Lectures for Young Researchers and Engineers:
Introduction to Risk–based Inspection
September 6th 2023, Tohoku University, Sendai

1. Application of Eddy Current Testing to Inspection of Structural Components

2. Risk-based Inspection

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CONTENS

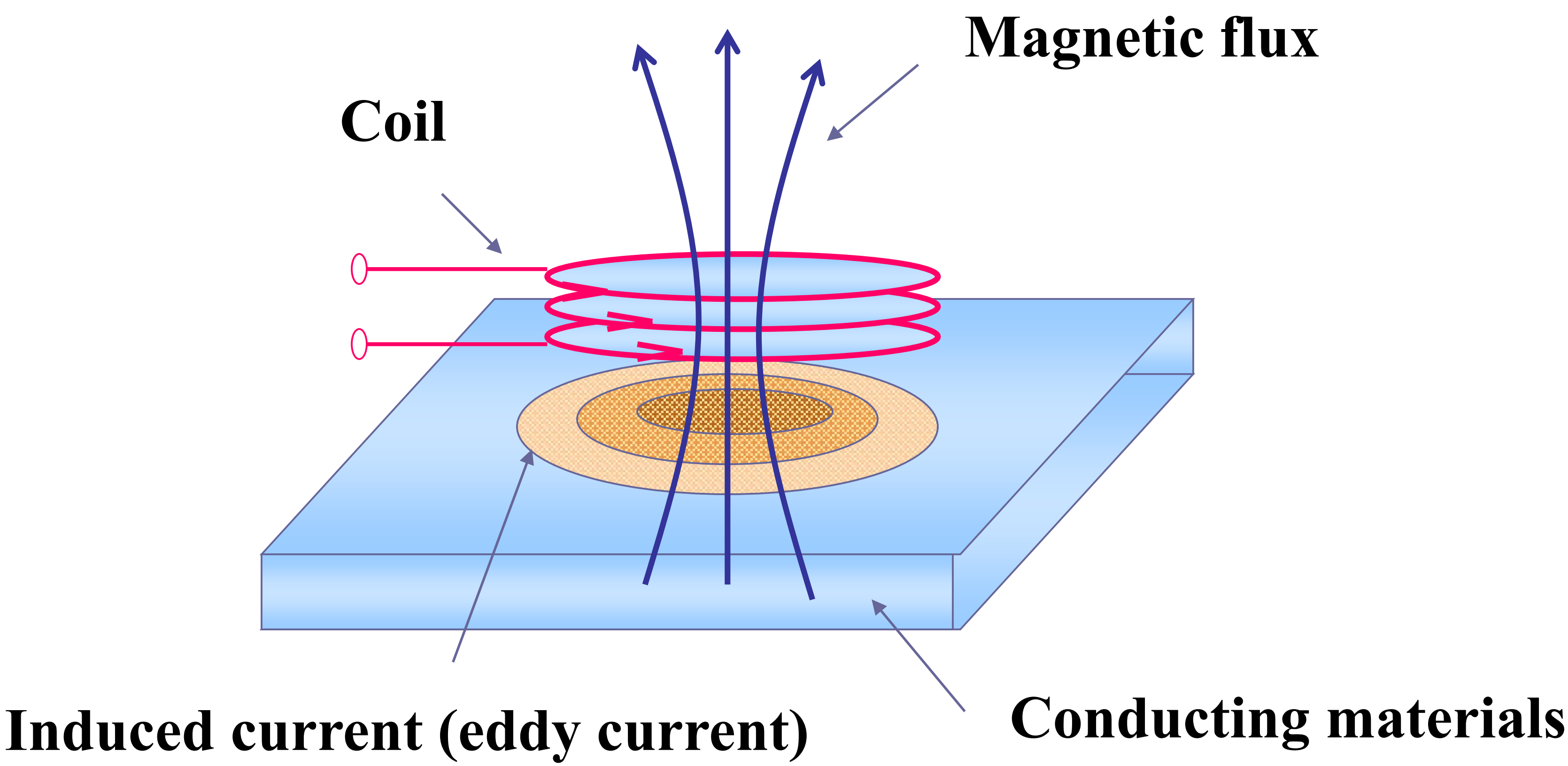
1. **Application of Eddy Current Testing to Inspection of Structural Component**

   A. Detection of Fatigue and SCC Cracks

   B. Inspection of Hydrogen Tank by ECT

2. **Risk-based Inspection**

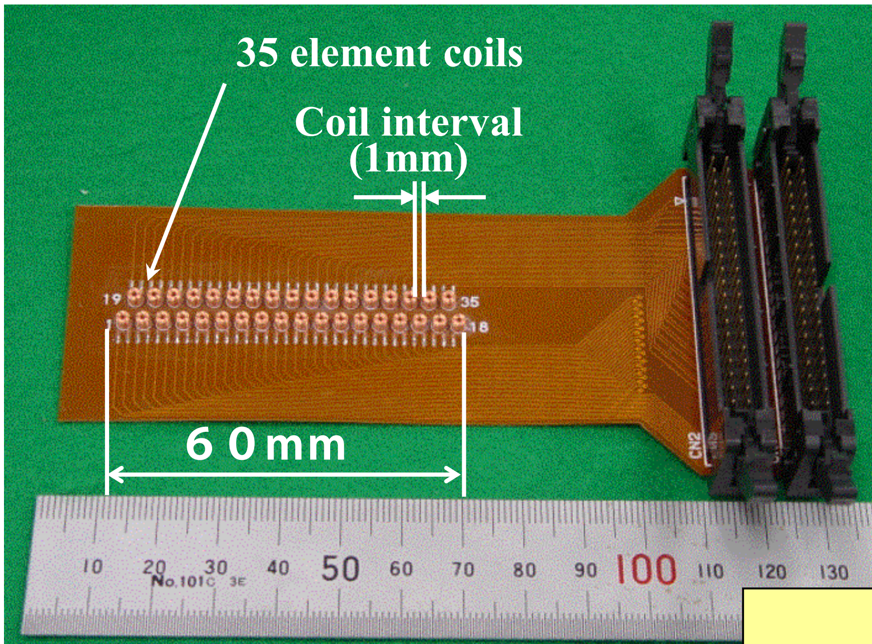
Principle of Eddy Current Testing



1. Detection/evaluation of cracks (geometrical singularity)
2. Evaluation of material properties

Flexible Multi-coil ECT sensor

- **Flexible substrate (polyimide film, 0.15mmt)**
- **High dense Cu interconnection realized by etching**

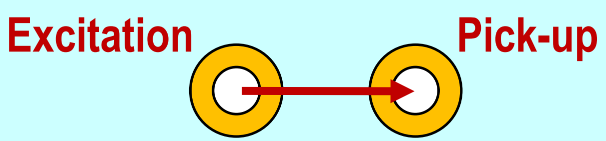


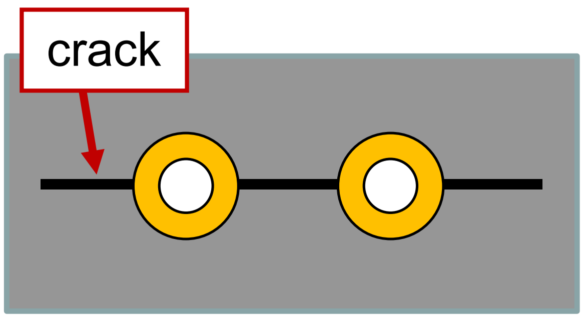
Adapt to curved surface of R20mm without any wire breaking and mutual interference of coils

Multi-coil ECT Probe

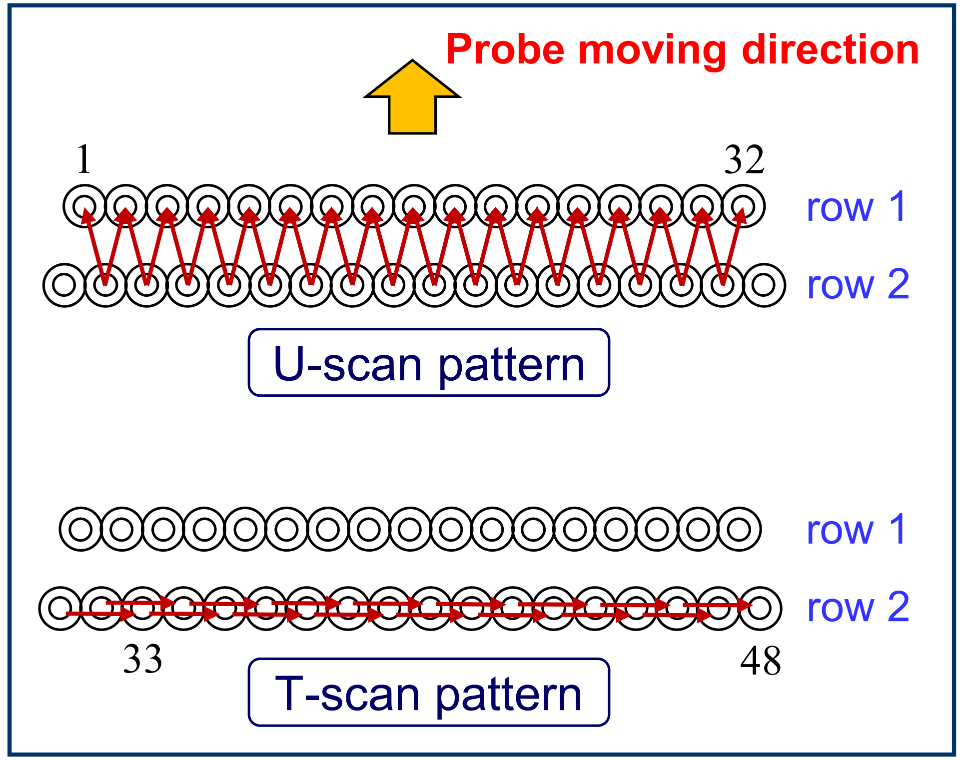
Each channel consists of one excitation coil and one pick-up coil.

Each arrow represents a pair of excitation and pick-up coils.





A strong indication appears when a pair of coils is aligned along a crack.

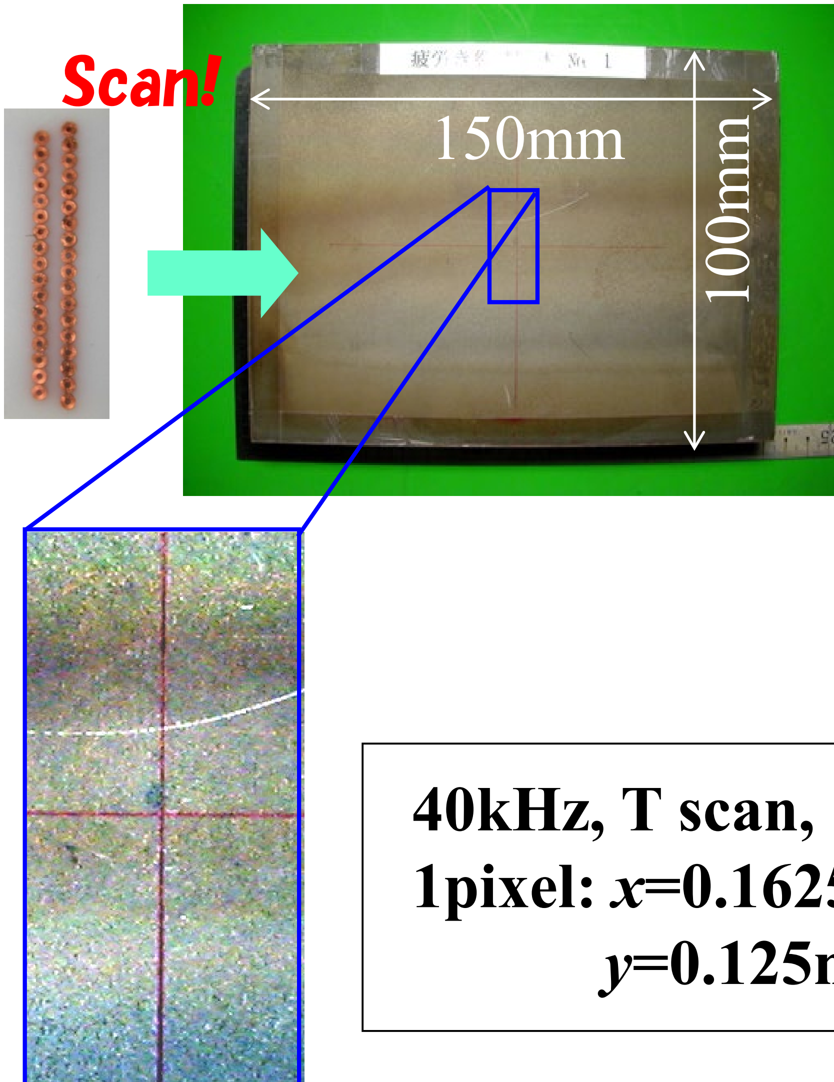


During inspection, these pairs of coils are used by turns.

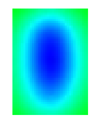
U-scan excels in detecting a crack **perpendicular** to the rows of coils.

T-scan excels in detecting a crack **parallel** to the rows of coils.

