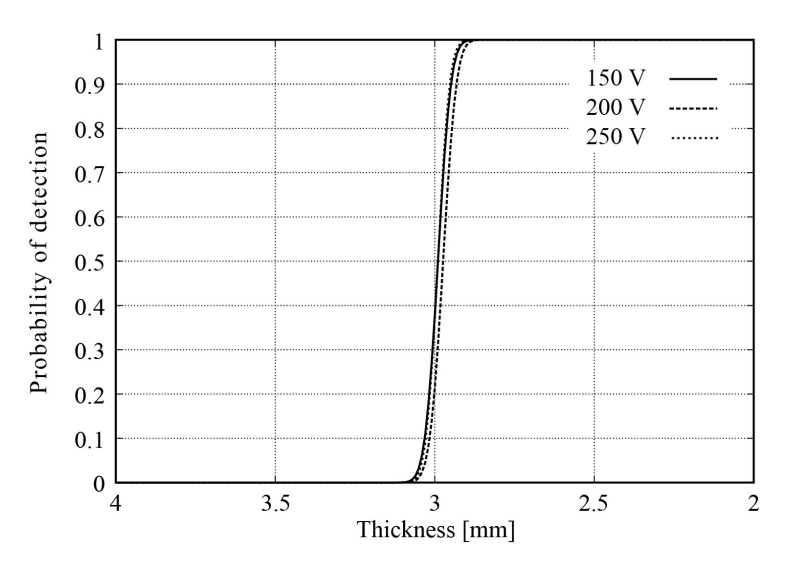


The sweep frequency intervals have been changed to 10, 50, or 100 kHz. The system has measured thicknesses of three specimens with each interval. The POD functions have been decided from the measured thicknesses.

$$\hat{a}_{dec} = 3.0$$

frequency interval [kHz]	a_{50} [mm]	a_{90} [mm]
10	2.97	2.95
50	2.97	2.93
100	2.97	2.95

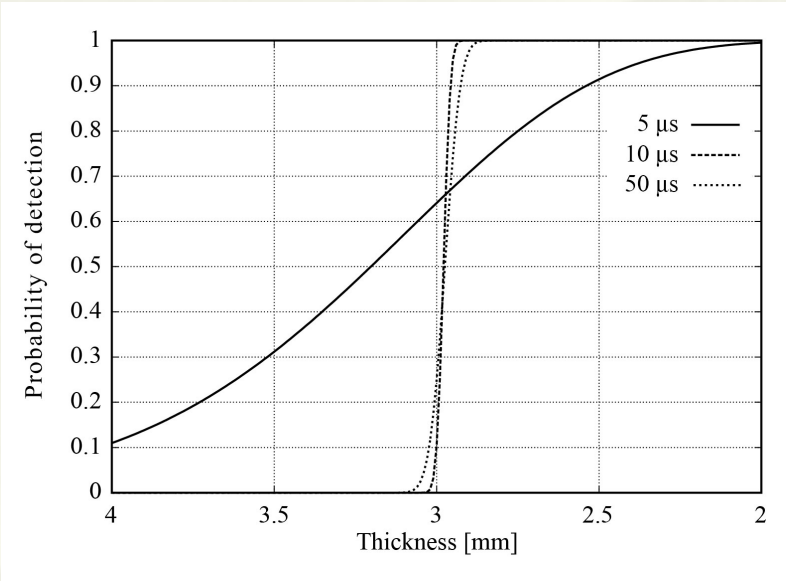
Case 2: Excitation voltage



The excitation voltages have been changed to 150, 200, or 250 V. The POD curves and parameters are almost equal in the three excitation voltages. The reliabilities of the measurement system set in the three excitation voltages are equivalent.

excitation voltage [V]	a_{50} [mm]	a_{90} [mm]
150	2.99	2.95
200	2.97	2.93
250	2.99	2.95

