KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

# Experiences of Loose Part Detection and Diagnosis in Korean NPPs

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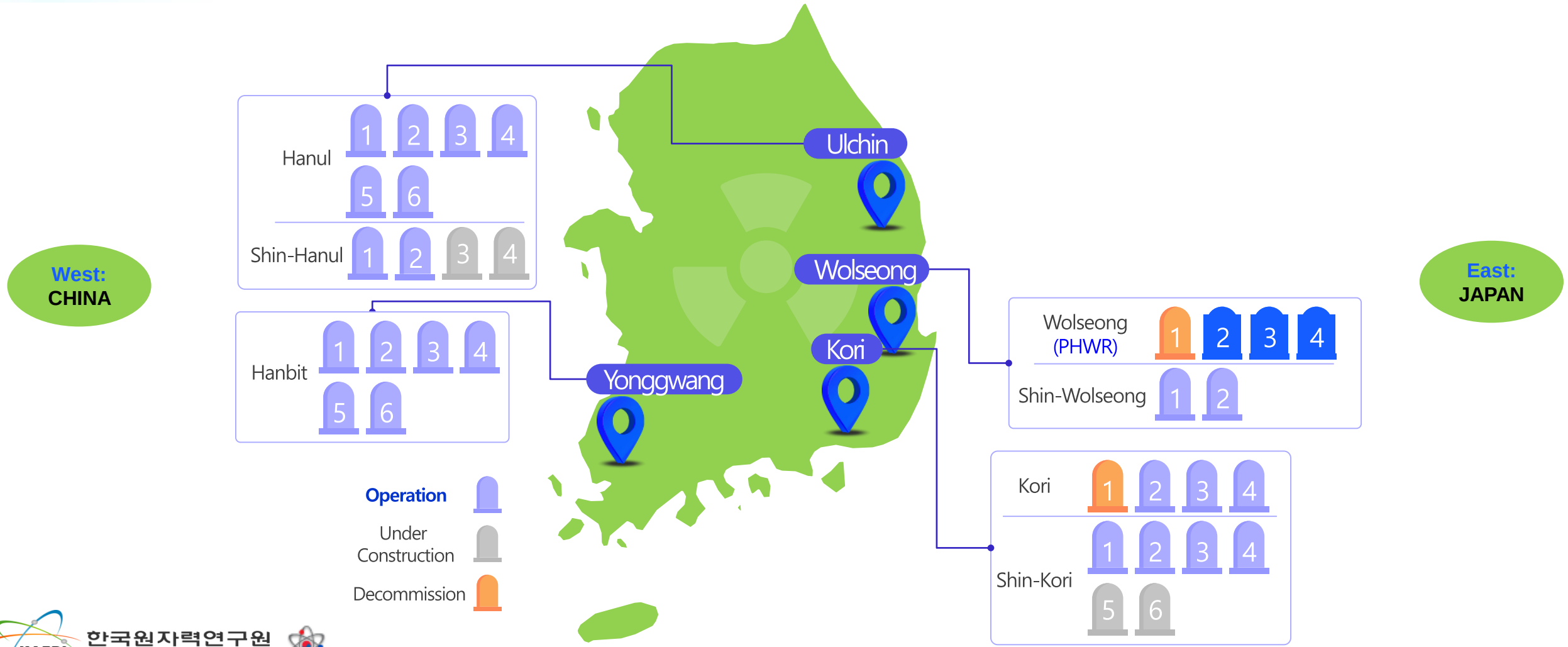
# Contents

# Introduction

## Status of Korean NPPs(2024. 9.)

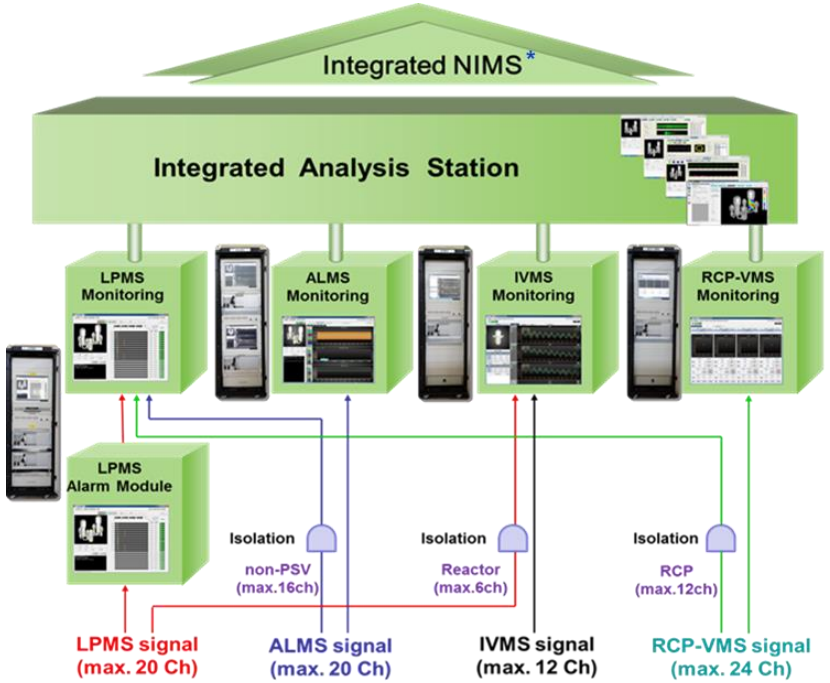
26 units in Operation, 4 units under Construction, 2 units Closed for Decommission



# Introduction

- **K-NIMS (Korean-NSSS structural Integrity Monitoring System)**

**Korean Standard Nuclear Power Plant**
**(OPR1000 & APR1400)**




**I-NIMS**
**(prototype, 2010)**

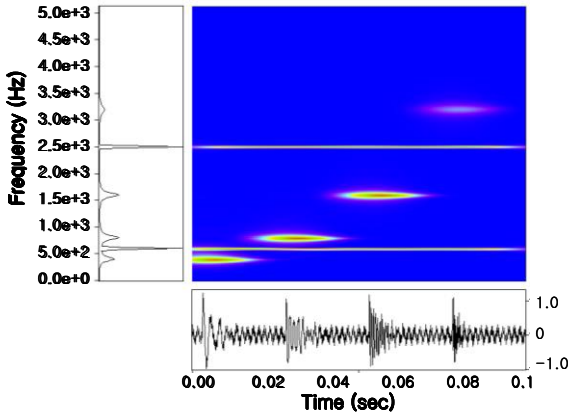
**K-NIMS**
**(Installed for operation, 2021~ )**
**By Realgain Co.**

* *[Ref] J.H. Park, Nuclear Plant Journal, Vol. 32, No. 3 (2014)*
*[Ref] J.H. Park et al, Patent Reg., Korea(2008), Germany(2011) and France(2017)*

# Loose Part Monitoring/Diagnosis Technique

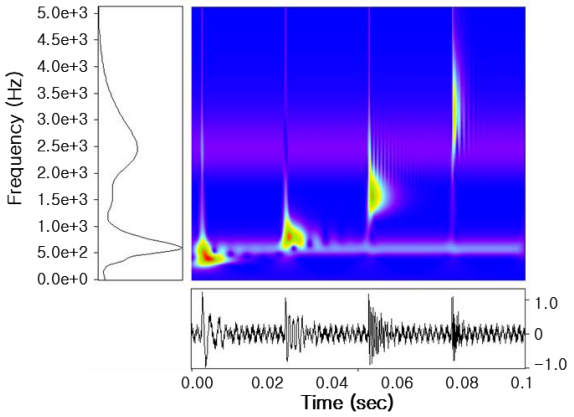
## Time-Frequency Analysis Technique (for Non-stationary signal)

Short Time Fourier Transform



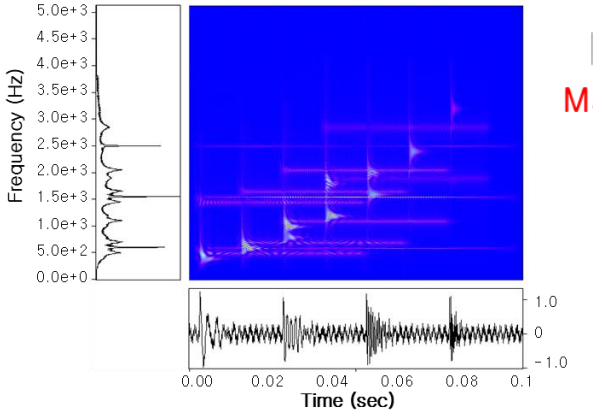

$$S(t,f)=\int_{-\infty}^{\infty}h^{*}(\tau-t)s(\tau)e^{-j2\pi f\tau}d\tau$$

Continuous Wavelet Transform




$$CWT(a,b)=\int_{-\infty}^{\infty}s(t)\psi^{*}\left(\frac{t-b}{a}\right)dt=\int s(t)e^{-\left(\frac{t-b}{a}\right)^{2}/\sigma^{2}}e^{j2\pi\frac{f_0}{a}(t-b)}dt$$

Wigner-Ville Distribution



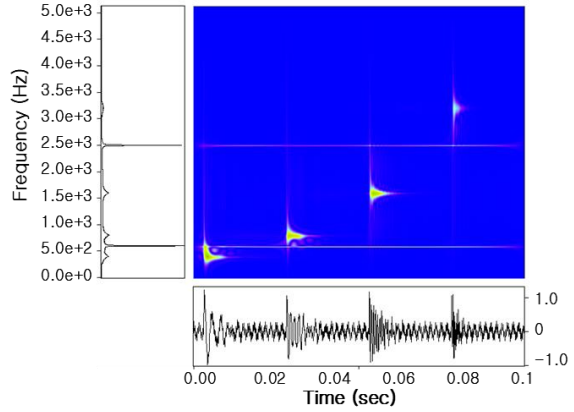

$$W(t,f)=\int_{-\infty}^{\infty}z(t+\frac{\tau}{2})z^{*}(t-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau$$

Mapping

$$A(\xi,\tau)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}W(t,f)e^{-j(2\pi\xi t-2\pi f\tau)}dtdf$$

Smoothing

$$\phi(\xi,\tau)\cdot A(\xi,\tau)$$




$$W_S(t,f)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi(\xi,\tau)z(u+\frac{\tau}{2})z^{*}(u+\frac{\tau}{2})e^{-j2\pi(\xi t+f\tau-\xi u)}d\xi du d\tau$$