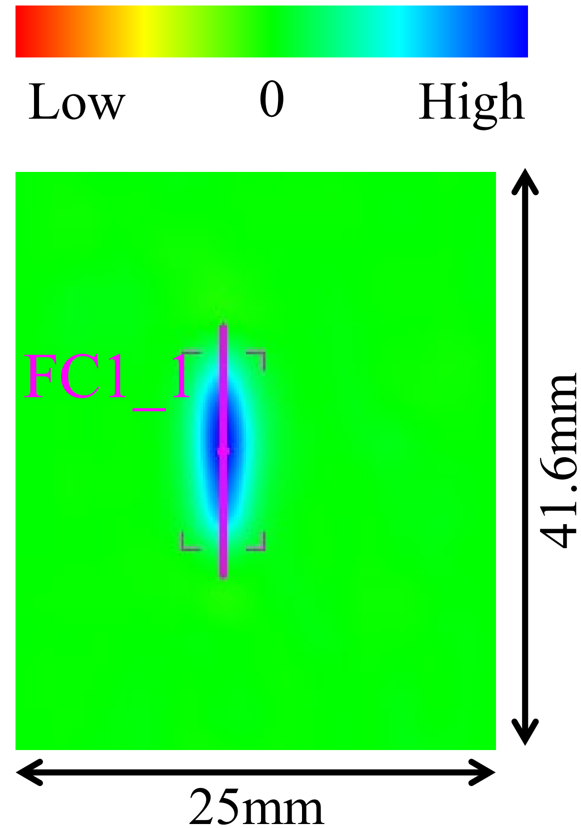
ECT Signal: Fatigue Crack (FC)



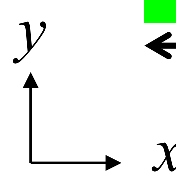
Template



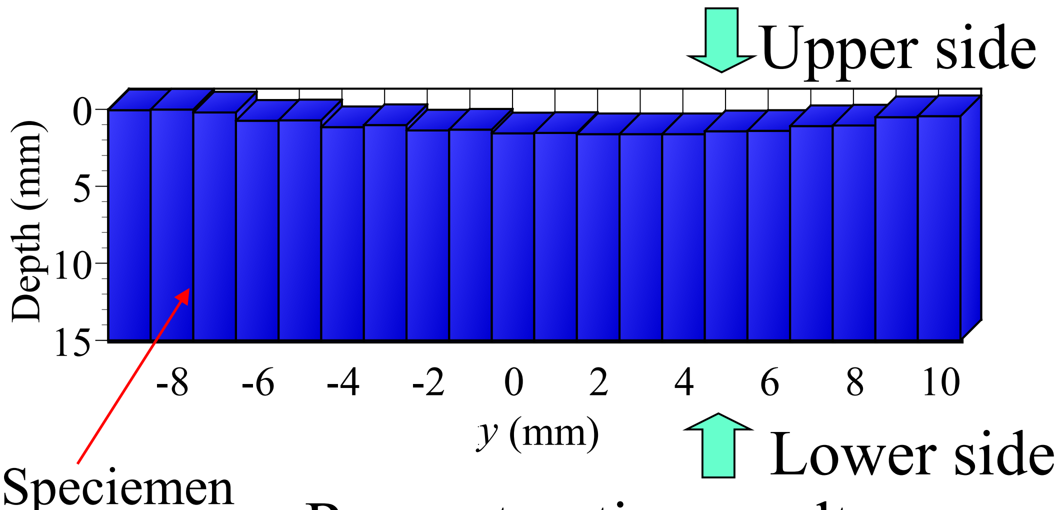
ECT signal (V)



40kHz, T scan, V_I
1pixel: x=0.1625mm
y=0.125mm

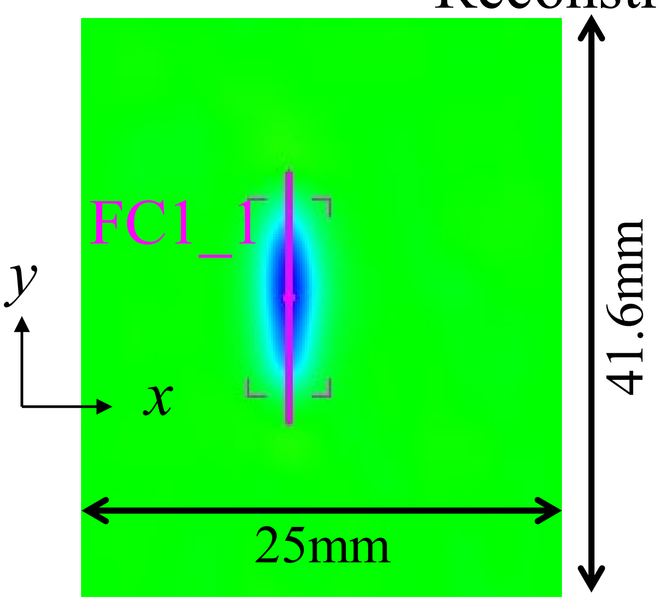


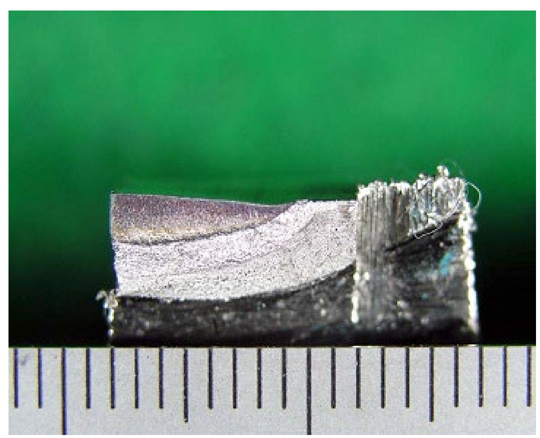
Reconstruction of Crack Shapes: FC



Reconstruction result

Estimate length: 18mm
depth: 1.6mm

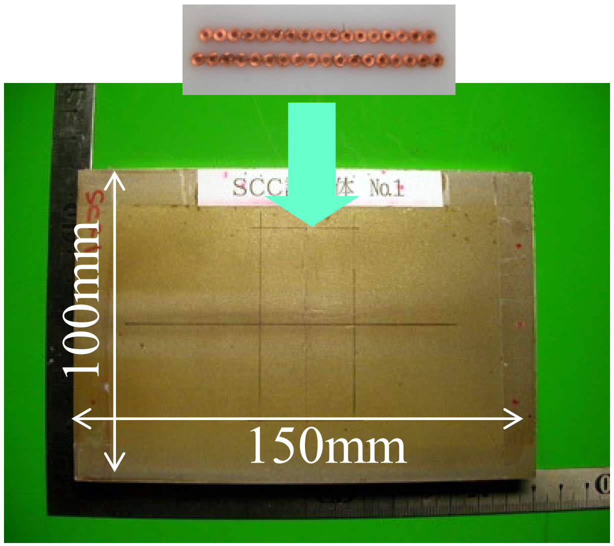


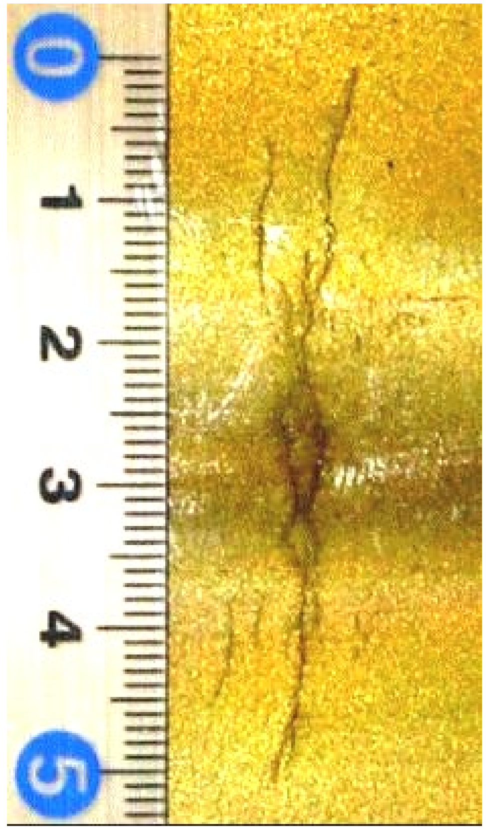


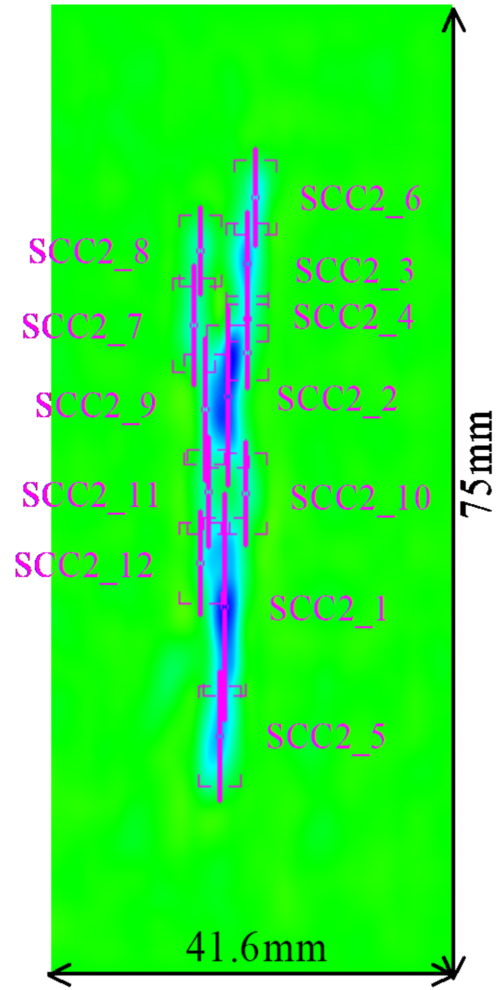
FC fractography

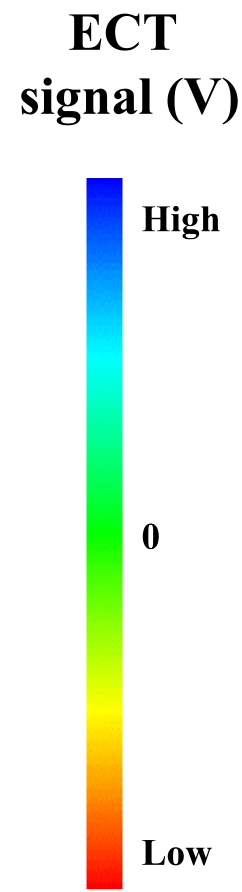
True length: 16mm
depth: 1.8mm

Identification of Surface Breaking: Stress Corrosion Cracking (SCC)



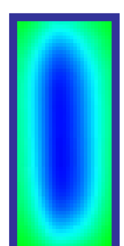






40kHz

Template
27 x 63 pixels

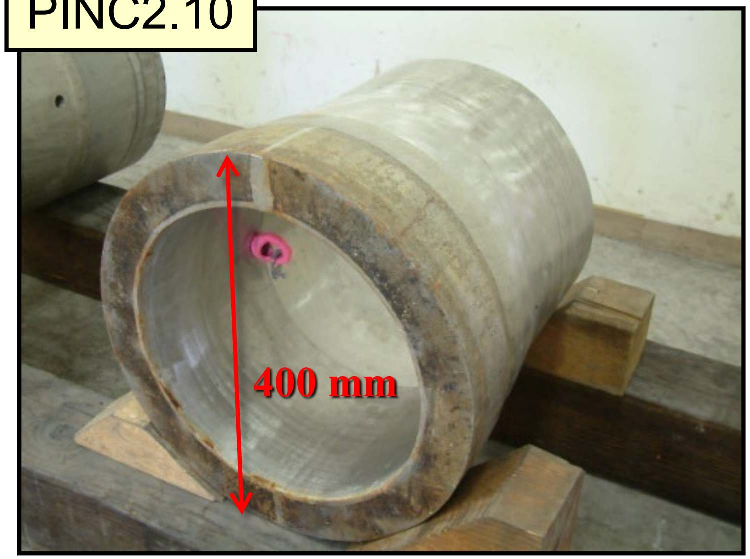


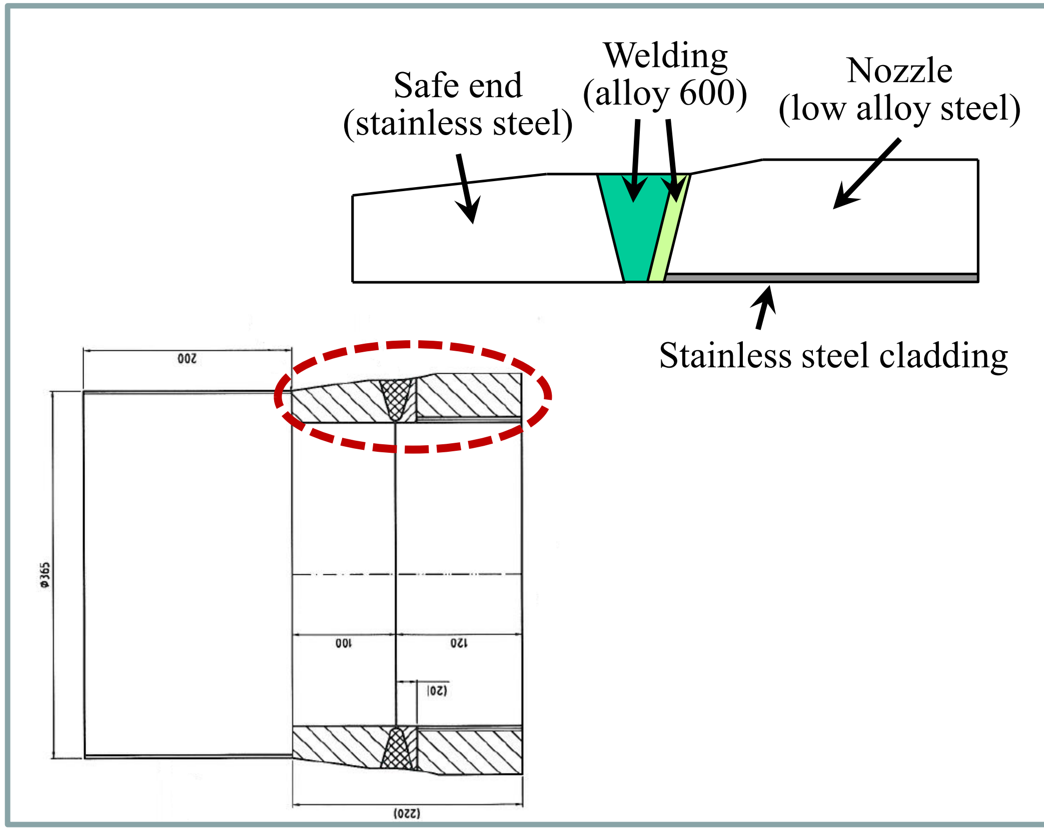
Result of template matching

Program for the Inspection of Nickel-alloy Components by the U.S. Nuclear Regulatory Commission (NRC)