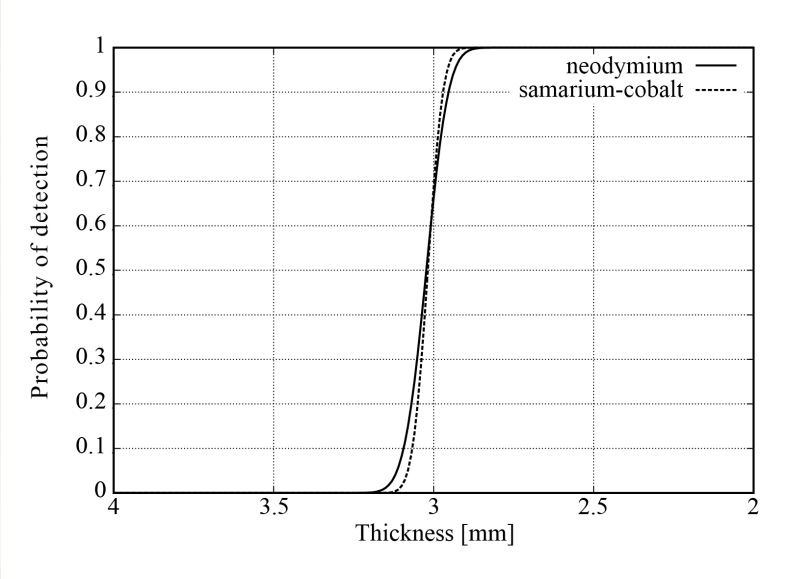
Case 3: Excitation time interval



The excitation time intervals have been changed to 5, 10, or 50 ms. The results indicate the reliability of the measurement system set in the excitation period of 5 ms is low. The other results denote the same tendencies with the results in 3.1 or 3.2. **The time interval of 5 ms was too brief to generate clear electro-magnetic resonances.**

excitation time interval [μs]	a_{50} [mm]	a_{90} [mm]
5	3.2	2.54
10	2.98	2.96
50	2.97	2.93

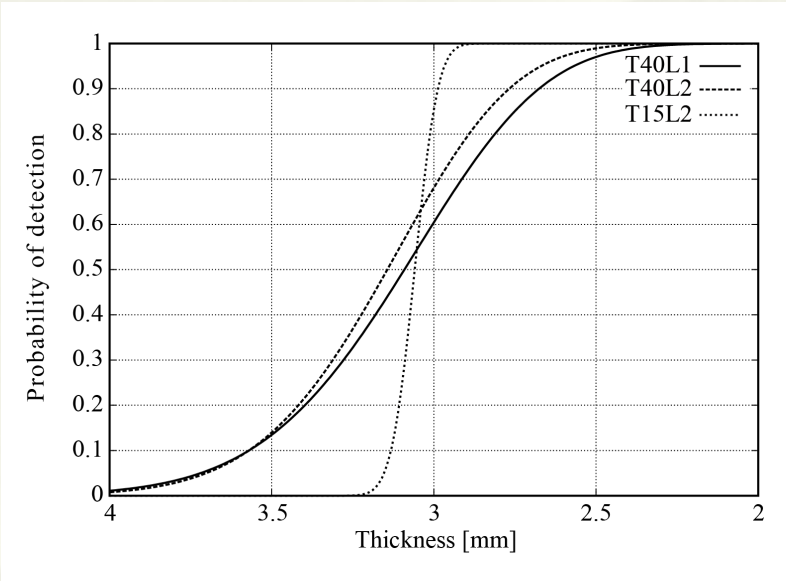
Case 4: Magnetic material



Permanent magnets of two types, neodymium and samarium-cobalt magnets, are used to create EMATs. The maximum errors for neodymium and samarium-cobalt were 0.15 mm and 0.18 mm, respectively. The difference in their maximum errors was small. a_{50} of the neodymium device coincides with that of the samarium-cobalt device. The values of a_{90} were slightly different.

Magnetic material	Neodymium	Samarium-cobalt
a_{50} [mm]	3.02	3.02
a_{90} [mm]	2.97	2.95

Case 5: Turns and layers of coil



Three coils of different specifications
(T40L1: 40 turns and 1 layer,
T40L2: 40 turns and 2 layers,
T15L2: 15 turns and 2 layers)
have been applied in samarium-cobalt EMATs. The T15L2 curve changes sharply at 3 mm in thickness. In contrast to T15L2, the curves of T40L1 and T40L2 change smoothly.
The results mean the coil of T15L2 is suitable for the measurement of pipe-wall thickness of 60.5 mm diameter.