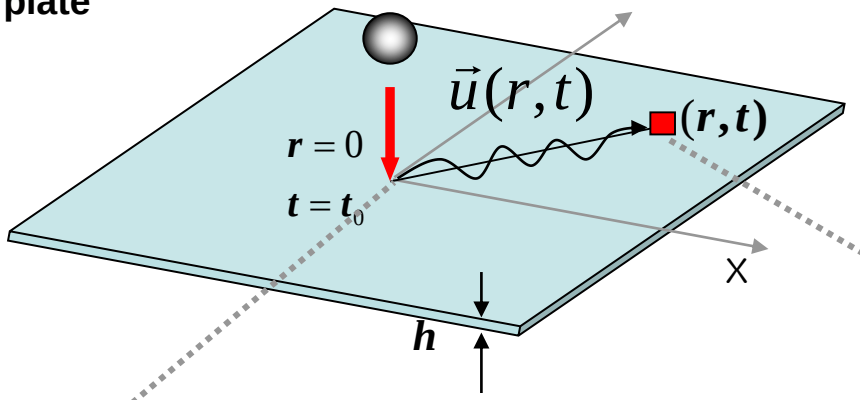
Smoothed WVD

[Ref] J.H. Park and Y.H. Kim, Measurement Science and Technology, Vol. 17, No.10 (2006)

# Loose Part Monitoring/Diagnosis Technique

## Dispersion Characteristics of Plate Type Metallic Structure

Ex) metal plate

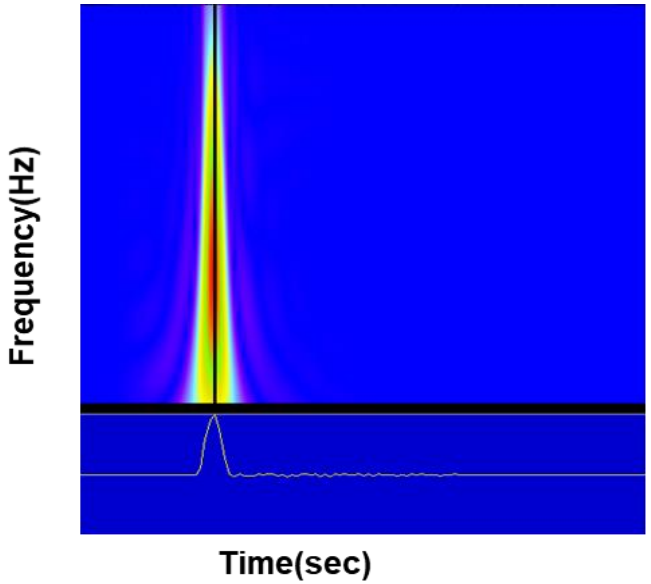



**Group Velocity**

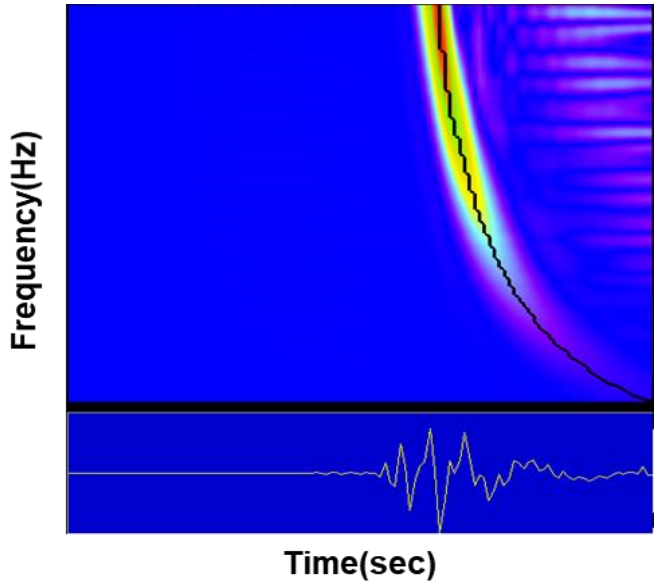
$$C_g = 2\sqrt{2\pi f}\left(\frac{D}{\rho h}\right)^{\frac{1}{4}} \cong \frac{r}{(t-t_0)_f}$$

$D$ : **Bending stiffness**

$\rho$ : **density**



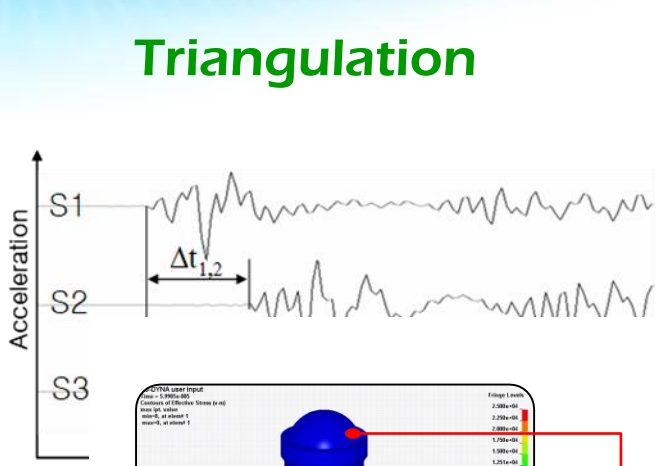

**Impact response in time-frequency domain (SWVD)**

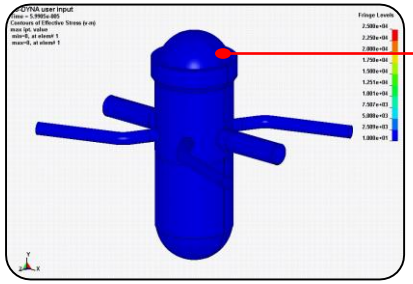


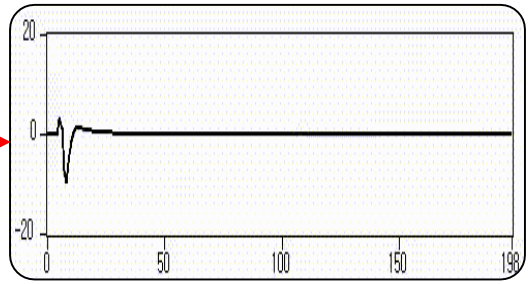
# Loose Part Monitoring/Diagnosis Technique

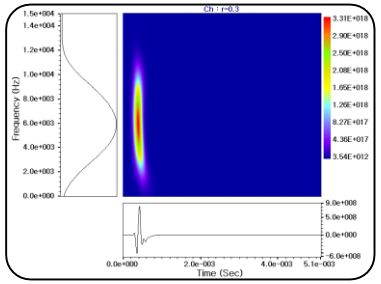
## Estimation of Time-of-Arrival Differences using Time-Frequency Analysis