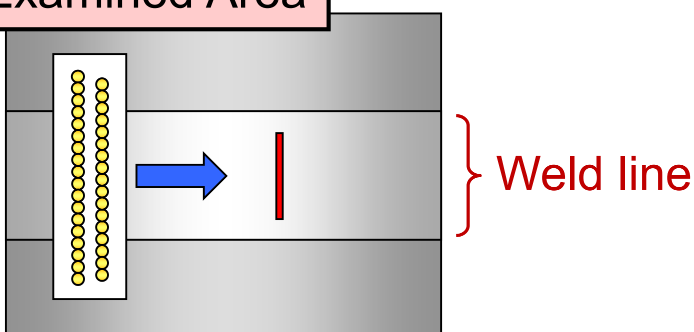
Dissimilar Metal Weld specimen for Round Robin Tests

PINC2.10

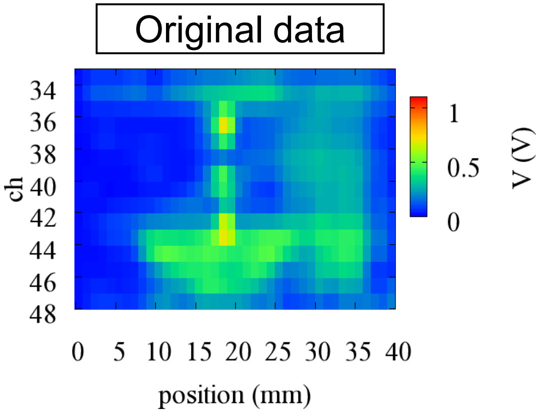


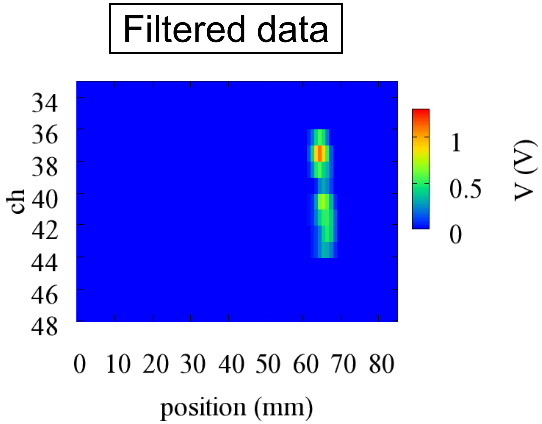


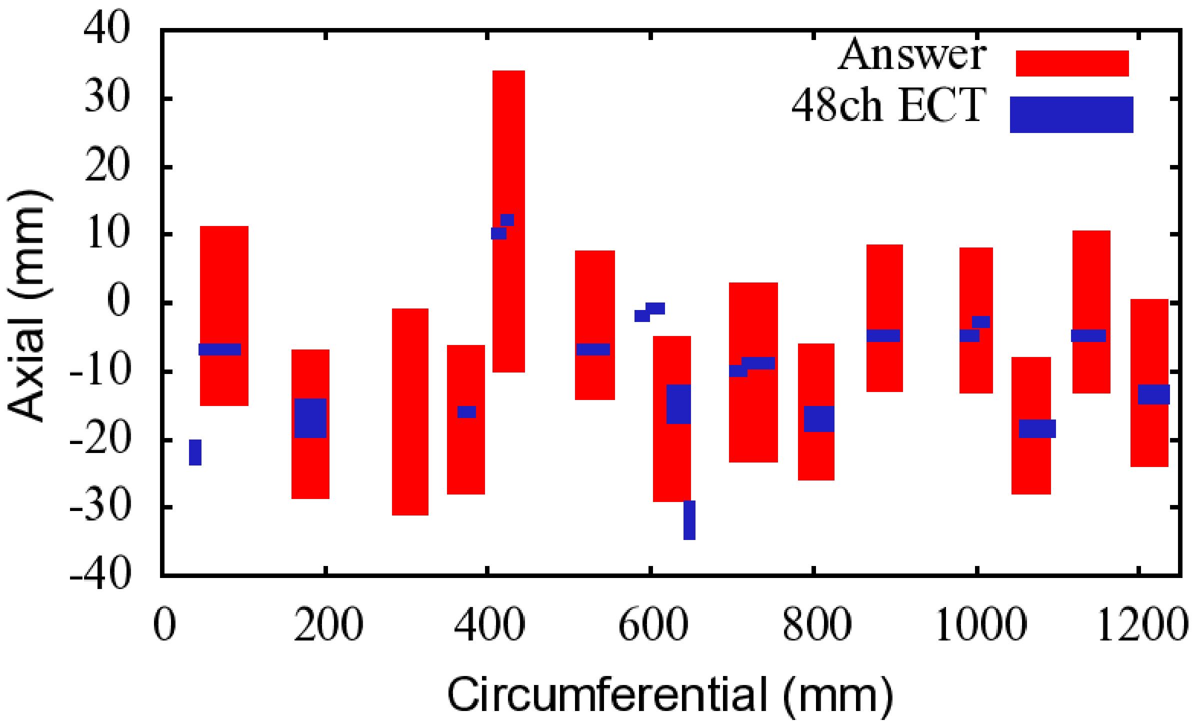
Examined Area



Results







Using only the main filter could not reduce the noises enough.
Using both filters successfully removed the noises.

CONTENS

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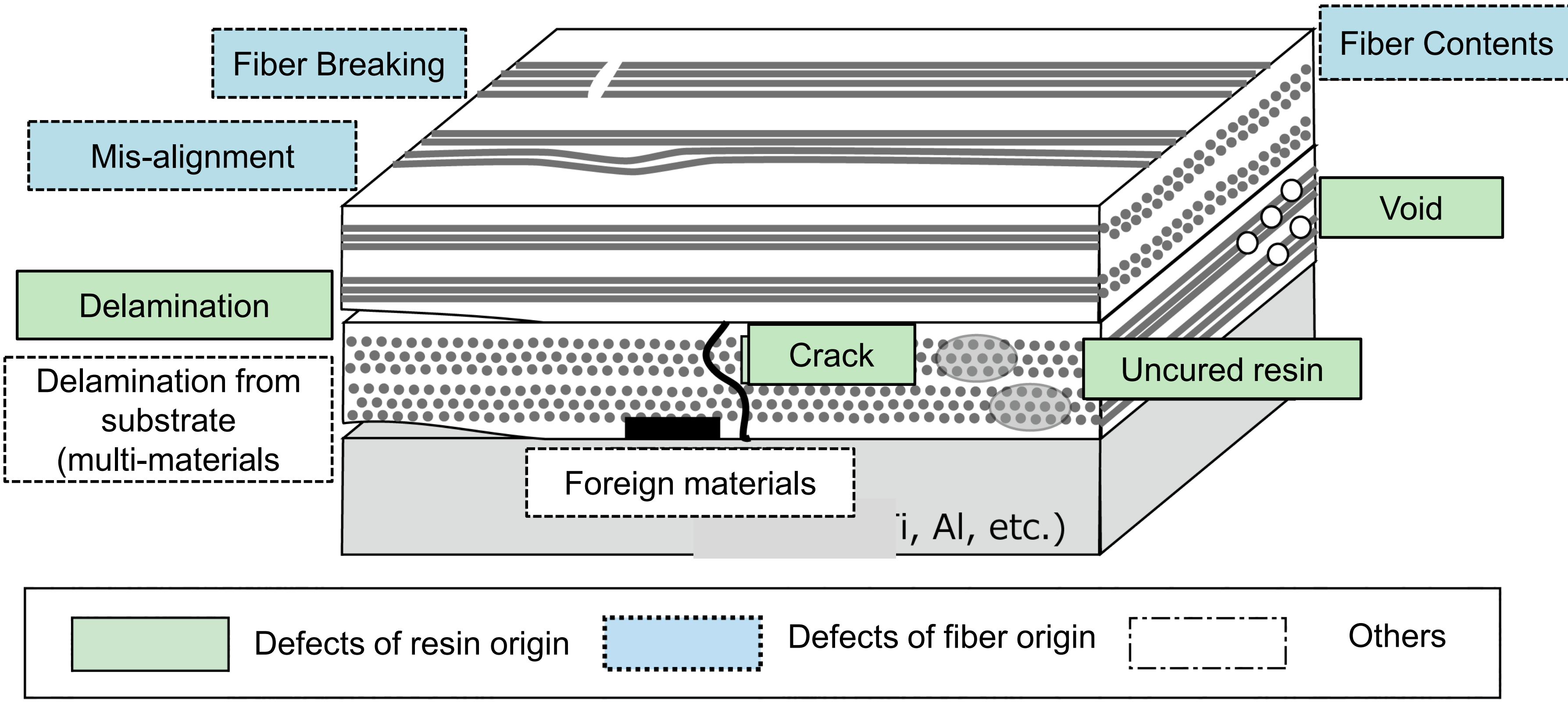
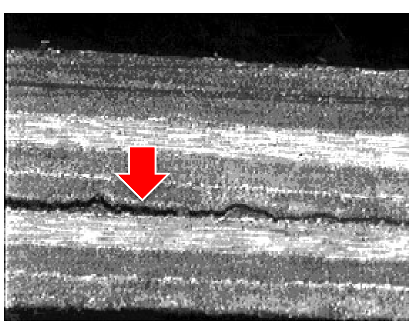
2. **Risk-based Inspection**

Representative Defects in CFRP

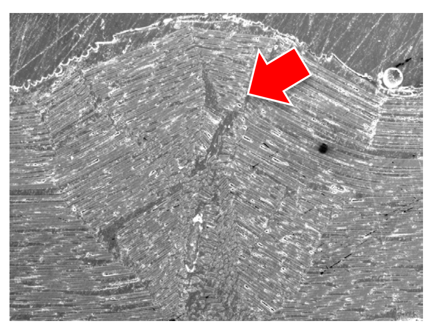


Delamination

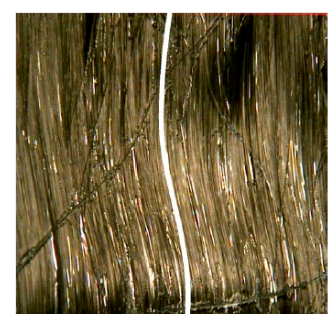


http://www.appropedia.org/

Fiber breaking



Fiber waviness



K. Potter et al./ Composites: Part A (2008)

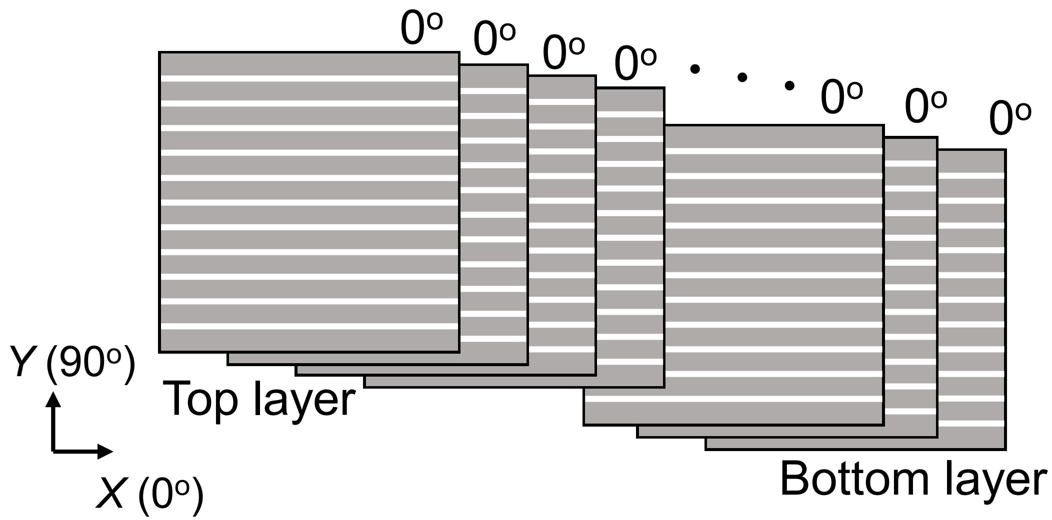
Applicability of Existing NDE to CFRP

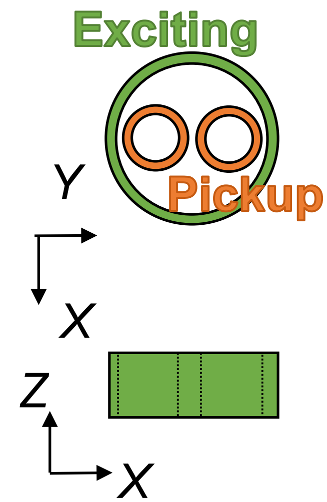
◎＞○＞△＞▲

	UT	RT	TT	ECT
Water Uptake	△	▲	◎	○
Foreign Matter	◎	◎	◎	○
Delamination	◎	○	◎	○
Void	◎	◎	○	▲
Crack	◎	◎	○	▲
Cure Extent	△	▲	○	○
Fiber Content	▲	○	△	○
Fiber Orientation	▲	○	▲	◎
Fiber Breaking	▲	○	▲	○