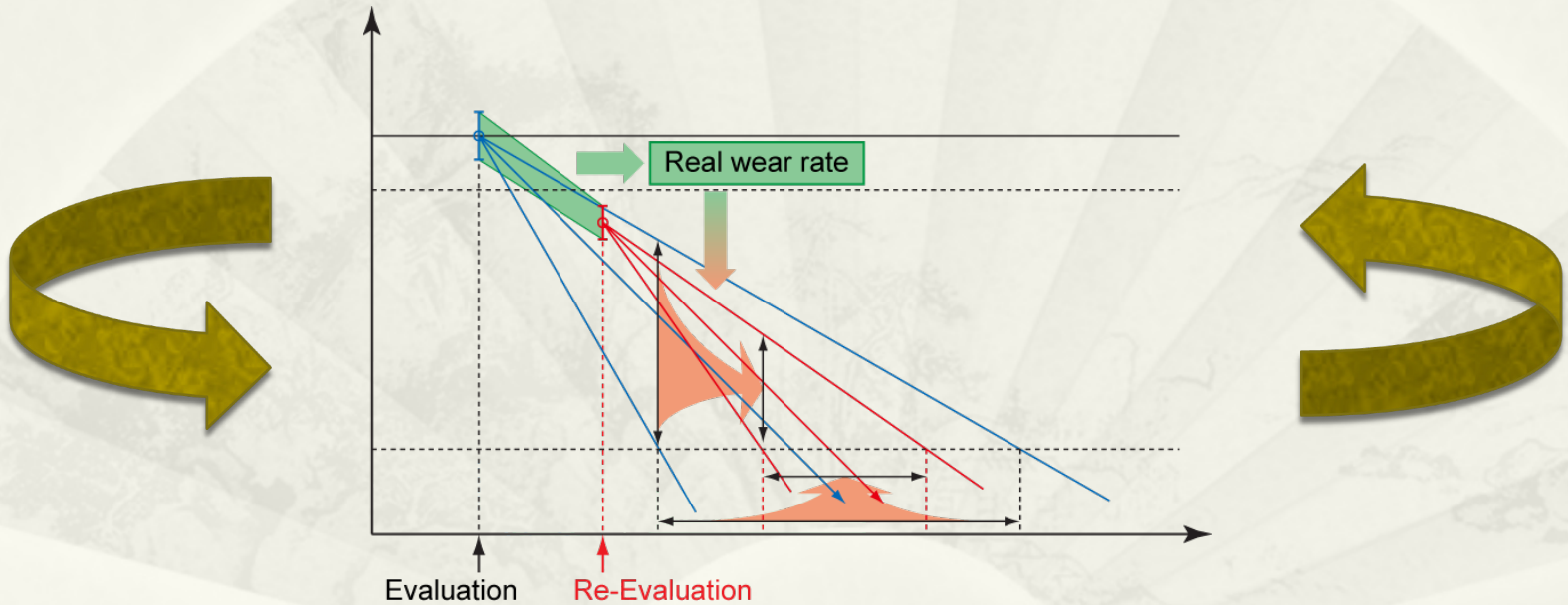
Index of coil	T40L1	T40L2	T15L2
a_{50} [mm]	3.09	3.14	3.06
a_{90} [mm]	2.68	2.77	2.99

Talk of the Scenario (Part IV)

- ✓ Pipe wall thinning management
- ✓ E-MAT based NDE system
- ✓ Probability of detection (POD)
- ■ **Application to risk management**

Hybrid use of simulation and monitoring

- Continuous surveillance using EMAT based NDE could provide the capability to use measured wear data to improve the accuracy of the wall thinning managements.



- Predictive plant model for piping system could utilize the results of wall thickness inspections to enhance the wall thinning predictions.

Basic strategies: Bayes formula

Inspection Reliability

$$\ln \hat{a} = \beta_0 + \beta_1 \ln \mu(a) + \delta$$
$$\delta \sim N(0, \sigma_\delta^2)$$

Model Uncertainty

$$\ln \frac{da}{dt} = \ln F(\theta) + \varepsilon \quad \varepsilon \sim \left(0, \sigma_\varepsilon^2\right)$$

σ_ε^2 **: factor**

$$\pi\left(\frac{da}{dt}\middle| a\right) \propto l\left(a \middle| \frac{da}{dt}\right) \pi\left(\frac{da}{dt}\right)$$

Risk evaluation

$$g(t) = \frac{1}{\sqrt{2\pi}\hat{\sigma}t} \exp\left\{-\frac{\left(\ln t - \hat{\mu}\right)^2}{2\hat{\sigma}^2}\right\}$$

$$\hat{\mu} = \ln a_{90/95} - \ln F(\theta)$$
$$\hat{\sigma} = \sqrt{\sigma_\delta^2 + \delta_\varepsilon^2}$$

Safety margin using POD

The safety margin under EMAT inspection can be evaluated from the POD curve based on *a-hat versus a* analysis. Suppose that t_{ap} implies the acceptable wall thickness. One possible method is to evaluate the attainable time margin between the remaining thickness and the acceptable wall thickness [1) 2)].