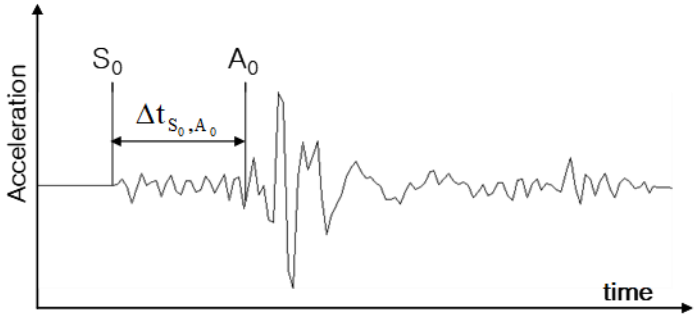
### Triangulation

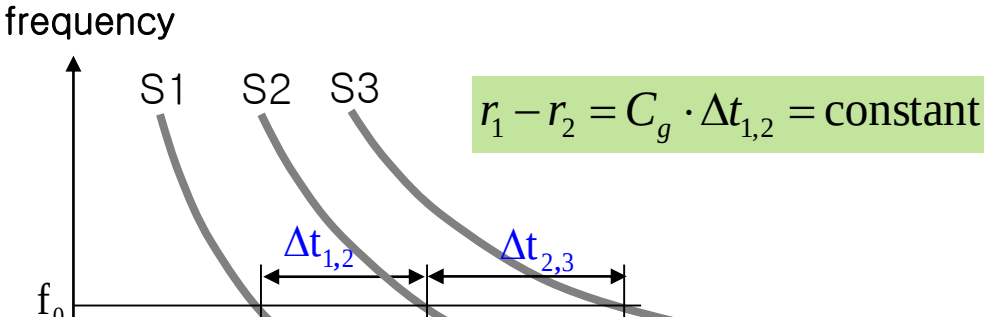




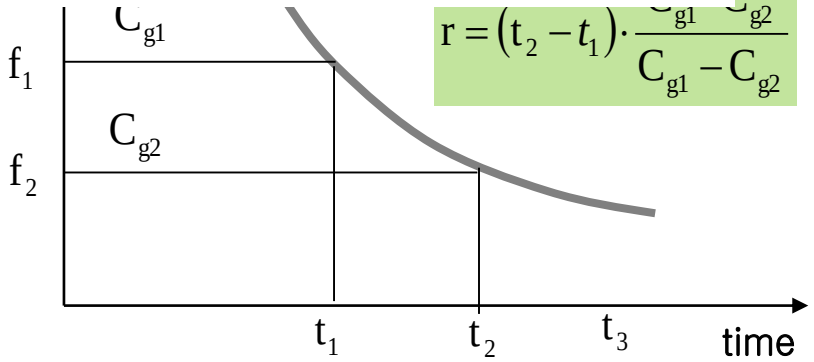






$$r_1 - r_2 = C_g \cdot \Delta t_{1,2} = \text{constant}$$

me




$$r = (t_2 - t_1) \cdot \frac{C_{g1} \; C_{g2}}{C_{g1} - C_{g2}}$$

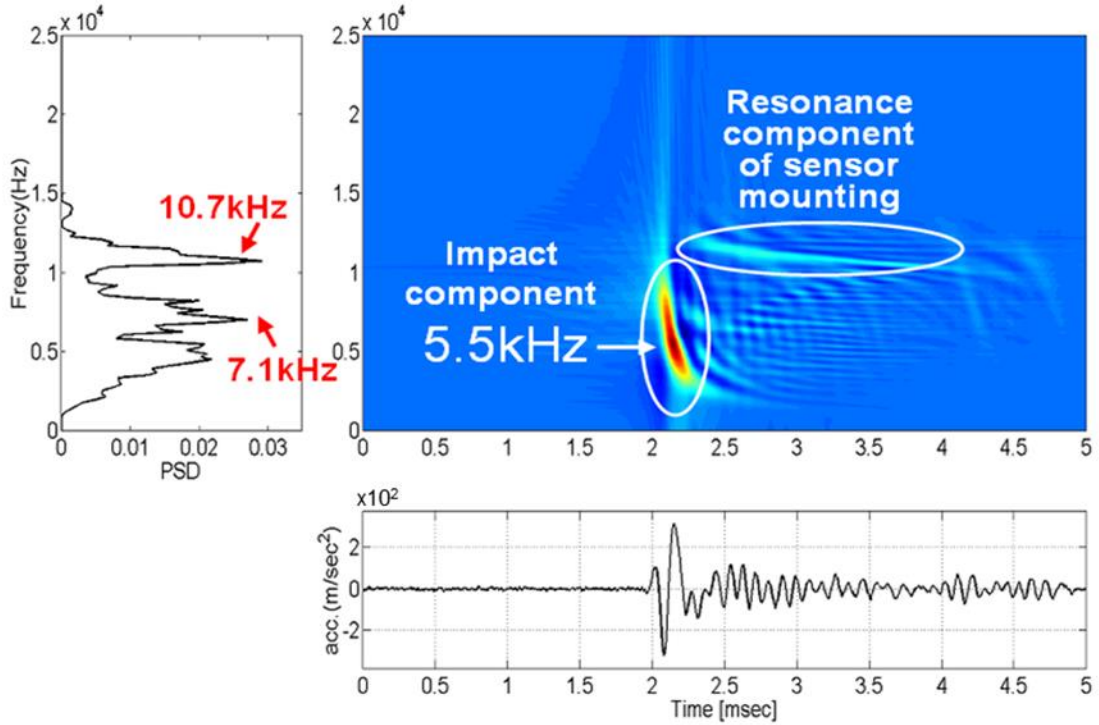
<One Dimensional Time Domain>

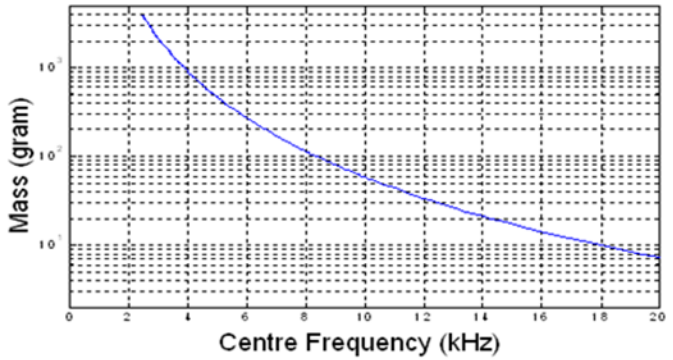
<Two Dimensional T-F Domain>

# Loose Part Monitoring/Diagnosis Technique

- **Finding Center Frequency of Impact Response using Time-Frequency Analysis**

## For an Impact of a Steel Ball(405 gram) on a plate




| Estimation | | | True mass (gram) |
|---|---|---|---|
| Center frequency | 5.5kHz | 7.1kHz | |
| Mass (gram) | 350 | 163 | 405 |

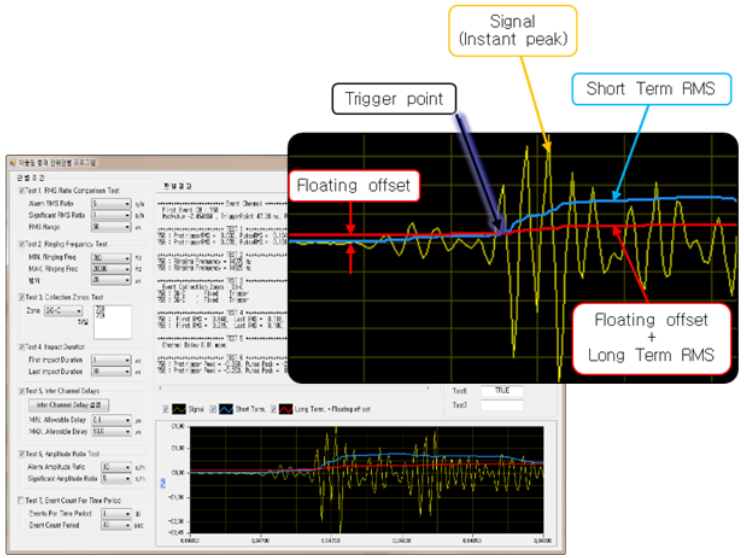
*[Ref] D.-B. Yoon, J.H. Park and C-Y Choi, "Enhancement of Impact Mass Estimation Algorithm for a Plate Type Structure", Material Transactions, Vol. 48 no.06 (2007), pp. 1249-1253.*

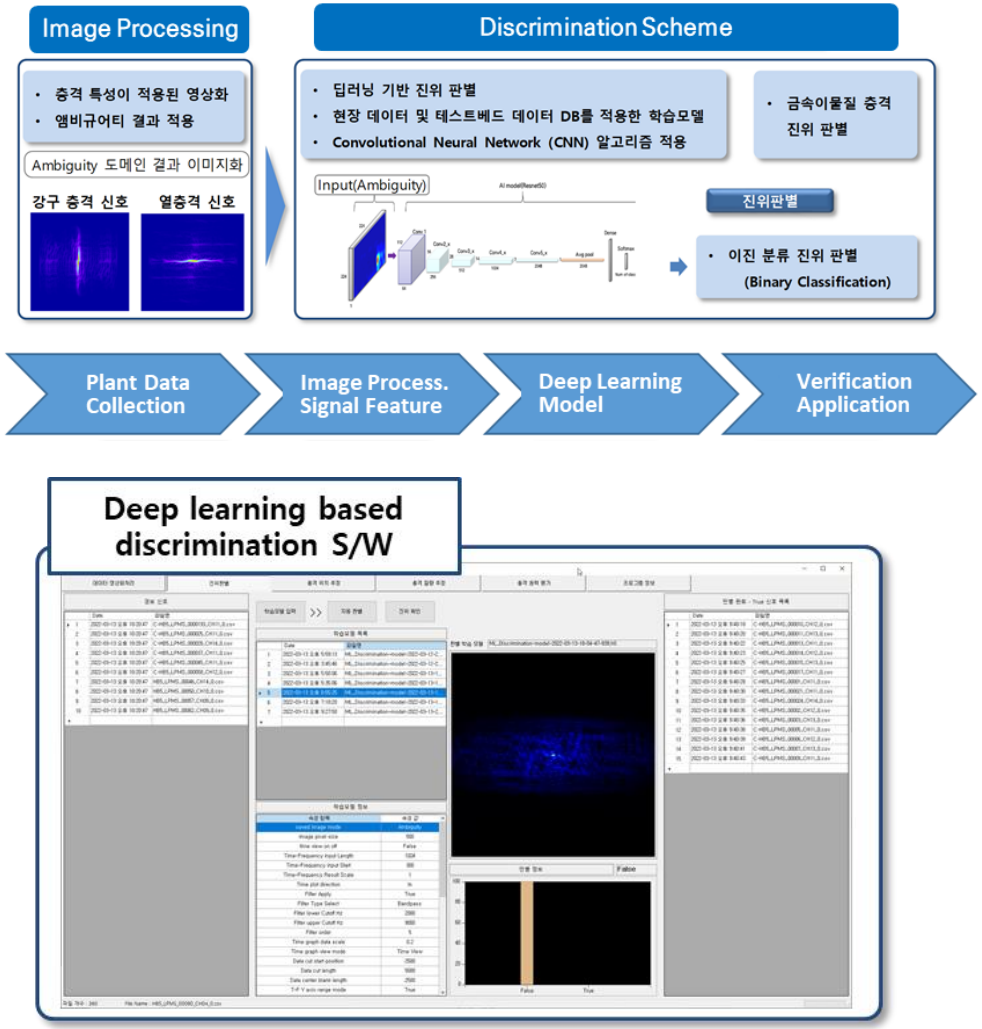
# Loose Part Monitoring/Diagnosis Technique

## ■ Establishment of Enhanced Loose Part Monitoring Process

### 1. Triggering and Discrimination rules

- RMS ratio comparison test
- Ringing frequency test
- Collection zones test
- Waveform ringdown(Impact duration test)
- Inter-channel delays
- Amplitude ratio test

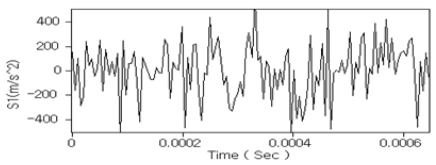


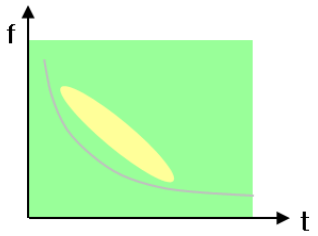
# Loose Part Monitoring/Diagnosis Technique