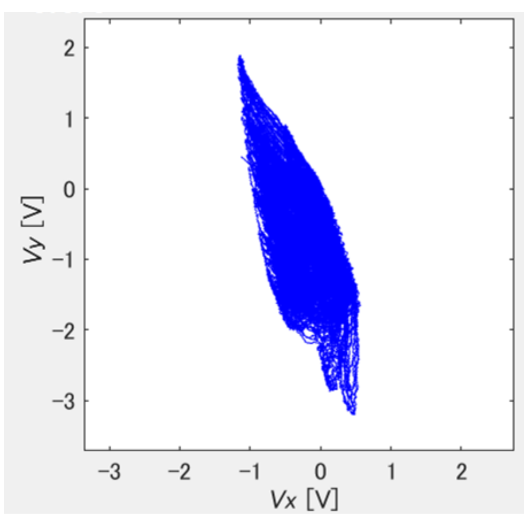
内田盛也　編, 先端複合材料の設計と加工(1988)より一部抜粋

ECT Signals of CFRP and Signal Processing

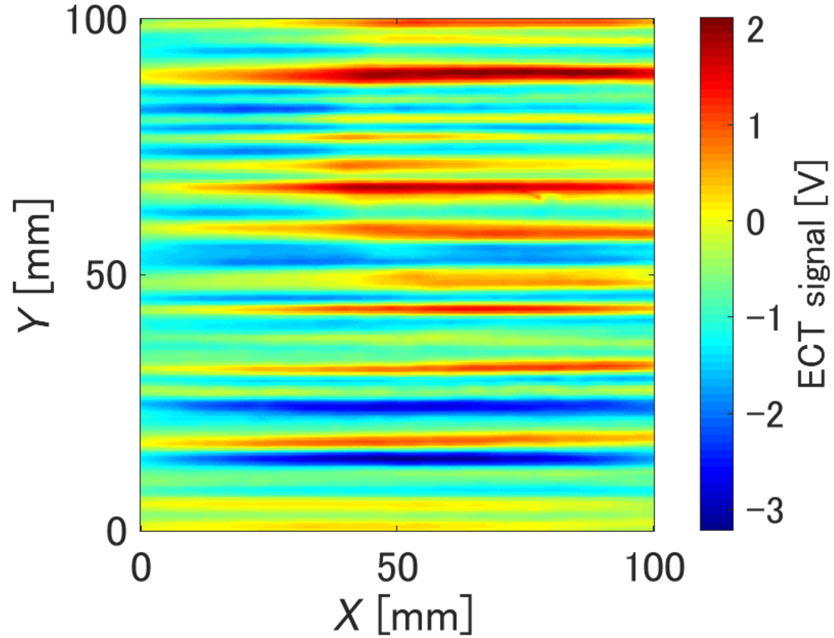




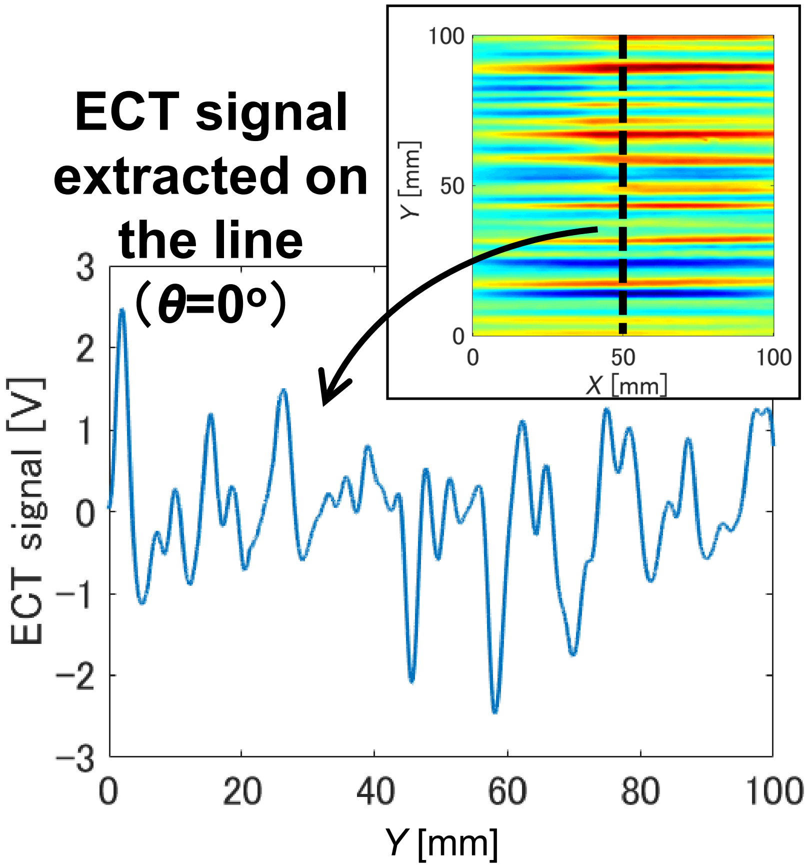
ECT Signals in phase plane

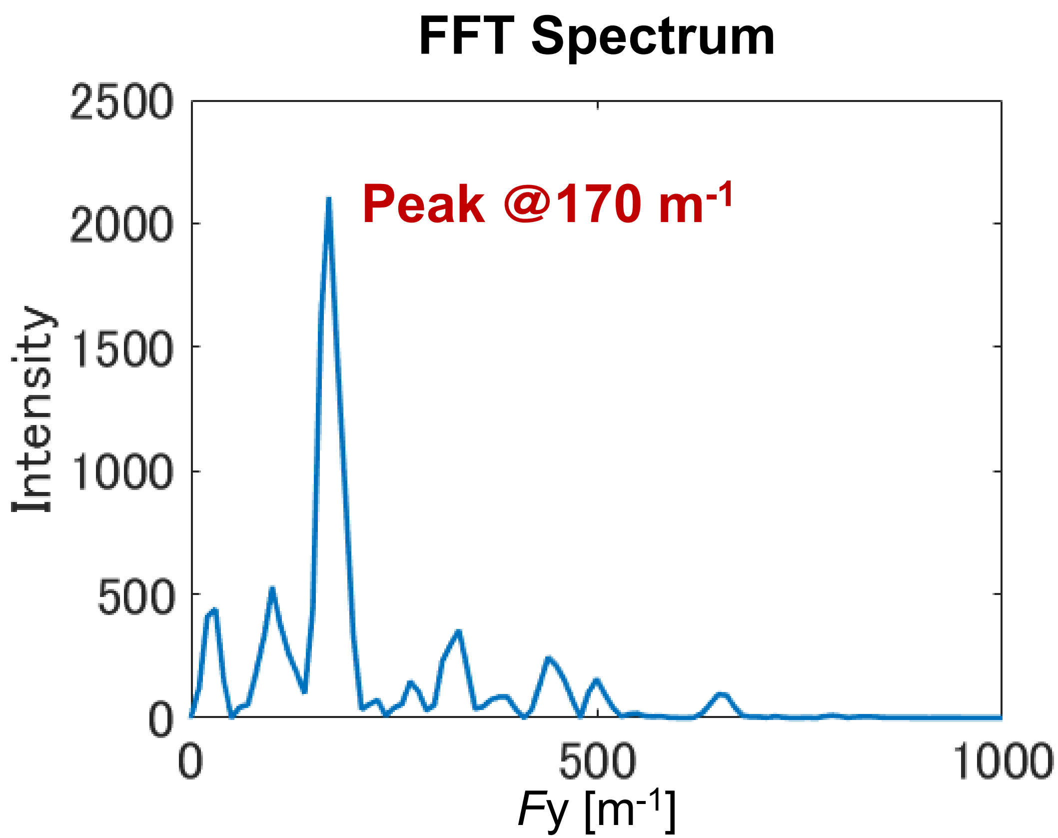


Spatial Distribution of ECT Signal (V_y)



ECT Signals of CFRP and Spatial Fourier Transform



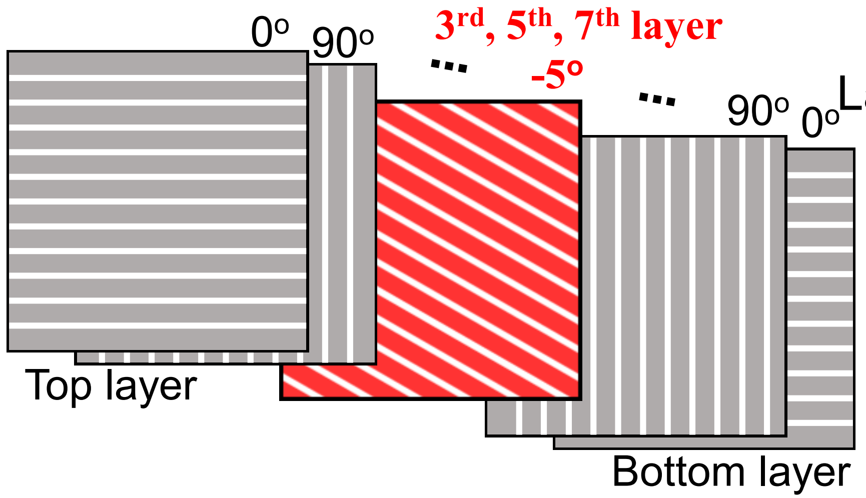


Spatial frequency of striped pattern: 170 m^{-1} (5.8 mm)

ECT may detect fiber bundle information in uni-directional pre-preg.

Detection of Macroscopic Mis-alignment by ECT

Specimens

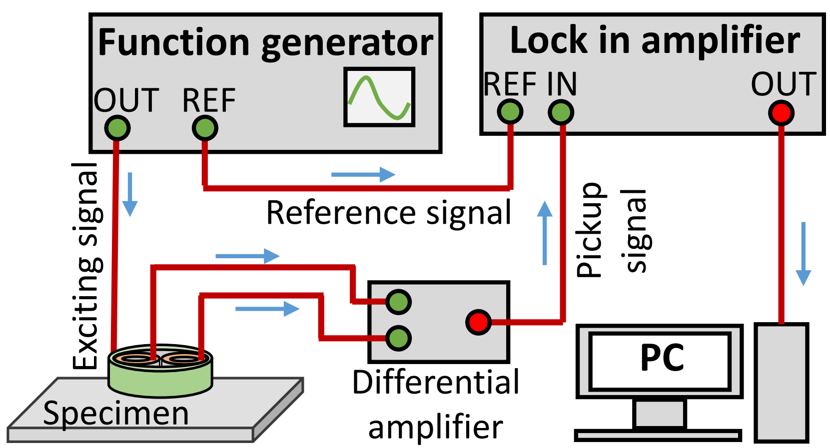


Pre-preg : P3252S-25
No. of laminates : 21 ply
Laminate configuration : $[(0/90)_n/\text{-}5/(90/0)_m]$
Size : $150 \times 150 \times 5$ mm^3

Specimen ID	β
Dep3-5	3rd Layer
Dep5-5	5th Layer
Dep7-5	7th Layer

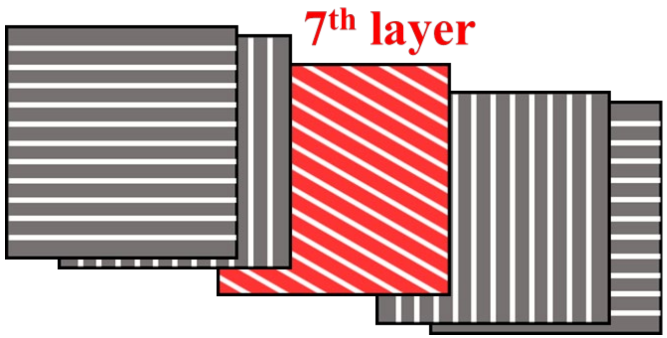
Mis-aligned layer of –5° lies on βth layer.

