KNS Aut. Meeting, Oct. 31, 2025 (Room 600A, 12E-6, No. 25A-282)

내부구조물진동감시계통(IVMS) 자료 평가에 의한 BNPP 3호기 노심지지배럴의 진동 특성

(Vibration Characteristics of Core Support Barrel in BNPP Unit 3 Reactor Vessel Based on the IVMS Data Evaluation)

한국전력기술㈜

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KEPCO E&C - 오양균/정택준/이지훈/박기찬

목 차

1. 서론 및 논문-요지

■ 논문 요지

- BNPP 3호기 NSSS 건전성감시계통(NIMS)의 부계통인 IVMS의 자료분석 결과와 본 연구에서 사용한 자료평가 방법, 결론 및 교훈에 대해 토론하고자 함.

- To find the vibration characteristics of CSB in reactor vessel of Barakah Nuclear Power Plant (BNPP) Unit 3, KEPCO E&C and KHNP have jointly evaluated the IVMS data.

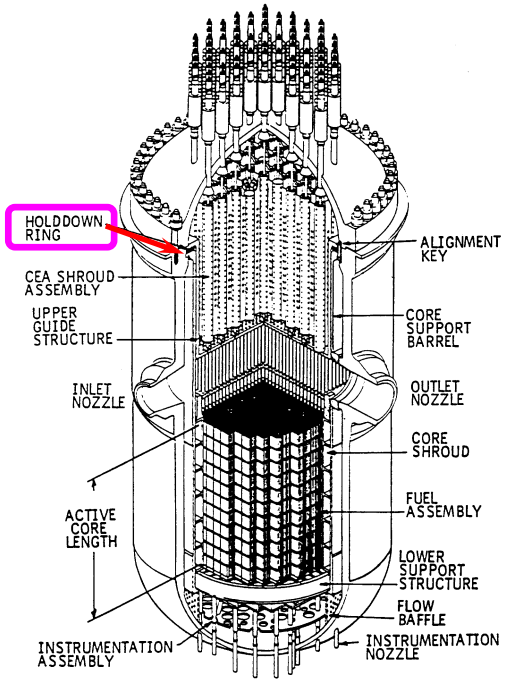
- This paper proposes simplified IVMS evaluation procedures (i.e., 3 Steps of Conditional Checks), and describes the evaluation results of CSB Beam Mode (BM) and Shell Mode (SM) vibration characteristics of BNPP Unit 3.

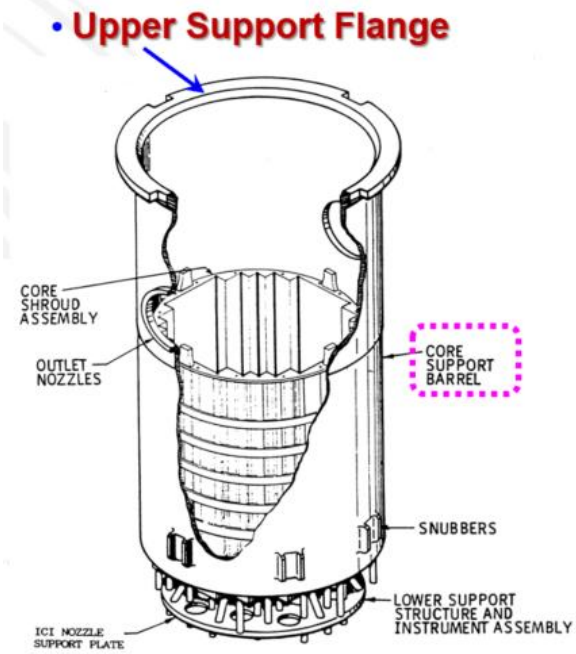
- As a result, the CSB Beam Mode vibrations are found in the frequency range of 9.0 Hz based on 180° phase shift, and high coherence value (> 0.5), and a peak value (> 10^{-8}) on NCPSD plot.

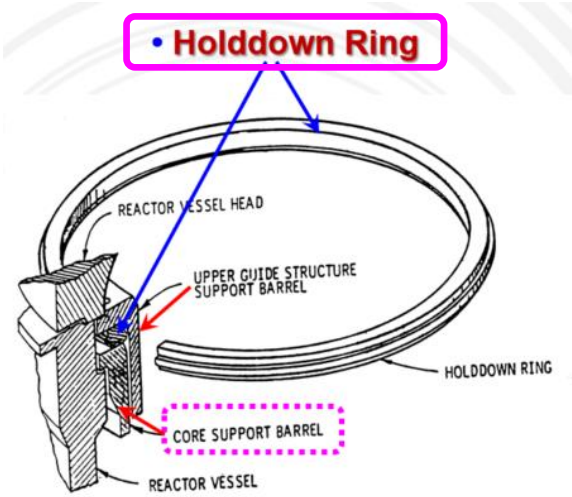
- The NIMS-IVMS analysis of coherence plots shows that the CSB Shell Mode vibration is NOT found (N/A) for the BNPP Unit 3.

1. 서론 및 논문요지

■ 원자로 및 노심지지배럴(Core Support Barrel: CSB)과 진동의 발생







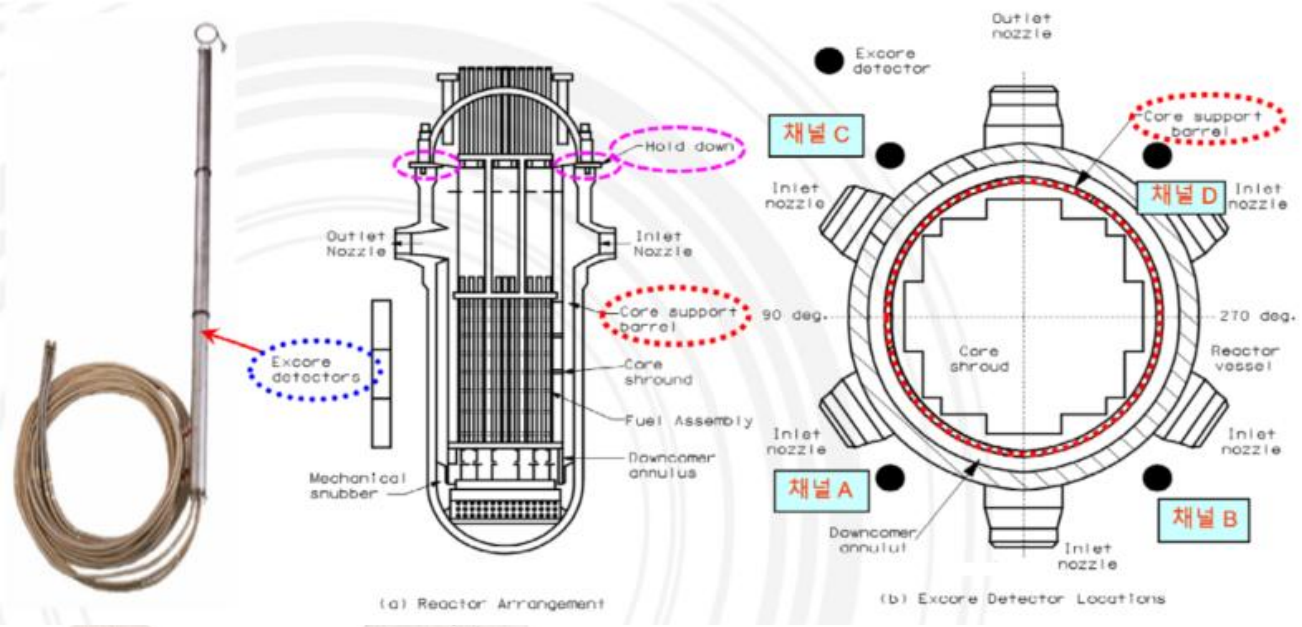
■ CSB의 진동발생 ➔ 평가 ➔ 후속조치

- CSB 상단 Upper Support Flange에서 수직방향의 체결력(Axial Preload)이 상실되면 ➔ 원자로냉각재 유동에 의한 CSB 진동이 발생 ➔ NIMS-IVMS로 CSB의 과도한 진동 여부 확인이 가능 ➔ 진동 평가 후 누름링(Holddown Ring) 교체를 검토

