

Data-based Prediction of Pressure Tube Diametral Creep for Wolsung NPPs

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소개

- 중수로 원전에 사용되는 Zr-2.5Nb 압력관은 고온, 고압, 중성자 조사 환경에서 치수 변형이 일어남
 - 길이방향 연신(elongation)
 - 반경방향 팽창(diametral creep)
- 크립에 의한 압력관의 치수 변형을 정확히 예측하지 못함으로 인해 운전조건을 최적화 하지 못하여 출력감소의 문제가 발생
- 따라서 크립의 양을 정확히 예측하여 적정의 운전조건을 확립하고, 압력관의 수명을 예측할 필요가 있음

소개

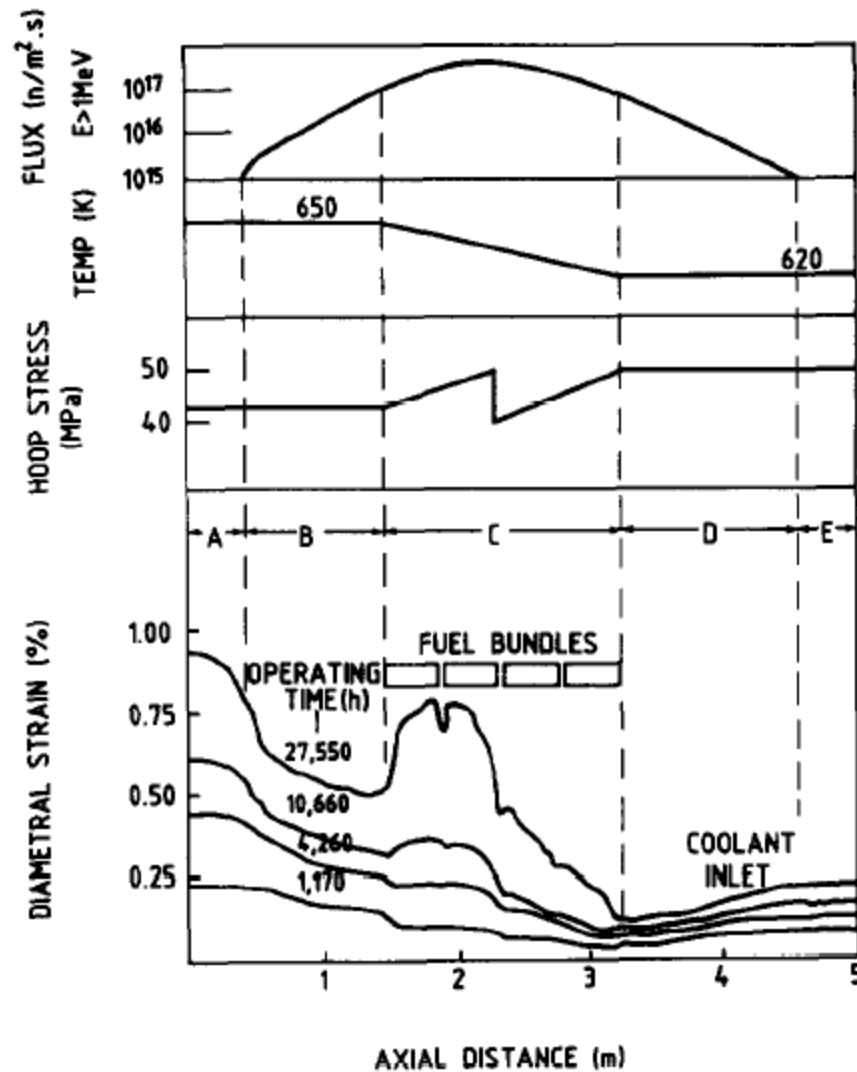
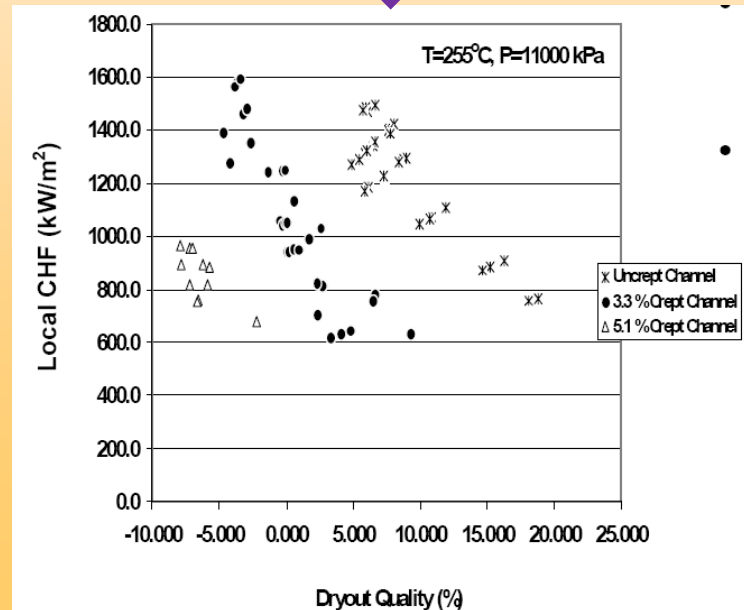
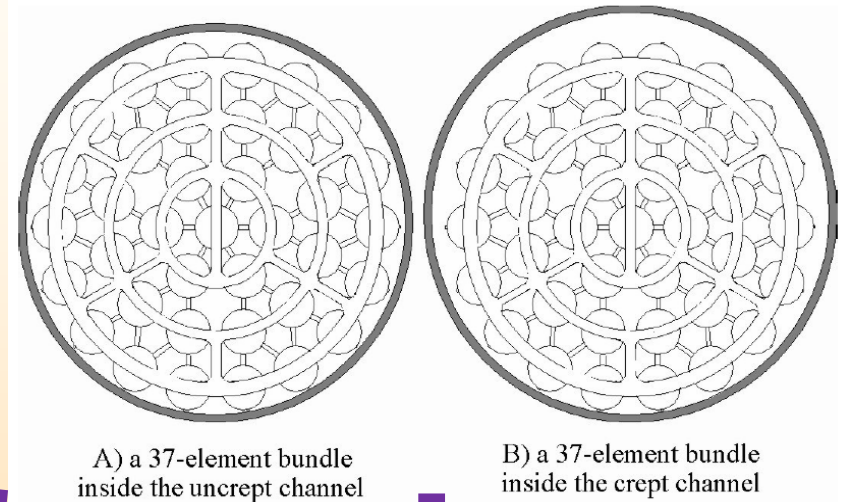


Fig. 8. Diametral creep of cold-worked Zr-2.5Nb loop tube in WR-1 reactor.



압력관 크립 자료

□ 수집자료

호기	측정시기	측정된 채널 수
1	1990년 (EFPD: 2136)	10개 채널
	1992년 (EFPD: 2967)	17개 채널
	1994년 (EFPD: 3383)	14개 채널
	2001년 (EFPD: 5726)	6개 채널
	2004년 (EFPD: 6577)	12개 채널
	2006년 (EFPD: 7336)	17개 채널
2	2002년 (EFPD: 1501.04)	12개 채널
	2003년 (EFPD: 1943.71)	7개 채널
	2007년 (EFPD: 3255.53)	6개 채널
3	2002년 (EFPD: 1324)	11개 채널
	2004년 (EFPD: 2184)	4개 채널
4	2002년 (EFPD: 937)	8개 채널
	2005년 (EFPD: 2153)	3개 채널

압력관 크립 자료

□ 수집자료

Unit No.	Channels	EFPD
2	L09, L13, M11, N03, N21, O08, O14, Q06, Q11, S07, S15 (11개)	1501.04
2	L13, N21, O08, O14, Q11, S07, T08 (7개)	1943.71
2	L13, N21, O08, O14, Q11, S07 (6개)	3255.53
3	L13, M11, N03, O08, O14, Q06, Q11, Q18, S07, T10, U11 (11개)	1324
3	O08, O14, Q11, U11 (4개)	2183
4	L13, M11, N03, O08, O14, Q06, Q11, U11 (8개)	937
4	O08, O14 (2개)	2154

압력관 크립 평가식 (인공지능)

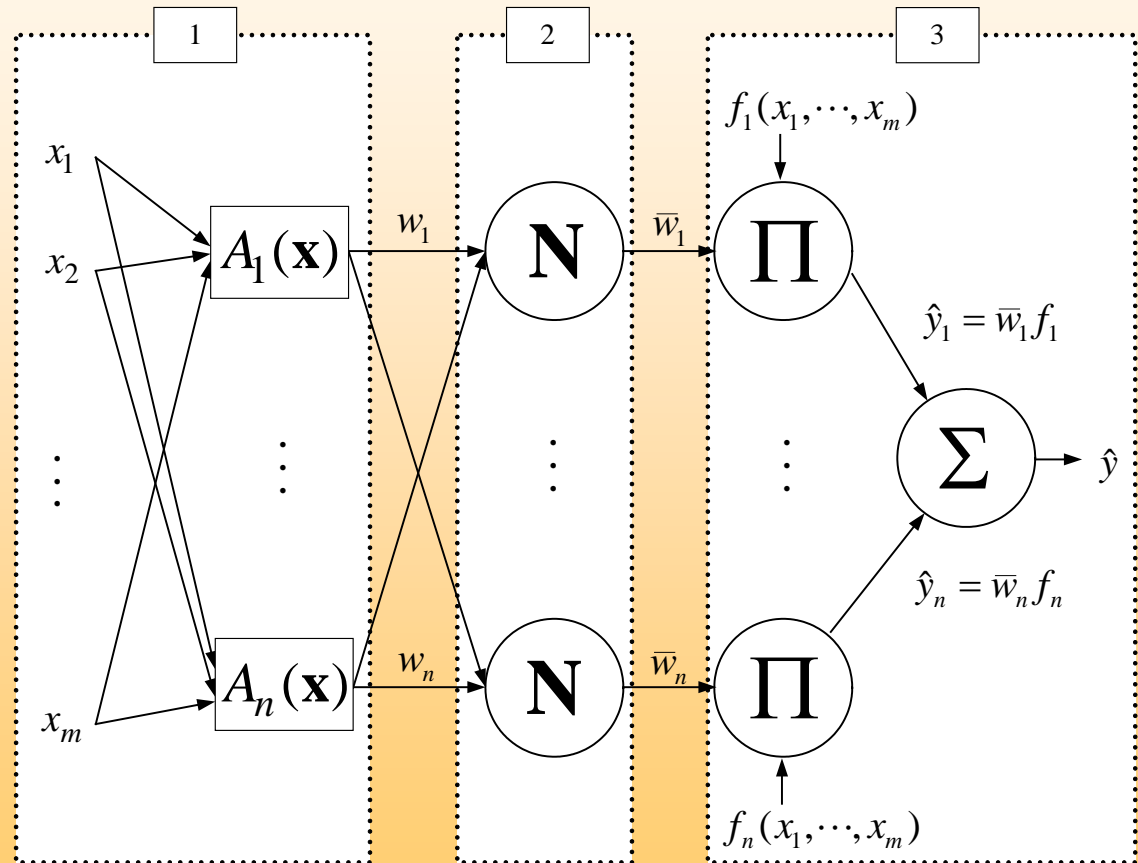
□ 데이터 기반 예측 모델 (FNN, SVR, GMDH 이용 예측 모델 개발)

$$A^i(\mathbf{x}(k)) = e^{-4\|\mathbf{x}(k) - \mathbf{x}^*(i)\|^2 / r_\alpha^2} \quad (1)$$

$$\bar{w}_i(k) = \frac{A_i(\mathbf{x}(k))}{\sum_{i=1}^n A_i(\mathbf{x}(k))} \quad (2)$$

$$\hat{y} = \sum_{i=1}^n \bar{w}_i f_i \quad (3)$$

$$f_i(x_1, \dots, x_m) = \sum_{j=1}^m q_{ij} x_j + b_i$$



압력관 크립 평가식 (인공지능)

□ 데이터 기반 예측 모델 (FNN, SVR, GMDH 이용 예측 모델 개발)

호기	EFPD	SVR (RMS error)		FNN (RMS error)	
		Training data (mm)	Test data (mm)	Training data (mm)	Test data (mm)
1	2136	0.3106	0.2755	0.2652	0.3342
	2967	0.2811	0.2770	0.2848	0.3006
	3383	0.2971	0.2838	0.2887	0.3152
	5726	0.3415	0.2482	0.2576	0.2593
	6577	-	0.3973	-	0.2874
	7336	-	0.4399	-	0.3088

압력관 크립 평가식 (BPLM/GA)