ECT System

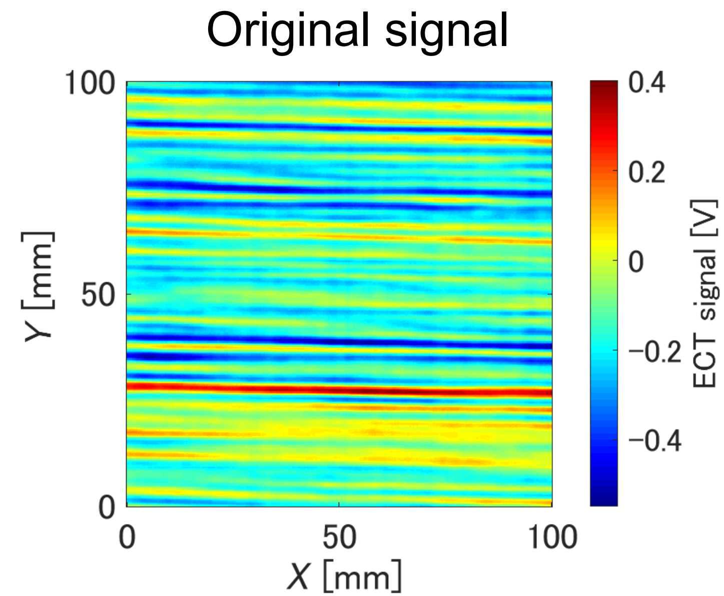


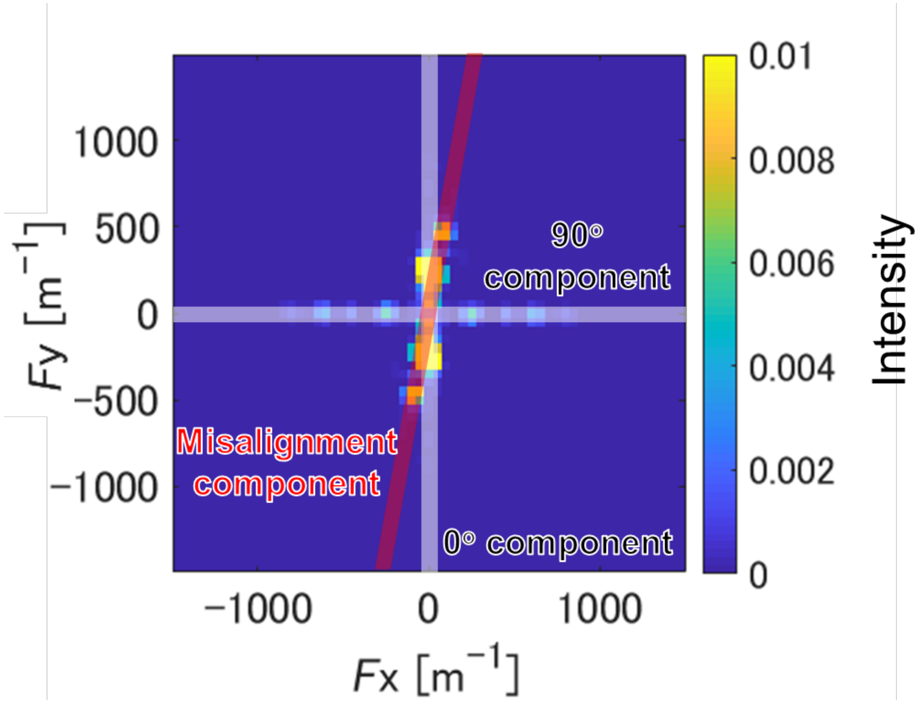
Test frequency : 1.70 MHz
Scan area : 100×100 mm^2
Scan interval : 0.25 mm

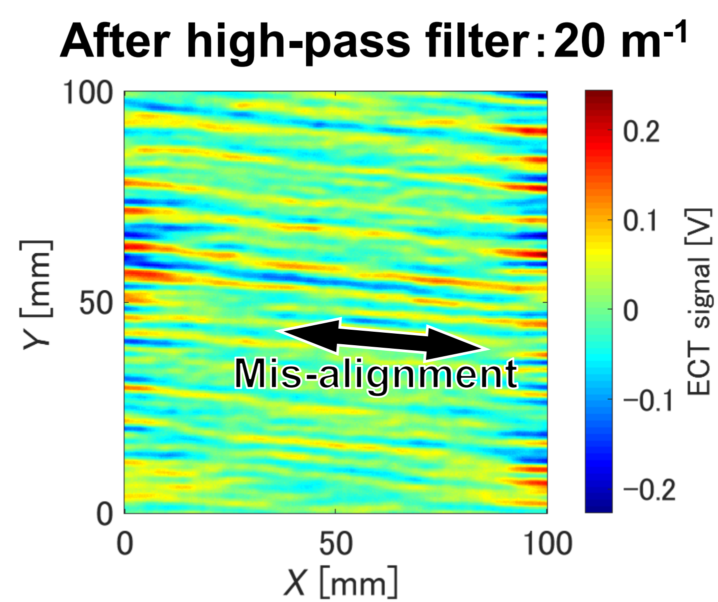
Application of Spatial Frequency Filtering



Mis-alignment layer lies on 7th in CP laminate.

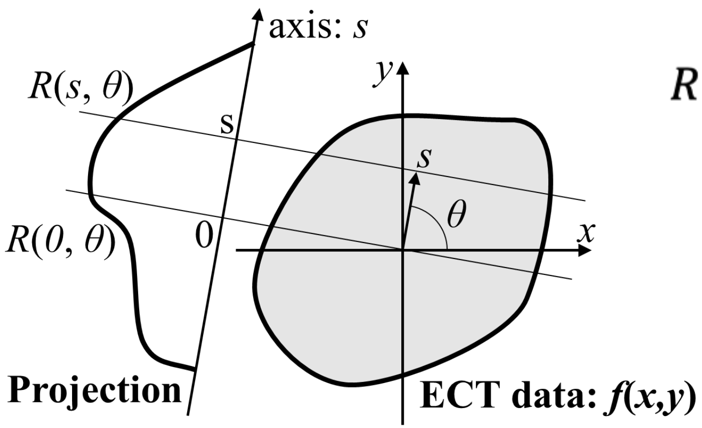






Quantitative Evaluation of Fiber Orientation

Radon Transformation Analysis *



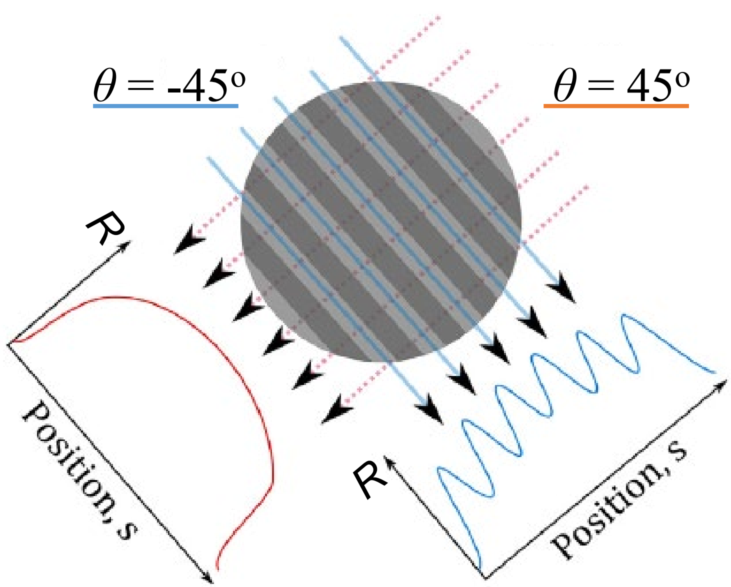
$$R(s,\theta) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y)\,\delta(x \cdot \cos\theta + y \cdot \sin\theta - s)$$

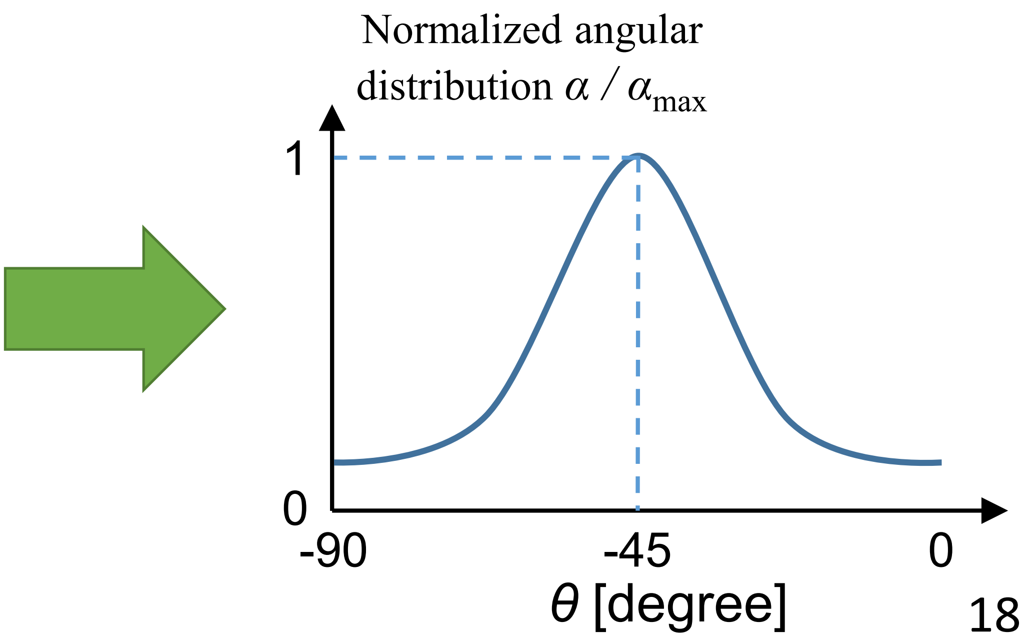
$$\alpha(\theta) = \frac{1}{L} \sum_{l=1}^{L} \left| \frac{\partial R}{\partial s} \right|_l$$

δ: Delta function

$f(x, y)$: 2 dimensional ECT data (M x N)

L: Number of measurement points on s axis

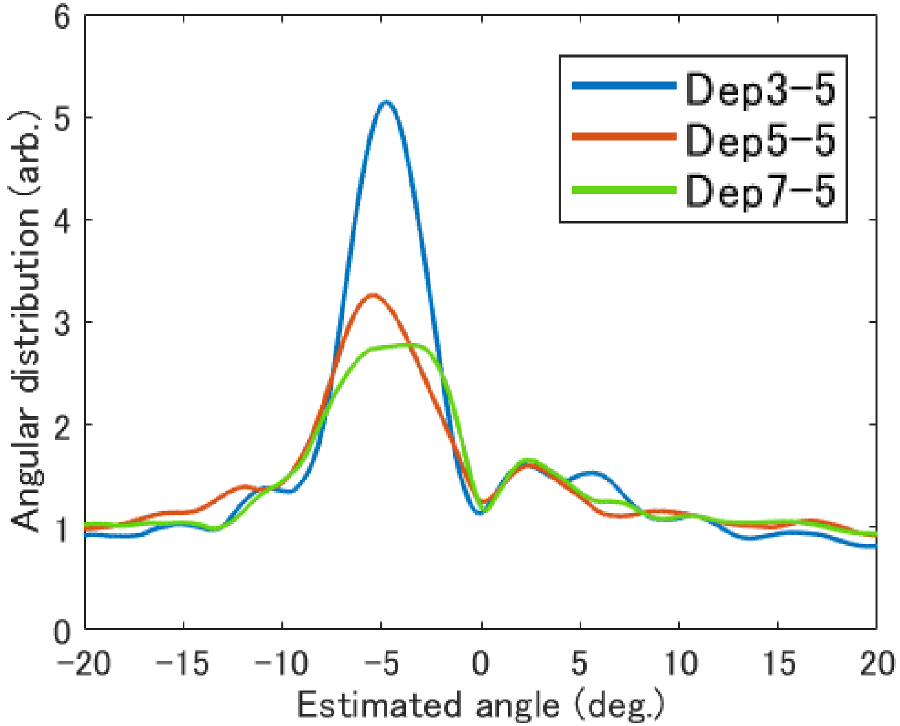




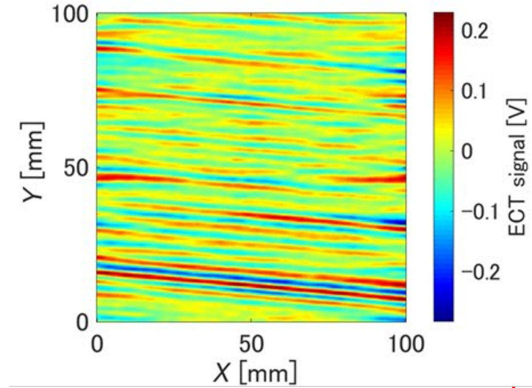
* R.R. Hughes, et al., Composites Part B, 148 (2018)