1. 서론 및 논문요지

NIMS-IVMS 기능

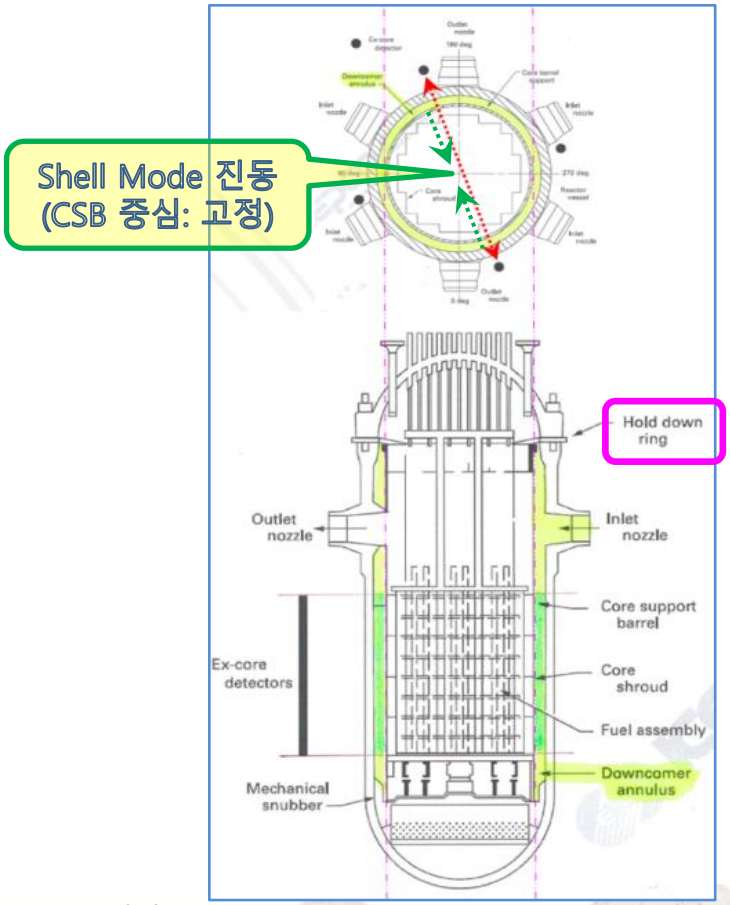
- All of the OPR1000 & APR1400 have the NSSS Integrity Monitoring System (NIMS), which has four subsystems as follows:
  - **Internals Vibration Monitoring System (IVMS)**
  - Acoustic Leak Monitoring System (ALMS)
  - Loose Parts Monitoring System (LPMS)
  - RCP Vibration Monitoring System (RCPVMS)
- NIMS-IVMS monitors the motions of the CSB, and provide the data that can be used to detect & evaluate the changes of the CSB motions.

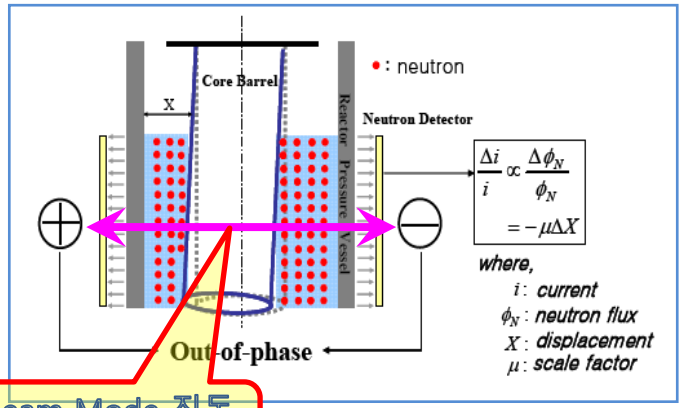


1. 서론 및 논문요지

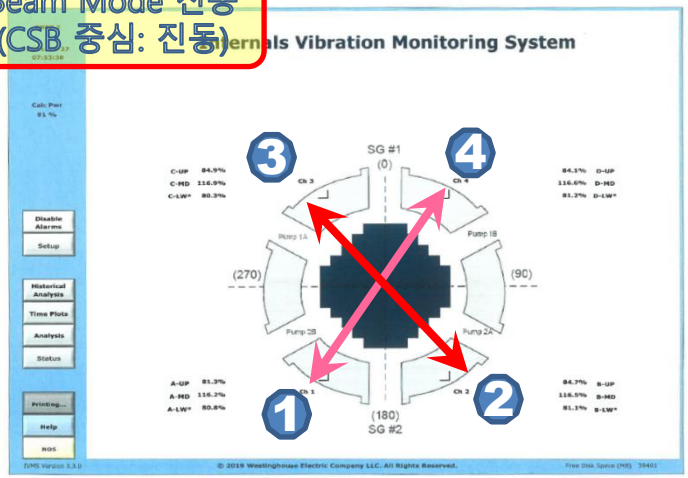
■ NIMS-IVMS 기능 (Beam Mode 진동 및 감시방법)

- 원자로와 주변에 설치된 노외중성자속감시계통(**ENFMS**) 검출기가 고정된 상황에서, **CSB**와 노심이 흔들리면 ➔ 노심과 **Ex-core** 검출기 사이 물-두께가 변화 ➔ 검출되는 중성자속의 변화 ➔ **ENFMS** 검출기의 전류 변화 ➔ **DC** 신호에 **AC** 잡음이 추가된다.



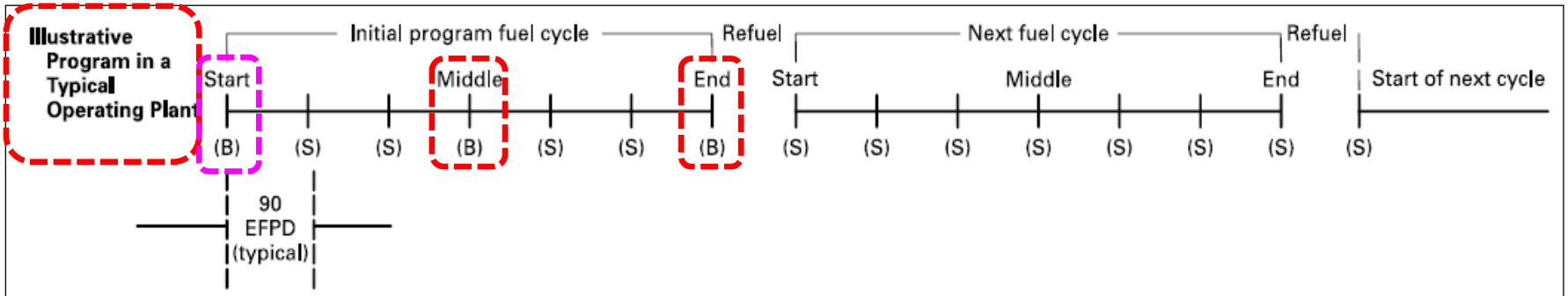


Beam Mode 진동
(CSB 중심: 진동)



2. BNPP 3호기 노심지지배럴의 진동평가

■ 표1. ASME OM, Part 5: 단계 별로 요약한 CSB 가동중 감시 프로그램



Program Phase	Frequency of Data	Data Acquisition	Data Reduction	Data Evaluation	Action
Baseline (B)	New plant: startup, middle, and end of first three fuel cycles to equilibrium Operating plant: startup, middle, and end of initial program cycle All: every significant change to core, internal, or operating conditions	Time history and DC level of each detector and each cross-core detector pair	NPSD, NCPSD, COH, and phase for each detector and all cross-core and adjacent pairs of detectors, wide- and narrow-band rms	Establish characteristic amplitude and frequency of core barrel beam motion; select wide and narrow frequency bands and establish baseline nrms values within them; develop data "trends" throughout fuel cycles	If normal, enter surveillance phase; if abnormal, enter diagnostic phase
Surveillance (S)	Start and end of each fuel cycle and every 90 EFPD during the cycle	DC levels and data for frequency analysis of each detector and two pairs of cross-core detectors separated by approximately 90 deg	NCPSD for two cross-core pairs of detectors separated by approximately 90 deg wide- and narrow-band nrms, or narrow-band nrms and beam motion center frequencies	Comparison of amplitude and frequency results with limits	If normal, continue surveillance phase; if abnormal, enter diagnostic phase
Diagnostic (D)	As indicated by surveillance results	Same as baseline	Same as baseline	Complete evaluation of data taken during surveillance phase and comparison with baseline to note changes in spectral character and magnitude	Determine cause and significance of signal anomalies; define future plant operation and/or program plan

