Development of Under-Sodium Inspection Technique Using Ultrasonic Waveguide Sensor

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Outline

- Under-Sodium Viewing (USV) Sensors
- Development of Plate-type Ultrasonic Waveguide Sensor
- Feasibility Tests in Water
- Under-Sodium Plate Waveguide Sensor
- Performance Tests in Sodium
- Summary

KAERI

Under-Sodium Viewing (USV) in SFR

❑ SFR (Sodium-cooled Fast Reactor)

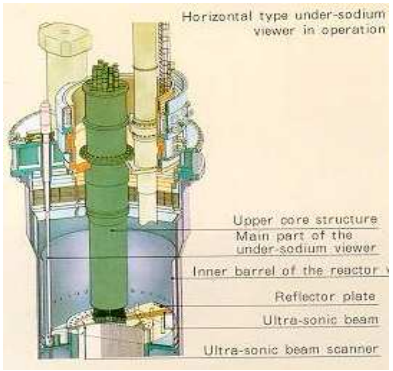
- – Sodium coolant : Opaque
- – Operation Condition
  - • High Temp. : 200~550 °C
  - • Low Pressure : 2~3 atm

❑ Under-Sodium Viewing (USV)

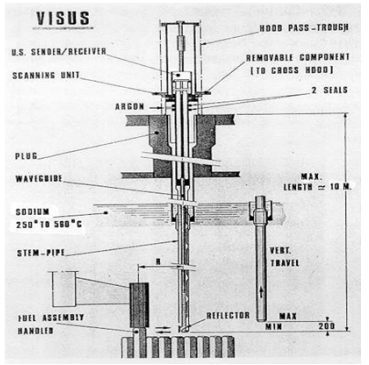
- – Could be essential for In-Service Inspection of reactor internal structures
- – Applications : Viewing, Ranging, Telemetry

❑ Technical Issue of USV

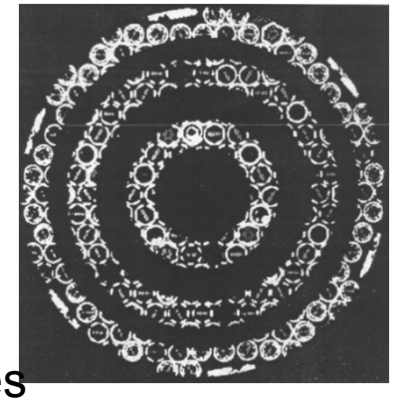
- – Development of reliable and sustainable ultrasonic sensors and inspection techniques in high temperature and high radiation sodium environment



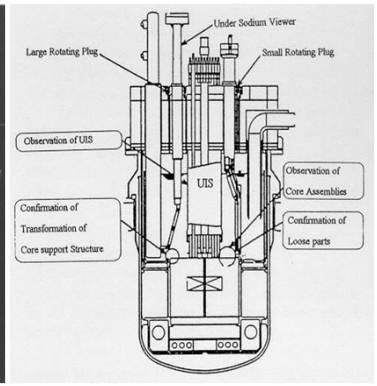
Under-Sodium Viewer of MONJU



VISUS of SPX



Ultrasonic Image of PFR Core



ISI of DFBR

KAERI

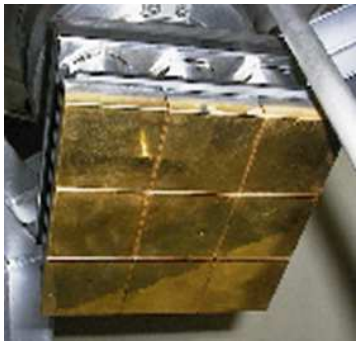
Under-Sodium Viewing (USV) Sensors in SFR

❑ Immersion Sensors

- High resolution imaging
- Short lifetime in hot sodium

➢ Single focus sensor
➢ Matrix array sensor

Single Element Sensor (France)

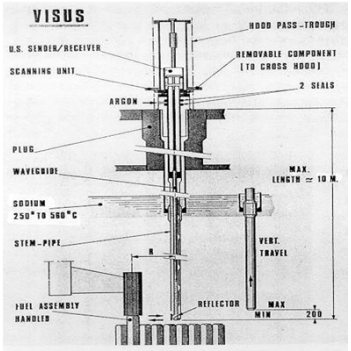


Matrix Array Sensor (Japan)

❑ Waveguide Sensors

- Alternative to immersion sensors
- Long lifetime in hot sodium
- Limitation of scanning and movement

➢ Rod-type Waveguide Sensor
  • VISUS
  • Rod WG sensor (ANL)
➢ Plate-type Waveguide Sensor
  • UKAEA (1982)



VISUS (France)

Rod Waveguide Sensor (USA, ANL)

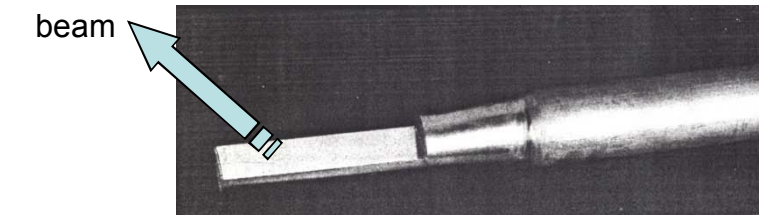


Plate Waveguide Sensor (UKAEA)

A Novel Plate-type Ultrasonic Waveguide Sensor

❑ Plate Waveguide Sensor

- Developed by KAERI
- Overcome limitations of previous USV sensors
- Guided wave technology
- Using A0 mode Lamb wave to create a leaky wave in a fluid
- Thin strip plate with an acoustic shield tube and a liquid wedge

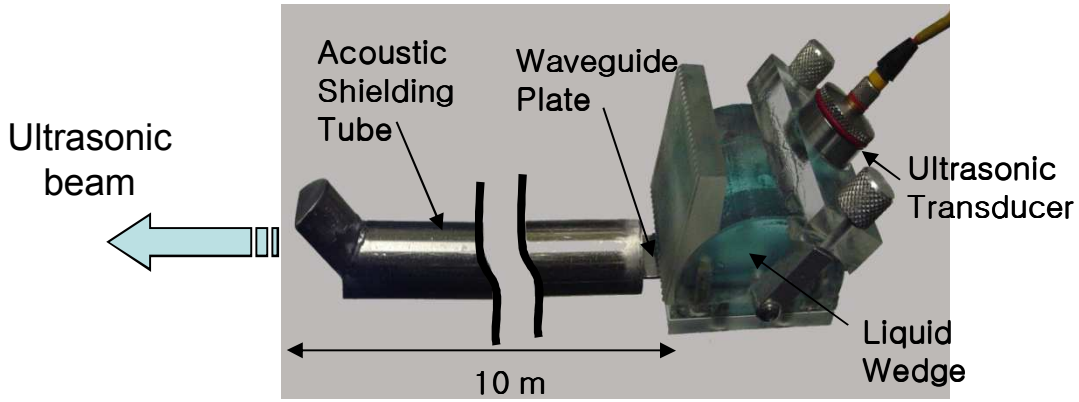


Plate Waveguide Sensor

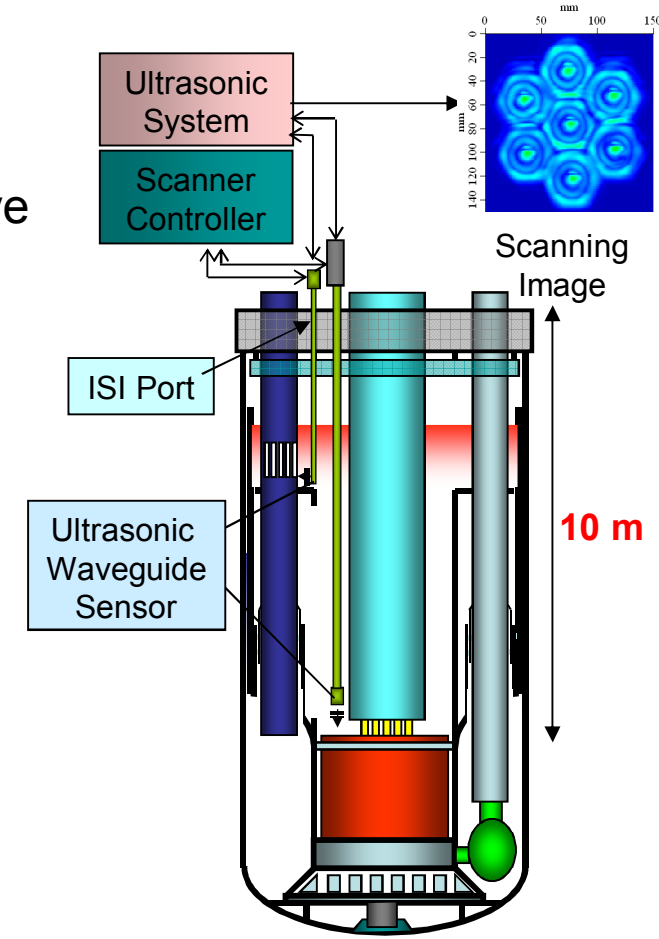


Plate Waveguide Sensor

❑ Liquid Wedge

– Effective generation of A_0 mode in the lower frequency range which has dispersive phase velocity