Detection of Mis-alignment in Deeper Ply

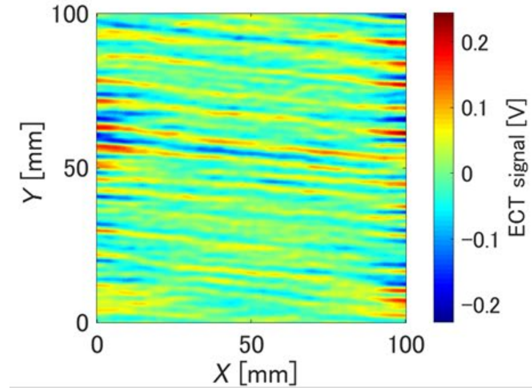
Angular Distribution



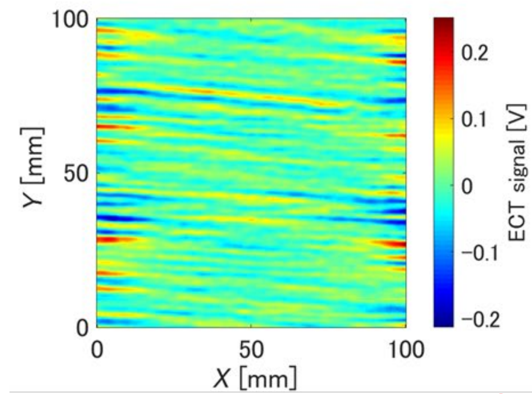
	Dep3-5	Dep5-5	Dep7-5
Estimated angle	-4.8°	-5.5°	-3.5°
Error	0.2°	0.5°	1.5°
Peak value	5.1	3.3	2.7



(a) Specimen Dep3-5 (3rd layer)



(b) Specimen Dep5-5 (5th layer)



(c) Specimen Dep7-5 (7th layer)

CONTENS

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   A. Detection of Fatigue and SCC Cracks

   B. Inspection of Hydrogen Tank by ECT

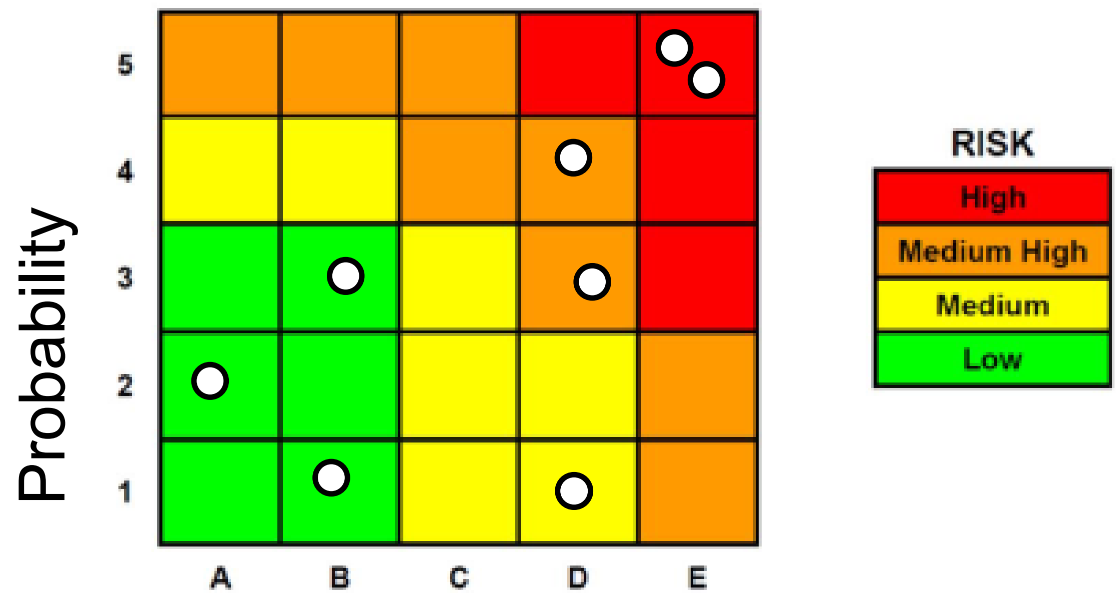
2. **Risk-based Inspection**

Risk-based Maintenance

Prioritize maintenance works of components in a plant based on the assessed risk

Damage factor

- Applicable damage mechanisms
- Inspection techniques



Consequence

Consequence area

- Leakage rate (flammable / toxic outcome)

Financial terms

- Environmental costs
- Const of lost production

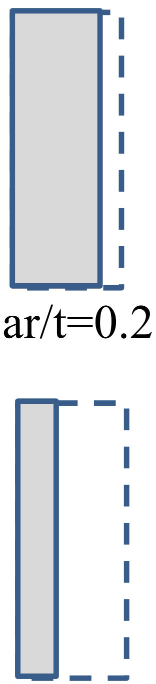
Example for Damage Factor for Pipe Wall Thinning

Standard for risk-based inspection, API 581
American Petroleum Institute (API)

- 2≦DF≦20
- 20< DF≦100
- 100< DF≦1000
- 1000< DF

Number of Inspection / Inspection Effectiveness (IE)

Thinning Rate



ar/t=0.2

ar/t=0.65

検査回数		1				2				3				4				5				6			
ar/t	検査無	IE				IE				IE				IE				IE				IE			
		P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1	7	2	1	1	5	1	1	1	4	1	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1	30	5	1	1	20	2	1	1	14	1	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1	100	15	1	1	70	7	1	1	50	3	1	1
0.2	400	300	210	110	15	290	120	20	1	160	60	5	1	180	20	2	1	120	10	1	1	100	6	1	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1	200	30	2	1	150	15	2	1	120	7	1	1
0.3	650	550	400	200	30	400	200	40	4	320	110	9	2	240	50	4	2	180	25	3	2	150	10	2	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5	440	90	10	4	350	70	6	4	280	40	5	4
0.4	900	800	700	400	130	700	400	120	30	600	200	50	10	500	140	20	8	400	110	10	8	350	90	9	8
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20	600	200	30	15	500	160	20	15	400	130	20	15
0.5	1200	1100	970	600	270	1000	600	200	60	900	360	80	40	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90	900	350	100	90	800	260	90	90	700	240	90	90
0.6	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210	1000	450	220	210	900	360	210	210	800	300	210	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500	1200	700	530	500	1100	640	500	500	1000	600	500	500

Bayes' Theorem

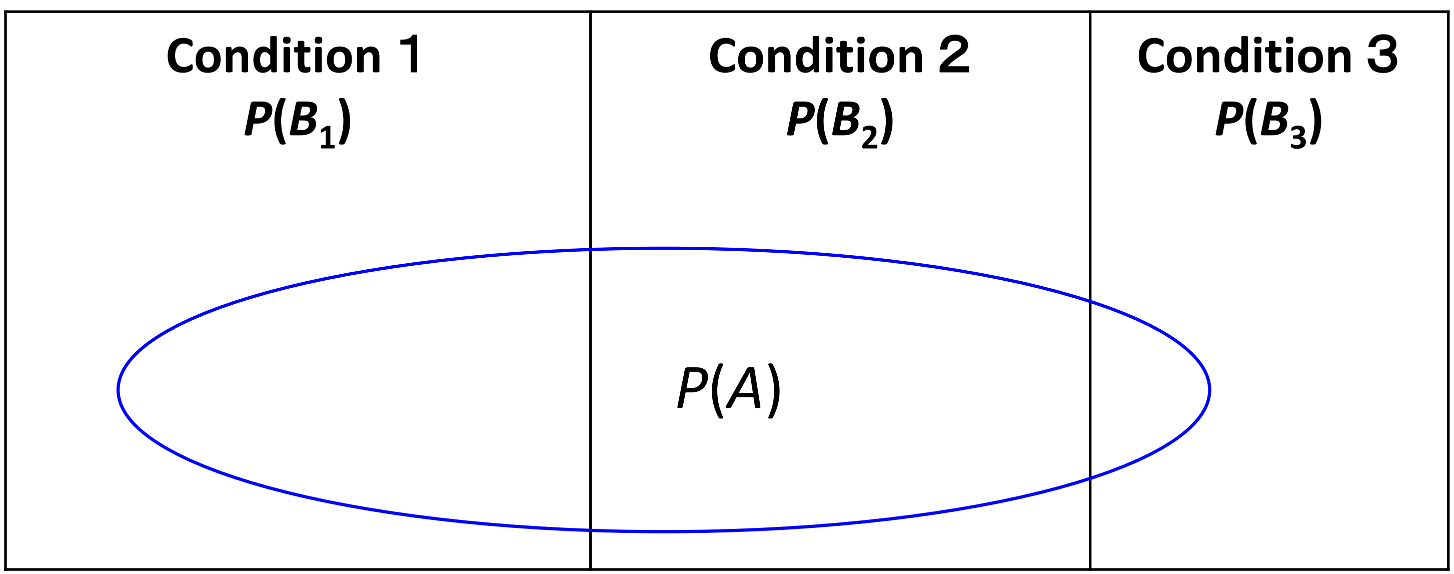
Theorem to calculate the probability that event A was caused by condition B_i from Conditional probability $P(A|B_i)$

$$P(B_i \mid A) = \frac{P(A \mid B_i) \times P(B_i)}{\sum_{j=1}^{n} P(A \mid B_j) \times P(B_j)}$$

$p(B_j)$ the probability of condition B_j occurring

$p(A \mid B_j)$ conditional probability:

the probability of event A occurring given that B_j is true



Example of Bayes' Theorem

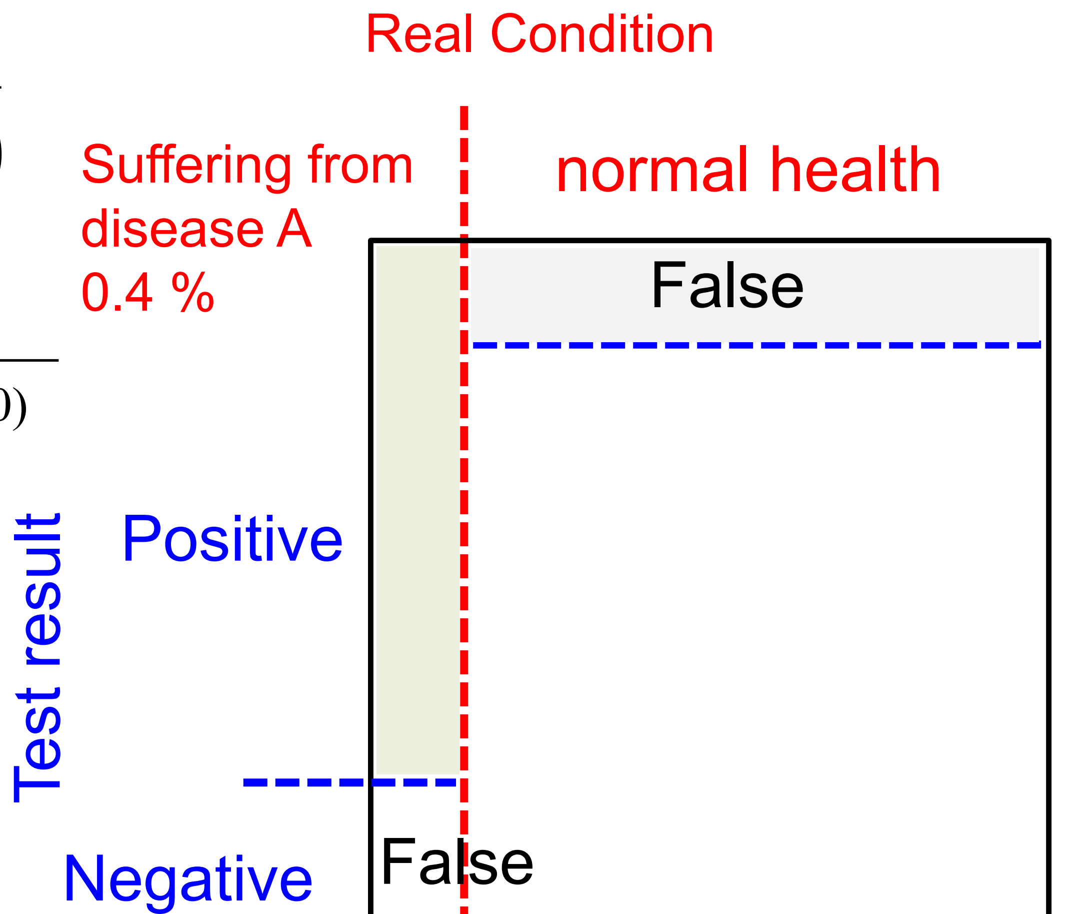
Health Checkup Problem: Disease A affects 40 persons per 10 000 in a country. If a person suffering from disease A undergoes medical check-up B, there is a 80% chance of a positive result. If a healthy person undergoes medical check-up B, there is a 90% chance of a negative result. What is the probability that the examinee has disease A if he/she tests positive by medical check-up B?

$$P(B_i \mid A) = \frac{P(A \mid B_i) \times P(B_i)}{\sum_{j=1}^{n} P(A \mid B_j) \times P(B_j)}$$

$$\frac{(8/10) \times (40/10000)}{(8/10) \times (40/10000) + (1/10) \times (1-40/10000)}$$