□ BPLM

- BPLM 이용 예측 모델 (유전자 알고리즘 이용 최적화)

$$\hat{y}_i = a_{i1}x_1 + a_{i2}x_2 + a_{io}$$

x_1 : 고속중성자속 x_2 : 평균냉각재온도

- 유전자 알고리즘

- ◆ RMS 오차 및 최대오차를 최소화하도록 하는 적합도 함수
- ◆ 유전자 연산자 (선택, 교배, 돌연변이)를 이용하여 최적화함

압력관 크립 평가식 (BPLM/GA)

□ 월성2,3,4호기

■ 학습 (70%) 및 시험 자료 (30%)

◆ 2호기 1501, 1944 EFPD, 3256 EFPD

◆ 3호기 1324, 2183 EFPD

◆ 4호기 937, 2154 EFPD

Data type	Data points	BPLM		FNN (2rule)		RC-1980	
		RMS error (mm)	Max. error (mm)	RMS error (mm)	Max. error (mm)	RMS error (mm)	Max. error (mm)
학습자료	468	0.0913	0.2868	0.0832	0.2565		
시험자료	120	0.0920	0.3741	0.0926	0.4207		
1500 EFPD	132	0.0782	0.1736	0.0775	0.2569	0.1503	0.2899

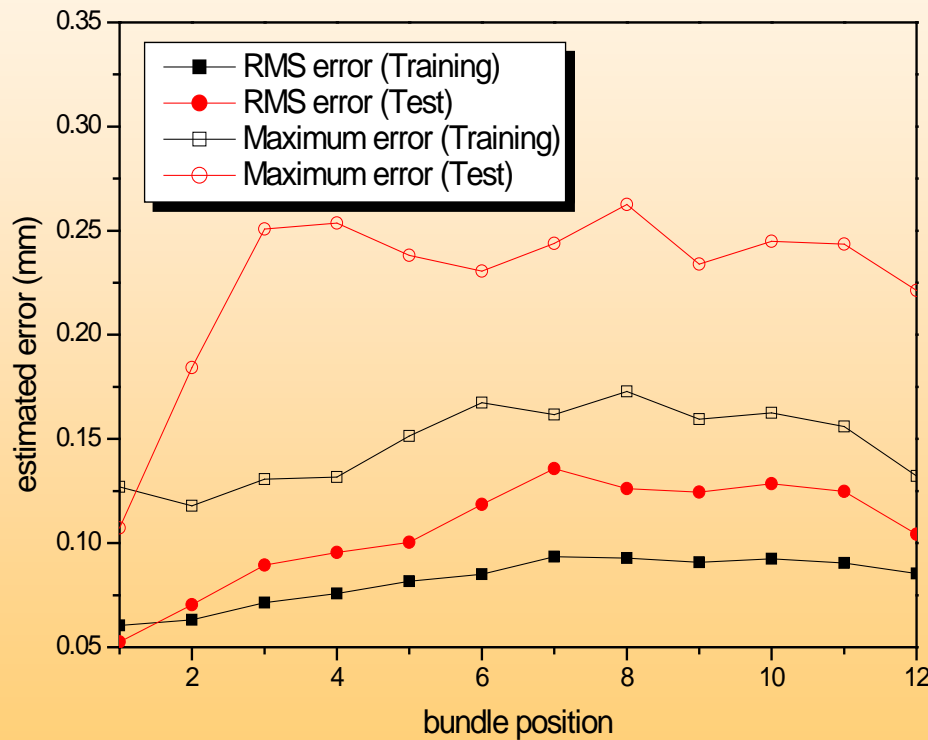
압력관 크립 평가식 (BPLM/GA)

□ BPLM과 일반 선형 모델의 비교

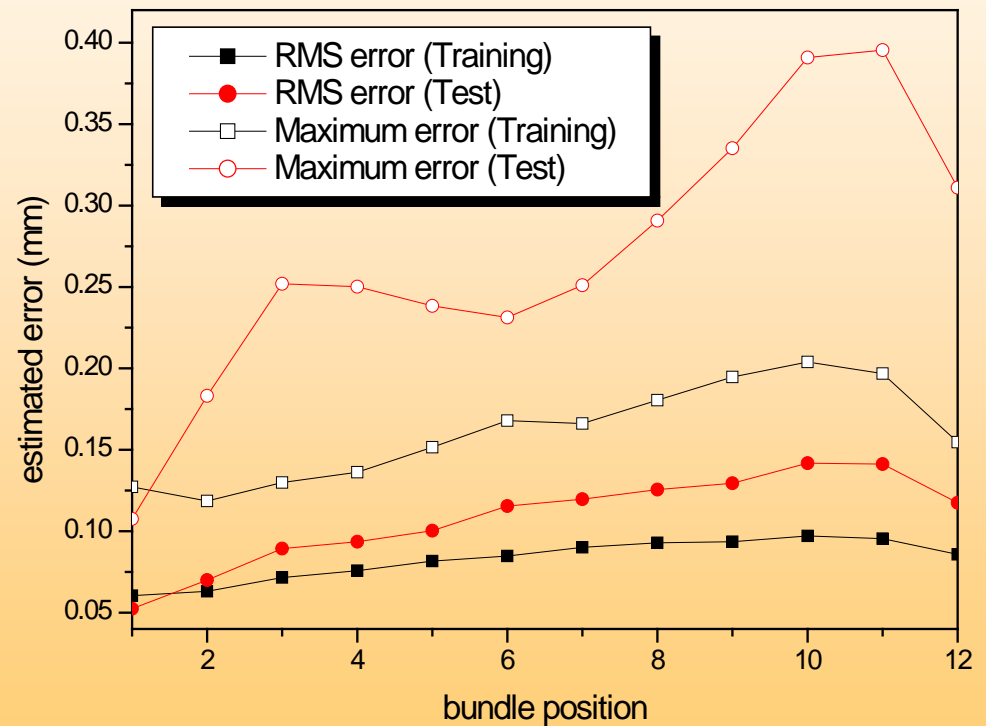
Data type	Data points	BPLM		General Linear Model	
		RMS error (mm)	Max. error (mm)	RMS error (mm)	Max. error (mm)
학습자료	468	0.0913	0.2868	0.1472	0.5944
시험자료	120	0.0920	0.3741	0.1351	0.3025

압력관 크립 평가식 (BPLM/GA)

- 입력변수로 EFPD 이용 여부에 따른 각각의 번들 위치에서의 RMS 오차 및 최대 오차



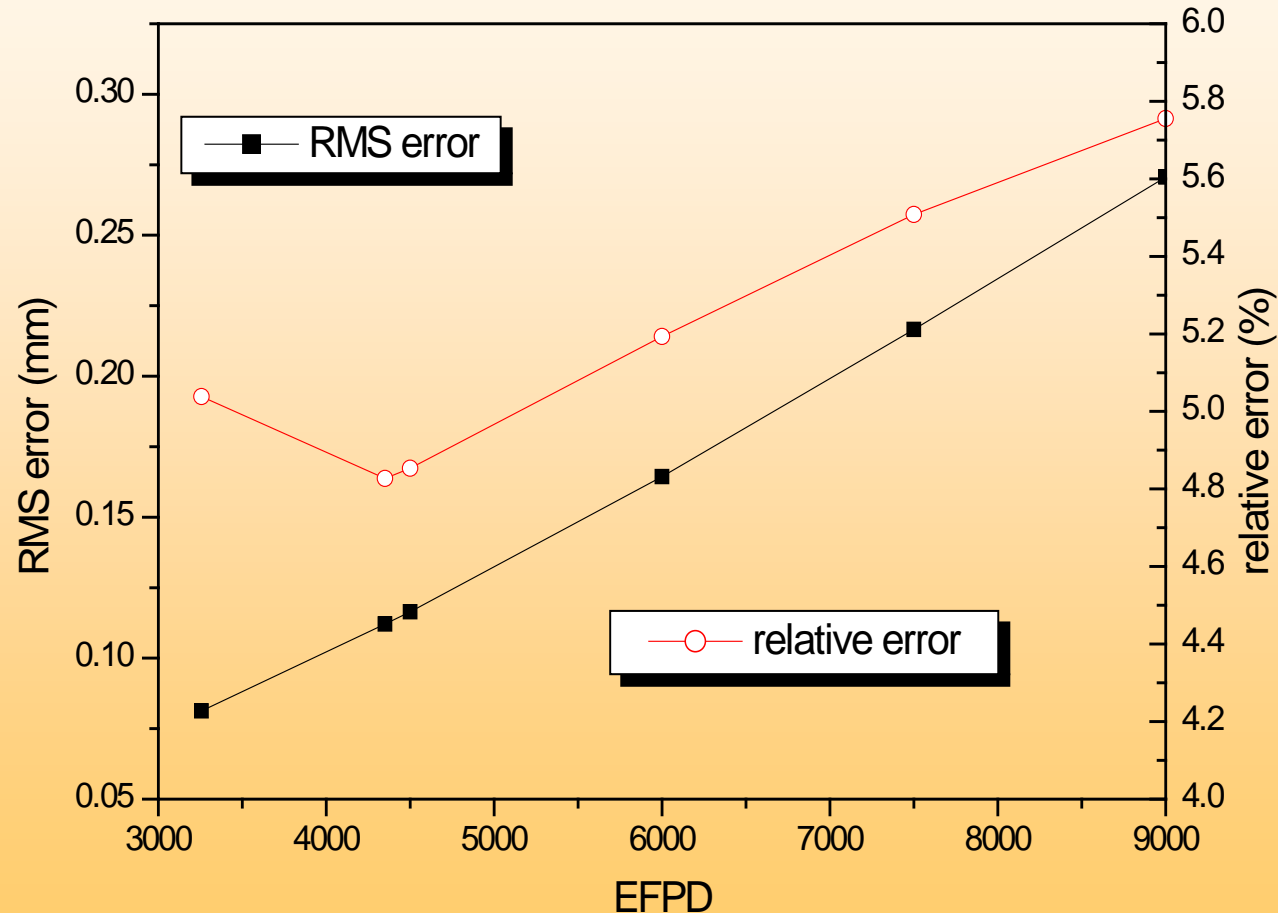
EFPD 이용



EFPD 이용하지 않은 경우

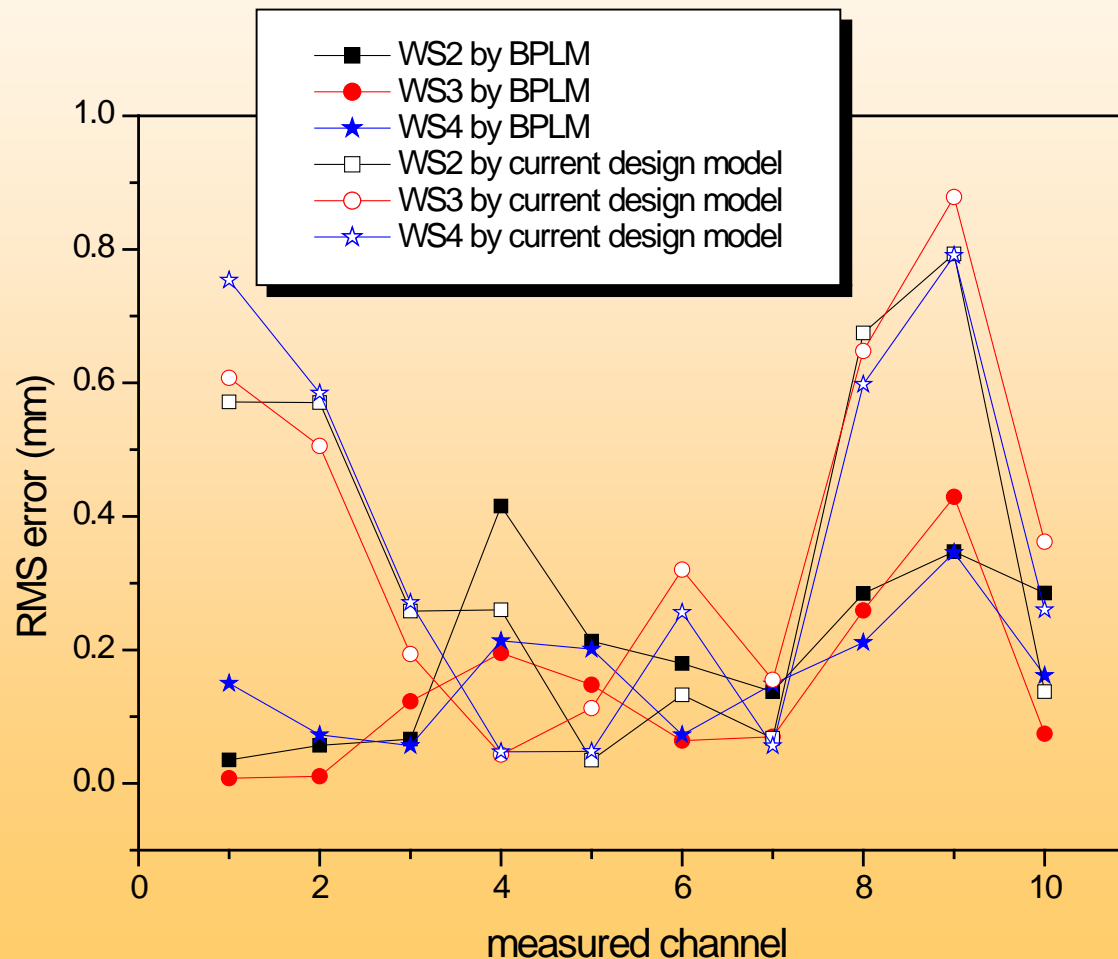
압력관 크립 평가식 (BPLM/GA)