– Teflon wedge (V_w= 1340 m/s) : Alternative use

❑ Radiation Beam Steering

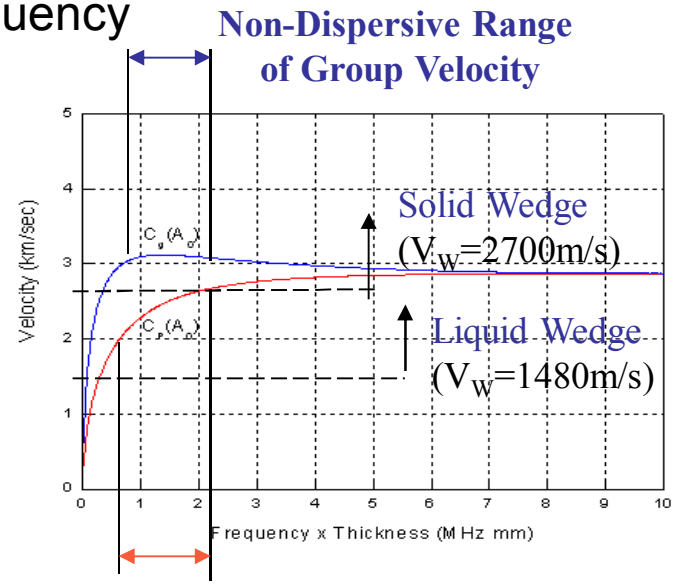
– Leaky wave in a fluid by mode conversion

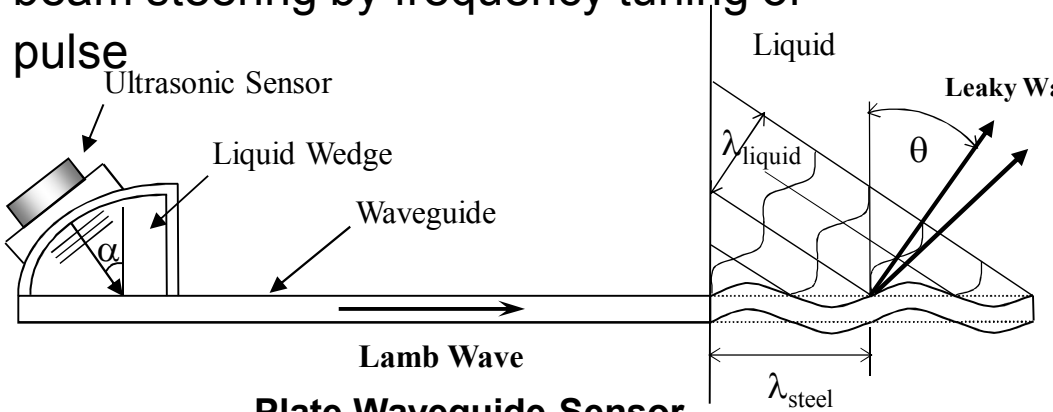
– Radiation beam angle : $\sin\theta(f) = \frac{V_L}{C_p(f)}$

– Frequency dependence of phase velocity of A_0 mode

- $C_p = C_p(f) \rightarrow \theta = \theta(f)$

– Radiation beam steering by frequency tuning of excitation pulse





$$\sin\theta(f) = \frac{V_L}{C_p(f)}$$

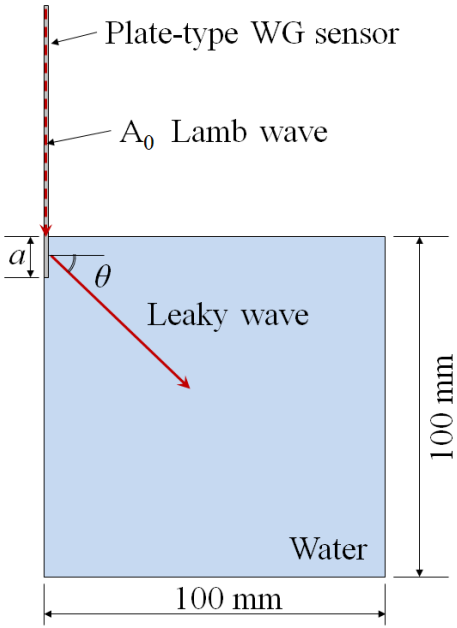
Plate Waveguide Sensor

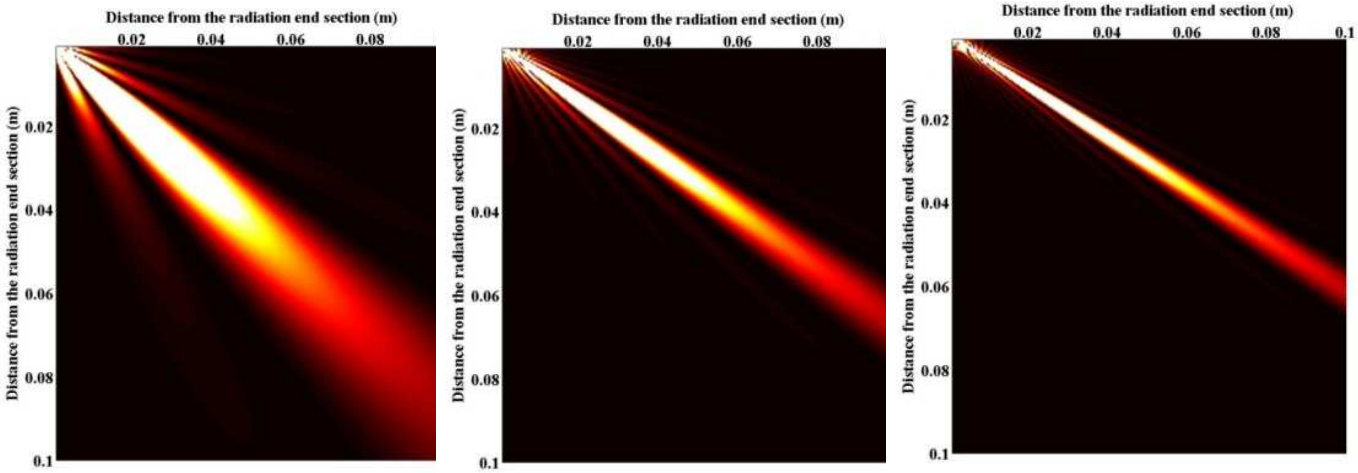
Radiation Beam of Plate Waveguide Sensor

❑ Theoretical Analysis of Radiation Beam Profile

– Radiation beam of leaky wave by far-field angular beam profile equation

$$\hat{p}^2 = \left(\frac{Ab\hat{p}_0}{r} \right)^2 \cdot \frac{1 - 2\cos(k_\theta a)e^{-\alpha a} + e^{-2\alpha a}}{\alpha^2 + k_\theta{}^2}$$





(a) 0.5 MHz (b) 1 MHz (c) 1.5 MHz

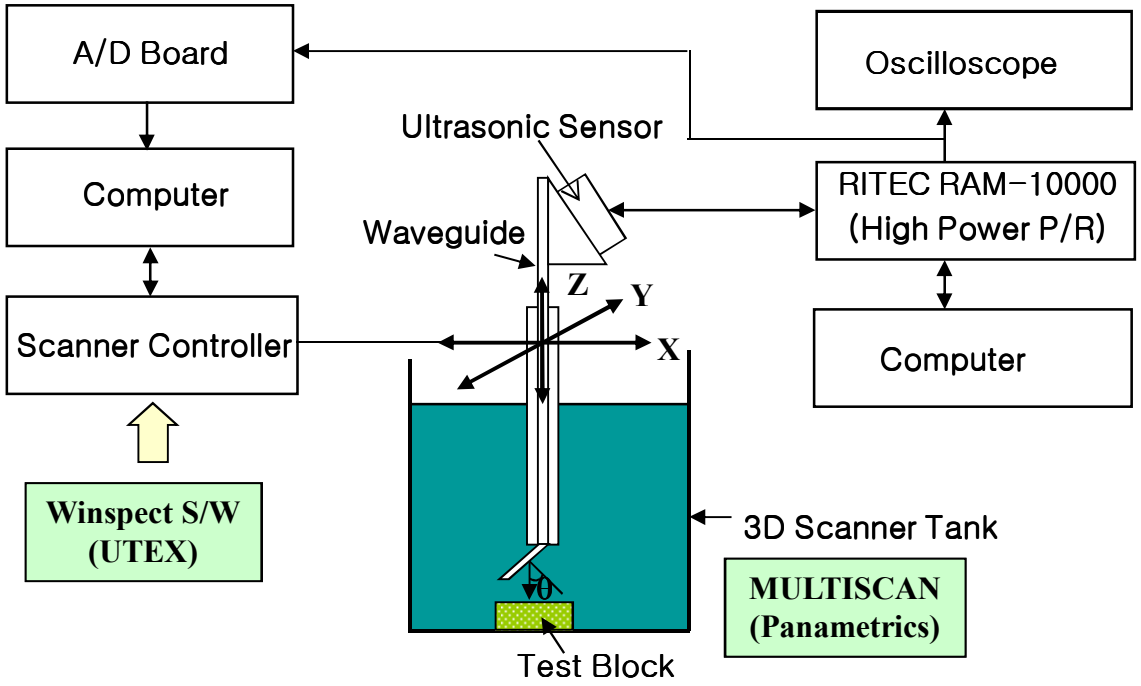
Radiation Beam Profiles (in Water)