References

1) SUZUKI, H., UCHIDA, S., NAITOH, M., OKADA, H., KOIKARI, S., HASEGAWA, K., KOJIMA, F., KOSHIZUKA, S., and LISTER, D.H.: Risk Evaluation of Flow-Accelerated Corrosion Based on One-Dimensional FAC Code, Nuclear Technology, 2012: MS# 12-129.
2) KOJIMA, F. and UCHIDA, S.: Advanced Management of Pipe Wall Thinning based on Prediction-monitor Fusion, International Journal of Nuclear Safety and Simulation, 2012, 3(3): 194-200.

Model uncertainty

Suppose that the predictive model for wall thinning rate can be represented as

$$\ln w = \ln F(\lambda) + \epsilon, \quad \epsilon \sim N\left(0, \sigma_\epsilon^2\right), \; w \in \mathbf{P}_{ROI}$$

where w, F(λ) and ε imply wear rate, the output of the predictive model with the operation parameter vector λ , and the corresponding model error factor σ_ε, respectively.

Inspection reliability

Suppose the the signal response model for EMAT inspection can be described by

$$\ln t = \hat{\beta}_0 + \hat{\beta}_1 \ln \mu(t) + \delta, \quad \delta \sim N\left(0, \hat{\sigma}_\delta^2\right),$$

where the parameters $\hat{\beta}_0$, $\hat{\beta}_1$, and $\hat{\sigma}_\delta$ are adjusted by the maximum likelihood estimation.

Probability of safety margin

The attainable time margin can be characterized by the logarithmic probability density function:

$$g(T) = \frac{1}{\sqrt{2\pi}\hat{\sigma}T} \exp\left\{-\frac{(\ln T - \hat{\mu})^2}{2\hat{\sigma}^2}\right\}$$

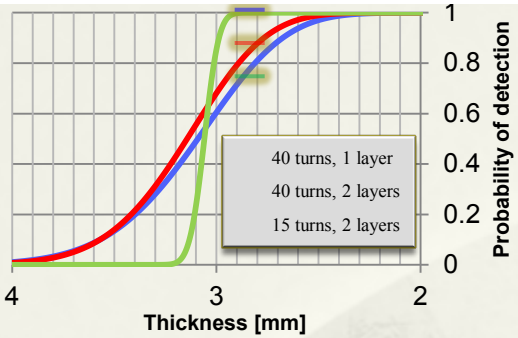
where

$$\hat{\mu} = \ln\left\{\mathbf{POD}^{-1}(\alpha)\right\} - \ln F(\lambda)$$

$$\hat{\sigma} = \sqrt{\hat{\sigma}_\epsilon^2 + \hat{\sigma}_\delta^2}$$

Methodology of Advanced Monitoring

Reliability assessment of monitoring

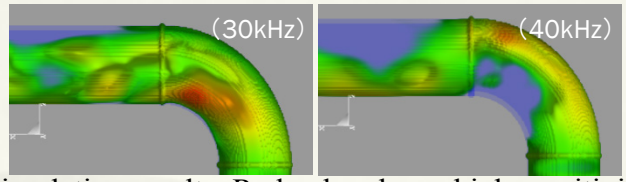


PODs of EMAT with three coils

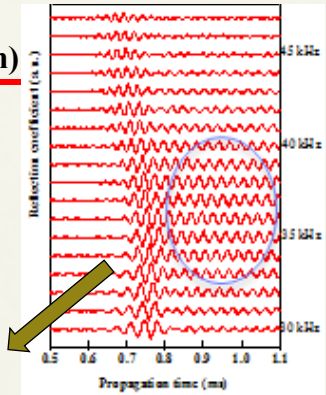
Assessments of
- inspection devices
- inspection settings
- human factors

Quantification of monitoring inspections by using POD

Broad-range monitoring (guided wave inspection)



Simulation results: Red color shows high sensitivity



Screening inspection of elbow pipes

High-accuracy position detection by using ringing effect

Probability density distribution of time of fatal damage

$$g(t) = \frac{1}{\sqrt{2\pi}\hat{\sigma}t}\exp\left\{-\frac{(\ln t - \hat{\mu})^2}{2\hat{\sigma}^2}\right\} \qquad \hat{\mu} = \ln a_{90/95} - \ln F(\theta) \qquad \hat{\sigma} = \sqrt{\sigma_\delta^2 + \delta_\varepsilon^2}$$

Reliability assessment of monitoring

$$\ln \hat{a} = \beta_0 + \beta_1 \ln \mu(a) + \delta \quad \delta \sim N(0, \sigma_\delta^2)$$