## ■ Establishment of Enhanced Loose Part Diagnosis Process

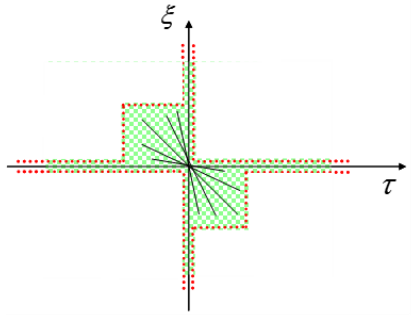
### 2. Source Localization Procedure



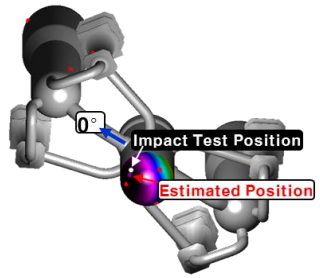

1. Measured Signal (Signal+Noise)

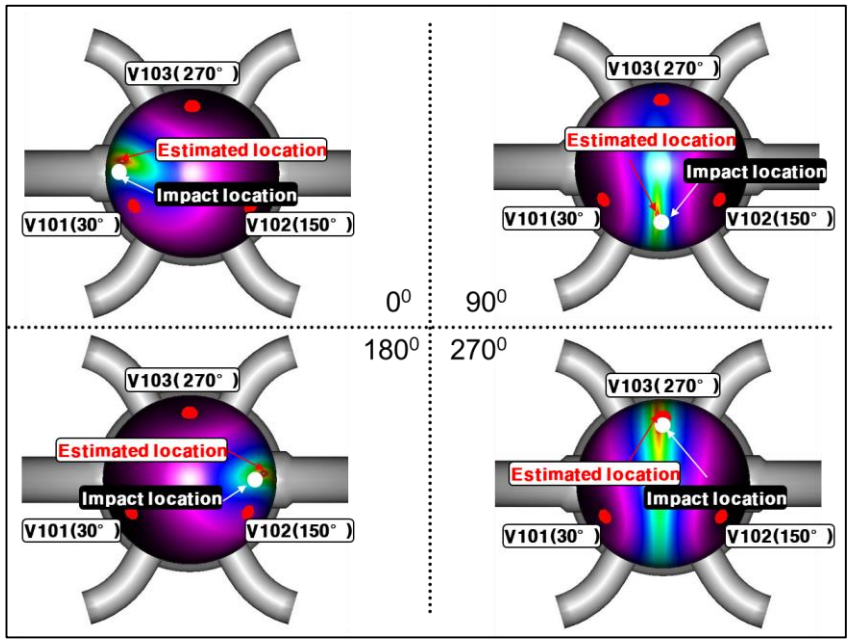


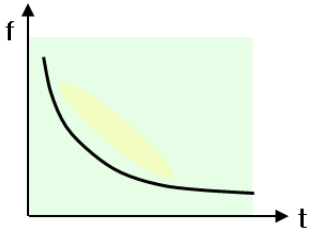

2. Wigner-Ville Distribution



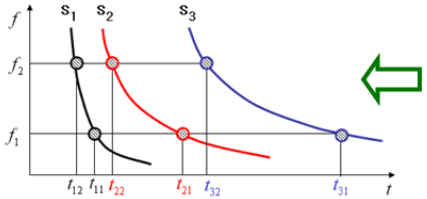

3. Ambiguity Domain (Smoothing)



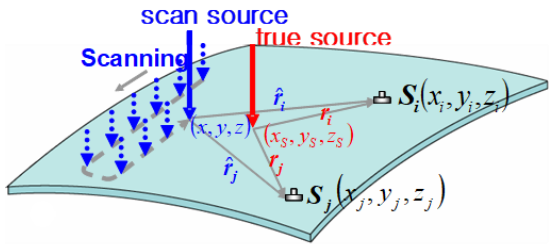




4. S. Wigner-Ville Distribution (Reduction of Cross- Term and Noise)




5. TOAD Measurement



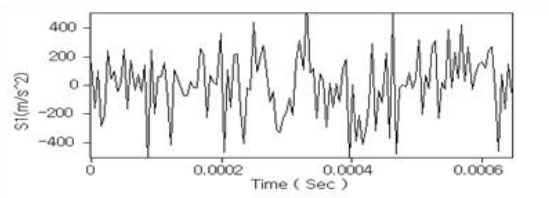

6. Estimation of Source Location* (Minimum Variance Scanning)

*[Ref] J.H. Park and Y.H. Kim, Measurement Science and Technology, Vol. 17, No.10 (2006)*

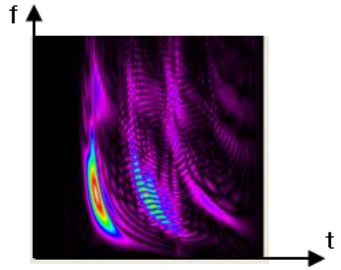
# Loose Part Monitoring/Diagnosis Technique