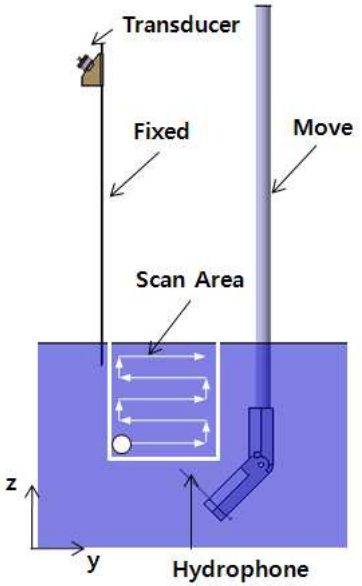
Experimental Setup for Beam Profile Measurement and C-Scan Test in Water

❑ Experimental Facility

- High power ultrasonic system
  - RITEC RAM-10000
    : Tone burst excitation
- C-scanning system
  - 3-D Scanner : MULTISCAN
  - S/W : Winspect™ (UTEX)

Experimental H/W Setup





Beam Profile Measurement (Scanning in Y-Z plane)

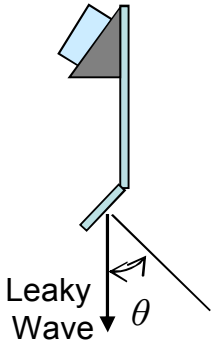
Radiation Beam Steering Technique of Plate WG Sensor

❑ Radiation Beam Steering

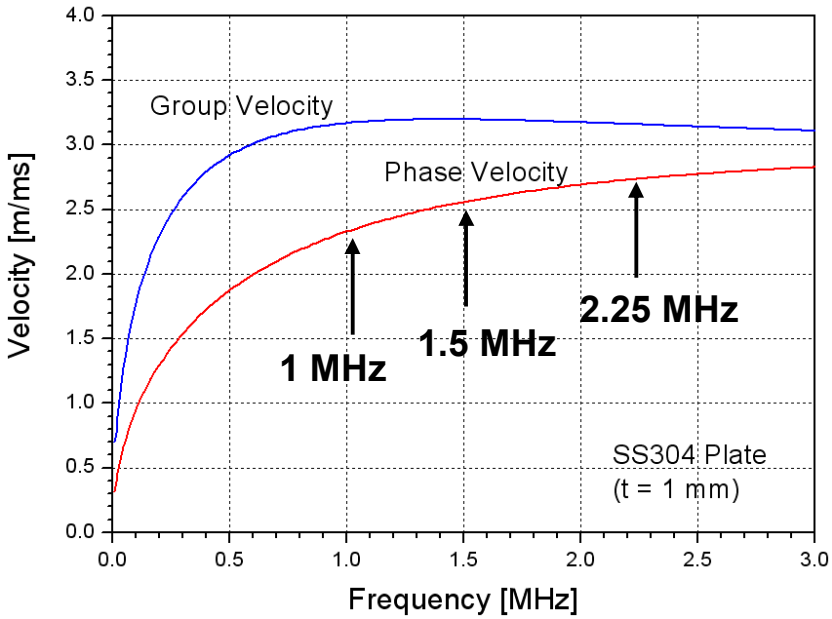
– Beam profile measurement for the verification of radiation beam steering

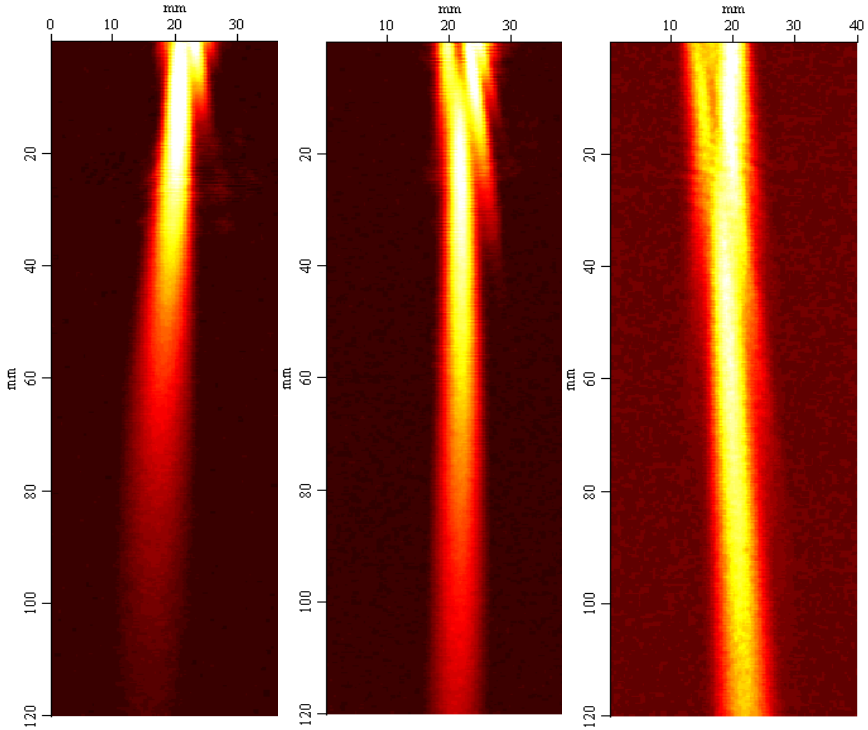
- Plate (t = 1 mm, L= 30 cm), 1, 1.5, 2.25 MHz Transducers

– Radiation beam can be steered by the electronics means of the excitation frequency tuning without mechanical movement



$$\theta(f) = Sin^{-1}\left(\frac{V_L}{C_p(f)}\right)$$



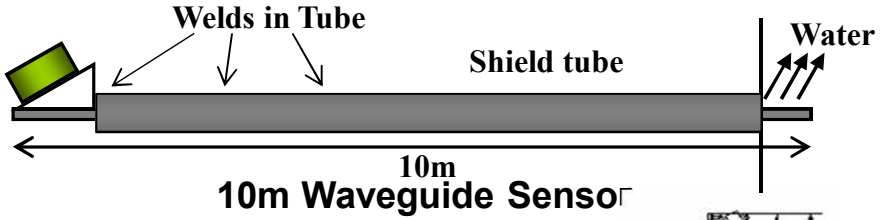


(a) 1 MHz (b) 1.5 MHz (c) 2.25 MHz

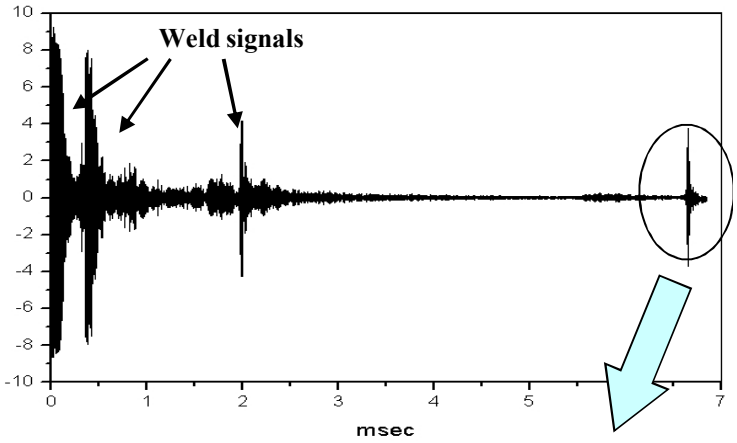
Sensitivity Test of Plate Waveguide Sensor

❑ Sensitivity Test

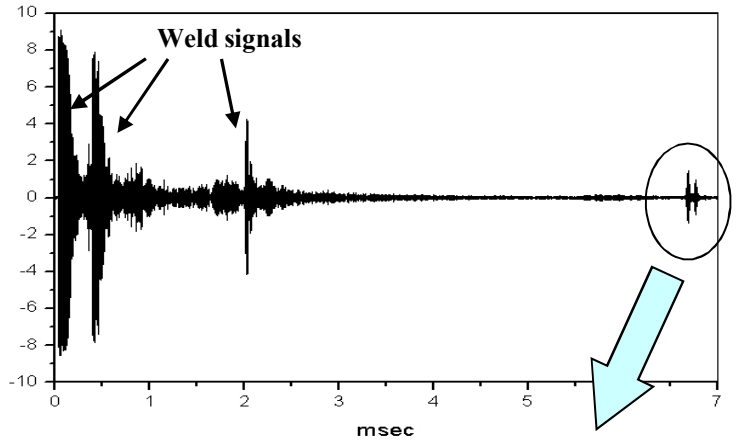
- Ultrasonic radiation beam echo signal from a target in water
- S/N ratio > 20dB