2.1 CSB 진동감시를 위한 IVMS 자료취득

■ **ENFMS 중성자속 신호로 IVMS 자료취득 → NCPSD, COH, Phase 평가**

- **Neutron noise (AC type) time history data acquired from ENFMS fission chambers can be reduced and transformed to the various forms, including Normalized Cross-Power Spectral Density (NCPSD), Coherence (COH), and Phase (Ø).**

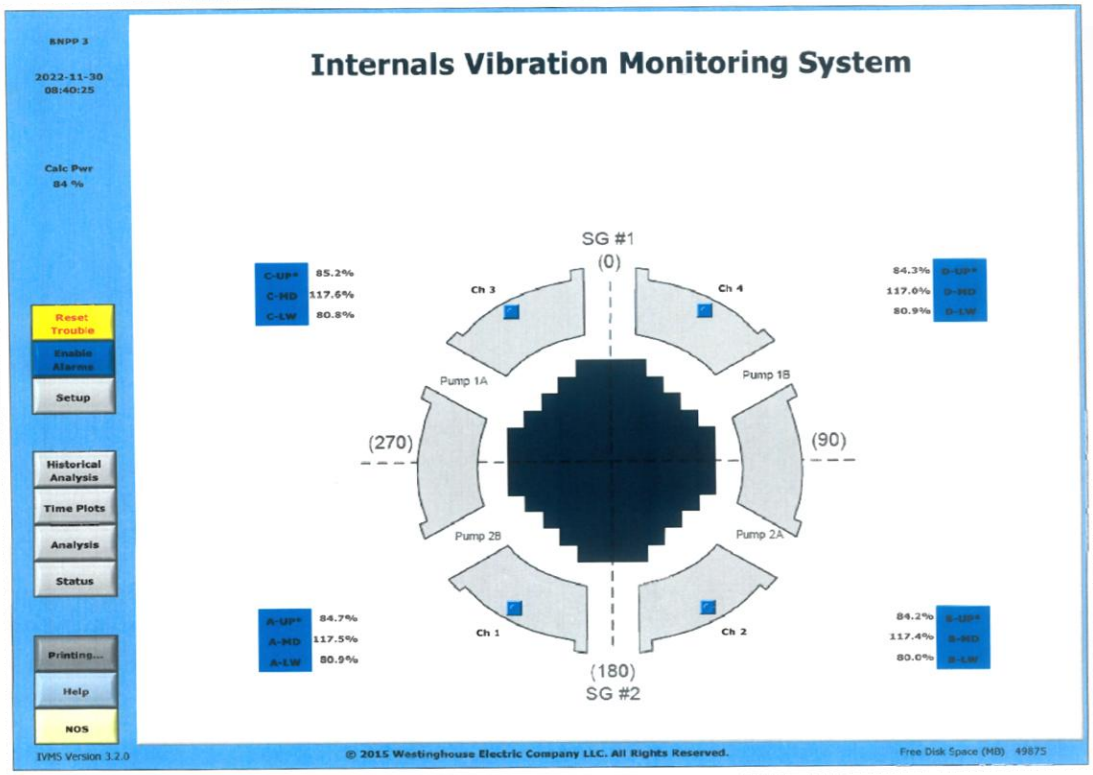


그림1. BNPP 3호기 IVMS 주-화면 디스플레이

2.2 IVMS 자료평가 절차를 제안

■ ENFMS 핵분열함 신호를 이용한 IVMS 자료취득

- BNPP 3호기 CSB의 Beam Mode (BM) 및 Shell Mode (SM) 진동 평가를 위해 3단계 조건부-검사를 제안하고 적용:

  - ✓ [C1] Check the frequency ranges corresponding to phase shift of 180° for Beam Mode, and 0° for Shell Mode vibration of the CSB. 마주보는 ENFMS 신호(G14, G23) 간 위상차(Phase Shift)가 180°로 유지되는 주파수 범위를 BM, 위상차가 0°로 유지되는 주파수 범위를 SM로 평가
  - ✓ [C2] Check the frequency of high coherence (> 0.5) within the frequency ranges selected by [C1]. 위 [C1] 검사로 확인된 주파수 범위에서 코히어런스 (COH) 값이 0.5를 초과하는 주파수 범위를 점검
  - ✓ [C3] Check the NCPSD magnitude of high peaks within the frequency ranges selected by [C1] & [C2] conditions. 위 [C1] 및 [C2] 조건으로 선택된 범위에서 NCPSD의 돌출된 최고값에 해당하는 주파수 성분의 존재-여부 및 해당 주파수 값을 확인

2.3 CSB Beam Mode 진동 평가

- 1st Step: PHASE vs. COH ➔ [C1] & [C2] 조건-검사

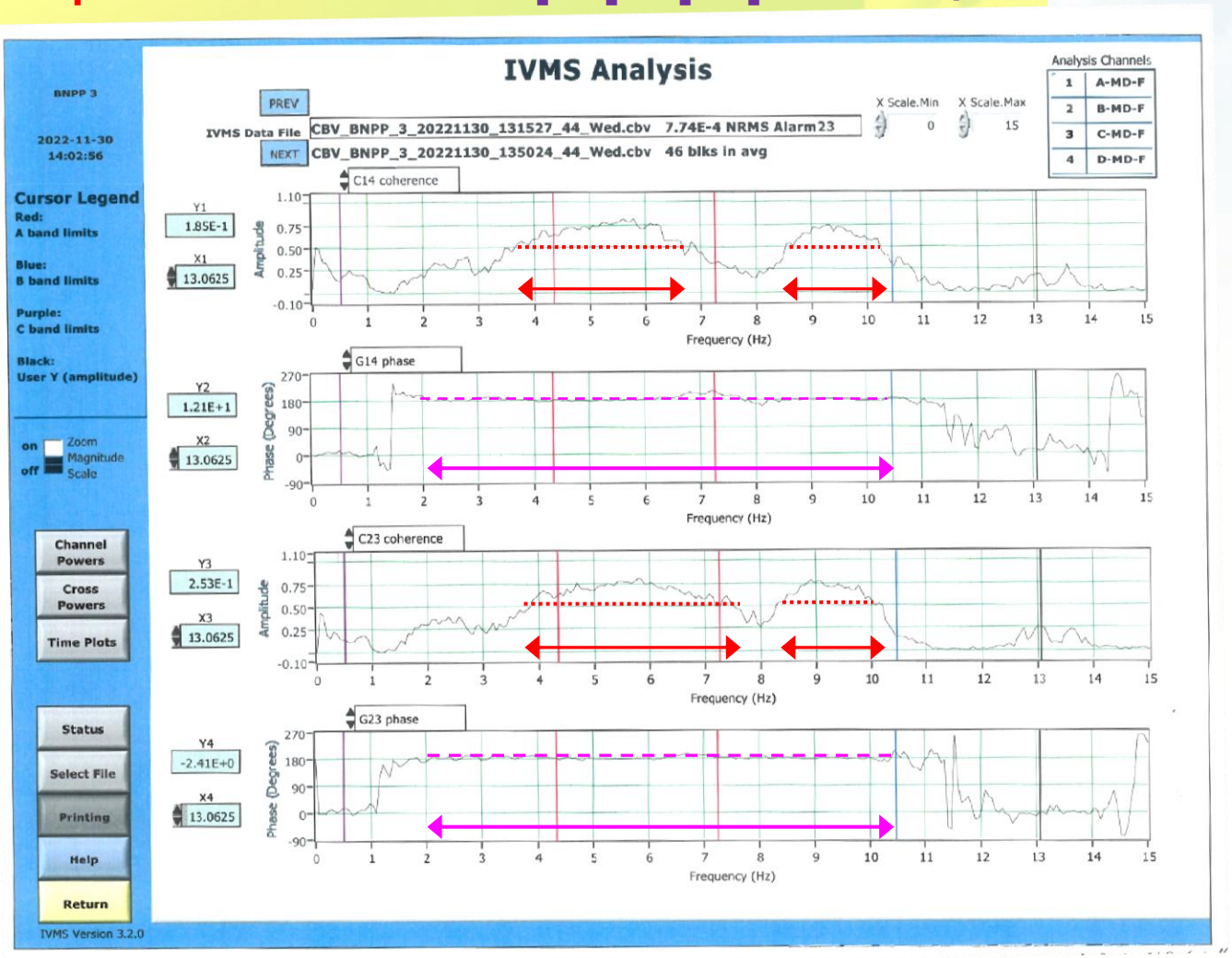


그림2. IVMS 신호의 빔-모드 진동주파수 분석 (Phase Shift vs. Coherence)