## Establishment of Enhanced Loose Part Diagnosis Process

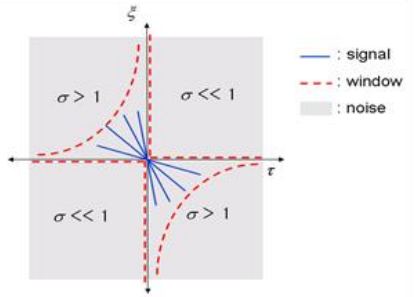
### 3. Mass Estimation Procedure



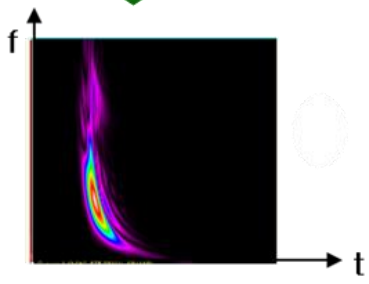

1. Measured Signal (Signal + Noise)



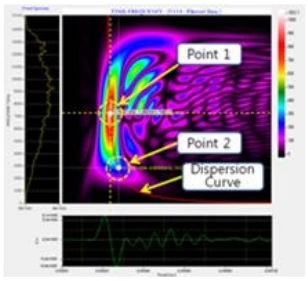

2. Wigner-Ville Distribution (Signal + Noise)



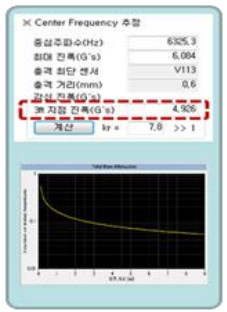

3. Ambiguity Domain (Smoothing)



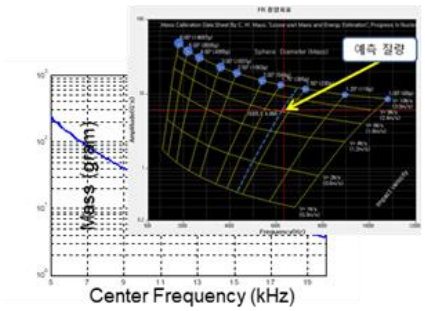

4. SWV Distribution (Reduction of Noise)




5. Finding of Center Frequency & Max. Magnitude




6. Distance Attenuation



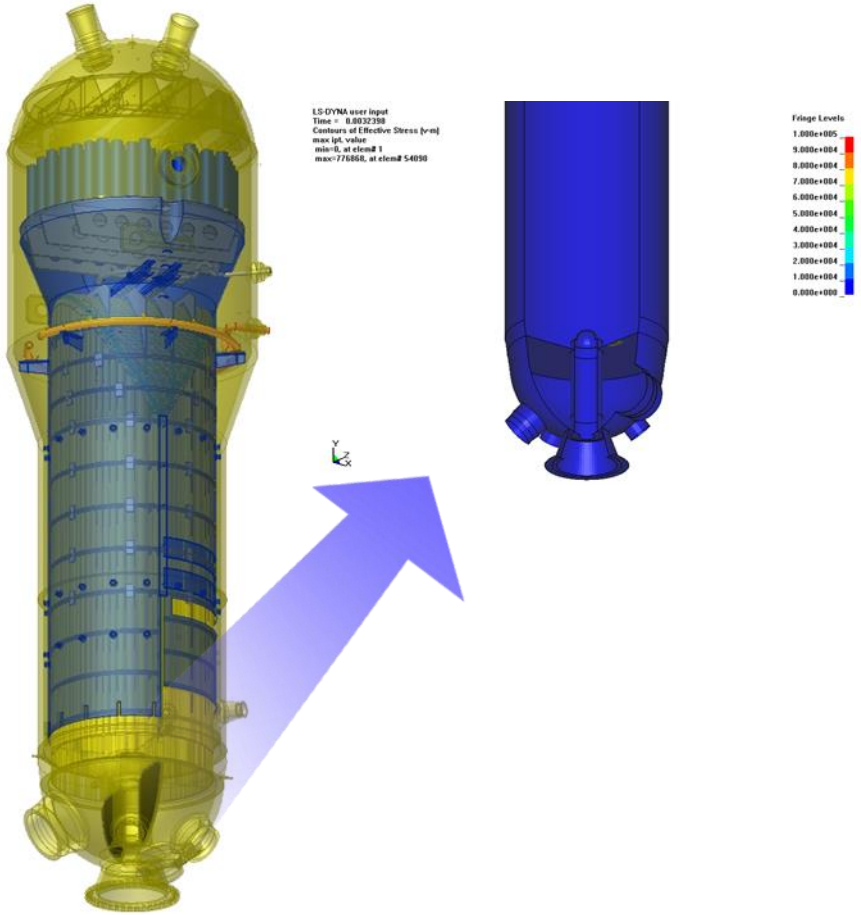

7. Estimation of Impact Mass (Modified Mass Index DB)

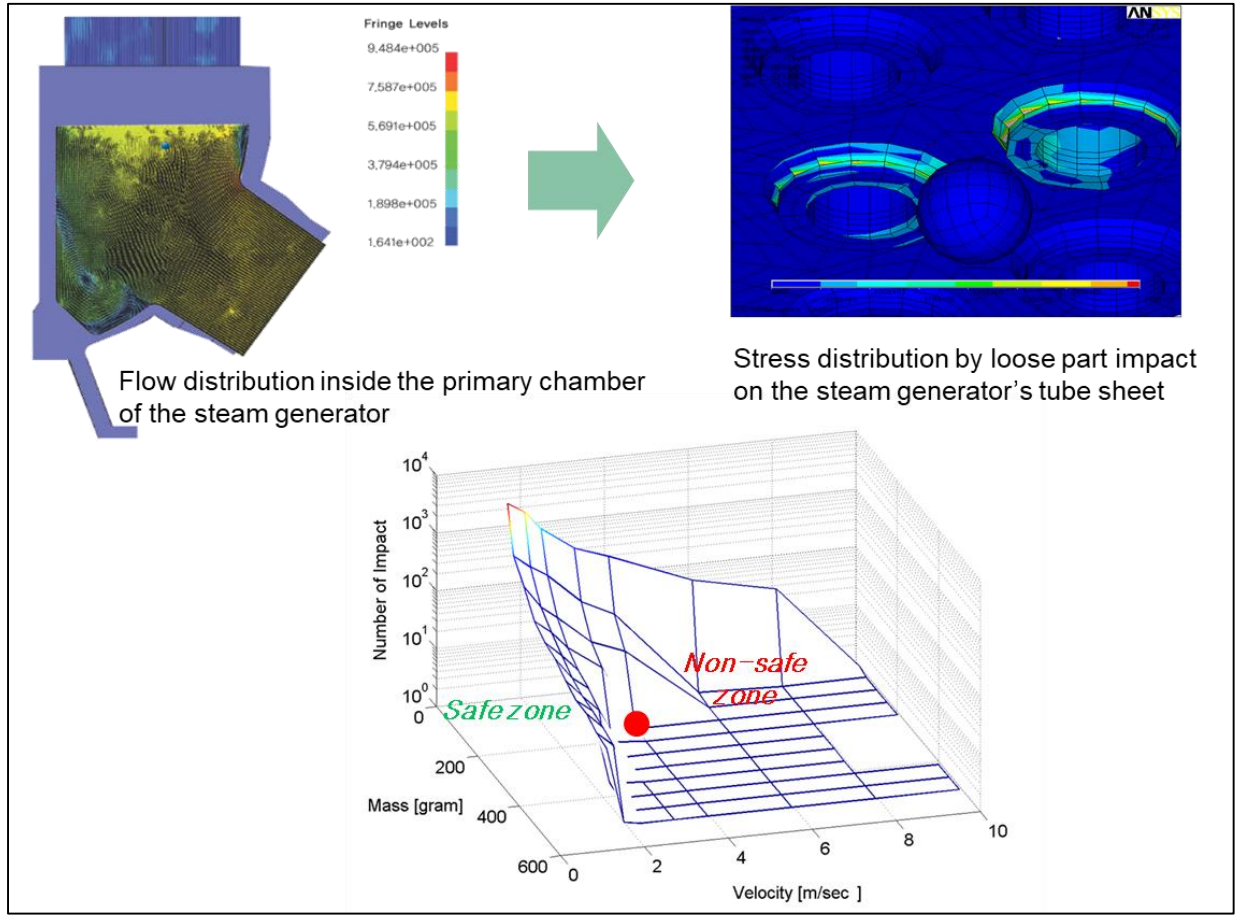
[Ref.1] C.W. Mayo, Progress in Nuclear Energy, Vol. 34, No.263 (1999)
[Ref.2] D.B. Yoon, J.H. Park et al, Material Transactions, Vol. 48, No. 6 (2007)
[Ref.3] S.H. Shin, J.H. Park et al, Nuclear Engineering and Technology, Vol. 43, No. 4 (2011)
[Ref.4] S.I. Moon, J.H. Park et al, Journal of Mechanical Science and Technology, Vol. 32(3) (2018)

# Loose Part Monitoring/Diagnosis Technique

## ■ Establishment of Enhanced Loose Part Diagnosis Process

### 4. Structural Integrity Evaluation Database



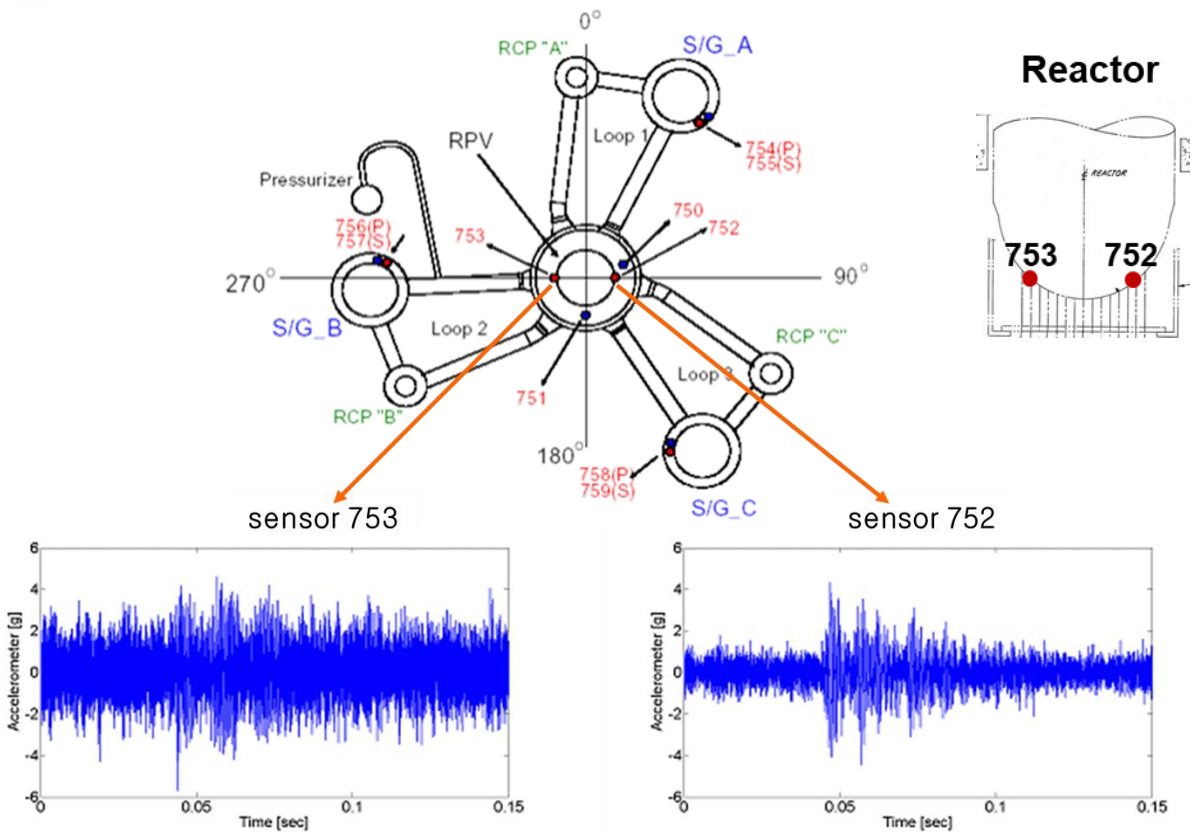



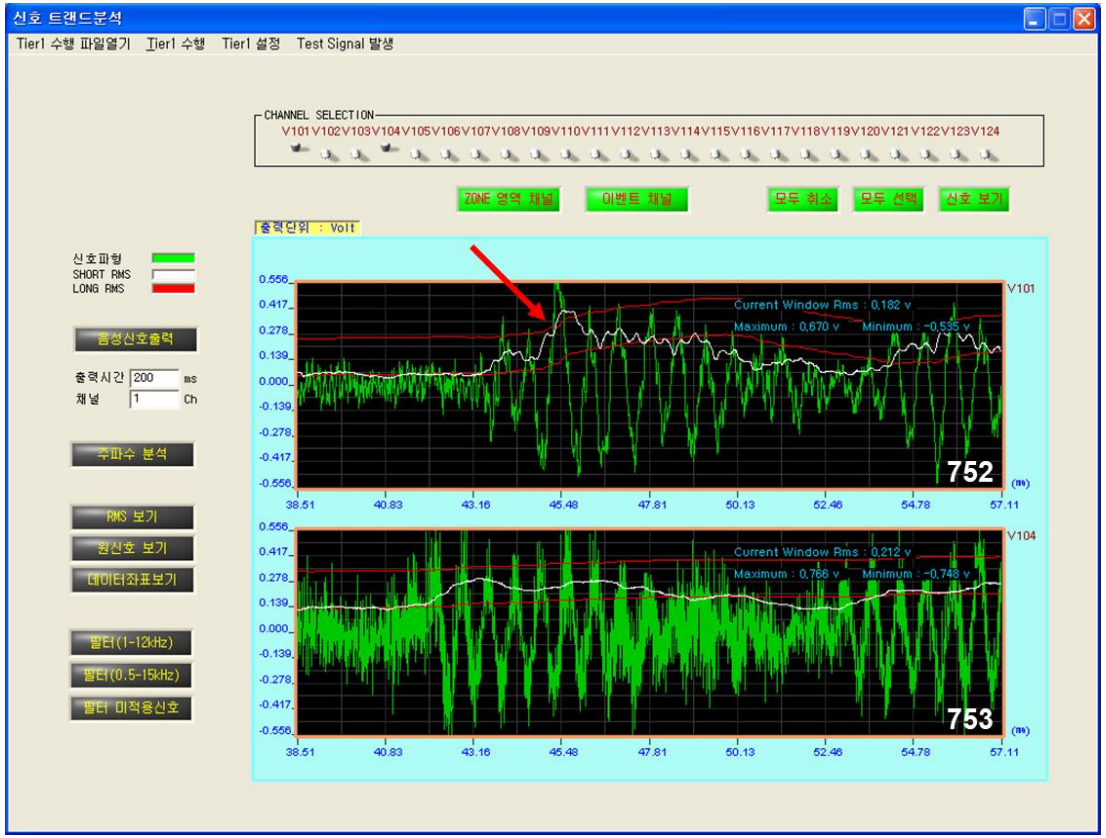
# Application Experiences of  LPM Technology