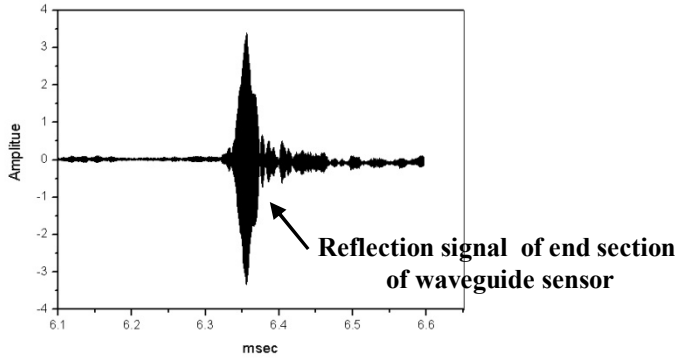


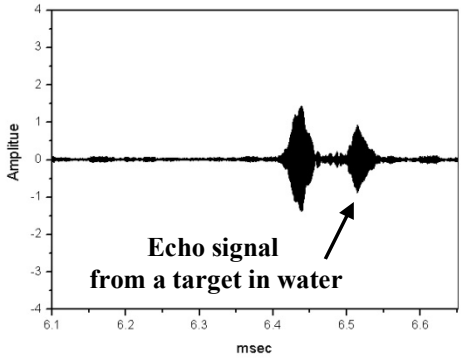
(a) Overall received signal in air

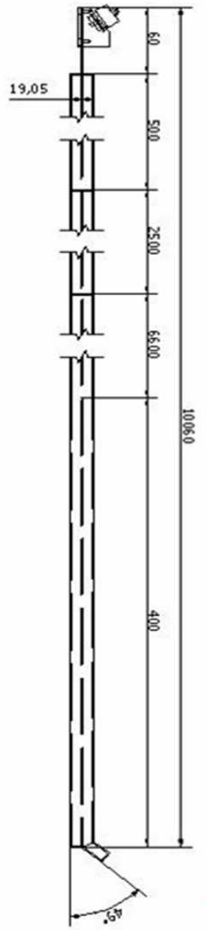


(b) Overall received signal in water





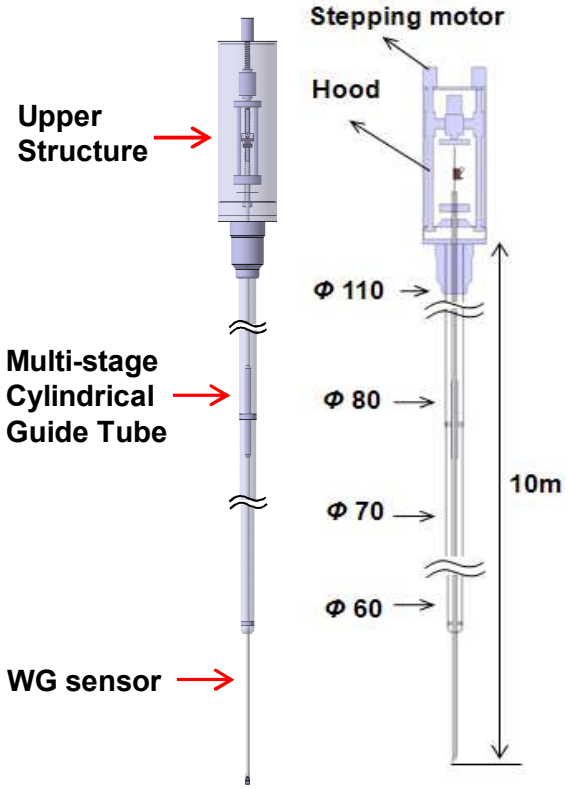




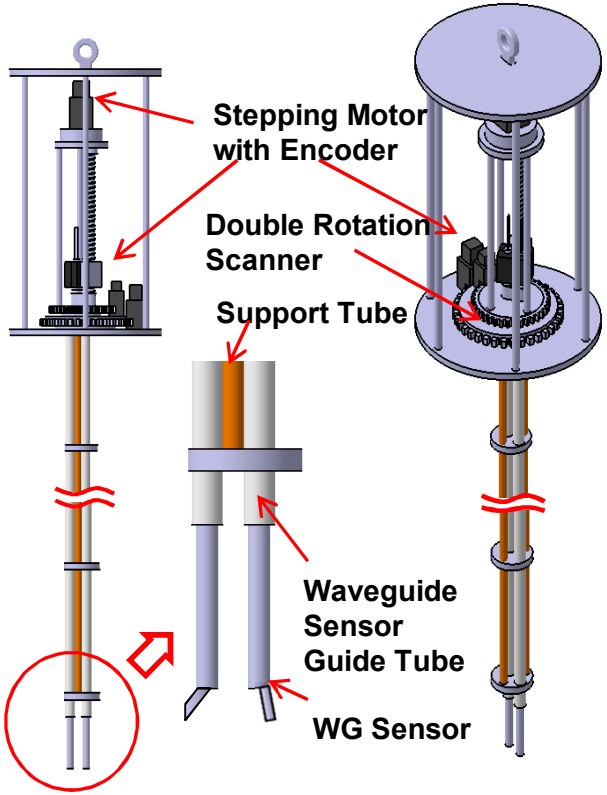
Prototype Waveguide Sensor Modules

❑ 10m Long Waveguide Sensor Modules

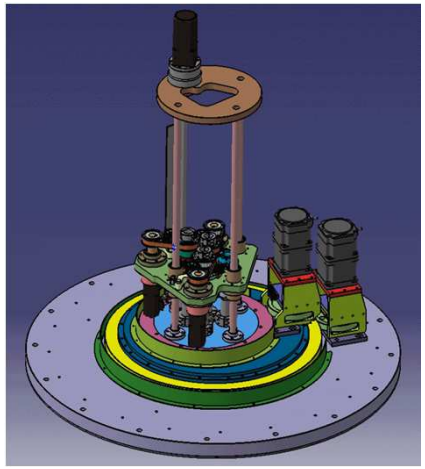
- Development for the applications to the remote under-sodium inspection
- Single waveguide sensor module : C-scan test in water
- Dual waveguide sensor module : Viewing application by self-scanning with internal double rotation scanner



Single Waveguide Sensor Module



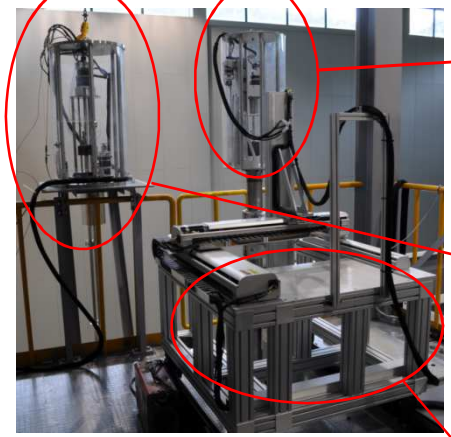
Dual Waveguide Sensor Module



Experimental Facility for Feasibility Test of Prototype Waveguide Sensor Modules

❑ Real Scale Experimental Facility for 10 m Waveguide Sensor Modules

13 m H-Beam Frame
(4m x 6m x 13m)

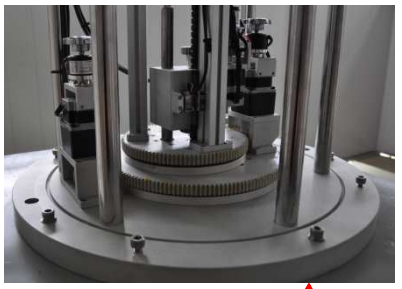


XYZ Scanner and
Waveguide Sensor Modules

Ultrasonic System and
Scanning Control System

Single Waveguide
Sensor Module
(XYZ Scanning)

XYZ Scanner

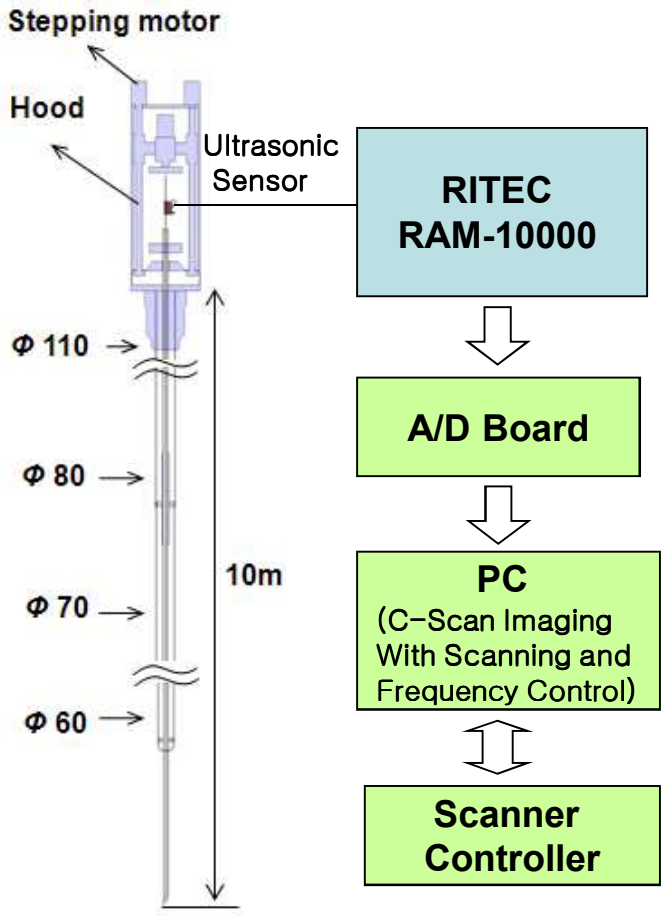


Dual Waveguide
Sensor Module
(Double Rotation
Scanning)