2.3 CSB Beam Mode 진동 평가

■ 2nd Step: NCPSD vs. PHASE ➔ [C1]&[C2] & [C3] 조건-검사

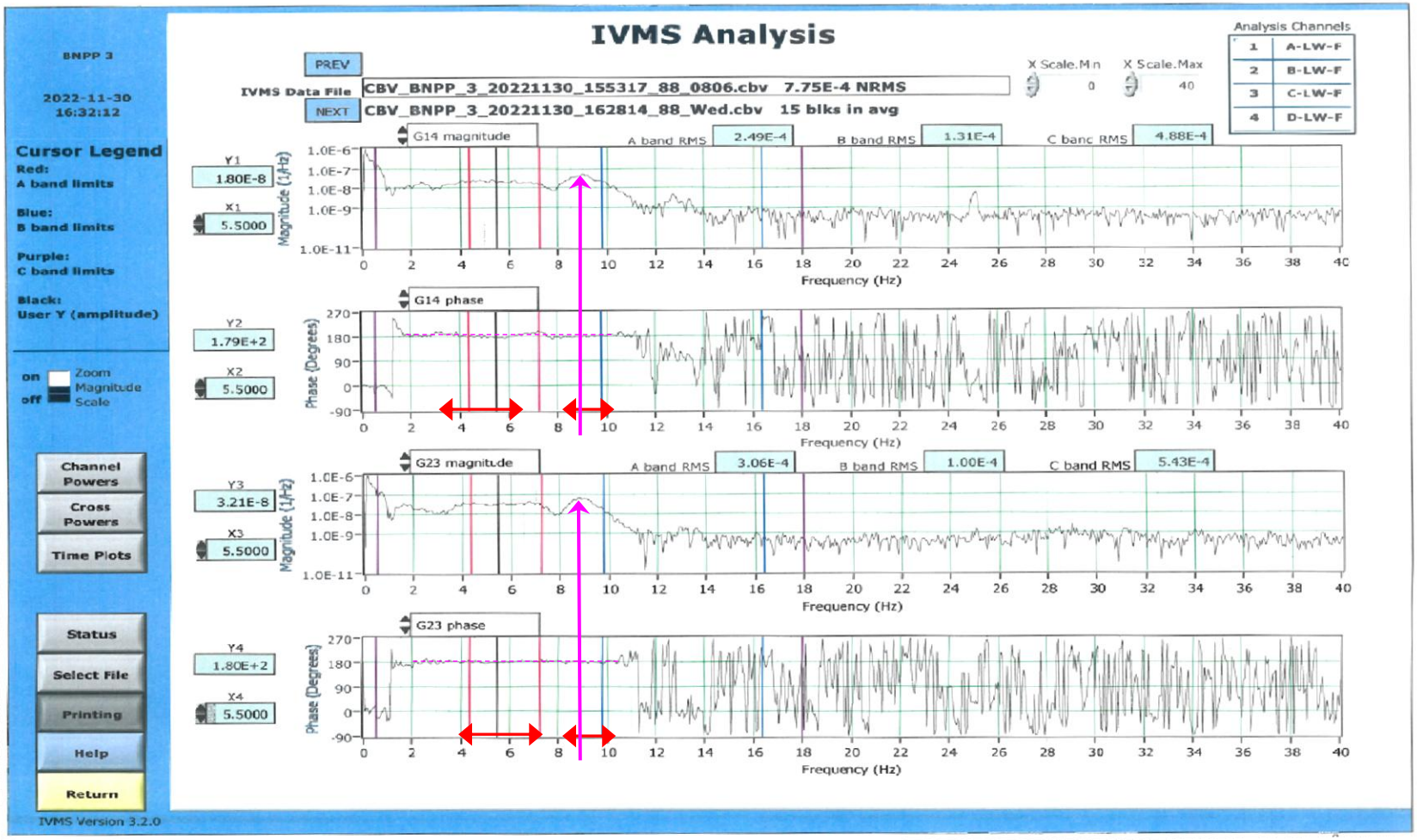


그림3. IVMS 신호의 빔-모드 진동주파수 분석 (NCPSD vs. Phase Shift)

2.3 CSB Beam Mode 진동 평가

■ **3rd Step:** [C1], [C2], [C3] 결과를 종합

- Fig. 2&3 종합 ➔ 4 ~ 6 Hz 범위는 BM 관련 [C1] 및 [C2] 조건은 만족하지만, [C3] 조건을 만족하지 못함 (4~6 Hz 범위는 NCPSD의 Peak 값이 확인되지 않음)
- Fig. 2&3 종합 ➔ BNPP #3 Beam Mode 진동을 9 Hz에서 확인 ([C1], [C2], [C3] 3개 조건을 모두 만족 ← Phase Shift + Coherence + NCPSD Peak 확인)
- Fig. 2&3 종합 ➔ BNPP #3 Beam Mode 진동은 ENFMS 검출기의 마주 보는 2쌍 방향에서 모두 확인됨 (ENFMS 검출기 1&4 및 검출기 2&3 방향)

2.4 CSB Shell Mode 진동 평가

■ 1st Step: PHASE vs. COH ➔ C1 & C2 검사 ➔ None meet C1 & C2 (없음).