□ EFPD에 따른 RMS 오차 및 상대 오차



압력관 크립 평가식 (BPLM/GA)

- 월성 2, 3, 4호기의 10개의 중복으로 측정된 압력관에서의 BPLM 및 RC-1980에 의해 예측된 RMS 오차



압력관 크립 평가식 (BPLM/GA)

□ PI 계산

■ BPLM 모델

$$y_k = f(\mathbf{x}_k, \boldsymbol{\theta}) + \varepsilon_k$$

■ 학습자료가 아닌 관측자료 \mathbf{x}_0 에서의 예측치는 다음과 같음

$$\hat{y}_0 \approx f(\mathbf{x}_0, \boldsymbol{\theta}) + \mathbf{f}_0^T \cdot [\hat{\boldsymbol{\theta}} - \boldsymbol{\theta}]$$

$$\mathbf{f}_0^T = \left(\frac{\partial f(\mathbf{x}_0, \boldsymbol{\theta})}{\partial a_{i0}} \quad \frac{\partial f(\mathbf{x}_0, \boldsymbol{\theta})}{\partial a_{i1}} \quad \dots \quad \frac{\partial f(\mathbf{x}_0, \boldsymbol{\theta})}{\partial a_{ip}} \right) = [1 \quad x_1 \quad \dots \quad x_p]$$

■ 예측오차의 분산

$$Var(y_0 - \hat{y}_0) = Var(\varepsilon_0) + Var(\mathbf{f}_0^T \cdot [\hat{\boldsymbol{\theta}} - \boldsymbol{\theta}])$$

$$\varepsilon_0 \sim N(0, \sigma^2) \text{ and } [\hat{\boldsymbol{\theta}} - \boldsymbol{\theta}] = N(0, \mathbf{S})$$

압력관 크립 평가식 (BPLM/GA)

□ PI 계산

■ 분산-공분산 행렬

$$\mathbf{S} = s^2 (\mathbf{F}^T \mathbf{F})^{-1}$$

$$s^2 = \frac{1}{N - p - 1} \sum_{k=1}^N (y_k - f(\mathbf{x}_k, \hat{\boldsymbol{\theta}}))^2$$

$$\mathbf{F} = \frac{\partial \mathbf{y}}{\partial \boldsymbol{\theta}} = \begin{bmatrix} \frac{\partial y}{\partial a_{i0}} & \frac{\partial y}{\partial a_{i1}} & \dots & \frac{\partial y}{\partial a_{ip}} \end{bmatrix}$$

$$\frac{\partial \mathbf{y}}{\partial a_{ij}} = \begin{bmatrix} \frac{\partial y_1}{\partial a_{ij}} & \frac{\partial y_2}{\partial a_{ij}} & \dots & \frac{\partial y_N}{\partial a_{ij}} \end{bmatrix}^T, \quad j = 0, 1, \dots, p$$

■ 예측치 분산

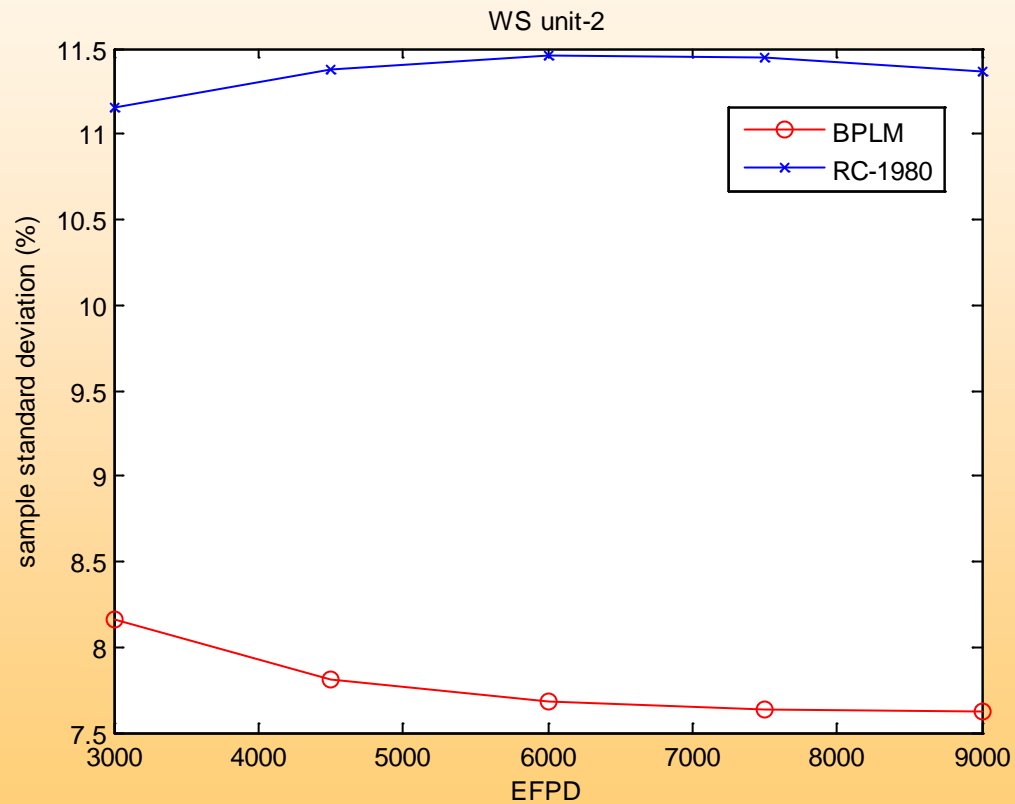
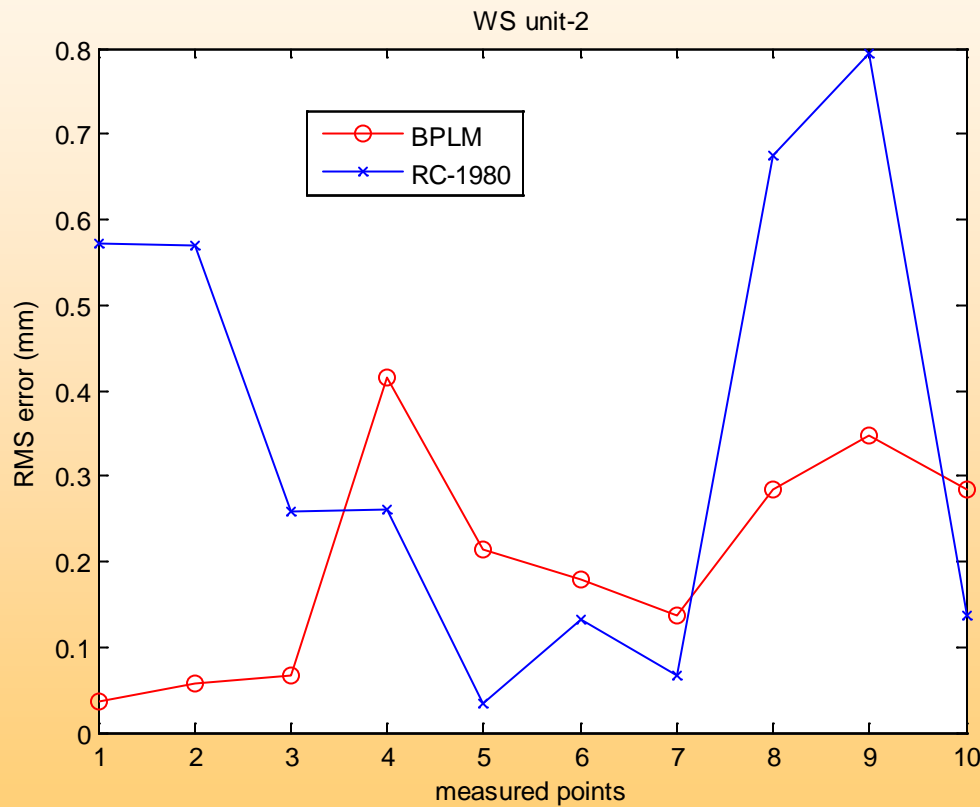
$$\text{Var}(y_0 - \hat{y}_0) \approx \sigma^2 + \mathbf{f}_0^T \mathbf{S} \mathbf{f}_0 \approx s^2 + s^2 \mathbf{f}_0^T (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{f}_0$$

■ 95%신뢰도를 갖는 예측치

$$\hat{y}_0 \pm 2s \sqrt{1 + \mathbf{f}_0^T (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{f}_0} = \hat{y}_0 \pm \delta$$

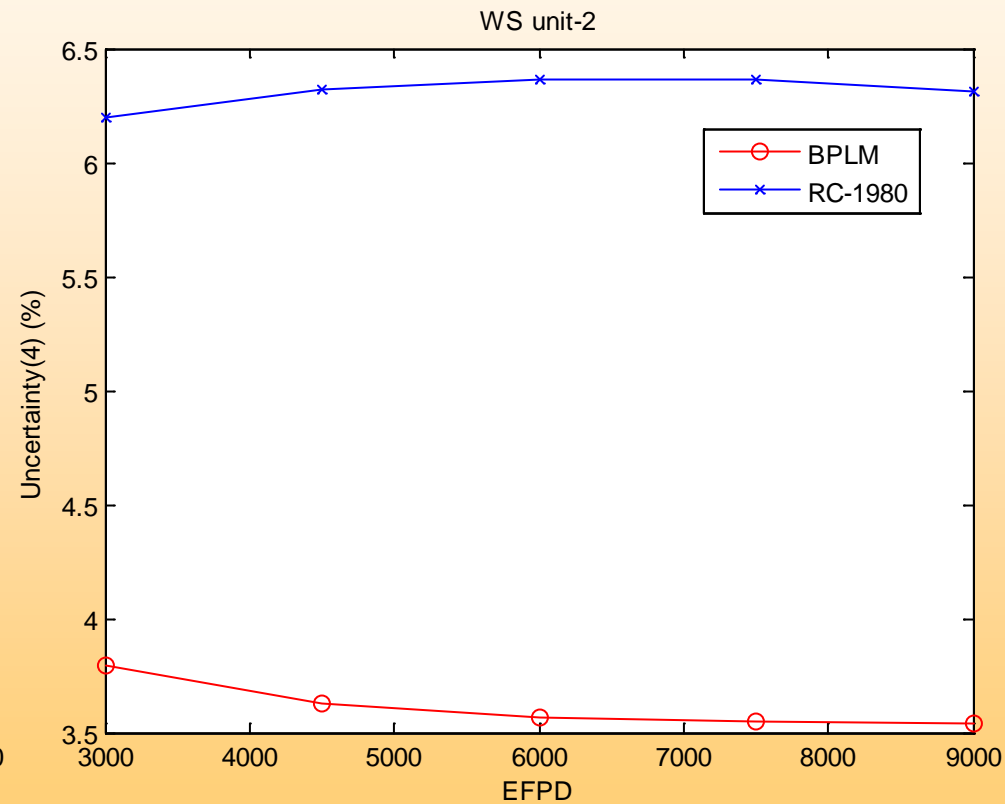
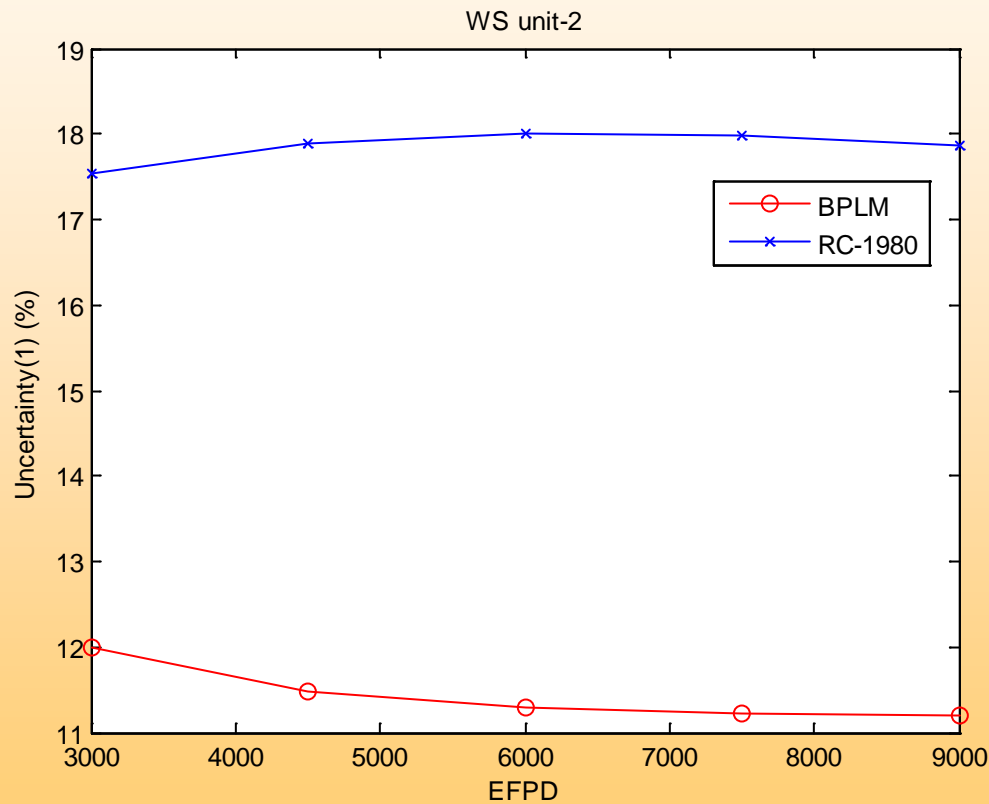
압력관 크립 평가식 (BPLM/GA)