Feasibility Test of Waveguide Sensor Modules in Water

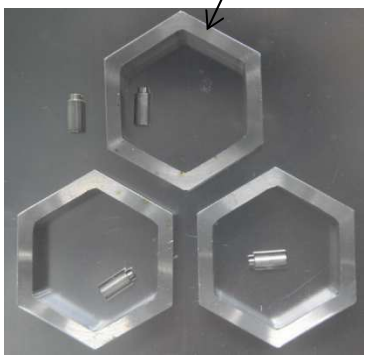
❑ C-Scan Imaging Resolution Test

- Test specimen : Core mockup, Loose part pins, Slits
- Resolution : 0.8 mm (1/32”)

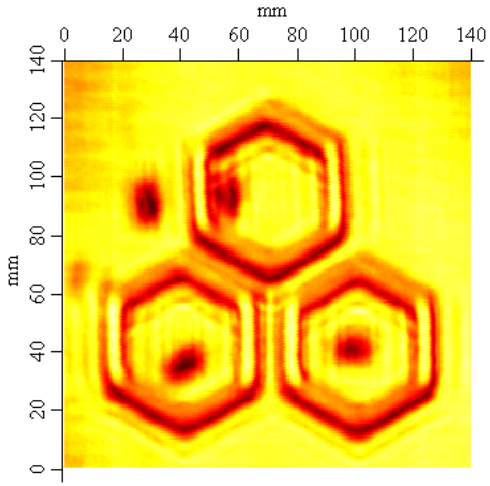


C-Scan Test of 10 m Single Waveguide Sensor Module

(W=5mm, L=30mm)

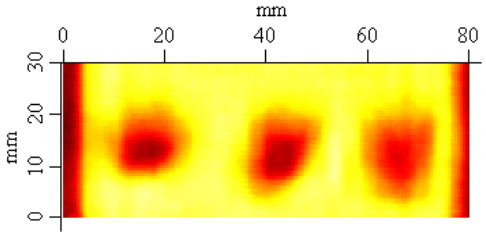


Core Mockup and Pins



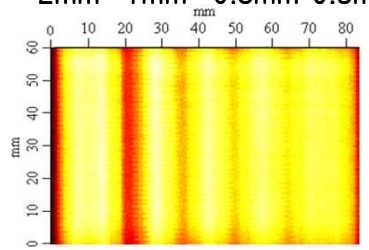
C-Scan Image

Loose-part Pins
(d=6mm, l=13mm)



C-Scan Image

2mm 1mm 0.8mm 0.5mm



C-Scan Image

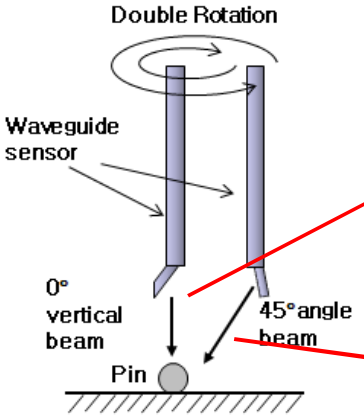
Development of Under-Sodium Visualization Program

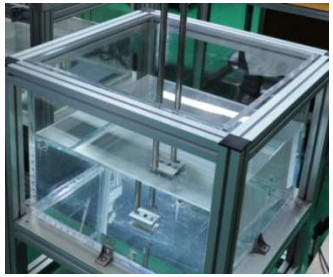
❑ Under-Sodium Visualization Program (US-MultiVIEW)

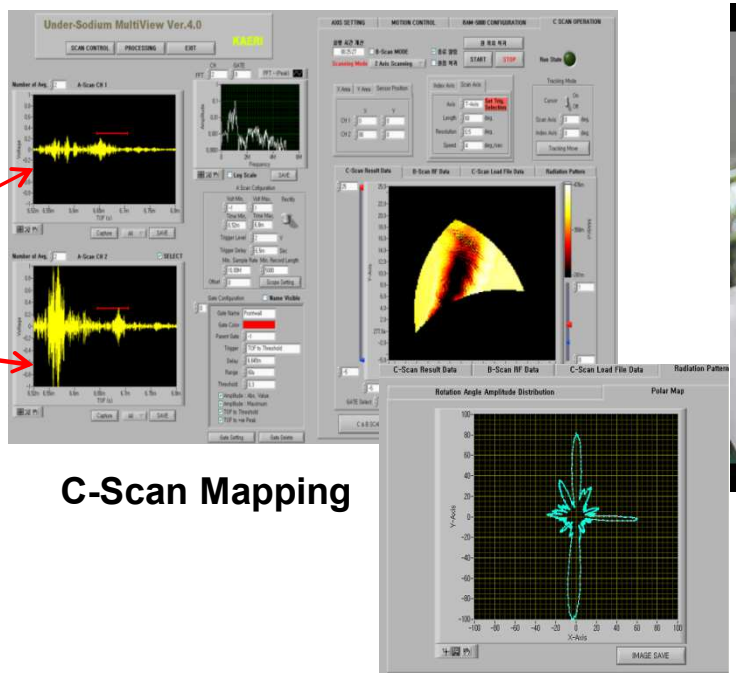
– Double rotation C-scan control and visualization mapping of dual WG sensor module using LabVIEW graphic language

– C-scan image and pattern mapping by self double rotation scanning in the localized area

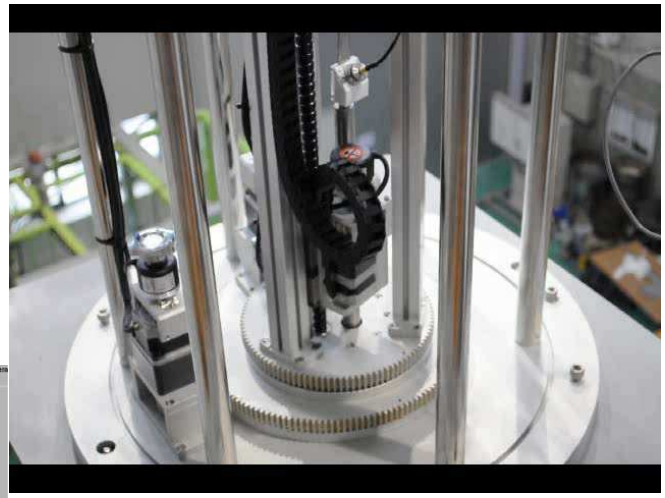
- C-scan mapping image by double rotation scanning of 0° vertical beam
- Loose parts identification by radiation pattern mapping of 45° angle beam







C-Scan Mapping



SRP : Φ 109 mm
LRP : Φ 180 mm
Off-set : 20.45 mm

Radiation Pattern Mapping

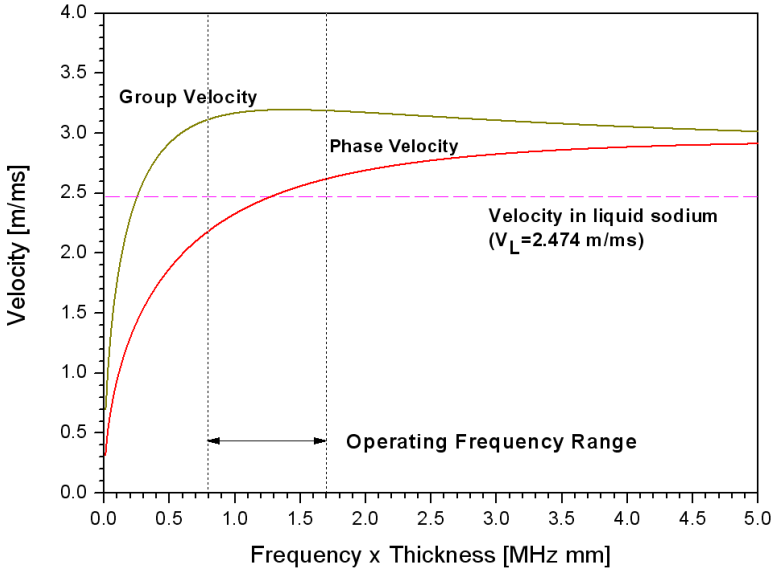
Under-Sodium Application of Plate Waveguide Sensor

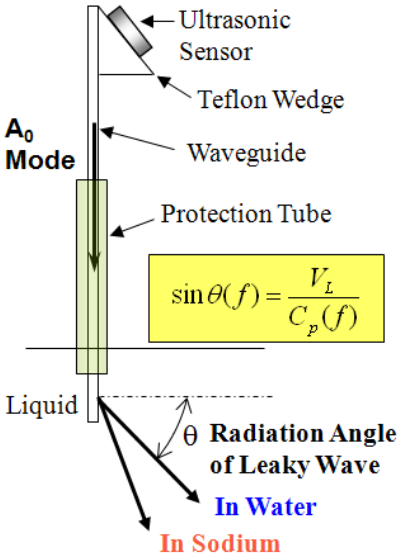
❑ Technical Aspects in Under-Sodium Application