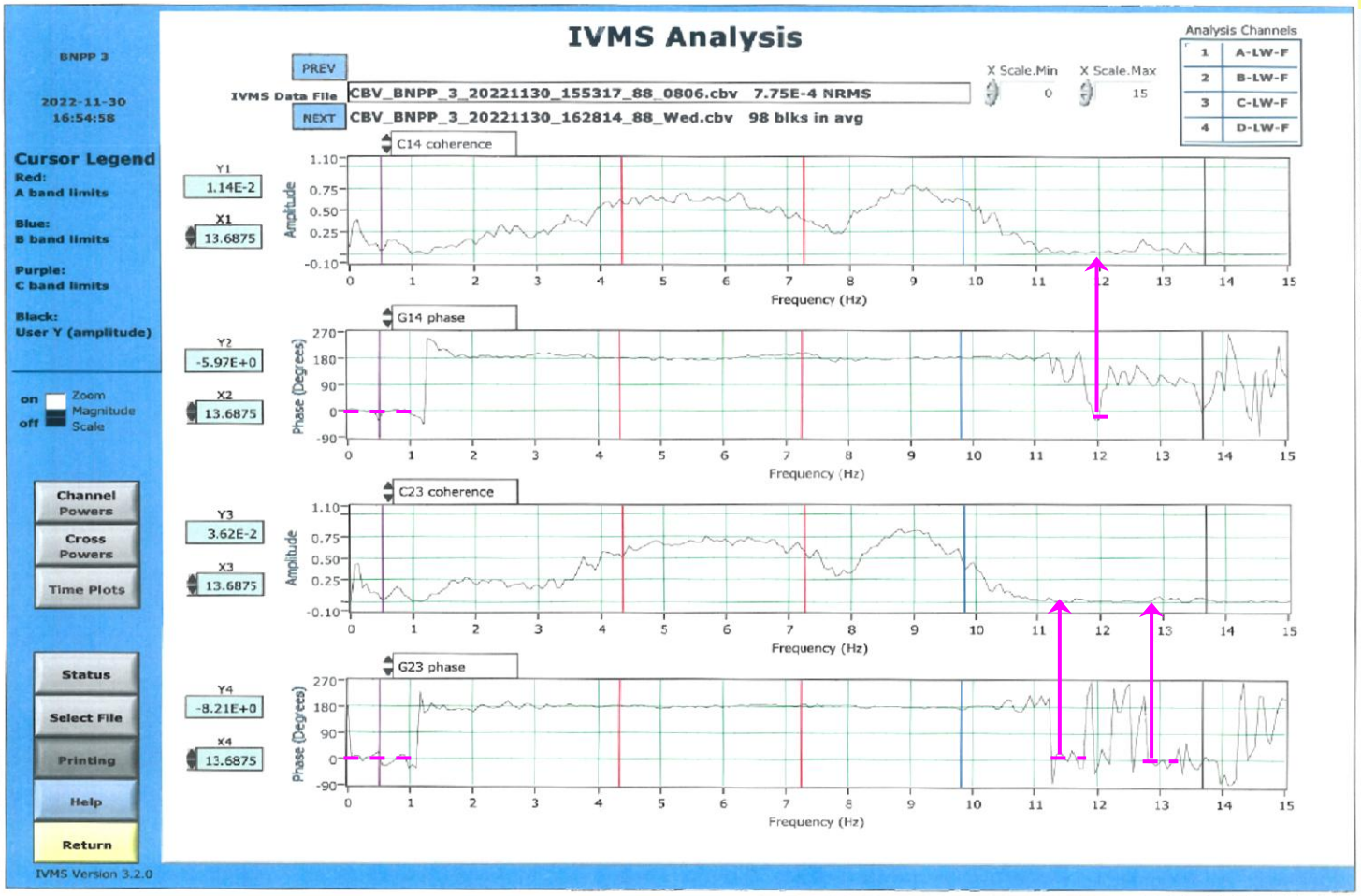


그림4. IVMS 신호의 쉘-모드 진동주파수 분석 (Phase Shift vs. Coherence)

2.4 CSB Shell Mode 진동 평가

■ 2nd Step: NCPSD vs. PHASE ➔ C1 & C3 검사 ➔ None meet C1 & C3 (없음).

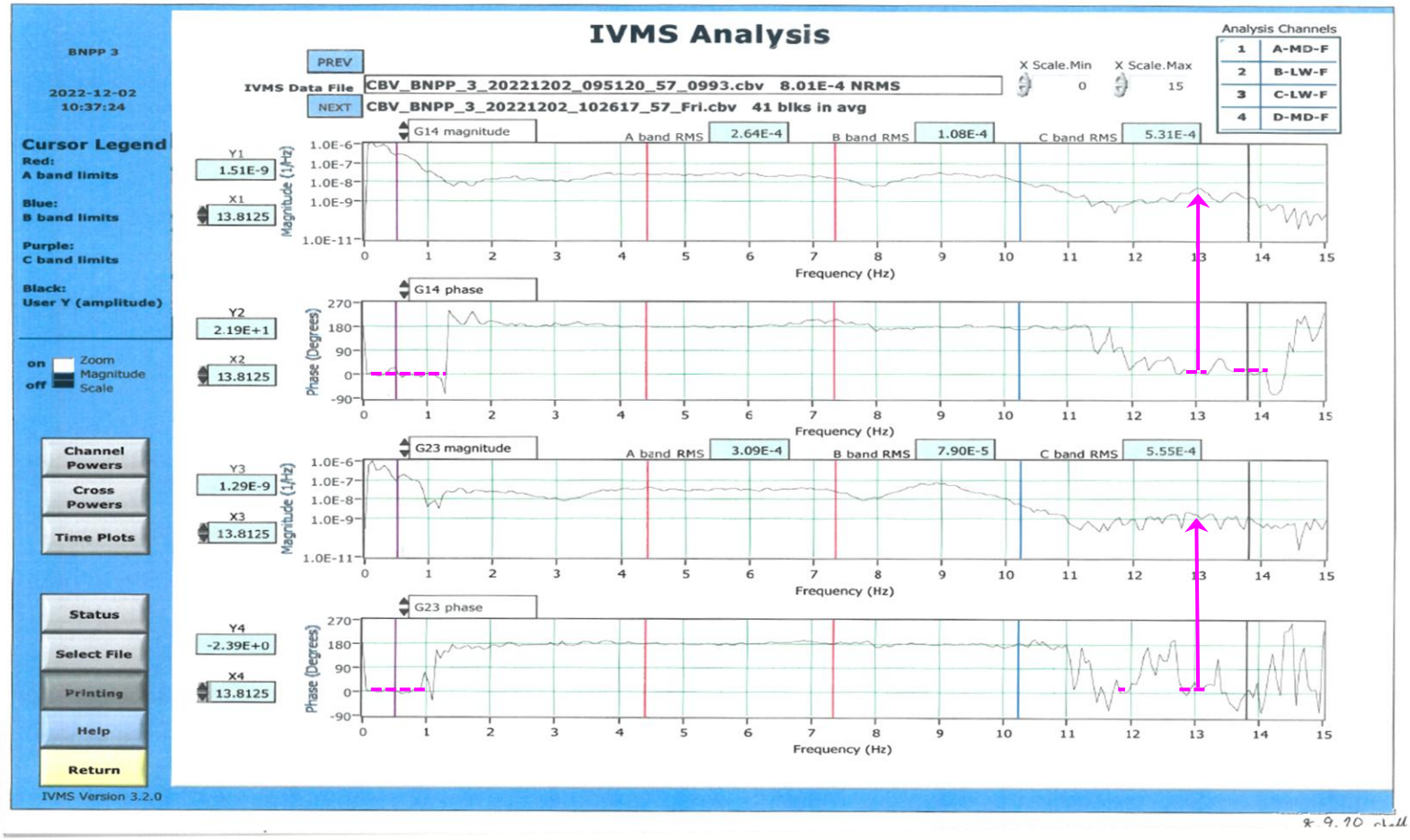


그림5. IVMS 신호의 쉘-모드 진동주파수 분석 (NCPSD vs. Phase Shift)

2.4 CSB Shell Mode 진동 평가

■ 3rd Step: [C1] & [C2] & [C3] 결과를 종합

- Fig. 4 ➔ [C1] & [C2] 조건을 만족하는 주파수 범위 없음.
- Fig. 5 ➔ [C1] & [C3] 조건을 만족하는 주파수 범위 없음.
- Fig. 4 & 5 ➔ [C1] & [C2] & [C3] 조건을 만족하는 주파수 없음 ➔ The IVMS analysis of phase & coherence plots shows that no significant CSB shell mode vibration is found for the BNPP unit 3. (쉘-모드 진동은 미약함 - N/A)
- ASME OM-2020, Part 5 ➔ 'Beam Mode'를 15회 언급함.
- ASME OM-2020, ➔ 'Shell Mode'는 전혀 언급 없음. ➔ 원자로의 노심지지배럴에 Shell Mode 진동이 CSB 건전성에 영향을 미칠 가능성이 거의 없음으로 이해.

2.5 발전소 별로 CSB BM/SM 주파수 비교

■ 표2. OPR1000/APR1400 원자로의 CSB BM 및 SM 진동 주파수

	CSB BM Freq.	CSB SM Freq.
Hanbit 3&4	8.0 Hz	14.5 Hz
Hanul 3	8.0 Hz	14.5 Hz
Hanul 1&2	8.0 Hz	SM vibration at 20 Hz caused by RCP 1X speed
BNPP 2	9.0 – 9.5 Hz	No significant SM vibration
BNPP 3	9.0 Hz	No significant SM vibration

2000/2002 논문 참조
(KAERI Dr. 박진호 외)

BM 진동: 1988 KNS 논문
(KAERI Dr. 윤원영 외)