□ BPLM을 이용한 10개 측정 채널에서 오차비교 (월성 2호기)



압력관 크립 평가식 (BPLM/GA)

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압력관 크립 평가식 (BPLM/MLE)

□ BPLM (Bundle Position-wise Linear Model)

$$y_{ij} = a_{ij0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \gamma_{ij}$$

$$\omega_{ij} = (d_{ij} - d_{ij0}) : i\text{-번들}, j\text{-채널 차등직경}$$

$$y_{ij} = (\omega_{ij} - m_{\omega}) / s_{\omega} : \text{차등직경의 정규화 값}$$

$$\gamma_{ij} : \text{measurement error } N(0, \sigma_{\gamma})$$

- The true normalized differential diameter can be modeled as a random value

$$y_{ij}^t = a_{i0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \delta_j$$

- The BPLM is described as follows:

$$y_{ij} = a_{i0} + a_{i1}x_{ij1} + a_{i2}x_{ij2} + \varepsilon_{ij}$$

$$\varepsilon_{ij} = \delta_j + \gamma_{ij}, \delta_j : \text{채널간 가변성을 나타내는 우연오차}$$

압력관 크립 평가식 (BPLM/MLE)

- The best estimated PT diameter is

$$\hat{d}_{ij}^s = \left[s_{\omega} \hat{y}_{ij}^s + m_{\omega} \right] + d_{ijo} = \left[s_{\omega} \left(\hat{a}_{i0} + \hat{a}_{i1} x_{ij1}^s + \hat{a}_{i2} x_{ij2}^s \right) + m_{\omega} \right] + d_{ijo}$$

- The epistemic error in predicting the PT diameter at a given fixed condition can be written as

$$\zeta_{ij} = d_{ij}^s - \hat{d}_{ij}^s = s_{\omega} \left(a_{i0} + a_{i1} x_{ij1}^s + a_{i2} x_{ij2}^s \right) - s_{\omega} \left(\hat{a}_{i0} + \hat{a}_{i1} x_{ij1}^s + \hat{a}_{i2} x_{ij2}^s \right) = s_{\omega} \mathbf{x}_{ij}^s (\mathbf{a}_i - \hat{\mathbf{a}}_i)$$

- The variance of the epistemic error is as follows:

$$V(\zeta_{ij}) = s_{\omega}^2 \mathbf{x}_{ij} \mathbf{\Omega} \mathbf{x}_{ij}^T \quad \text{where} \quad \mathbf{\Omega} = \text{Var}(\mathbf{a}_i - \hat{\mathbf{a}}_i) = (\mathbf{X}^T \mathbf{V}^{-1} \mathbf{X})^{-1}$$

- The BPLM is described as follows:

$$y_{ij} = a_{i0} + a_{i1} x_{ij1} + a_{i2} x_{ij2} + \varepsilon_{ij} = \mathbf{x}_{ij} \mathbf{a}_i + \varepsilon_{ij}$$

$$\mathbf{y} = \mathbf{X} \mathbf{a} + \boldsymbol{\varepsilon}$$

압력관 크립 평가식 (BPLM/MLE)

- The likelihood function is used to solve the model coefficient \mathbf{a} with the covariance \mathbf{V}

$$L(y; \mathbf{a}, \sigma_\delta^2, \sigma_\gamma^2) = (2\pi)^{-n/2} |\mathbf{V}|^{-1/2} e^{\left(-\frac{1}{2}(\mathbf{y} - \mathbf{X}\mathbf{a})^T \mathbf{V}^{-1}(\mathbf{y} - \mathbf{X}\mathbf{a})\right)}$$

- The log-likelihood function is defined as

$$l = \ln L(y; \mathbf{a}, \sigma_\delta^2, \sigma_\gamma^2) = -\frac{n}{2} \ln(2\pi) - \frac{1}{2} \ln |\mathbf{V}| - \frac{1}{2} (\mathbf{y} - \mathbf{X}\mathbf{a})^T \mathbf{V}^{-1} (\mathbf{y} - \mathbf{X}\mathbf{a})$$

- From $\frac{\partial l}{\partial \mathbf{a}} = \frac{\partial l}{\partial \sigma_\delta^2} = \frac{\partial l}{\partial \sigma_\gamma^2} = \mathbf{0}$

$$\hat{\mathbf{a}} = (\mathbf{X}^T \mathbf{V}^{-1} \mathbf{X})^{-1} \mathbf{X}^T \mathbf{V}^{-1} \mathbf{y}$$

$$\hat{\sigma}_\delta^2 = \frac{(\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})^T (\mathbf{E} - \mathbf{I}_n)(\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})}{n(M-1)}, \quad \hat{\sigma}_\gamma^2 = \frac{(\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})^T (M\mathbf{I}_n - \mathbf{E})(\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})}{n(M-1)}$$

- $(\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})$ should be modified into $s_\omega (\mathbf{y} - \mathbf{X}\hat{\mathbf{a}})$ to express the variances of the measurement error and the aleatory error in PT diameters rather

압력관 크립 평가식 (BPLM/MLE)

- The unbiased estimates of the variances can be solved taking the expectation of the biased variances

$$\hat{\sigma}_{\delta}^2 = \frac{n(M-1)\hat{\sigma}_{\delta}^2}{n(M-1) - \left(\hat{\sigma}_{\gamma}^2 / \hat{\sigma}_{\delta}^2\right) \left\{ \text{tr} \left[(\mathbf{E} - \mathbf{I}_n) \mathbf{X} \left(\mathbf{X}^T \left(\mathbf{I}_n - \frac{\mathbf{E}}{\left(\hat{\sigma}_{\gamma}^2 / \hat{\sigma}_{\delta}^2\right) + M} \right) \mathbf{X} \right)^{-1} \mathbf{X}^T \right] \right\}}$$

$$\hat{\sigma}_{\gamma}^2 = \frac{n(M-1)\hat{\sigma}_{\gamma}^2}{n(M-1) - \text{tr} \left[(M\mathbf{I}_n - \mathbf{E}) \mathbf{X} \left(\mathbf{X}^T \left(\mathbf{I}_n - \frac{\mathbf{E}}{\left(\hat{\sigma}_{\gamma}^2 / \hat{\sigma}_{\delta}^2\right) + M} \right) \mathbf{X} \right)^{-1} \mathbf{X}^T \right]}$$

압력관 크립 평가식 (BPLM/MLE)

- The prediction interval (PI) with 95% confidence is defined as

$$PI_{ij} = \hat{y}_{ij} + t_{0.05/2}^{n-3M} \left(\sqrt{Var(\lambda_{ij})} \right)$$

$$Var(\lambda_{ij}) = diag \left(\mathbf{x}_{\cdot j} \mathbf{\Omega} \mathbf{x}_{\cdot j}^T - \mathbf{x}_{\cdot j} \mathbf{\Omega} (\mathbf{X}^T \mathbf{V}^{-1}) (\sigma_{\delta}^2 \mathbf{W} \mathbf{w}_j^T) - (\sigma_{\delta}^2 \mathbf{w}_j \mathbf{W}^T) (\mathbf{V}^{-1} \mathbf{X}) \mathbf{\Omega} \mathbf{x}_{\cdot j}^T + \sigma_{\delta}^2 \mathbf{1}_{M \times M} + \sigma_{\gamma}^2 \mathbf{I}_M \right)$$

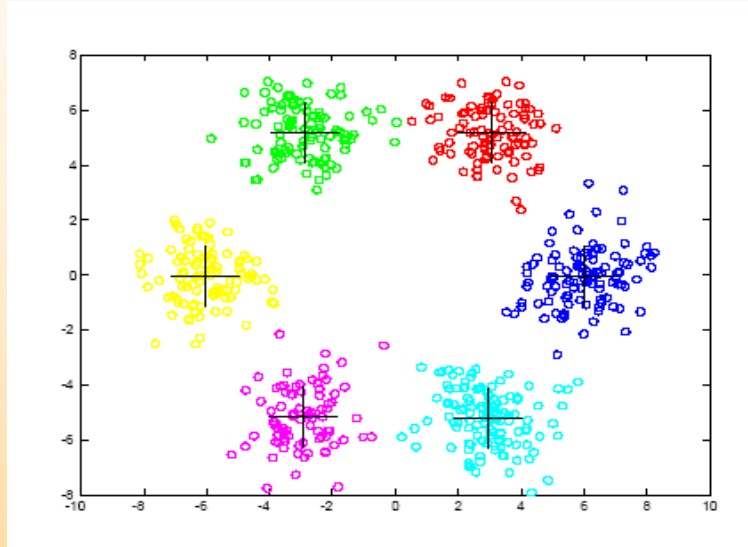
$$\mathbf{\Omega} = Var(\mathbf{a}_i - \hat{\mathbf{a}}_i) = (\mathbf{X}^T \mathbf{V}^{-1} \mathbf{X})^{-1}$$

$$\mathbf{W} = \mathbf{I}_J \otimes \mathbf{1}_{M \times 1}$$

$$\mathbf{w}_j^T = \mathbf{I}_J(:, j) \times \mathbf{1}_{1 \times M}$$

압력관 크립 평가식 (BPLM/MLE)

□ Selection of Training Data



■ Subtractive Clustering (SC) Method

$$P_1(k) = \sum_{j=1}^n e^{-4\|\mathbf{x}_k - \mathbf{x}_j\|^2 / r_\alpha^2} \quad k = 1, 2, \dots, n$$

$$P_{i+1}(k) = P_i(k) - P_i^c e^{-4\|\mathbf{x}_k - \mathbf{c}_i\|^2 / r_\beta^2}, \quad k = 1, 2, \dots, n$$

압력관 크립 평가식 (BPLM/MLE)

□ 적용

■ 49 채널 데이터 (월성 2,3,4호기)

- ◆ Unit 2 : 1501, 1944, 3256 EFPDs
- ◆ Unit 3 : 1324, 2183 EFPDs
- ◆ Unit 4 : 937, 2154 EFPDs

■ 학습자료: 39개 채널 자료 (습득자료 80%, SC 방법을 이용하여 선정)

■ 검증자료: 10개 채널 자료 (나머지 자료)

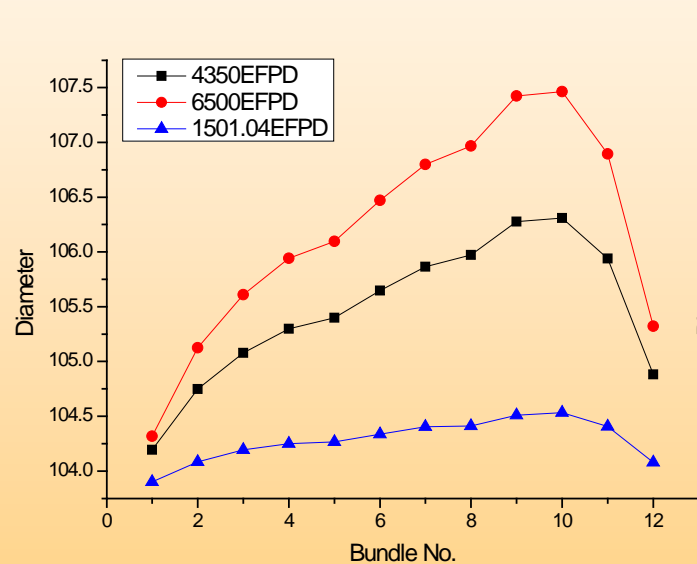
압력관 크립 평가식 (BPLM/MLE)