- Longitudinal velocity of liquid sodium (2474 m/s) is higher than the phase velocity of A0 mode Lamb wave

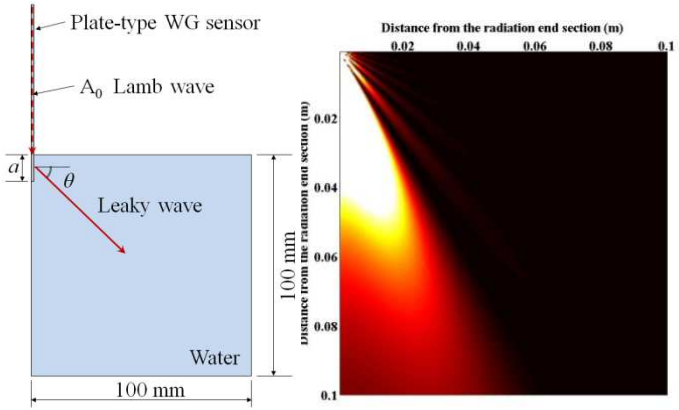
  ⇒ Inability of generating an acoustic beam in sodium

  Generation of large angle beam and wide beam spread





fd	C_p (A_0) [m/s]	Radiation Angle (θ) [degree]	
		Sodium (V_L=2474m/s)	Water (V_L=1480m/s)
0.5	1846	-	53.3
1.0	2290	-	40.3
1.5	2511	80.2	36.1
2.0	2640	69.6	34.1
2.5	2715	65.7	33.0
3.5	2803	62.0	31.9



Radiation Beam Profiles in Sodium

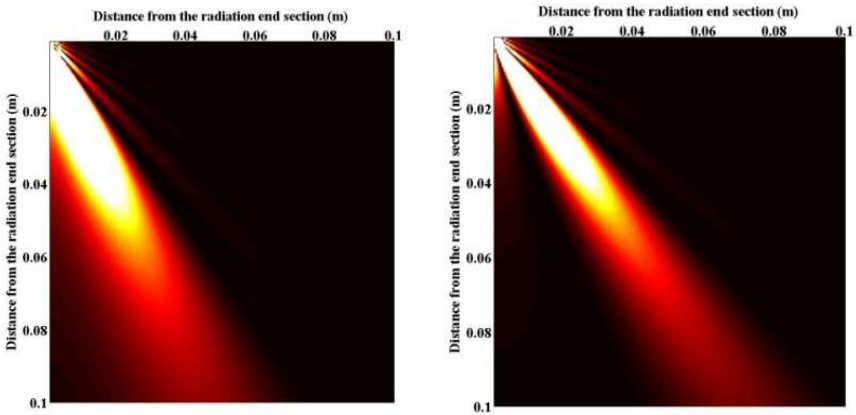
Plate Waveguide Sensor with a Beryllium Coating Layer

❑ Performance Improvement of Radiation Beam in Sodium

- Requirement of high phase velocity of the waveguide plate
- Fundamental idea to coat the waveguide plate surface with a thin layer of high velocity material
- Beryllium (Be) : Fastest ultrasonic velocity among natural material
- Effect of Be coating : Increasing phase velocity

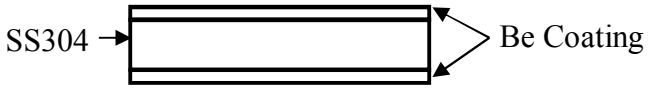
※Beryllium : - ρ : 1820 kg/m^3
- V_L : 12,900 m/s, V_s : 8,800 m/s

SS304 : - ρ : 8030 kg/m^3,
- V_L : 5,690 m/s, V_s : 3,040 m/s

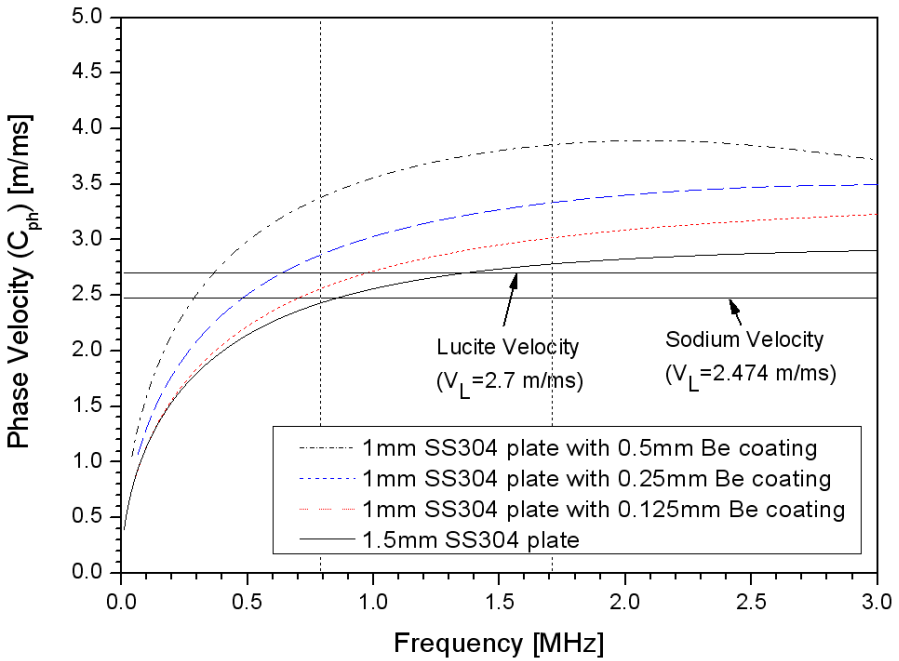


(a) 0.125mm Be Coating (b) 0.25mm Be Coating

Radiation Beam Profiles of SS304 Plate with Be Coating Layers (in Sodium)



Be Coating Plate



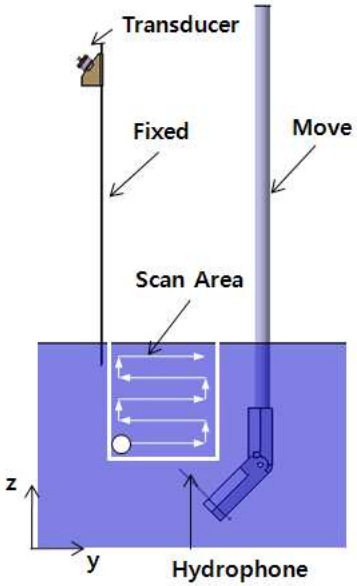
Phase Velocity of Be Coating Plate

Experimental Verification of Be Coating Effect

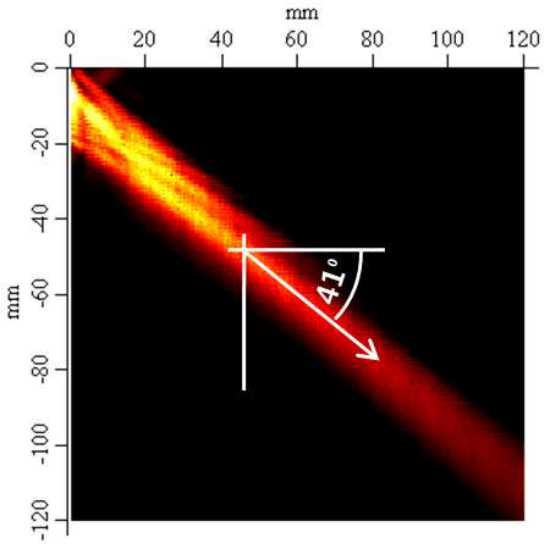
❑ Radiation Beam Profile Measurement

- Experimental verification by beam profile measurement of Be coating WG sensor
  - SS304 plate (t=1 mm, w=15 mm, L=400 mm)
  - SS304 plate coated with Be (both side 0.25 mm)
  - Hydrophone scanning in Y-Z plane
- Radiation beam angle decreases from 41° to 31 ° due to the increase of the phase velocity of A_0 mode by the Be coating effect.
- The measured radiation angles coincide with the theoretical calculation results

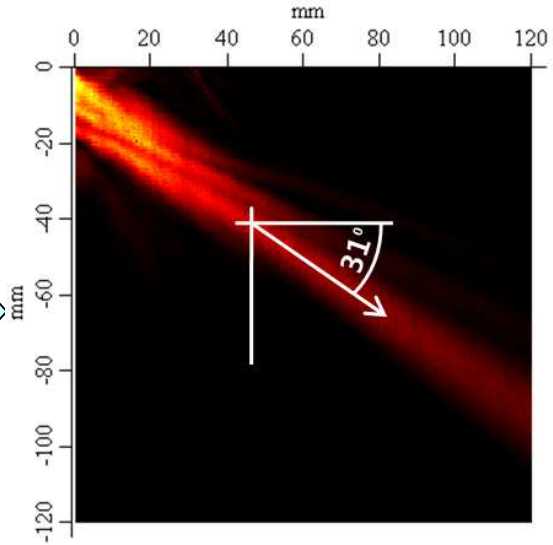
Be Coating Plate



Beam Profile Measurement (Scanning in Y-Z plane)