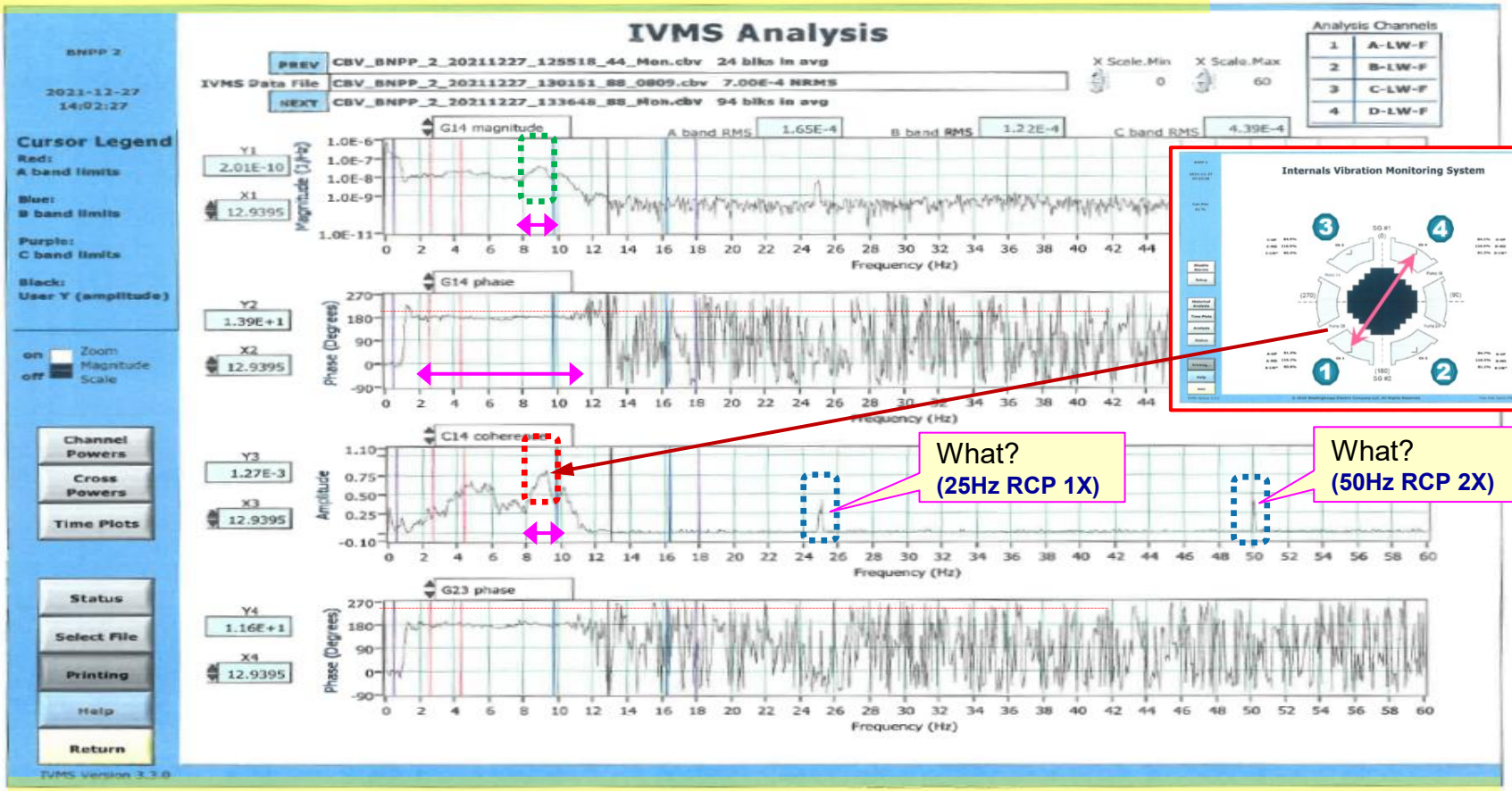
SM: 1999 KAERI 보고서
(KAERI Dr. 박진호 외)

2023 KNS 춘계 논문
(한기-SD와 KHNP 공저)

2025 KNS 추계 논문
(한기-SD와 KHNP 공저)

2.5 발전소 별로 CSB BM/SM 주파수 비교

- 참조: **BNPP 2호기 원자로의 CSB BM 진동 주파수 분석결과**



- **The highest value of coherence (> 0.75) and High values of NCPSD are found at 9.0 to 9.5 Hz within the frequency range of 180° phase shift of acquired signals from the pair of ENFMS channels A&D sensors.**

2.6 신규발전소 Baseline 자료특성 (붕소 희석의 보상을 검토)

■ 그림6. 핵연료주기의 NRMS vs. 붕소농도 변화 (100% 원자로 출력이 유지되면서, 붕소농도가 약 500 ppm 감소되면, NRMS 값은 약 2배 이상 선형적 증가를 보임)