□ 12 BPLM 모델 파라미터

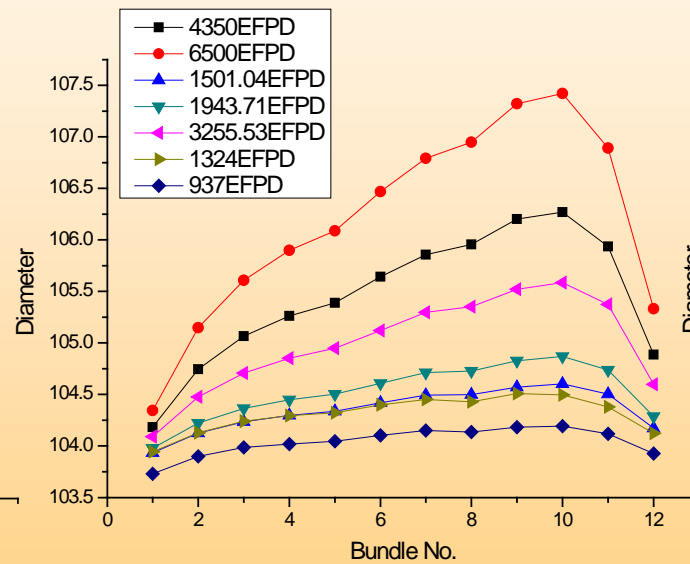
Bundle position	a_{i0}	a_{i1}	a_{i2}
1	2.2172	0.1078	2.3428
2	1.6243	0.4505	1.6468
3	0.6178	0.5187	0.9638
4	0.0620	0.5726	0.5416
5	-0.1707	0.6400	0.2226
6	-0.1264	0.7201	0.1653
7	-0.0223	0.8183	0.1478
8	0.0126	0.9141	0.2613
9	0.0354	1.0410	0.4150
10	0.1006	1.1967	0.5332
11	0.3816	1.3927	0.4824
12	1.0625	1.4730	0.0760

압력관 크립 평가식 (BPLM/MLE)

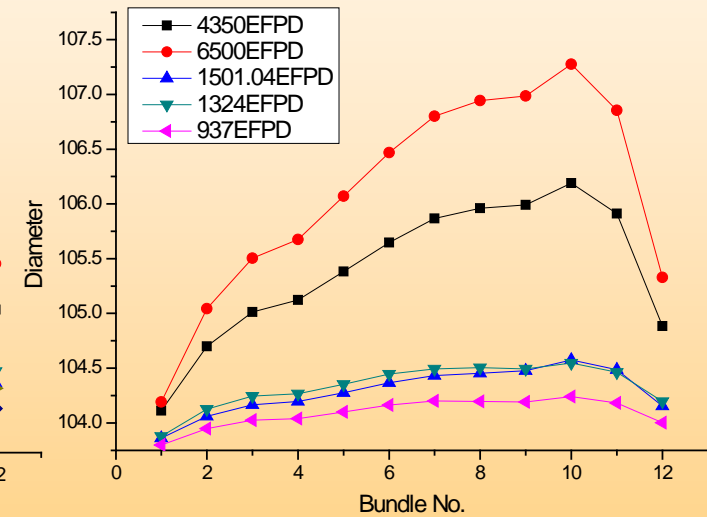
□ EFPD에 따른 예측된 직경



Channel L09



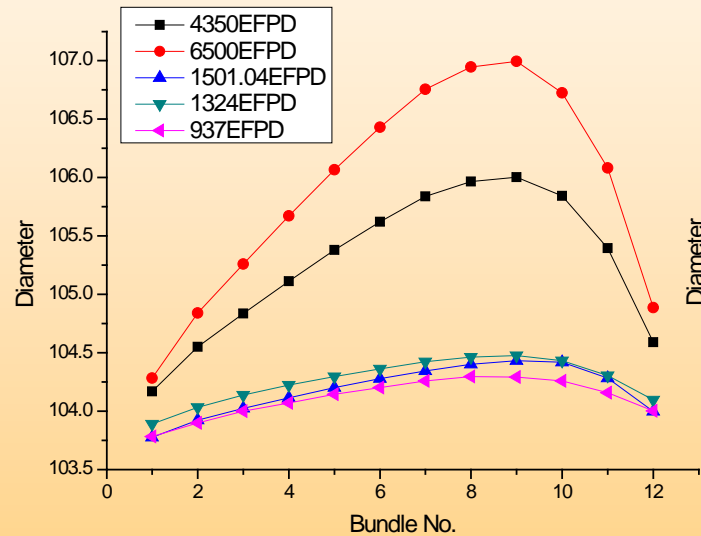
Channel L13



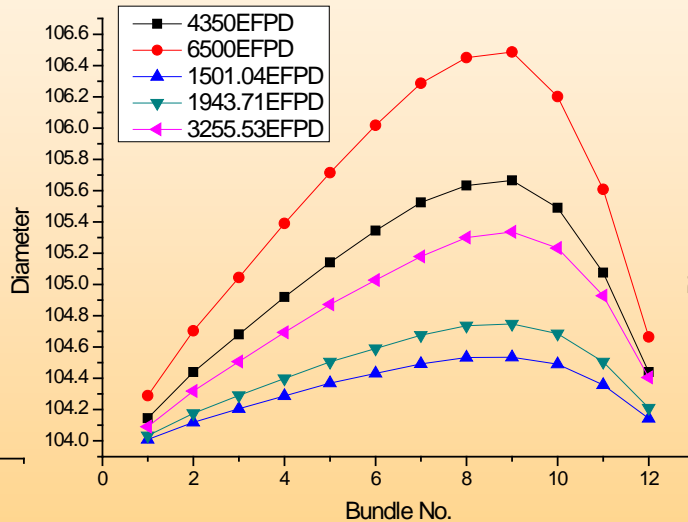
Channel M11

압력관 크립 평가식 (BPLM/MLE)

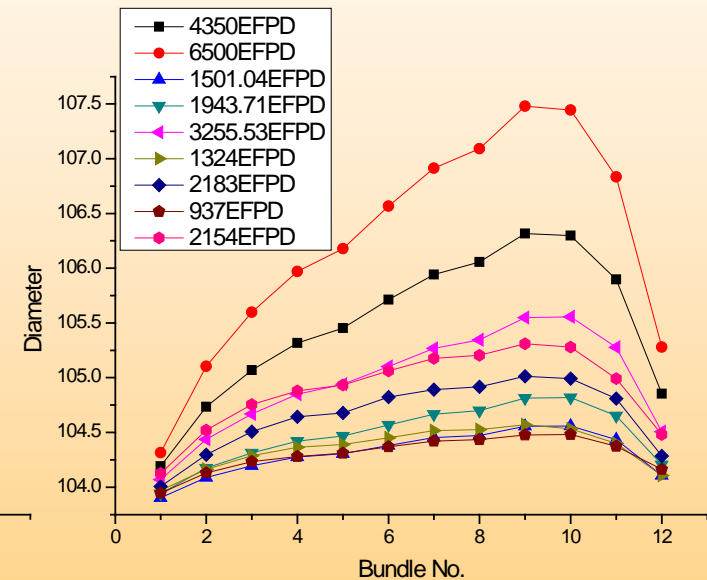
□ EFPD에 따른 예측된 직경



Channel N03



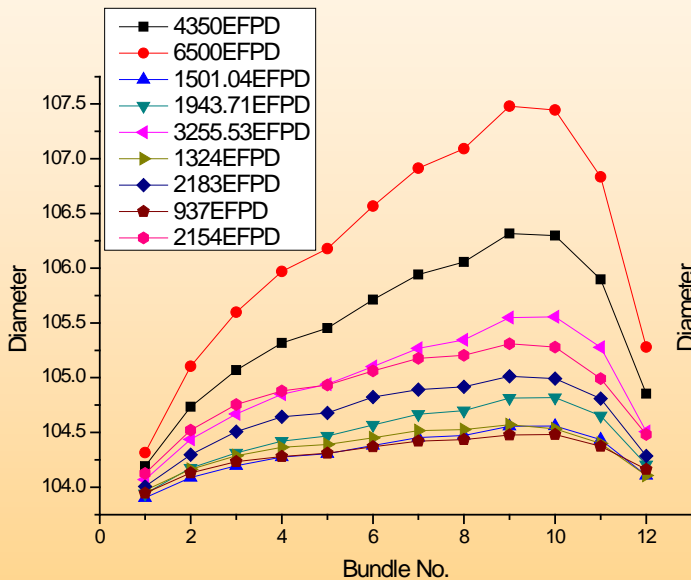
Channel N21



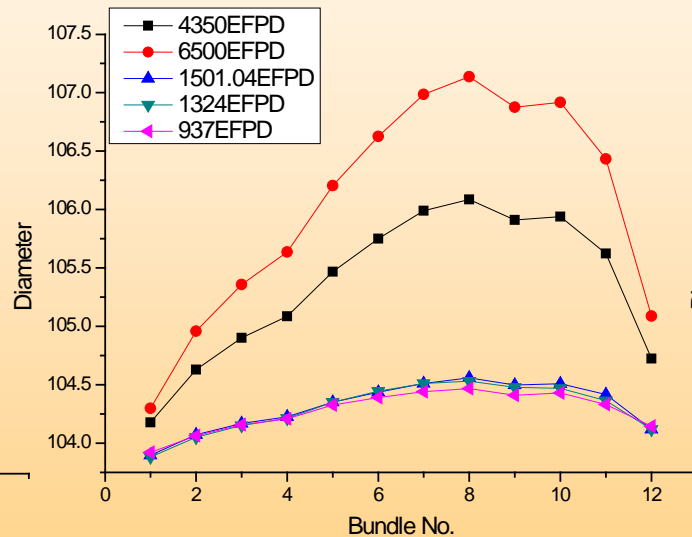
Channel O08

압력관 크립 평가식 (BPLM/MLE)

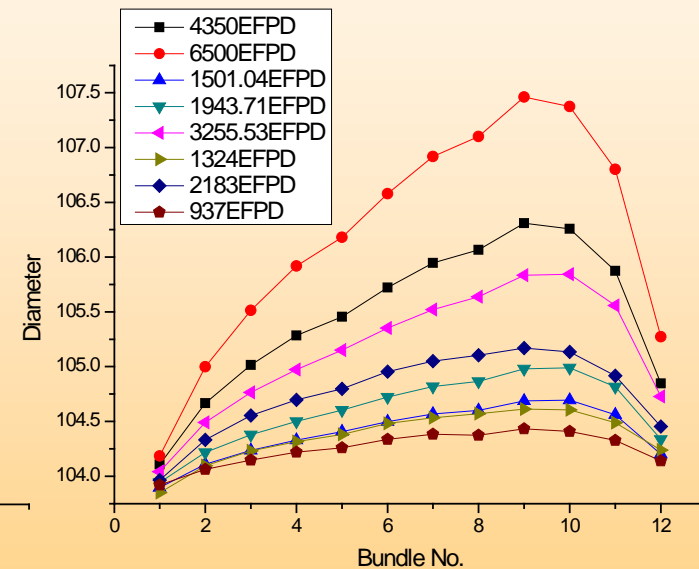
□ EFPD에 따른 예측된 직경



Channel O04



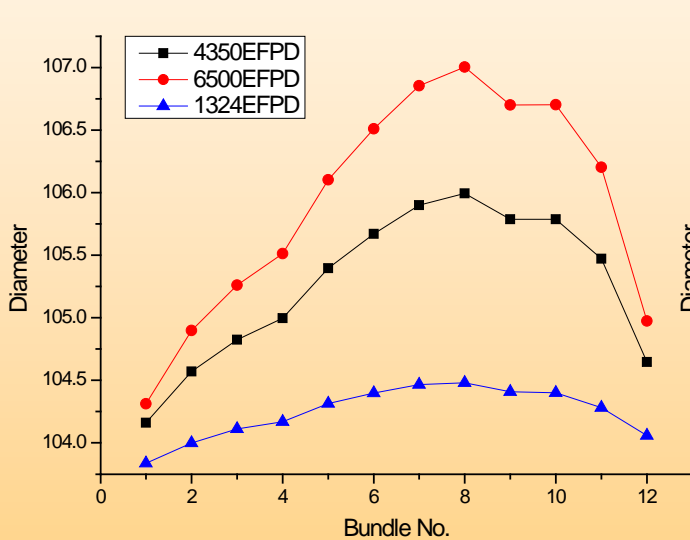
Channel Q06



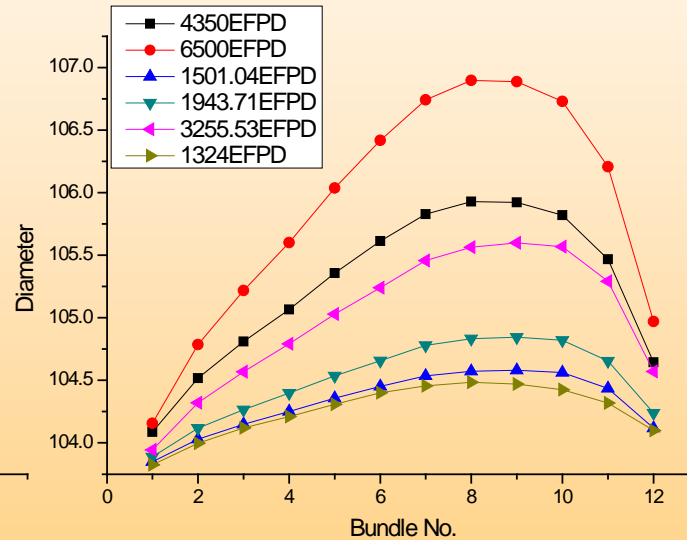
Channel Q11

압력관 크립 평가식 (BPLM/MLE)