# Case 1: Decision Making of a Loose Part

## LPMS Events at Reactor Bottom Region

- Similar to typical impact response signals caused by a metallic loose part



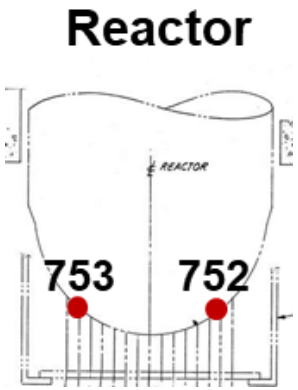



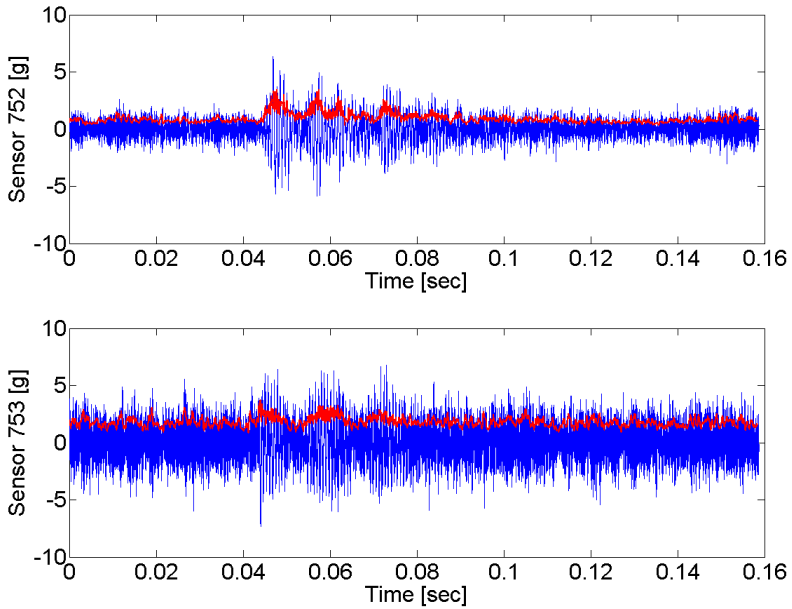

<Triggering & Discrimination >

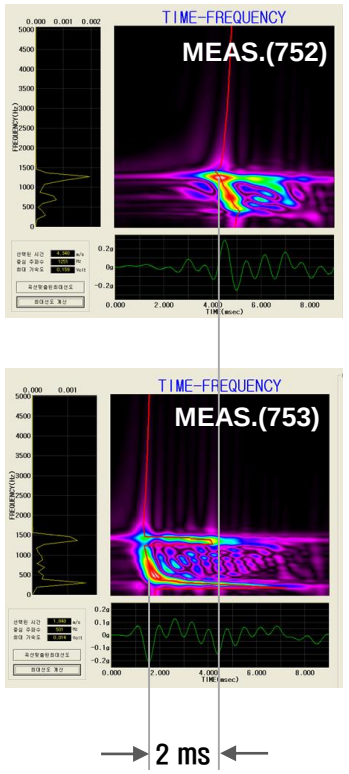
# Case 1: Decision Making of a Loose Part

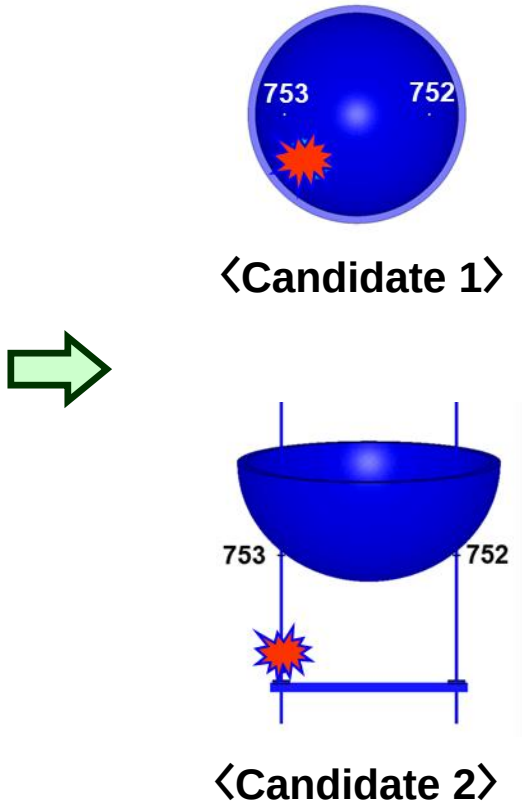
## Estimation of Source Location

- 753 signal arrives faster than 752's (delays 2 ms) → equivalent to the distance btw. two sensors)
- Predicted that the source ranges approx. 1.5 meters from 753 and more than 6 meters from 752
- Where is the impact source? Inside the reactor or outside?



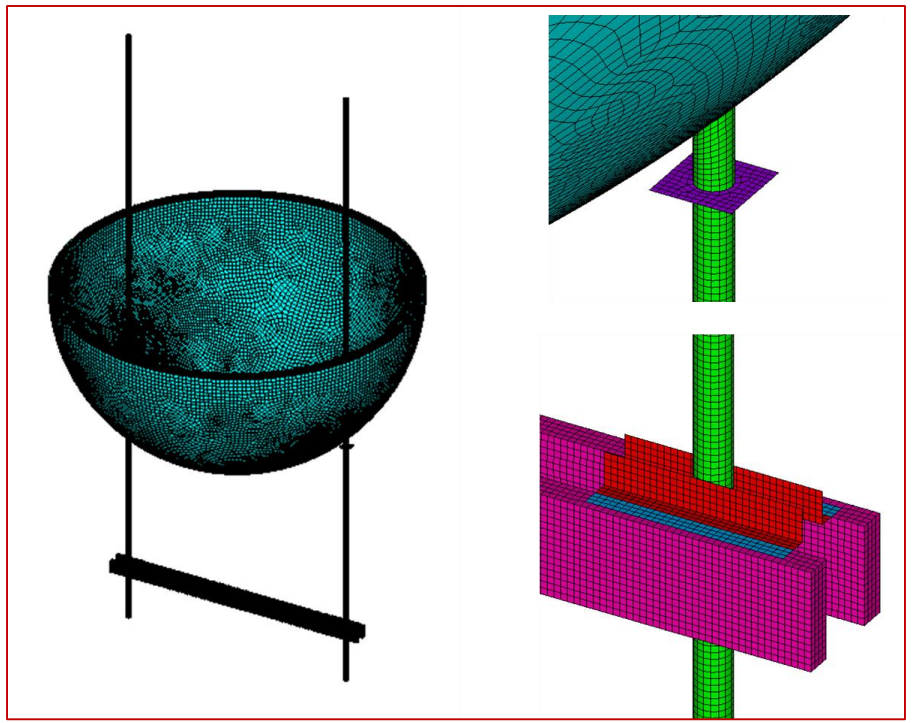



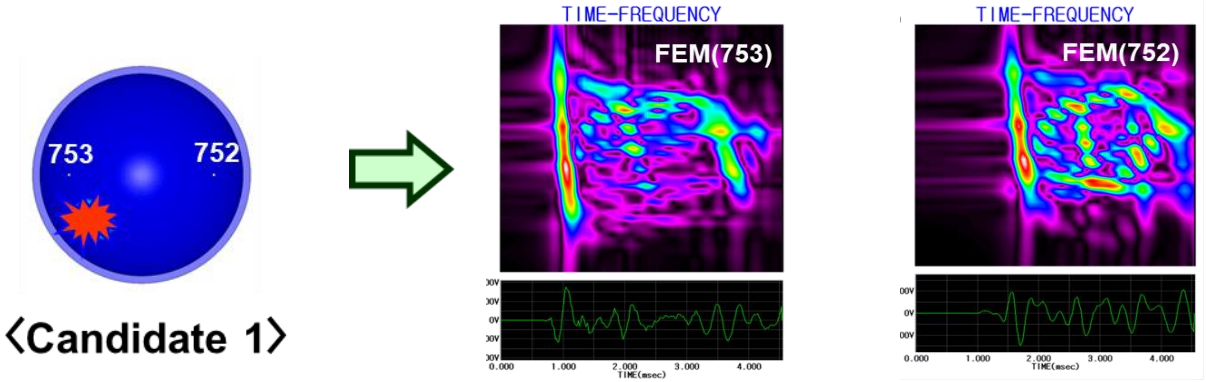



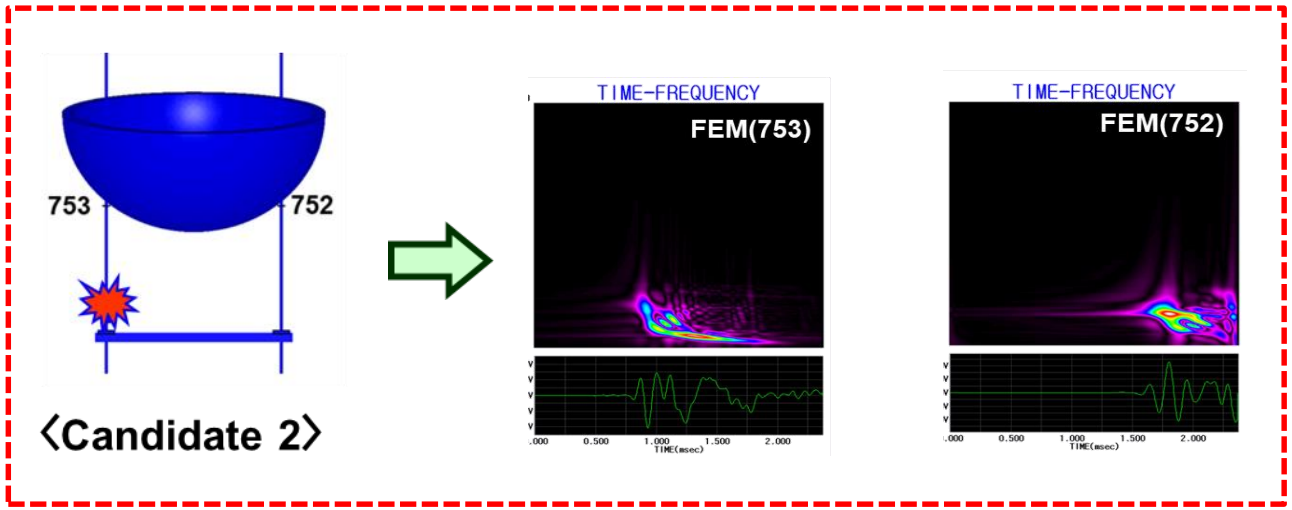
# Case 1: Decision Making of a Loose Part

## Simulation of Impact Responses for the two Candidates

- Dispersion shapes in each Time-Frequency domain give a clear conclusion of where the impact is occurred
- It turned out that the event signals came not from inside the reactor but from outside it → ICI tube impact