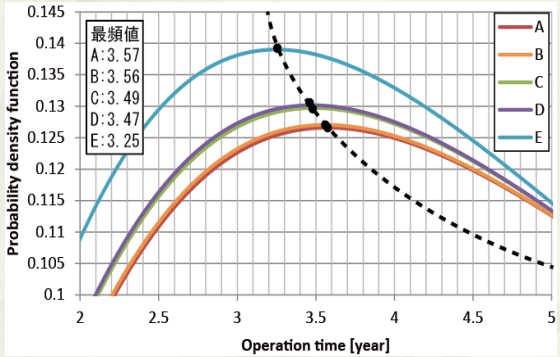
Fusion of Prediction and Monitoring

$$\ln \frac{da}{dt} = \ln F(\theta) + \varepsilon \quad \varepsilon \sim (0, \sigma_\varepsilon^2)$$

σ_ε^2 : factor 2

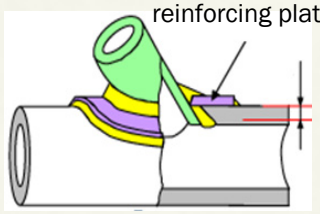
Reliability assessment of prediction

Hazard rate by fusion of prediction and monitoring

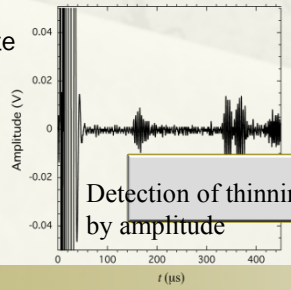


Thinning detection of various parts

Acquisition of inspection results

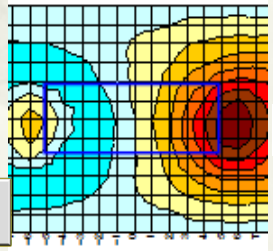


SH wave EMAT



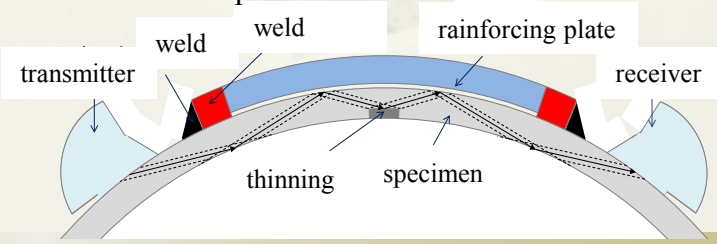
Detection of thinning by amplitude

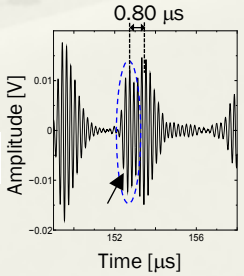
Magnetic leakage flux method



Detection of thinning by AC energization

Ultrasonic multiple reflection method





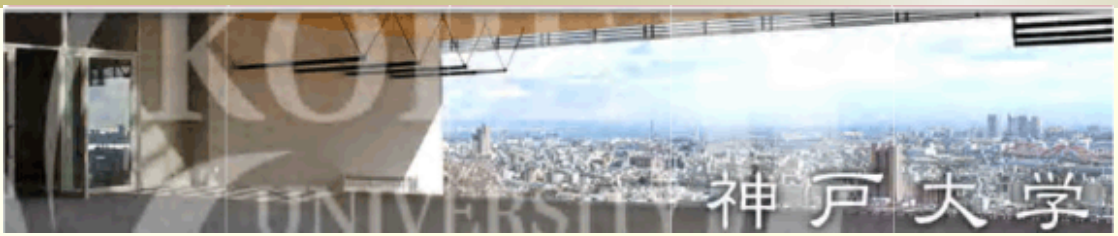
Detection of thinning by reflection wave

Concluding Remarks

- Current investigation on pipe wall thinning management is summarized.
- E-MAT based NDE system is introduced and showed how it could work.
- Probability of detection plays an essential role in the management.
- Contribution to risk management is discussed.

Acknowledgements

This work has been performed as a part of the National Research Project for Technical Evaluation against the Ageing of Nuclear Power Plants sponsored by the Nuclear Regulation Authority (**NRA**) in Japan since 2012 (also **NISA** during 2007-2011). This research was also supported in part (F. Kojima) by the Asian Office of Aerospace Research and Development (AOARD) and by Nondestructive Evaluation Branch, Air Force Research Laboratory at Writer-Patterson AFB, OH USA.



Thank you very much for your kind attention!