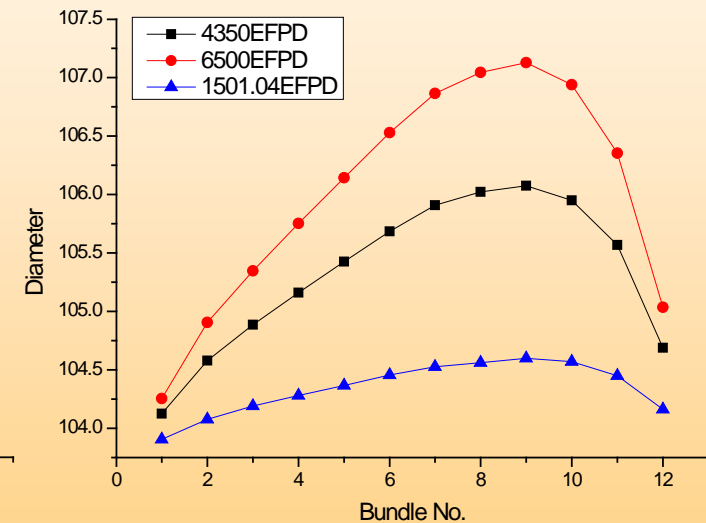
□ EFPD에 따른 예측된 직경



Channel Q18



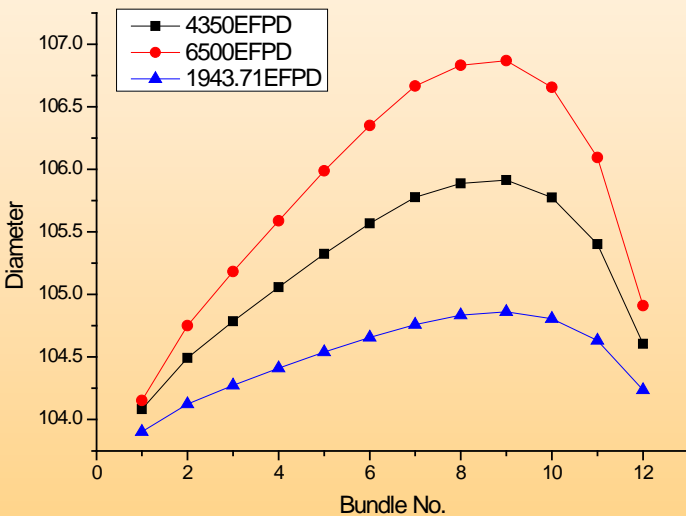
Channel S07



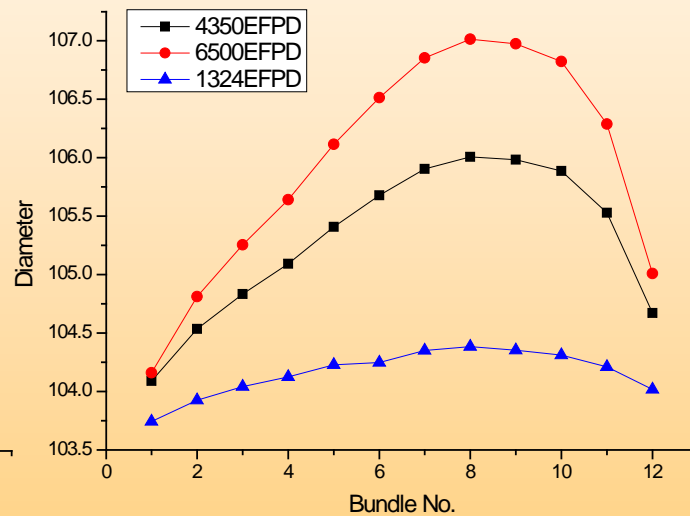
Channel S15

압력관 크립 평가식 (BPLM/MLE)

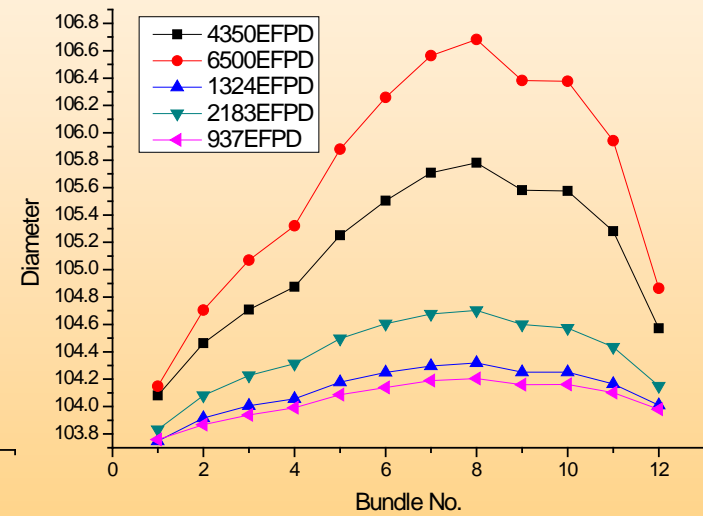
□ EFPD에 따른 예측된 직경



Channel T08



Channel T10



Channel U11

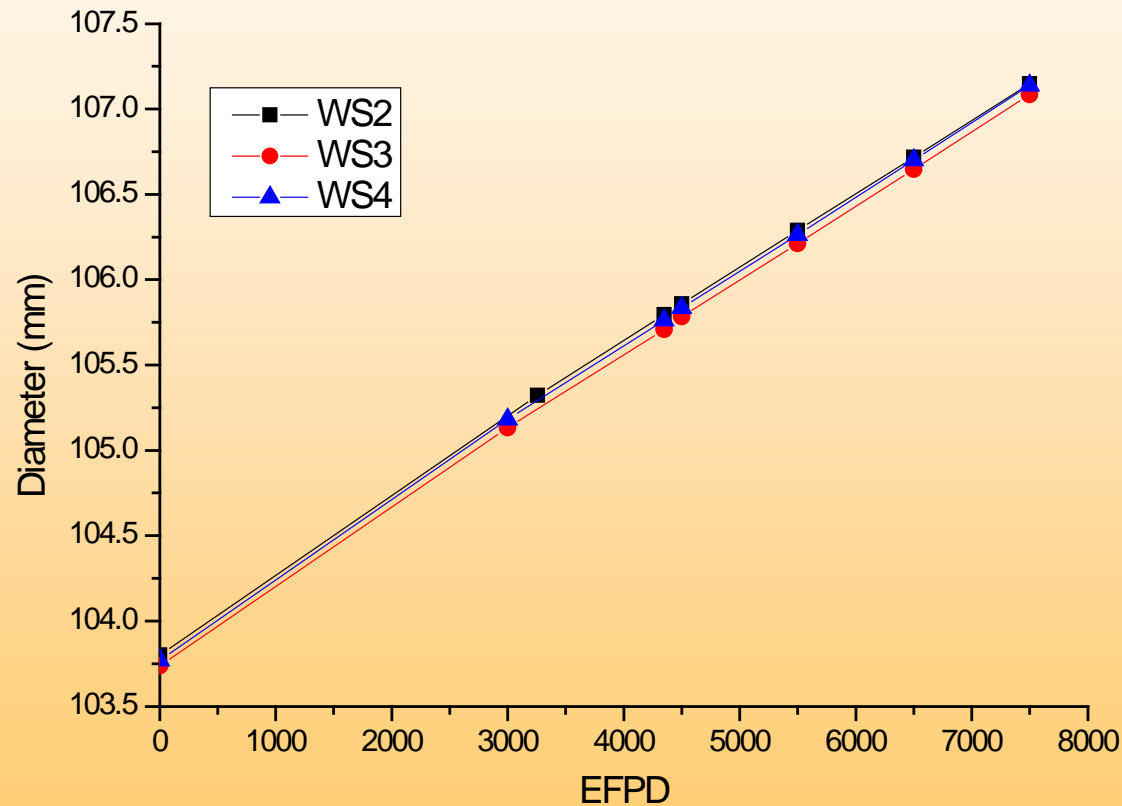
압력관 크립 평가식 (BPLM/MLE)

□ 번들 위치에 따른 에러

Bundle Position	Training data		Test data	
	RMS error (mm)	Max. error (mm)	RMS error (mm)	Max. error (mm)
1	0.0719	0.1827	0.0654	0.1316
2	0.0840	0.2630	0.0716	0.1511
3	0.0950	0.2988	0.0791	0.1460
4	0.0975	0.2908	0.0799	0.1396
5	0.0984	0.2732	0.0801	0.1510
6	0.1039	0.2756	0.0821	0.1627
7	0.1046	0.2793	0.0837	0.1666
8	0.1085	0.2588	0.0933	0.1826
9	0.1098	0.2426	0.0987	0.1926
10	0.1155	0.2867	0.1009	0.2002
11	0.1058	0.2822	0.0877	0.1915
12	0.0867	0.1925	0.0680	0.1455

압력관 크립 평가식 (BPLM/MLE)

□ EFPD에 따른 직경 예측



압력관 크립 평가식 (BPLM/MLE)

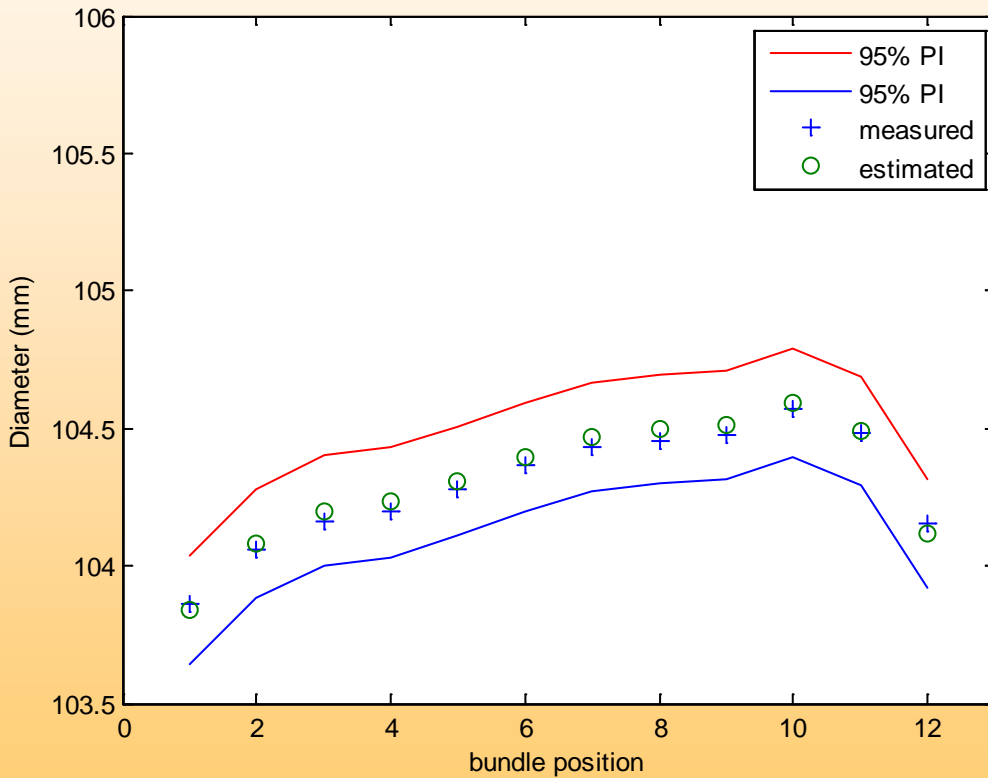
□ Uncertainties of the BPLM model

Data type	σ_{ε} (mm)	σ_{δ} (mm)	σ_{γ} (mm)	Epistemic error (mm)	RMS error (mm)
Train data	0.0998	0.0910	0.0368	0.0200	0.0959
Test data	0.0998	0.0910	0.0368	0.0197	0.0875