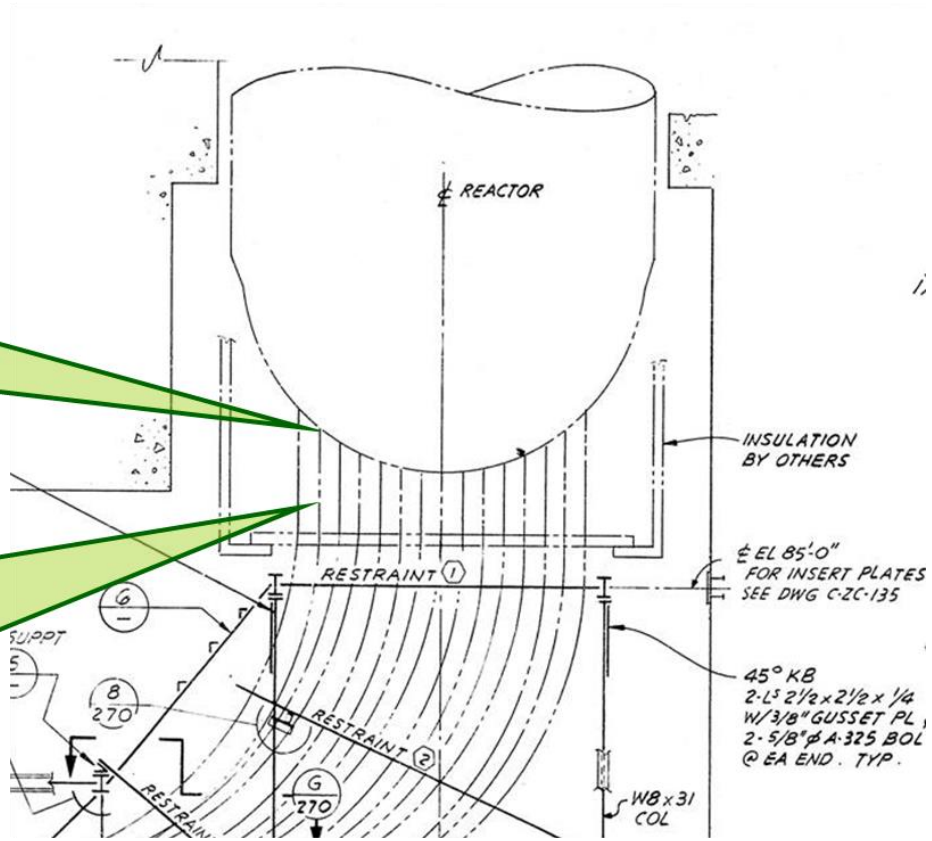


# Case 1: Decision Making of a Loose Part

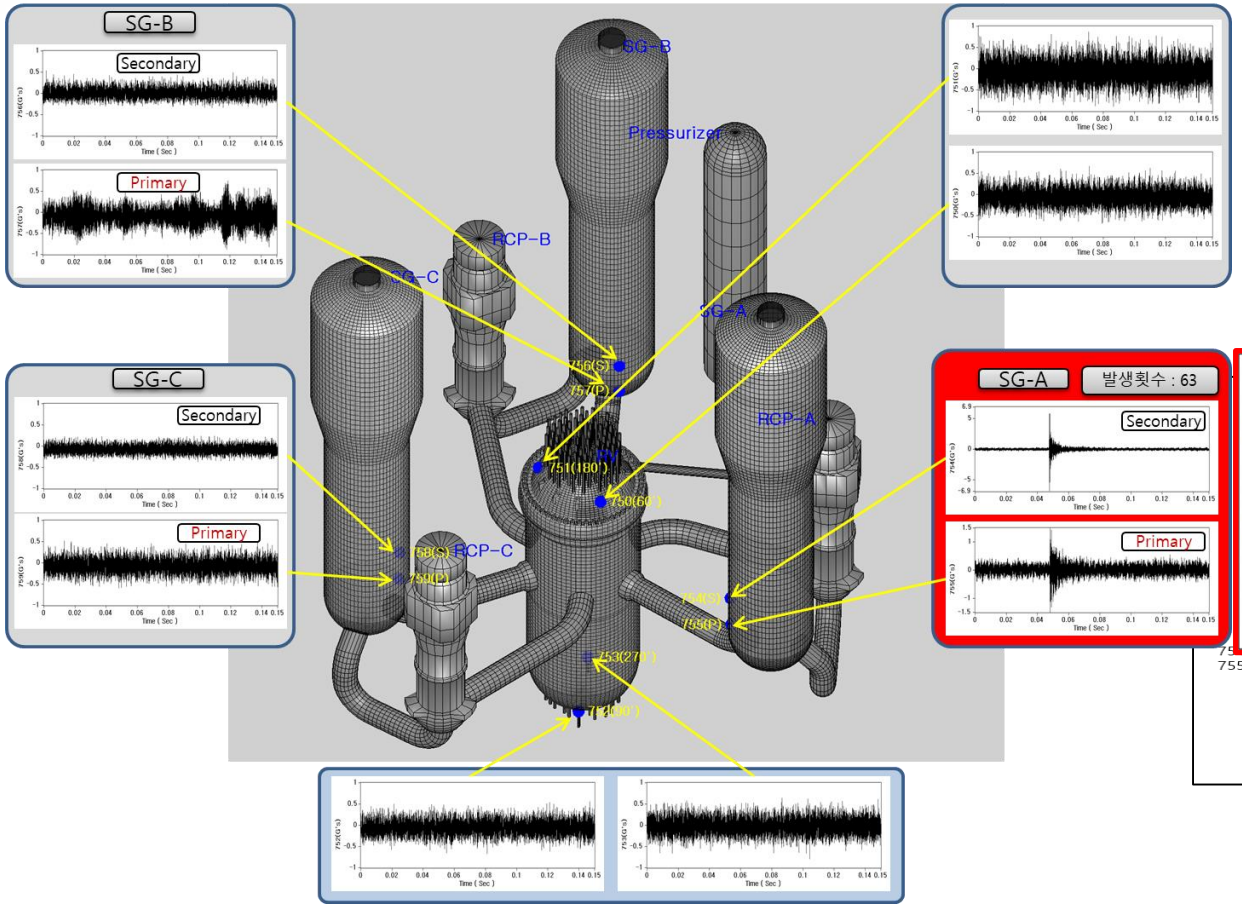
## Identification and follow-up action

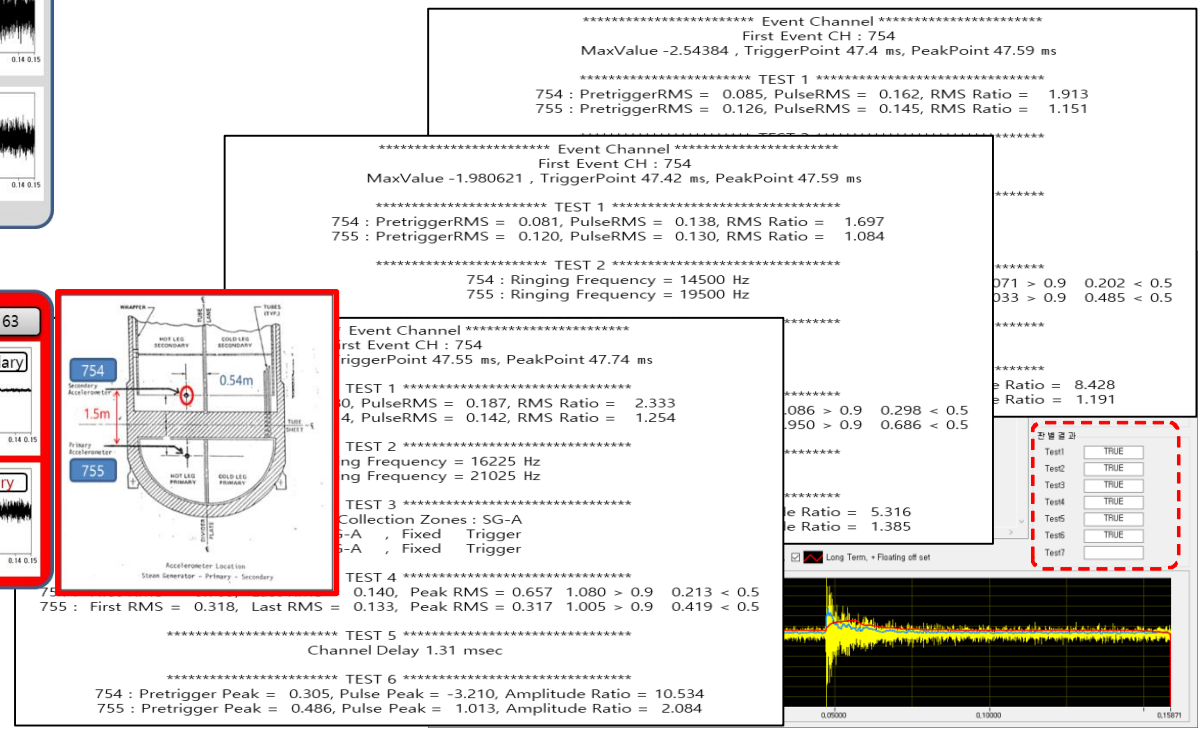
- Root cause: Intermittent impacting by the connector of the 753 sensor's hard cable with ICI tube
- No plant shutdown and the connector was fastened during the following OH period



# Case 2: A Foreign Object in a SG Shell Side

- **Event Signals Triggered at SG bottom sensor(754) during normal operation**
  - Typical impact response signals caused by a metallic loose part