SS304 Plate Sensor
(T= 1 mm)
Frequency : 1 MHz, 4 Cycles
Beam Angle : 41º (in water)

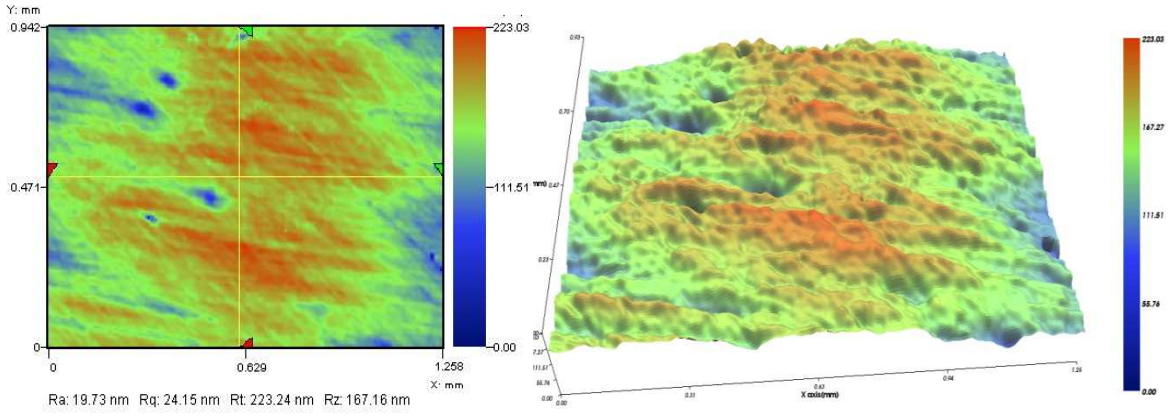


Be Coating Plate Sensor
(Both side : Be 0.25mm)
Frequency : 1 MHz, 4 Cycles
Beam Angle : 31º (in water)

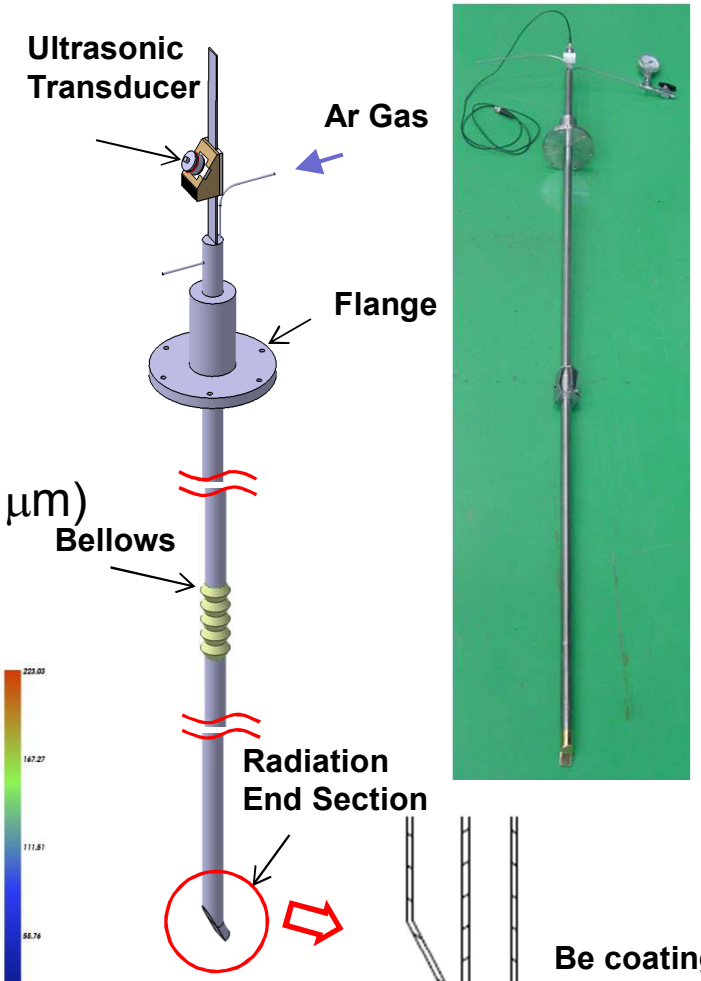
Under-Sodium Plate Waveguide Sensor

❑ Under-Sodium Plate Waveguide Sensors

- SS304 Plate : t=1.5mm, L=1.7 m / 10 m
- Ultrasonic Transducer : 1 MHz, Dia. 0.25”
- Inside surface of radiation end section
  : Be coating (0.25 mm)
  → Decrease of radiation angle in sodium
  (V_L= 2474 m/s) : 75° → 62°
- Outside surface of radiation end section
  : Ni coating (0.1 mm) and Polishing (0.01~0.02 μm)
  → Improvement of sodium-wetting



Average Roughness (R_a=0.019 μm)



Under-Sodium Waveguide Sensor Module

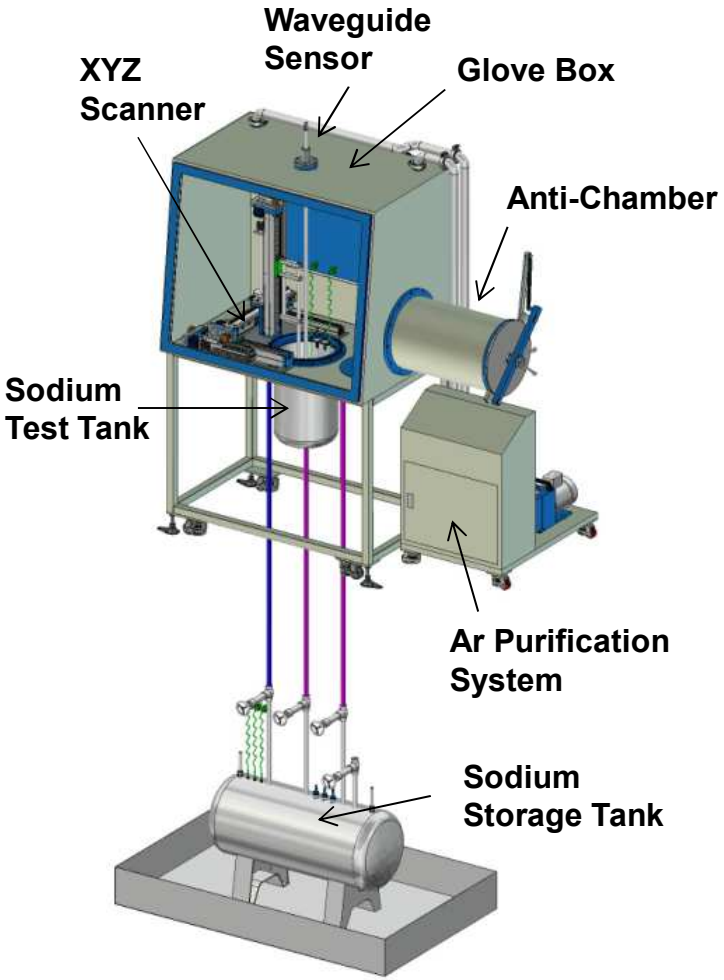
Sodium Test Facility

❑ Design and Construction of Sodium Test Facility

– Performance demonstration of ultrasonic waveguide sensor in sodium condition

- Glove box system with anti-chamber
- Ar Purification System
- Sodium storage tank and piping lines
- Sodium test tank : Open-type
- XYZ Scanner

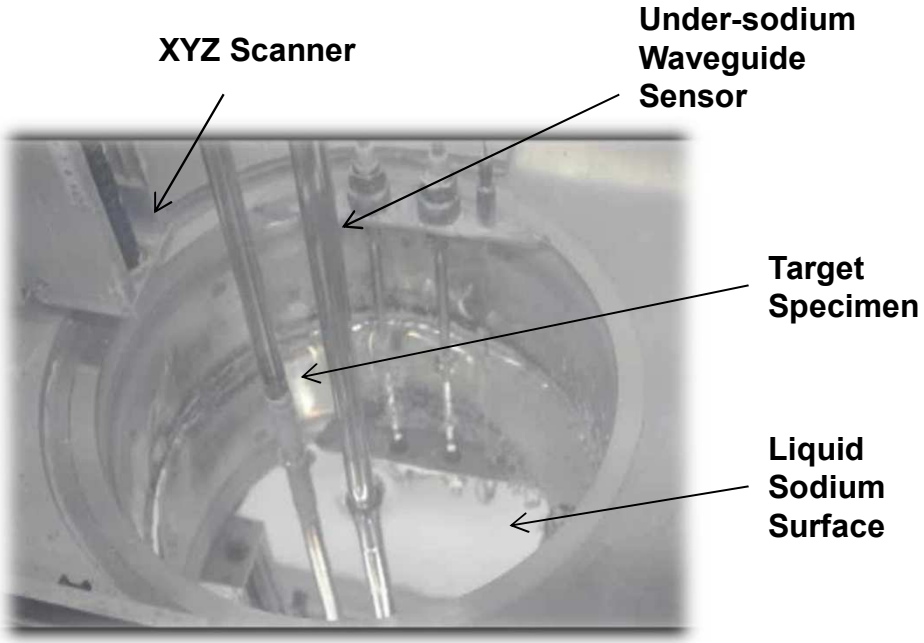
Sodium Test Experimental Facility
(Glove Box System and Sodium Tanks)