압력관 크립 평가식 (BPLM/MLE)

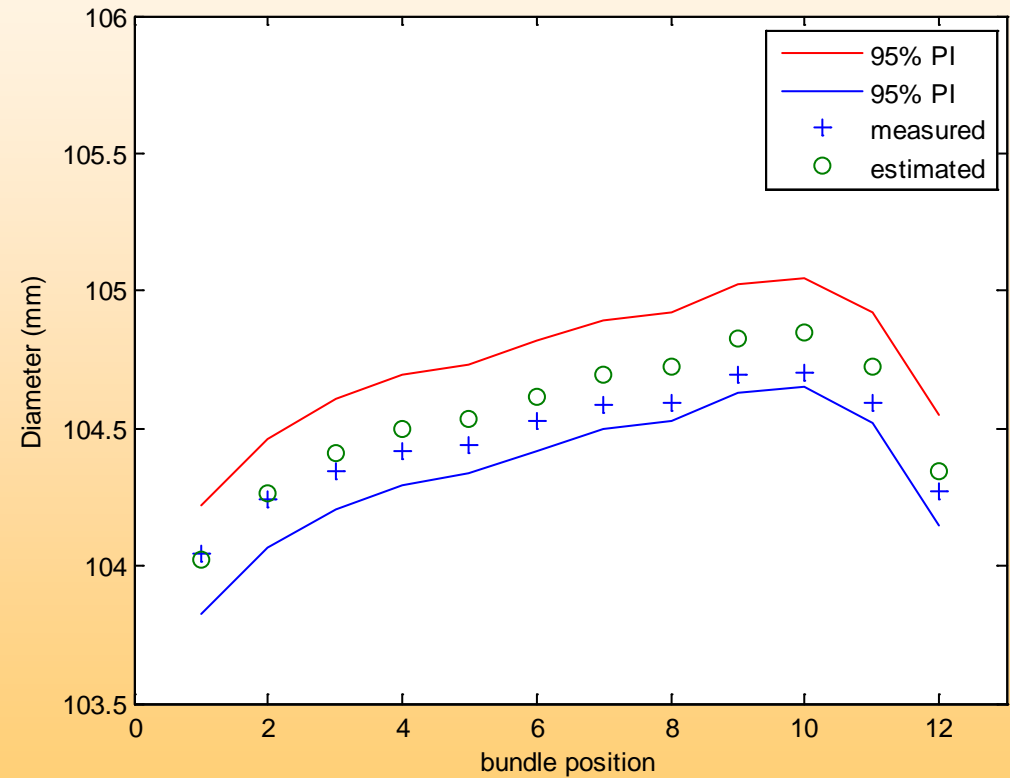
□ Prediction intervals for test data (Wolsung Unit 2)

M11 channel



Channel M11, 1501 EFPD

O14 channel

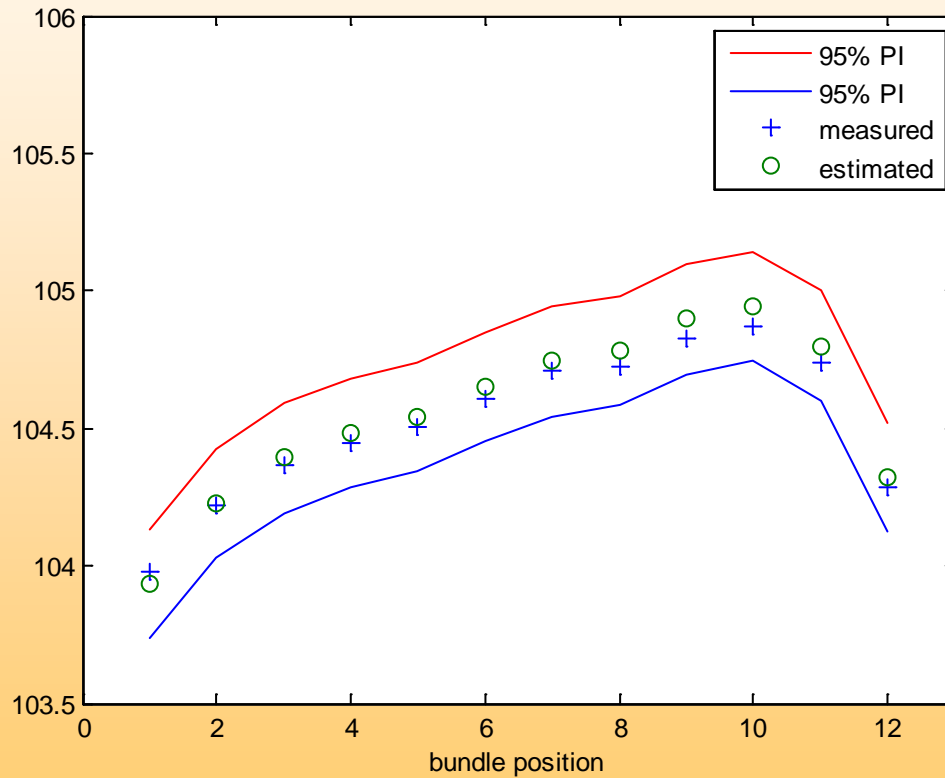


Channel O14, 1501 EFPD

압력관 크립 평가식 (BPLM/MLE)

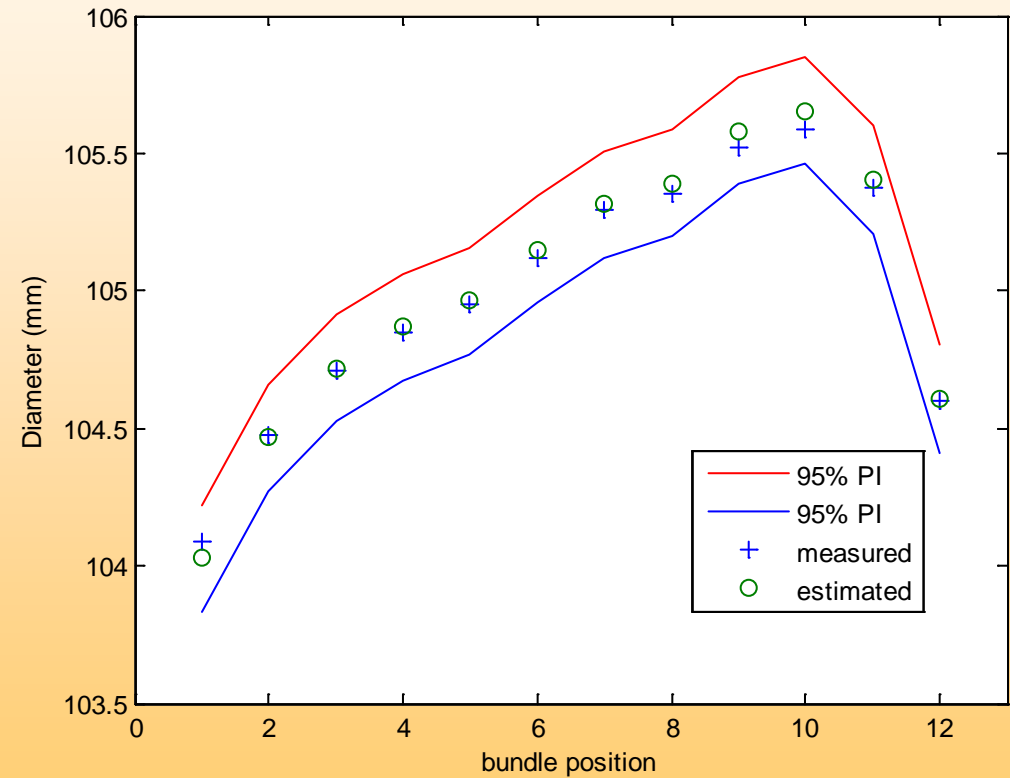
□ Prediction intervals for test data (Wolsung Unit 2)

L13 channel



Channel L13, 1944 EFPD

L13 channel

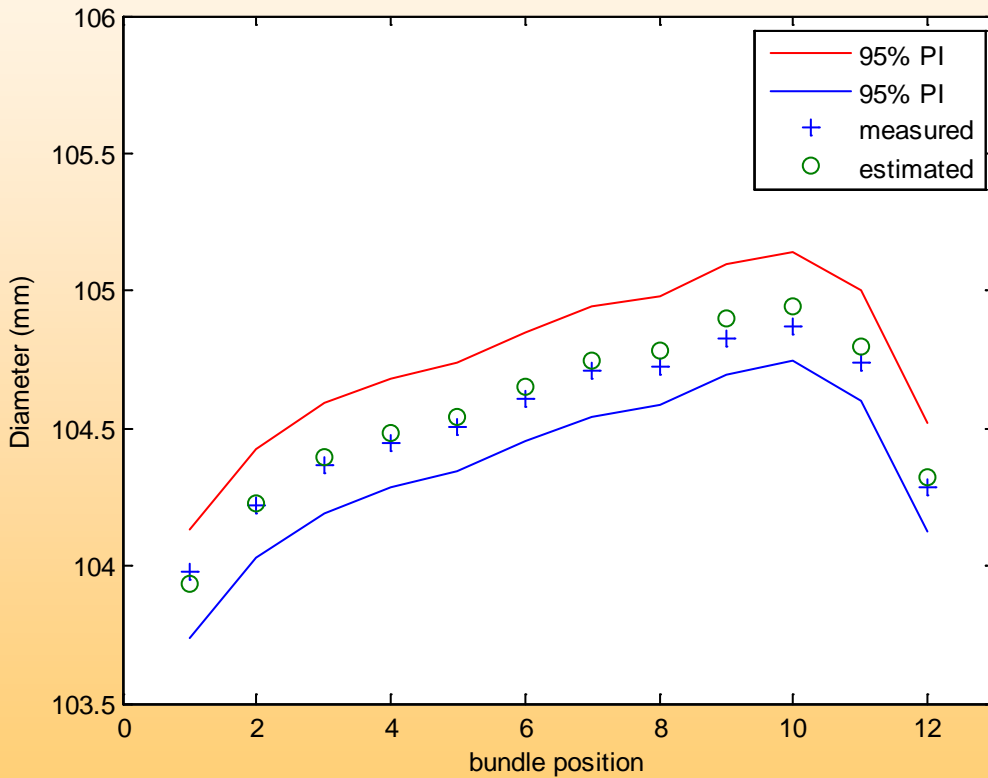


Channel L13, 3256 EFPD

압력관 크립 평가식 (BPLM/MLE)

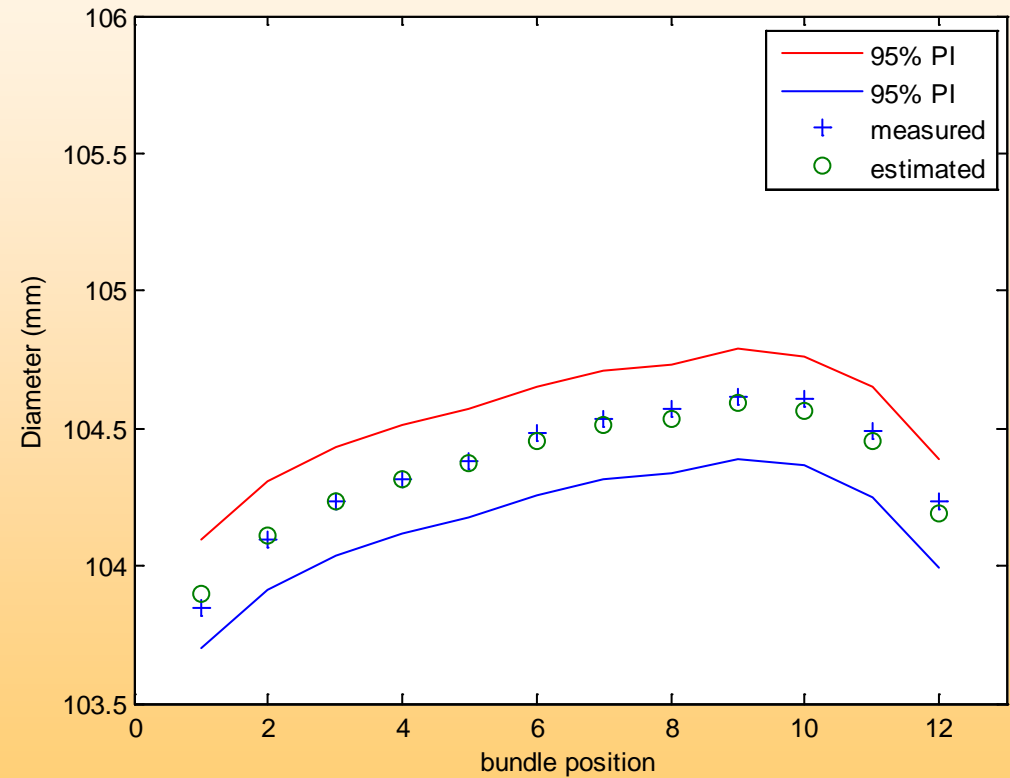
□ Prediction intervals for test data (Wolsung Unit 3)