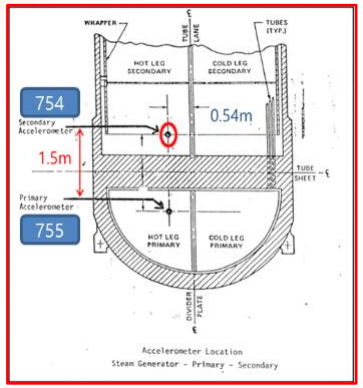


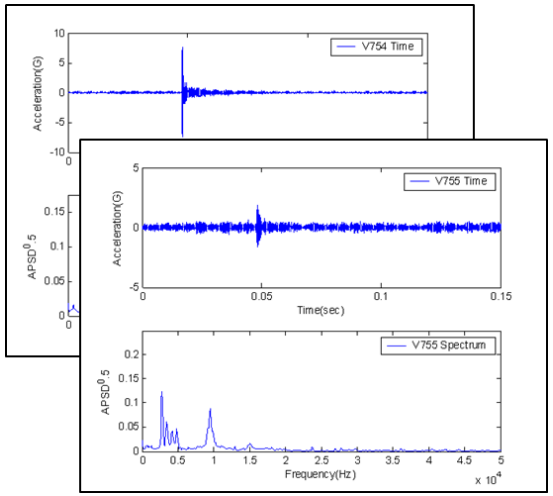



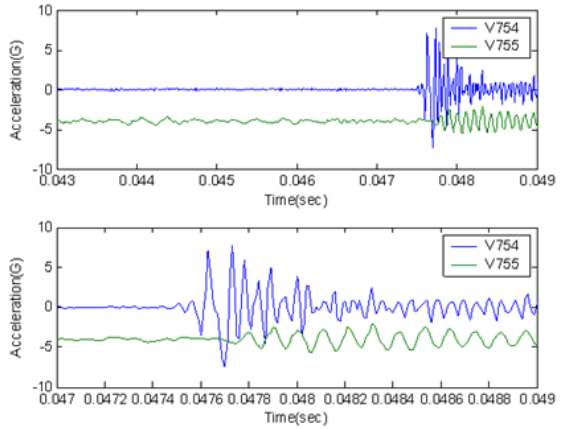

<Screened by Discrimination Rules>

# Case 2: A Foreign Object in a SG Shell Side

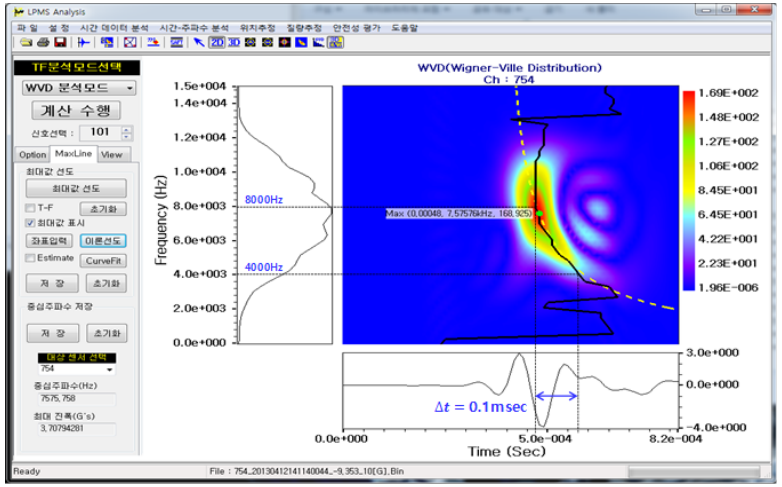
- **Estimation of the Distance from the Source to 754 Sensor(the nearest one)**

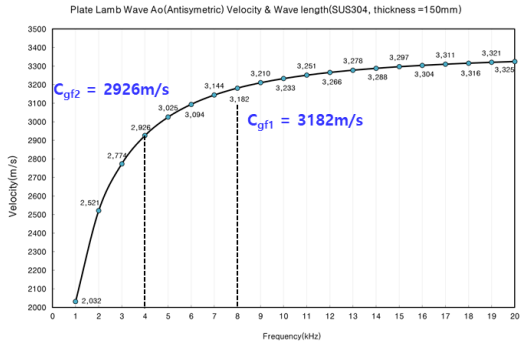



The 754 signal arrives faster than 755's (0.2 ms) : equivalent to the distance between the two sensors)



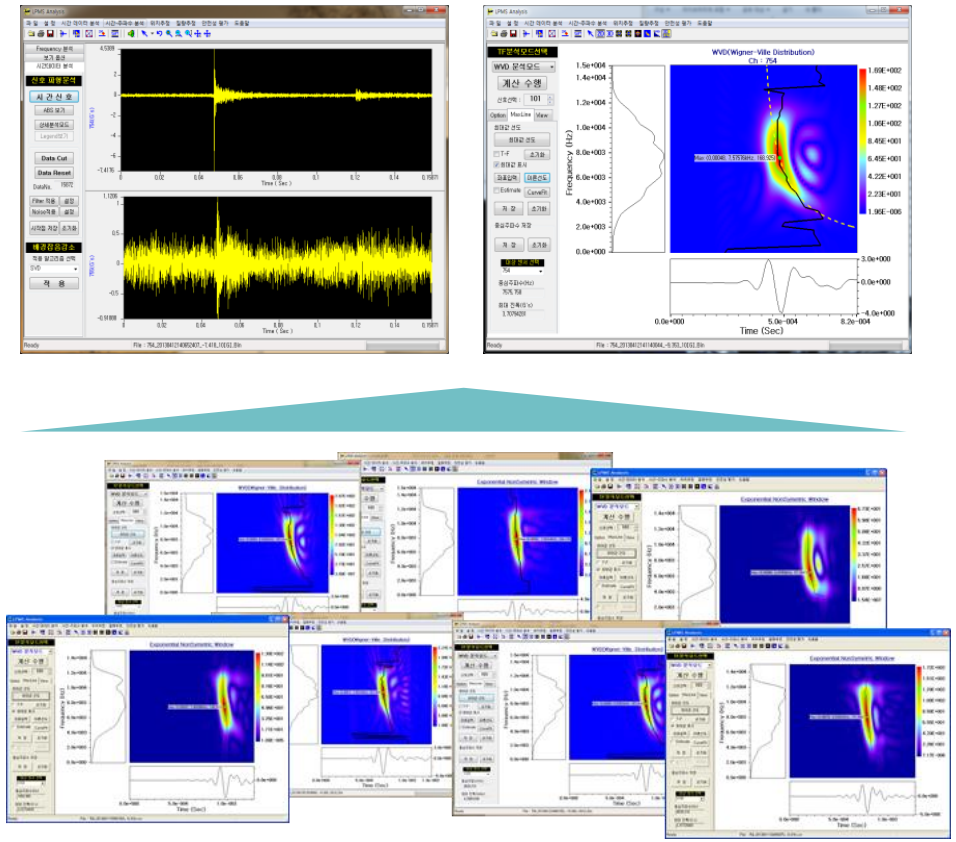

$$S = \Delta t \times \frac{C_{gf1} \times C_{gf2}}{C_{gf1} - C_{gf2}} \fallingdotseq 3.6m$$

The source is supposed to be located at around 3.6 meters from 754 sensor in the shell side : above the tube sheet

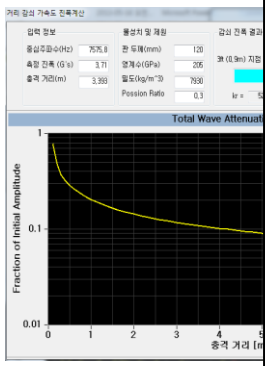
# Case 2: A Foreign Object in a SG Shell Side

## Mass Estimation of the Impacted Source

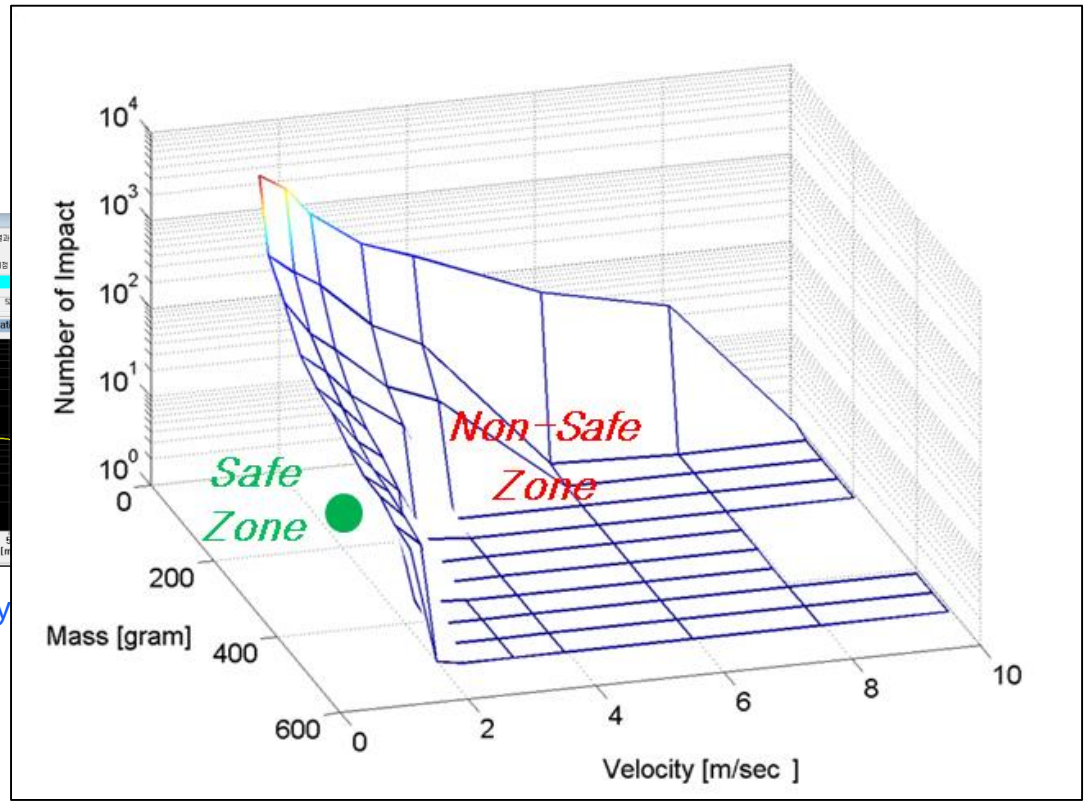
- Based on ensemble averaged center frequency and the peak magnitude of the nearest sensor(754) signals
- Impacted mass is presumed to be approx. 165 grams



<Ensembles of Event Signals >



<Attenuation by



# Case 2: A Foreign Object in a SG Shell Side

- **Identification and follow-up action**
  - Root cause: A dropped magnet used for hooking a light fixture
  - Removed safely and inspection completed

Intentionally Blanked

# Summary

# Summary

## Enhancement of Loose Part Monitoring/Diagnosis

- Advantages of Time-Frequency analysis technique
  - Event screening
  - Estimating Time-of-Arrival Difference between sensors
  - Source localization
  - Mass estimation

## Lessons Learned from Experiences

- Both technical expertise and empirical knowledge are important for the reliable loose part monitoring/diagnosis
- Loose part could be originated from outside the pressure boundary

## Plan

- Participate to update the relevant IAEA TECDOC
- Recommend to revise the associated Standards and Guides (IEC, ASME/ANSI OM Guide, etc)

*Thank You Very Much.*

감사합니다.