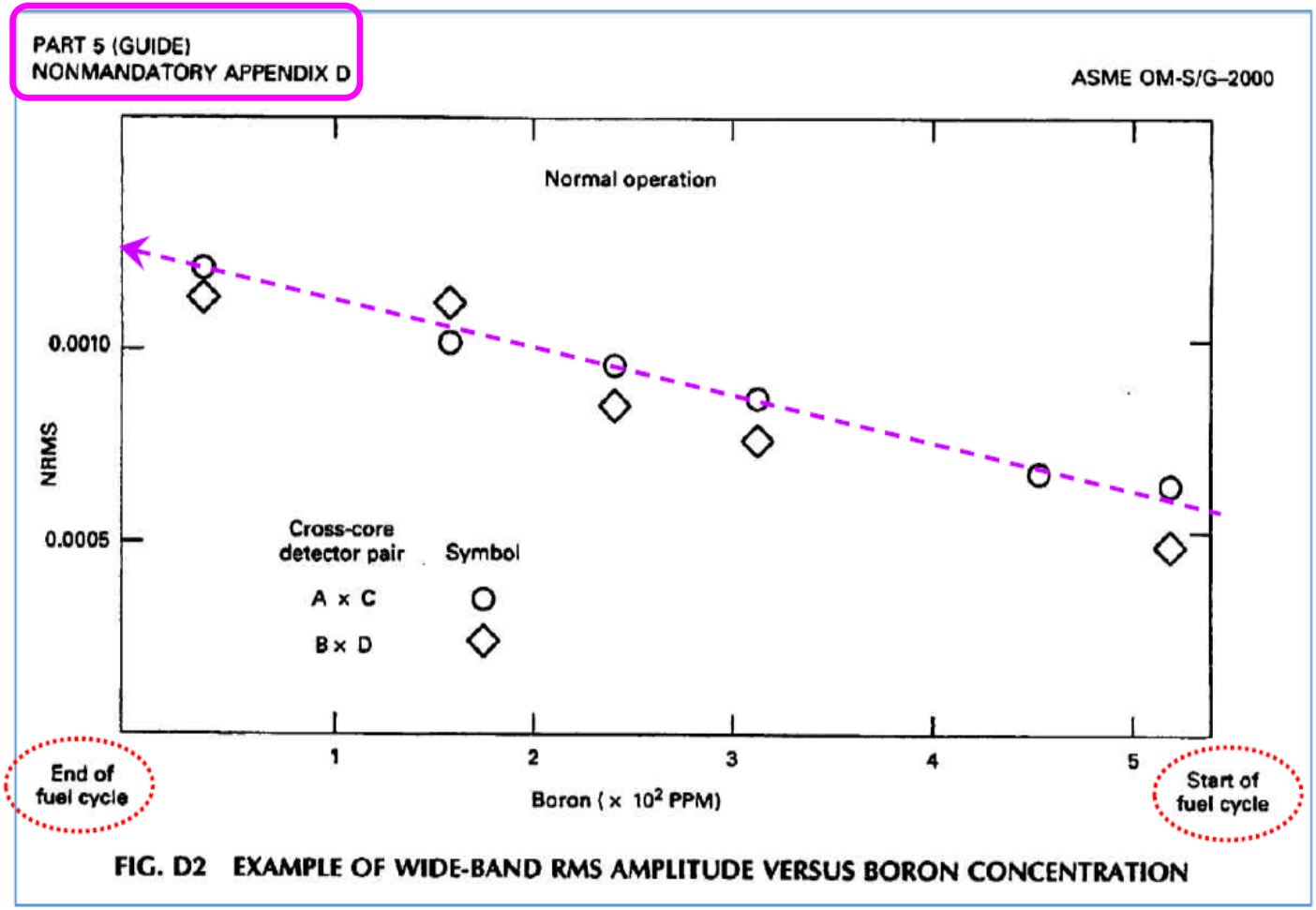


FIG. D2 EXAMPLE OF WIDE-BAND RMS AMPLITUDE VERSUS BORON CONCENTRATION

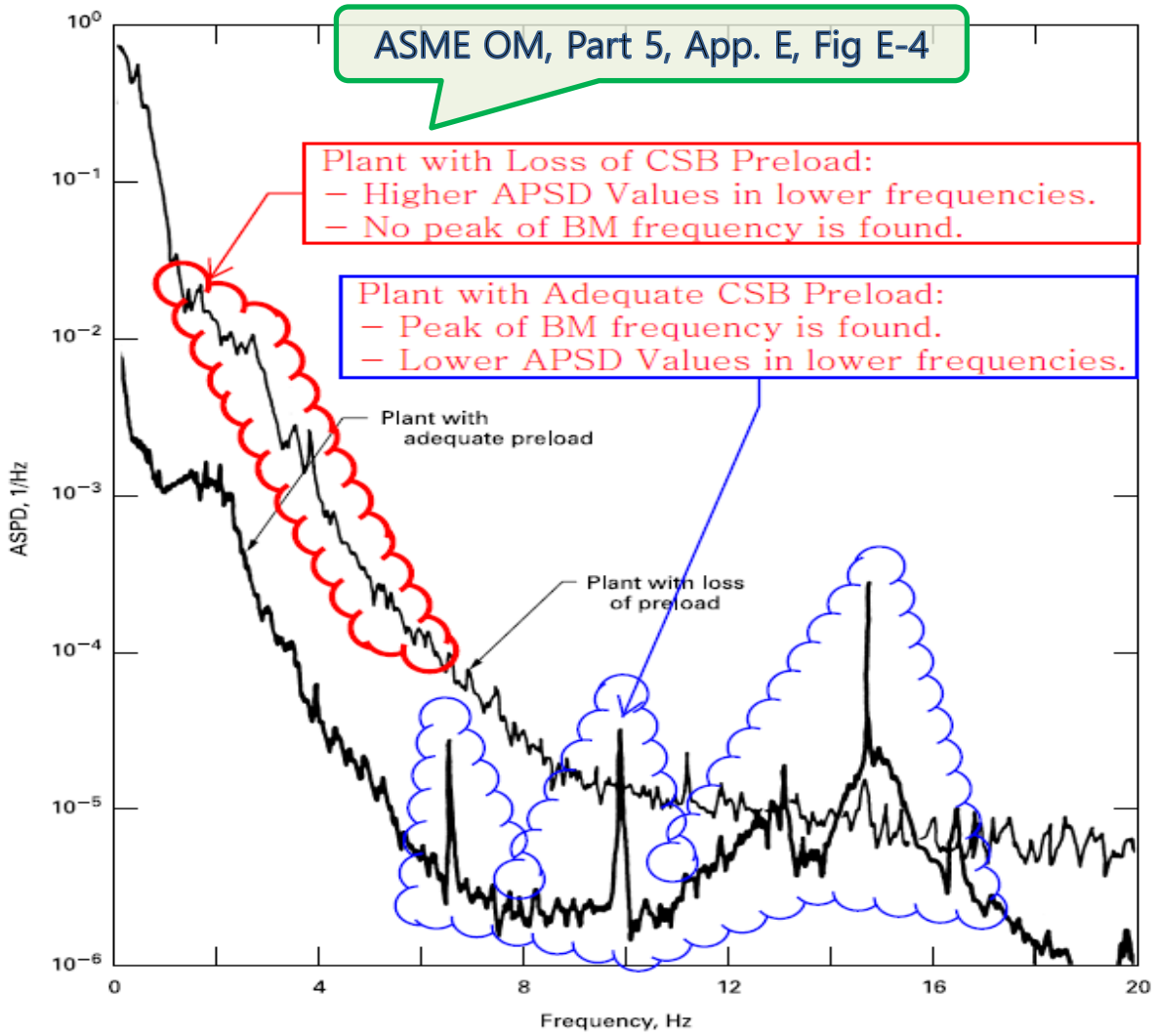
2.6 신규발전소 Baseline 자료특성 (붕소 희석의 보상을 검토)

■ 신규발전소 경우: 붕소농도 변화에 대해 불필요한 IVMS 경보-억제 위해

- 1st 핵연료주기 ➔ (IVMS 경보는 금지시키고) 붕소농도 보상장치를 미작동(OFF) 상태로 IVMS 자료를 취득한다.
- 2nd 핵연료주기 ➔ (IVMS 경보는 금지시키고) 붕소농도-보상장치는 작동(ON)시키면서, 붕소농도 변화에 따른 보상비율은 '2'로 입력하고, 붕소농도 최대값과 최저값을 입력하여 IVMS 자료를 취득한다.
- 3rd 핵연료주기 ➔ (필요 시 IVMS 경보는 금지시키고) 2nd 핵연료주기의 붕소농도 보상결과를 점검하고, 필요 시 붕소농도 변화에 따른 보상 비율을 적절히 조정(2 ±α)한다.

2.7 검사/진단 단계의 IVMS 자료 (기준자료 대비 변화를 검토)

■ 그림7. CSB의 수직방향 체결력 상실 시 APSD 변화 사례



3. 결론 및 후속연구 추천

■ 결론

- BNPP 3호기의 시운전-초기에 취득된 IVMS 신호의 분석결과에 의하면 CSB 쉘-모드 진동은 확인되지 않았으며, CSB 빔-모드 진동은 9 Hz 주파수에서 분명하게 확인됨.
  그 근거는 다음 3단계 검사-조건을 모두 만족함을 확인함.
  - ✓ C1: 180° 위상차 확인 (마주 보는 ENFMS 검출기 신호 간에)
  - ✓ C2: 0.5를 초과하는 높은 수준의 Coherence 값
  - ✓ C3: NCPSD 도표에서 돌출된 최대값 확인

- KHNP가 한기-SD로 BNPP #2 현장자료 제공 ➔ 한기-SD는 KHNP와 협력하여 2023년 KNS 춘계 학회에 논문 발표 ➔ 결과: BNPP 2호기 CSB 진동 특성을 확인

- 한기-SD는 WEC로 NIMS 기술 매뉴얼 개정을 요청 (2호기 IVMS 평가 결과와 2023년 KNS 춘계학회 발표논문 및 기타 자료를 참조) ➔ WEC는 2025년 2월의 TM 개정본 BNPP NIMS Tech. Manual(Rev.6)에 한기-SD의 TM 개정 요청을 반영 ➔ KHNP와 KEPCO-E&C, WEC가 모두 BNPP를 위해 협력하여 연구 및 현장지원한 사례임.

- KHNP가 한기-SD로 BNPP #3 IVMS 현장자료 제공 ➔ 한기-SD는 KHNP와 협력하여 2025년 KNS 추계 학회에 논문 발표 (3단계 BM 및 SM 진동평가방법을 제안 및 적용) ➔ BNPP 3호기 CSB의 진동 특성을 확인

3. 결론

한기-SD 요청 ➔ WEC's TM 반영-전(위) 및 반영-후(아래)

Westinghouse

9-614-Z-W-431-V01

Westinghouse Proprietary Class 2

BNPP 1,2,3&4
Emirates Nuclear Energy Corporation
Korea Electric Power Corporation

Internals Vibration Monitoring System (IVMS)
NIMS Technical Manual

WNA-GO-00141-BRAKA1,
Rev. 1
Book 3

Table Y-06-2, Item 1
Status 1

Non-Nuclear Safety Related

July 2020

The revision of NIMS-IVMS technical manual is requested because of the following reasons:

1) Band A (Beam Mode) Frequency Range
- Current description in NIMS TM, R1, Book 3, Table 6.4-6: 4 - 7 Hz
- Test Results (with 180 degree Phase) in BNPP Unit 3: 2 - 11 Hz
=> Note that the test results of Beam Mode frequency range is extended up to 11 Hz.
Refer to the test results of IVMS at BNPP Unit 3.

2) Band B (Shell Mode) Frequency Range
- Current description in NIMS TM, R1, Book 3, Table 6.4-6: 9 - 12 Hz
- Test Results (with 0 degree Phase) in BNPP Unit 3: 11.5 - 17 Hz
=> Note that the test results of Shell Mode frequency range is much higher than that of NIMS TM.
Refer to the test results of IVMS at BNPP Unit 3.

3) The use of Coherence data to determine Beam/Shell Mode frequencies of CSB
- ASME-OM-S/G, Part 5: NCPSD, Coherence, and Phase should be evaluated. (Refer to Section B.3.)
- Current NIMS TM, R1, Book 3: No specific explanation is described about how to use the coherence.
=> Note that it is difficult to differentiate the CSB vibration and any noise without the use of coherence.
Section 8.1 should provide a summary of IVMS data evaluation procedure.