L13 channel



Channel Q06, 1324 EFPD

Q11 channel

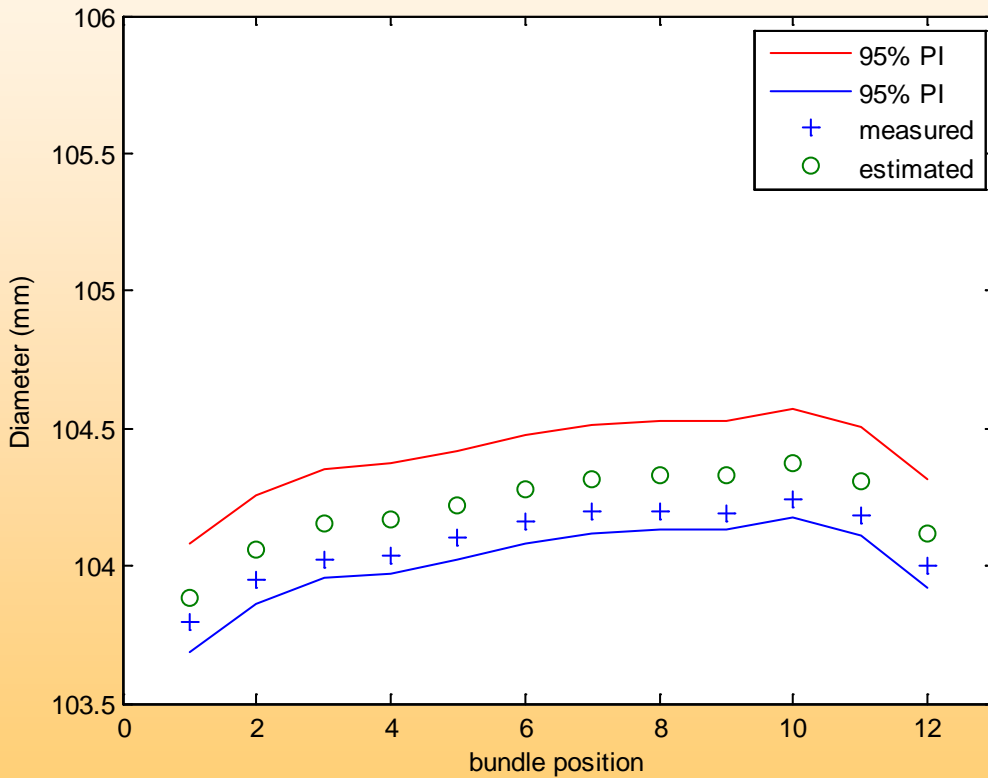


Channel Q11, 1324 EFPD

압력관 크립 평가식 (BPLM/MLE)

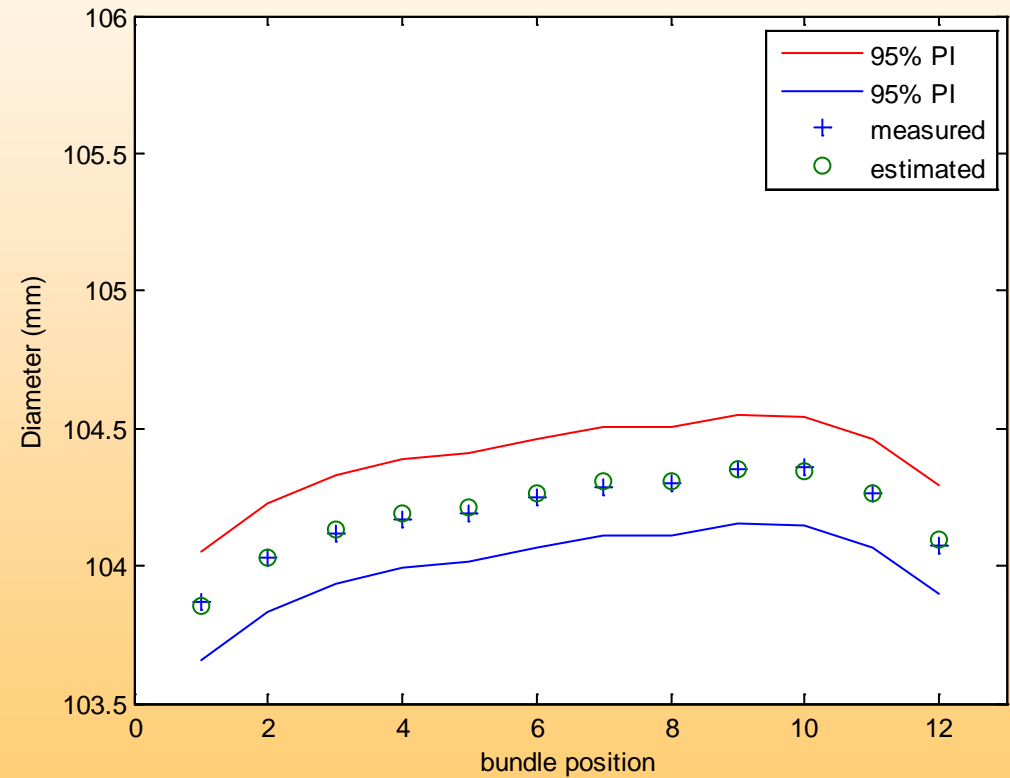
□ Prediction intervals for test data (Wolsung Unit 4)

M11 channel



Channel M11, 937 EFPD

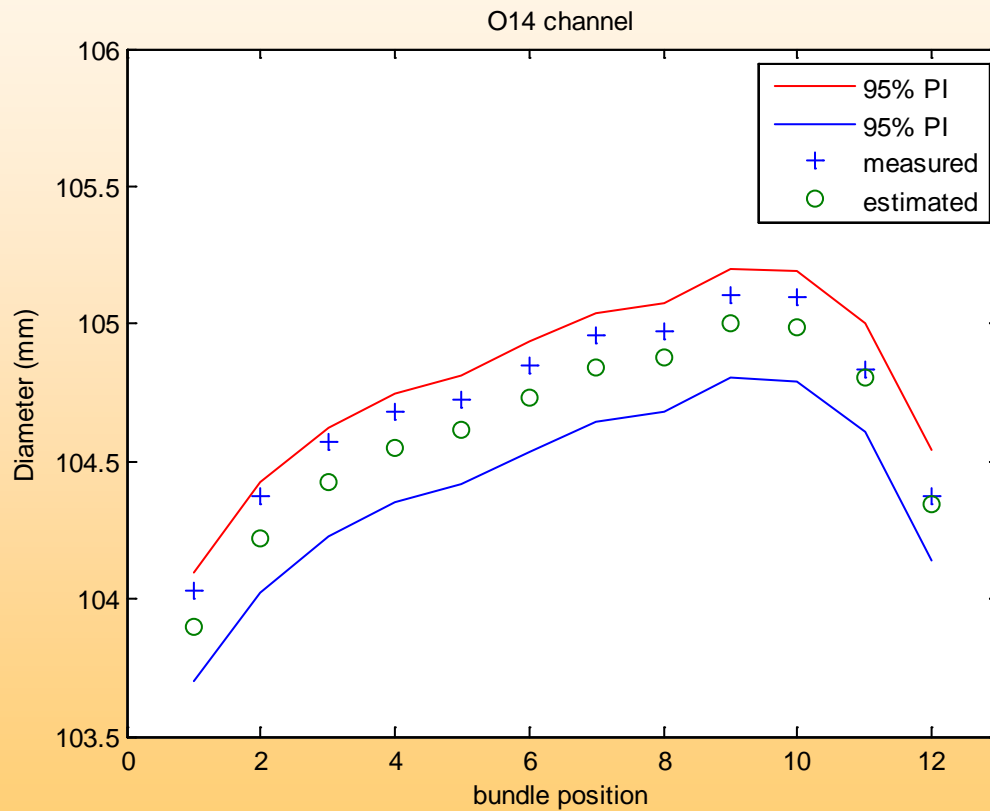
O14 channel



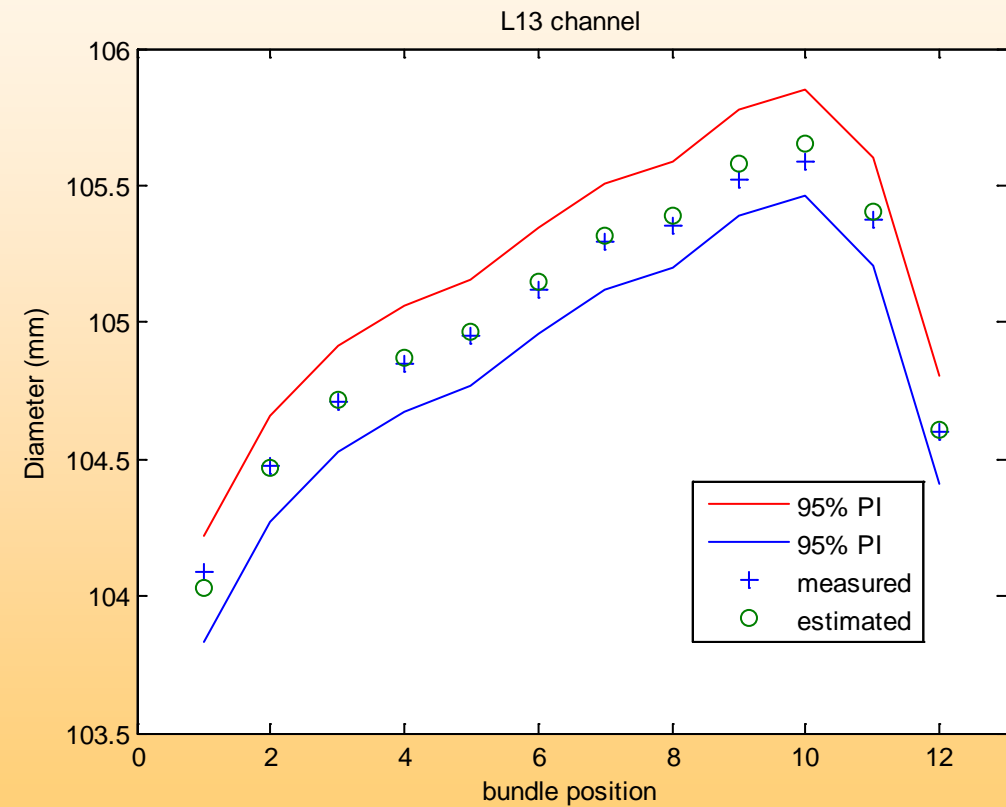
Channel O14, 937 EFPD

압력관 크립 평가식 (BPLM/MLE)

- Prediction intervals for test data (Wolsung Unit 4, Unit 2)



Channel O14, 2154 EFPD



Channel L13, 3256 EFPD

압력관 크립 평가식 (BPLM/MLE)

□ 불확실도 분석

- 월성 2, 3, 4호기 데이터를 이용하여 3000~8500 EFPD 까지 예측식을 개발
- 기존의 불확실도 분석법을 이용
 - ◆ Sample standard deviation(%): $(\text{크립실측치} - \text{크립예측치}) / \text{크립예측치} \times 100$ 의 표준편차
 - ◆ Uncertainty(1): sample standard deviation $\times \text{SQRT}((n-1)/\text{CHIINV}(90\%, n-1))$
 - ◆ Uncertainty(4): Uncertainty(1)/SQRT(n)

□ 모델 비교 (2호기)

EFPD	BPLM			RC-1980		
	S	UNC(1)	UNC(4)	S	UNC(1)	UNC(4)
3000	7.67	11.26	3.56	11.16	17.53	6.20
4350	8.69	12.77	4.04	11.38	17.89	6.32
4500	8.85	13.00	4.11	11.38	17.89	6.32
5500	9.83	14.44	4.57	11.46	18.01	6.37
6500	10.63	15.62	4.94	11.46	18.01	6.37
7500	11.27	16.56	5.24	11.45	17.99	6.36