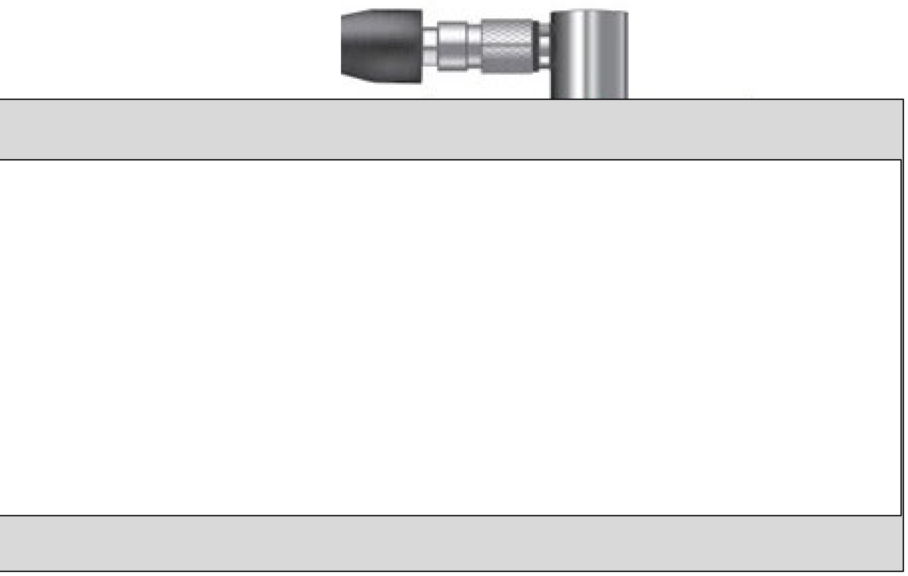
$$\simeq 0.031$$

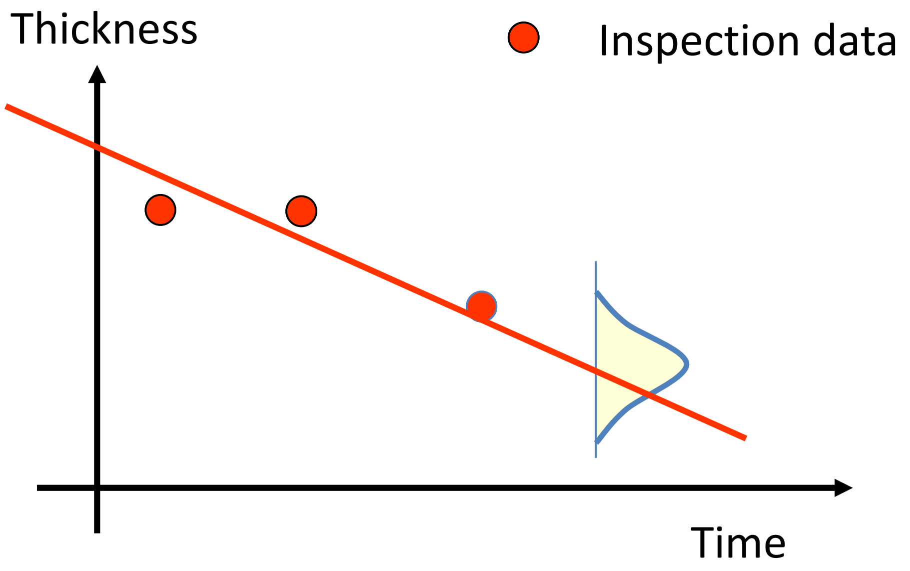
0.4 % → 3 %



Application of Bayes' Theorem in API581

According to nondestructive testing of pipe wall thickness, corrosion rate was measured as 1 mm/y. How is a probability distribution of actual corrosion rate ?





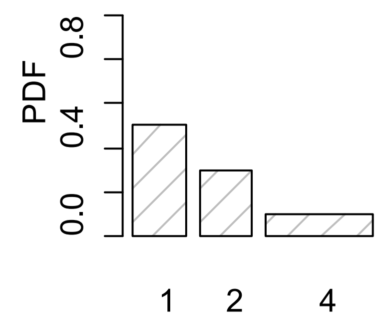
Application of Bayes' Theorem in API581

According to nondestructive testing of pipe wall thickness, corrosion rate was measured as 1 mm/y. How is a probability distribution of actual corrosion rate ?

<u>Corrosion rate based on model or experimental data (reliability of model)</u>

$$p(B_j)$$

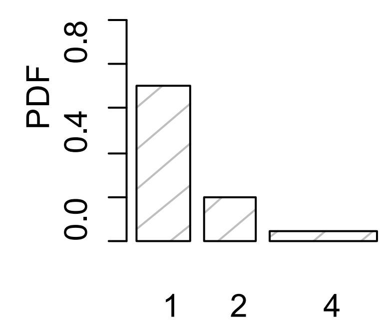
Actual corrosion rate	Probability
less than estimated rate < 1 mm/y	0.5
less tan twice the estimated rate $1 < a < 2$ mm/y	0.3
less tan four times the estimated rate $2 < a < 4$ mm/y	0.2



<u>Probability that NDT measures 1mm/y (effectiveness of inspection)</u>

$$p(A \mid B_j)$$

Actual corrosion rate	Probability
less than measured rate < 1 mm/y	0.7
less tan twice the measured rate $1 < a < 2$ mm/y	0.2
less tan four times the measured rate $2 < a < 4$ mm/y	0.1



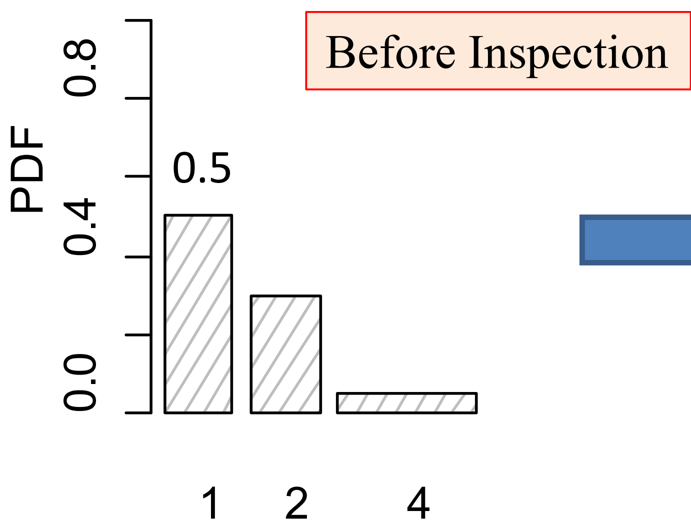
Confidence Updates by Inspection

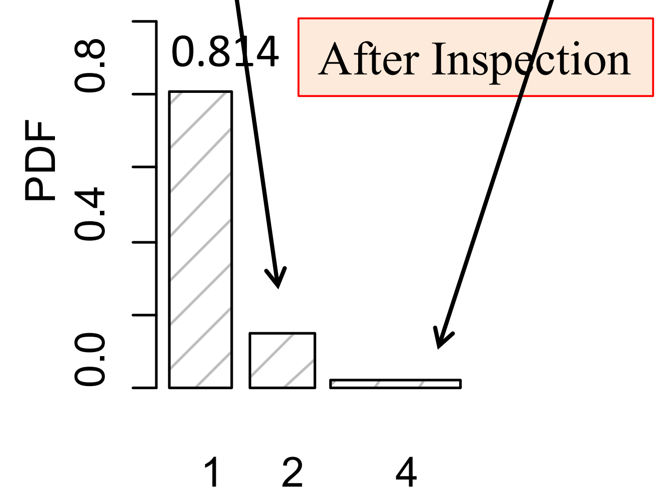
All possible case (Measured rate 1mm/year)

0.5 × 0.7=0.35	Actual rate 1 mm/y Measured rate 1 mm/y	Actual rate 1 mm/y Measured rate 2 mm/y	Actual rate 1 mm/y Measured rate 4 mm/y
0.3 × 0.2 =0.06	Actual rate 2 mm/y Measured rate 1 mm/y	Actual rate 2mm/y Measured rate 2 mm/y	Actual rate 2mm/y Measured rate 4 mm/y
0.2 × 0.1 =0.02	Actual rate 4 mm/y Measured rate 1 mm/y	Actual rate 4 mm/y Measured rate 2 mm/y	Actual rate 4 mm/y Measured rate 4 mm/y

$$\frac{0.35}{0.35+0.06+0.02}=0.814$$

$$\frac{0.06}{0.35+0.06+0.02},\quad \frac{0.02}{0.35+0.06+0.02}$$

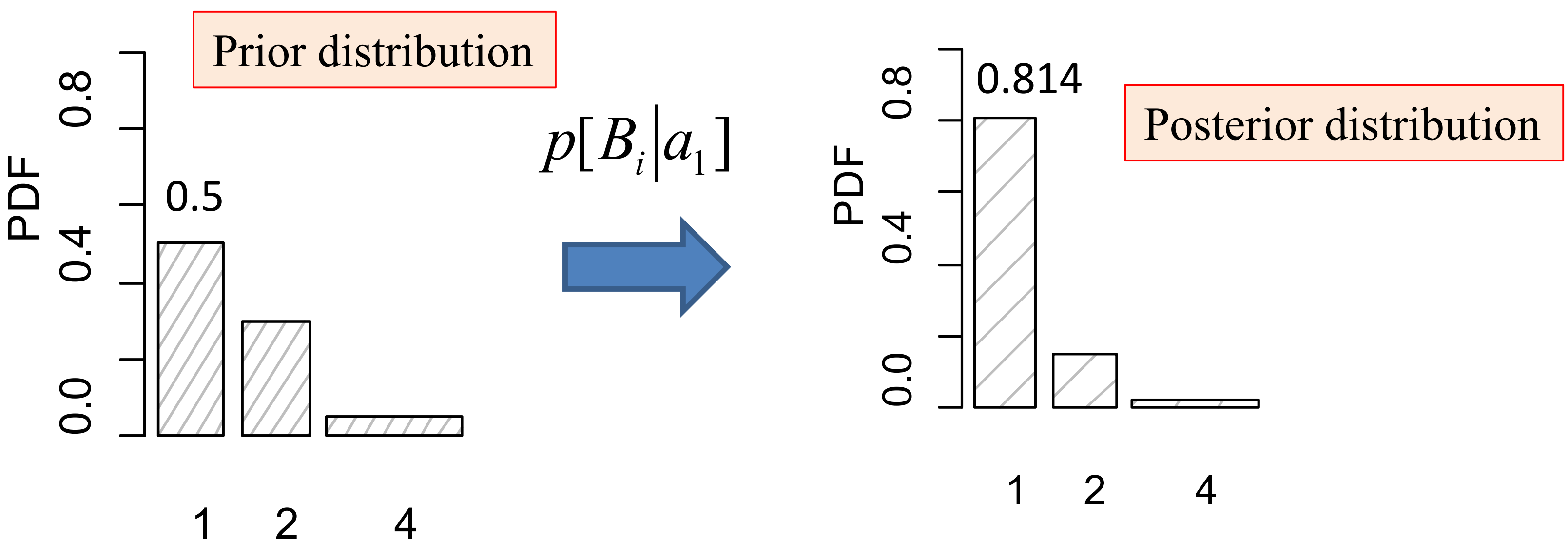




Confidence Updates by Inspection

$$p[B_i|a_1] = \frac{p[a_1|B_i]p[B_i]}{\sum_{j=1}^{j=n} p[a_1|B_j]p[B_j]}$$

$$\frac{0.35}{0.35+0.06+0.02} = 0.814$$



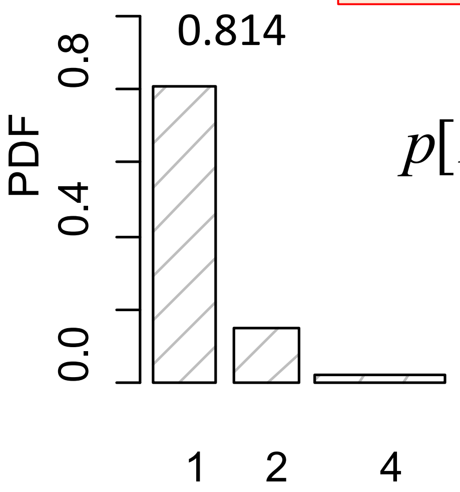
Inspection increase the probability that rate is less than 1 mm/y

Confidence Updates by Multiple Inspection

Posterior distribution of 1st inspection is used for prior distribution of 2nd inspection

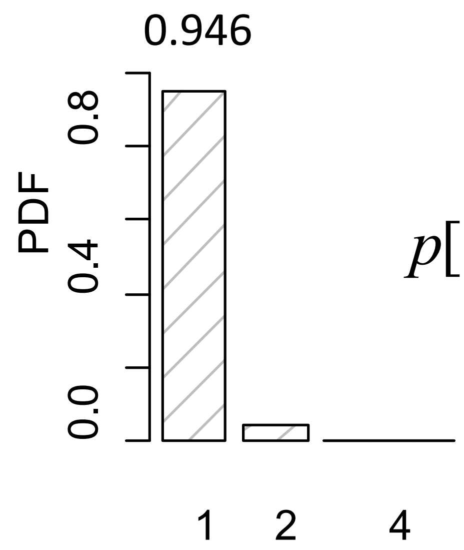
$$p[B_i|a_1, a_2] = \frac{p[a_2 \mid B_i]p[B_i \mid a_1]}{\sum_{j=1}^{j=n} p[a_2 \mid B_j]p[B_j \mid a_1]}$$