Coherence ← Please add an additional explanation for the use of Coherence plot to determine Beam Mode and Shell Mode frequencies of the CSB as shown in next page.

The XPSD is an absolute measurement of the commonality between two channels. It is most convenient to represent the similar character in relative terms – relative to the individual PSDs. The coherence is

defined as a ratio of the square of the magnitude of the XPSD and the product of the individual PSDs and is bounded between 0 and 1. If the coherence is 1, the two signals are said to be fully coherent and the corresponding phase data is valid. Uncorrelated signals will have a coherence that approaches 0, rendering any phase data meaningless. Therefore, for XPSD phase data to be meaningful, it must also maintain a relatively high coherence. A Coherence filter is provided in the Historical Analysis program to selectively display only signals with relatively high coherence.

Amplitude Probability Density (APD)

The APD is a descr ((ADD)) High coherence values (0.5 to 1.0 for cross-core detector pairs), in conjunction with phase and NCSD, are considered as the most reliable indicator of the CSB motion in accordance with the explanation in ASME OM-S/G Part 5, Appendix D1.3. value. It is used pri mechanical restrain distribution, which is the familiar "Bell Shaped" curve. Any imposed limitation of the signal will be indicated by either a large discontinuity, skewness, or unusual peaking (Kurtosis) of the APD.

Root Mean Square (RMS)

The RMS signal level can be used as a convenient parameter to describe the level of core barrel motion. For stationary data, it provides a consistent descriptor of the general level of the motion and can be related, through the APD, to an expected maximum and minimum swing of the barrel.

Table 6.4-6. Frequency Bands and Initial Alarm Setpoints

	Band A	Band B	Band C
Lo_Freq (Hz)	4.0	~~9.0~~ 11.0	0.5
Hi_Freq (Hz)	~~7.0~~ 10.0	~~12.0~~ 17.0	20.0
Lo_Setpt (NRMS)	1.50E-3	1.50E-3	2.00E-3
Hi_Setpt (NRMS)	3.00E-3	3.00E-3	3.50E-3

Table 6.4-7. Power Setpoints and Channel Selection

	P1 volts	P1 %pwr	P2 volts	P2 %pwr	Channels to Analyze
A-UP	0.0	0.0	5.00	100.0	Not checked
B-UP	0.0	0.0	5.00	100.0	Not checked
C-UP	0.0	0.0	5.00	100.0	Not checked
D-UP	0.0	0.0	5.00	100.0	Not checked
A-MD	0.0	0.0	5.00	100.0	Not checked
B-MD	0.0	0.0	5.00	100.0	Not checked
C-MD	0.0	0.0	5.00	100.0	Not checked
D-MD	0.0	0.0	5.00	100.0	Not checked

SECTION 8
MAINTENANCE

8.1 PERIODIC MAINTENANCE

Periodic review of the IVMS screens should be done to verify the system is functioning.

Daily

- Verify IVMS power is on.
- Verify there are no trouble or alarm indicators on the IVMS main screen.

Monthly

- Review IVMS Status screen for Blocks Discarded.
- Enter/update the plant boron concentration level (ppm) in the Setup Screen if in manual mode.

Quarterly

- Verify no changes to configuration parameters on the Setup screen and print the screen.
- Make hard copies (print screen) of the Channel Power, Cross Powers, and Coherence (C_{14} and C_{23}) plots from the Analysis screen for a recently completed file.
- See Section 8.3.

Each Fuel Cycle

- At the beginning of the fuel cycle, change the four selected active channels to collect and establish baseline data for future analysis. Collect data at each elevation of the core. After

* Any changes of Beam Mode and Shell Mode frequencies of the CSB should be evaluated based on the combination of following three conditions together:
[C1] Phase: 180 degree for Beam Mode, and 0 degree for Shell Mode
[C2] Coherence: more than 0.5 within frequency ranges selected by [C1]
[C3] Magnitude: the highest peak within the frequency ranges selected by [C1]&[C2]
When no specific frequency is found to meet the above three conditions, describe as "Not Found (NF)" in test sheet. Please note that the highest peak at lower frequencies between 0 to 5 Hz can be caused by the neutronic effects (i.e. not by the CSB motion) in accordance with the data evaluation guide of ASME OM-S/G-2000, Part 5.

recognition between subsequent fuel cycles when, in time, more data is archived. For example,

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Westinghouse

9-614-Z-W-431-V01

Westinghouse Proprietary Class 2

BNPP 1,2,3&4
Emirates Nuclear Energy Corporation
Korea Electric Power Corporation

Internals Vibration Monitoring System (IVMS)
NIMS Technical Manual

WNA-GO-00141-BRAKA1,
Rev. 6

Book 3
Table Y-06-2, Item 1
Status 1

Non-Nuclear Safety Related

February 2025

APPROVALS

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*Electronically approved records are authenticated in the electronic document management system.

Cross Power Spectral Density (XPSD or CPSD)

Because of the motion-induced "out of phase" relationship between two opposite channels, it is important to provide a descriptor of the commonality and the phase between them. The XPSD (CPSD) function provides a spectral decomposition of the correlation between two variables and presents it in a form similar to the PSD.

Coherence

The XPSD is an absolute measurement of the commonality between two channels. It is most convenient to represent the similar character in relative terms – relative to the individual PSDs. The coherence is defined as a ratio of the square of the magnitude of the XPSD and the product of the individual PSDs and is bounded between 0 and 1. If the coherence is 1, the two signals are said to be fully coherent. Uncorrelated signals will have a coherence near 0, rendering any phase data meaningless. Therefore, for XPSD phase data to be meaningful, it must also maintain a relatively high coherence. A Coherence filter is provided in the Historical Analysis program to selectively display only signals with relatively high coherence. Higher coherence values for cross-core detector pairs, in conjunction with phase and XPSD, are considered as the most reliable indicator of the CSB motion in accordance with the explanation in ASME OM-S/G Part 5, Appendix D1.3 (Reference 4).

Table 6.4-6. Frequency Bands and Initial Alarm Setpoints

	Band A	Band B	Band C
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Lo_Setpt (NRMS)	1.50E-3	1.50E-3	2.00E-3
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B-UP	0.0	0.0	5.00	100.0	Not checked
C-UP	0.0	0.0	5.00	100.0	Not checked
D-UP	0.0	0.0	5.00	100.0	Not checked
A-MD	0.0	0.0	5.00	100.0	Not checked
B-MD	0.0	0.0	5.00	100.0	Not checked

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MAINTENANCE

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  - [C1] Phase: 180 degree for Beam Mode, and 0 degree for Shell Mode
  - [C2] Coherence: relatively high within frequency ranges selected by [C1]
  - [C3] Magnitude: the highest peak within the frequency ranges selected by [C1]&[C2]
  - When no specific frequency is found to meet the above three conditions, describe as "Not Found (NF)" in test sheet. Please note that the highest peak at lower frequencies between 0 to 4 Hz can be caused by the neutronic effects (i.e. not by the CSB motion) in accordance with the data evaluation guide of ASME OM-S/G-2000, Part 5 (Reference 4).

4. 후속연구 및 Q&A

■ 후속연구 추천

- 불필요한 IVMS 경보발생 억제를 위해, 1개 핵연료주기 중에 붕소농도 감축에 따른 APSD 증가를 보상하는 방법은 실제 적용사례 관련 국내/국외 자료를 찾기 곤란함 ➔ 원전 운영사와 설계사 간 자료공유와 협력을 통해 최적화된 절차 확립을 추천함.
- 본 논문은 최초-핵연료주기의 초기에 IVMS에 취득된 ENFMS 신호 기록을 바탕으로 분석한 것이며, 이는 일부 Baseline 자료의 신호특성을 분석한 것임 ➔ 첫 핵연료주기 중간 및 말기 시점에서는 어떤 변화가 있는지? 또한 제2주기와 제3주기에서는 대체로 어떤 변화가 보이는지? Holddown Ring 교체 경험이 있는지? 등에 대한 논문을 찾기 어려움 ➔ 국내 원전의 여러 IVMS 분석자료 축적이 필요한 바, 운영사와 설계사 및 연구기관 간에 협력 및 논문-공저-발표를 추천함.

■ Q&A

If today were the last day of my life, would I want to do what I am about to do today?

- Steve Jobs' 2005 Stanford Commencement Address -