2nd Prior distribution
= 1st posterior distribution



$p[B_i|a_1]$

2nd Posterior distribution

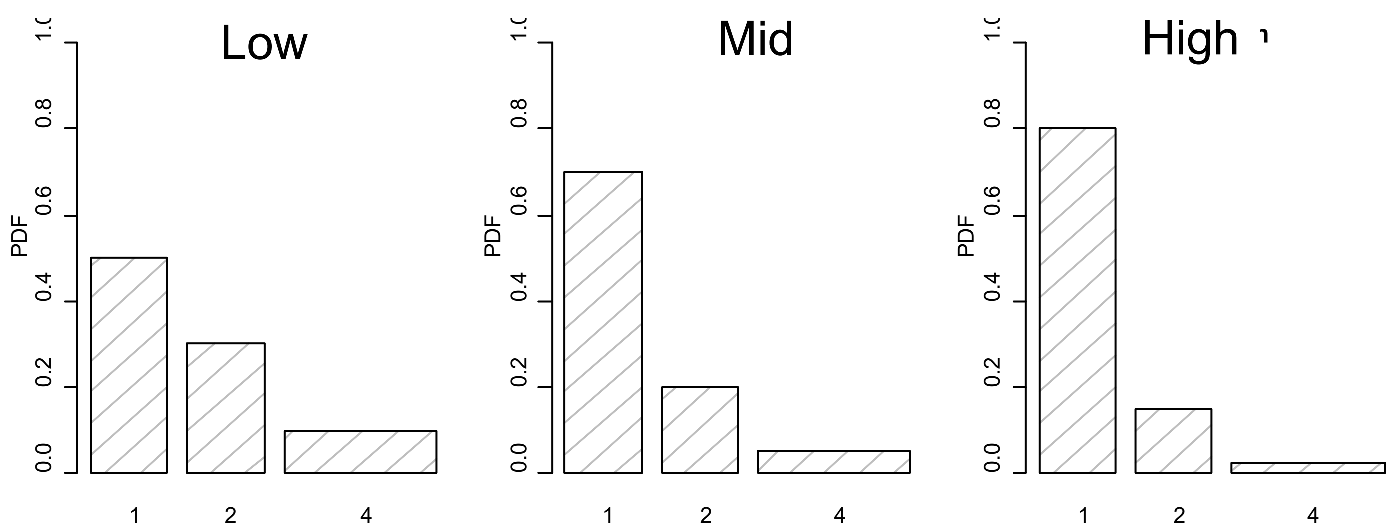


$p[B_i|a_1, a_2]$

Evaluated Corrosion Rate (Prior Probability)

<u>Corrosion rate based on model or experimental data</u>

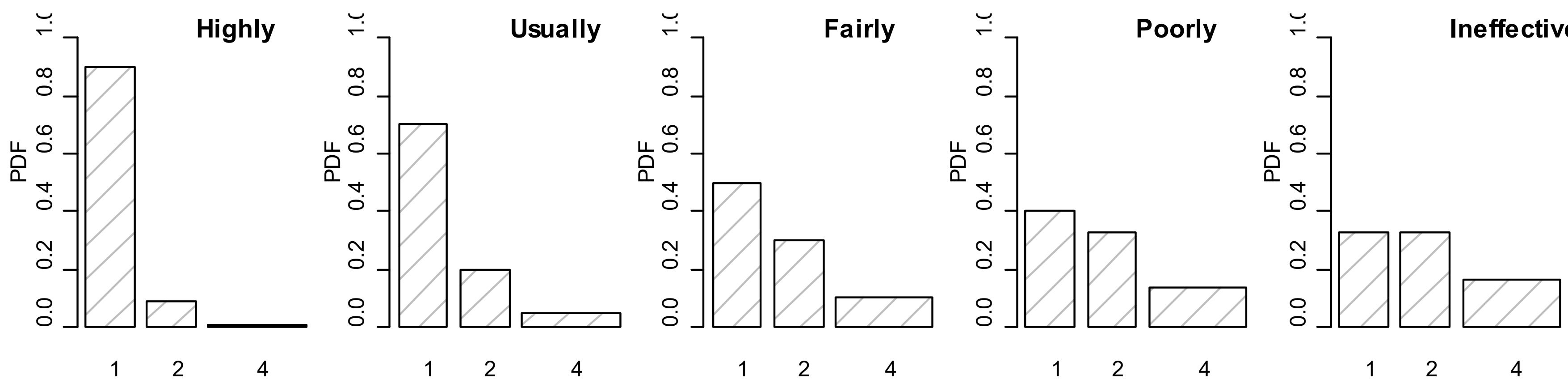
Actual corrosion rate	Reliability of Data		
	Low	Mid	high
less than estimated rate	0.5	0.7	0.8
less tan twice the estimated rate	0.3	0.2	0.15
less tan four times the estimated rate	0.2	0.1	0.05



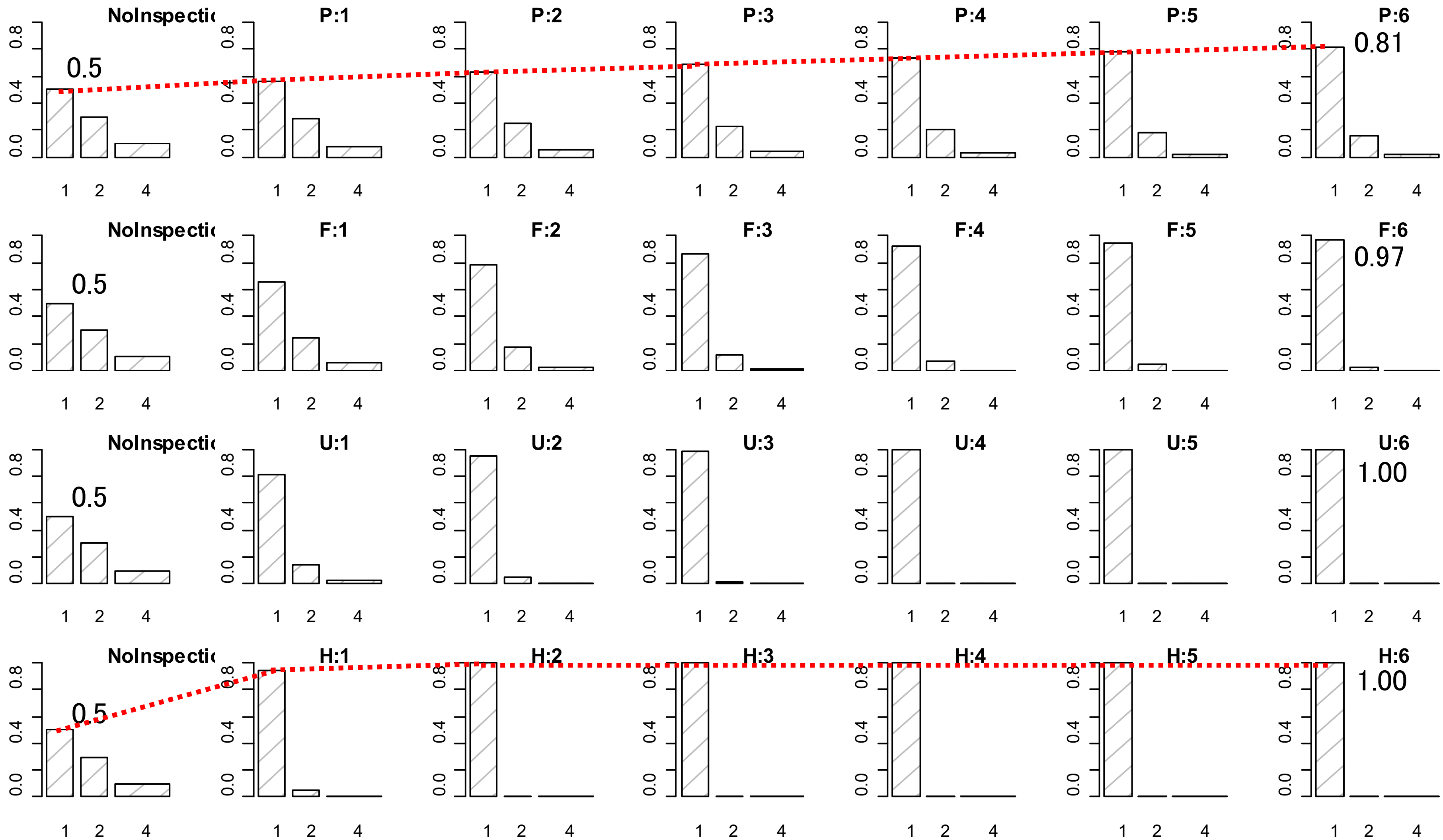
Effectiveness of Inspection Methods

Effectiveness of each inspection method is determined in expert panel.

Actual corrosion rate	Highly	Usually	Fairly	Poorly	Ineffective
less than measured rate	0.9	0.7	0.5	0.4	0.7
less tan twice the measured rate	0.09	0.2	0.3	0.33	0.2
less tan four times the measured rate	0.01	0.1	0.2	0.27	0.1



Confidence Update by Various Inspection (Low Reliability Data)

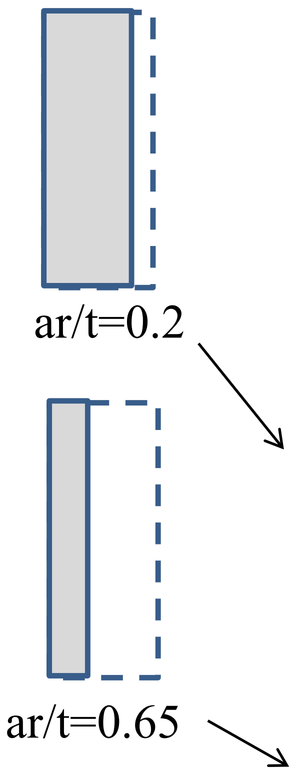


Example for Damage Factor for Pipe Wall Thinning (API 581)

- 2≦DF≦20
- 20< DF≦100
- 100< DF≦1000
- 1000< DF

Number of Inspection / Inspection Effectiveness (IE)

Thinning Rate



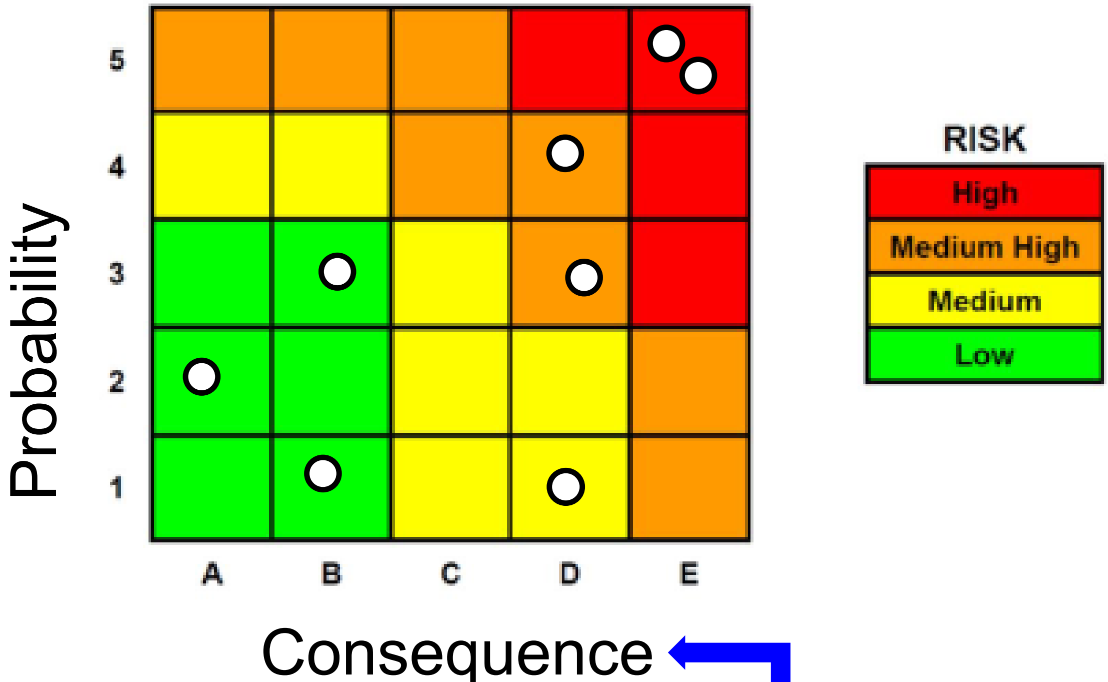
検査回数		1				2				3				4				5				6			
ar/t	検査無	IE				IE				IE				IE				IE				IE			
		P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H	P	F	U	H
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1	7	2	1	1	5	1	1	1	4	1	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1	30	5	1	1	20	2	1	1	14	1	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1	100	15	1	1	70	7	1	1	50	3	1	1
0.2	400	300	210	110	15	290	120	20	1	160	60	5	1	180	20	2	1	120	10	1	1	100	6	1	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1	200	30	2	1	150	15	2	1	120	7	1	1
0.3	650	550	400	200	30	400	200	40	4	320	110	9	2	240	50	4	2	180	25	3	2	150	10	2	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5	440	90	10	4	350	70	6	4	280	40	5	4
0.4	900	800	700	400	130	700	400	120	30	600	200	50	10	500	140	20	8	400	110	10	8	350	90	9	8
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20	600	200	30	15	500	160	20	15	400	130	20	15
0.5	1200	1100	970	600	270	1000	600	200	60	900	360	80	40	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90	900	350	100	90	800	260	90	90	700	240	90	90
0.6	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210	1000	450	220	210	900	360	210	210	800	300	210	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500	1200	700	530	500	1100	640	500	500	1000	600	500	500

Risk-based Maintenance

Prioritize maintenance works of components in a plant based on the assessed risk

Damage factor

- Applicable damage mechanisms
- Inspection techniques



Consequence area

- Leakage rate (flammable / toxic outcome)

Financial terms

- Environmental costs
- Const of lost production