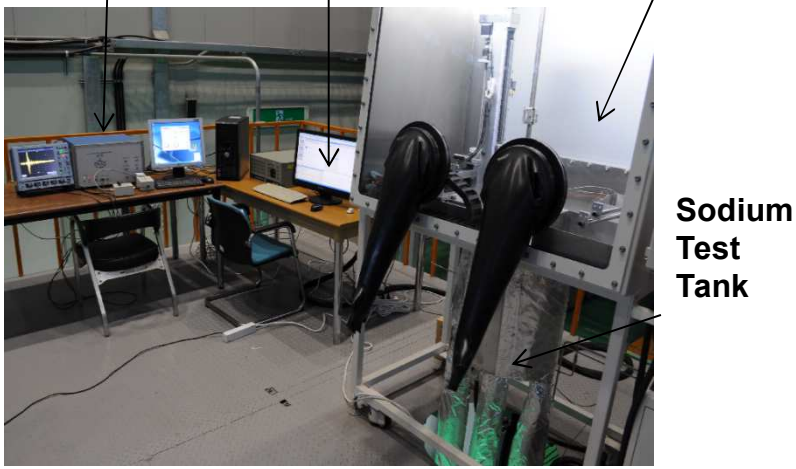
Glove Box and Sodium Tank

Performance Test of Under-Sodium WG Sensor in Sodium

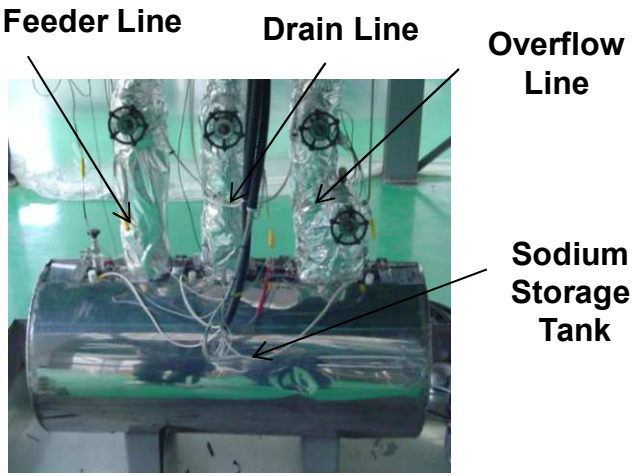
- **Ultrasonic Wave Propagation Test and C-Scan Test in Sodium**
  - XYZ scanning system
  - High power UT system
  - Sodium Temperature : 200 ~ 250 °C



C-Scan Imaging Test in Sodium



Glove Box with Sodium Test Tank And UT System

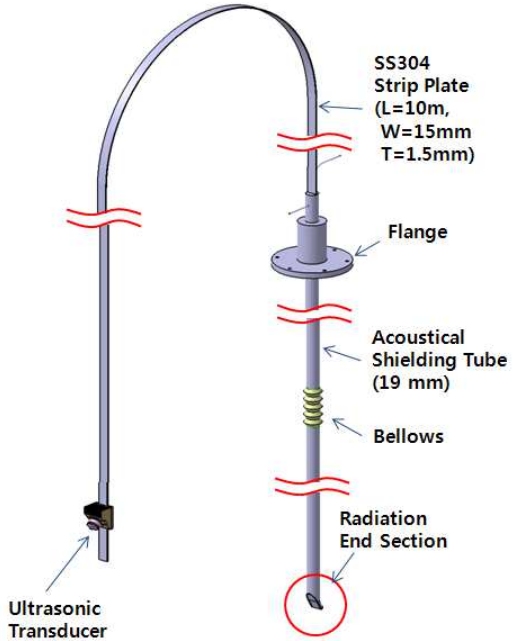


Sodium Storage Tank

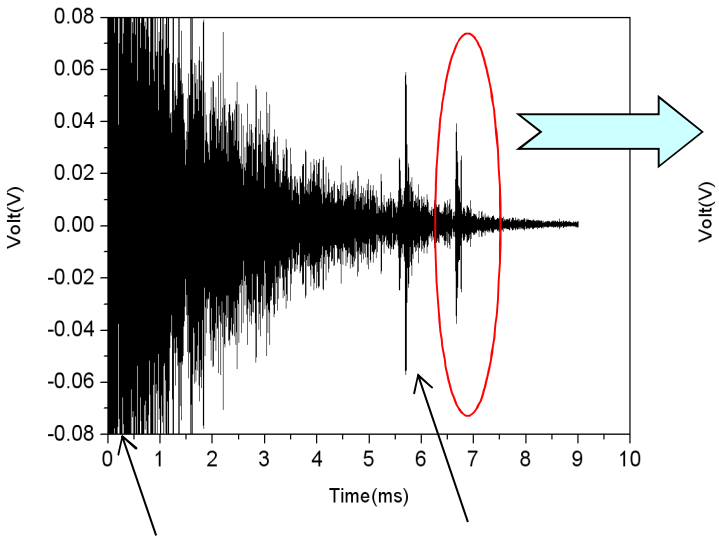
Performance Test of Under-Sodium WG Sensor in Sodium

❑ Ultrasonic Wave Propagation Test in Sodium

- 10 m long under-sodium plate waveguide sensor
  : 1.5t SS304 Plate, Teflon Wedge, 1MHz
- Excitation frequency : 1.0 MHz, Pulse : 8 cycles
- Sodium temperature : 200 °C
- Signal to Noise (S/N) ratio = 10 dB
  (Signal = 28 mV, Noise = 8 mV)

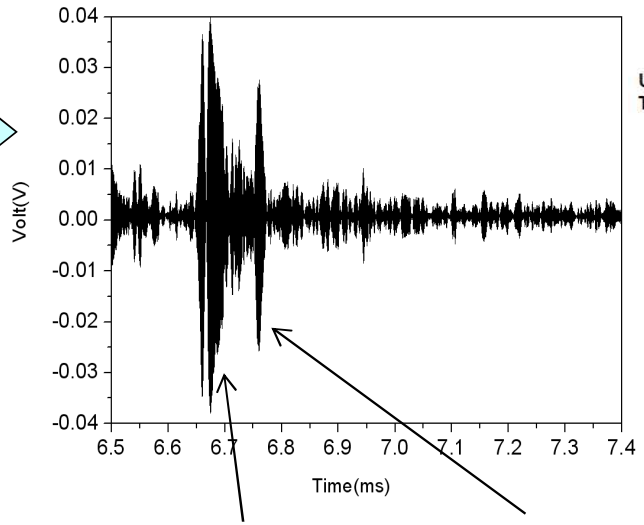


10 m Plate WG Sensor



Main Bang
Initial Signal

Weld Reflection Signal
in Waveguide Sensor



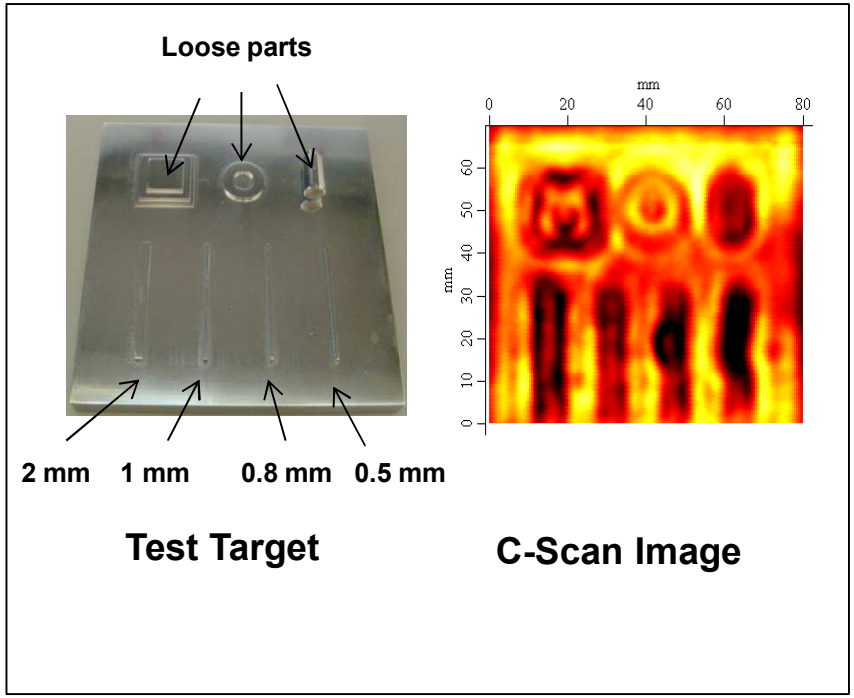
End Reflection Signal
from Waveguide Sensor

Target Reflection
Signal

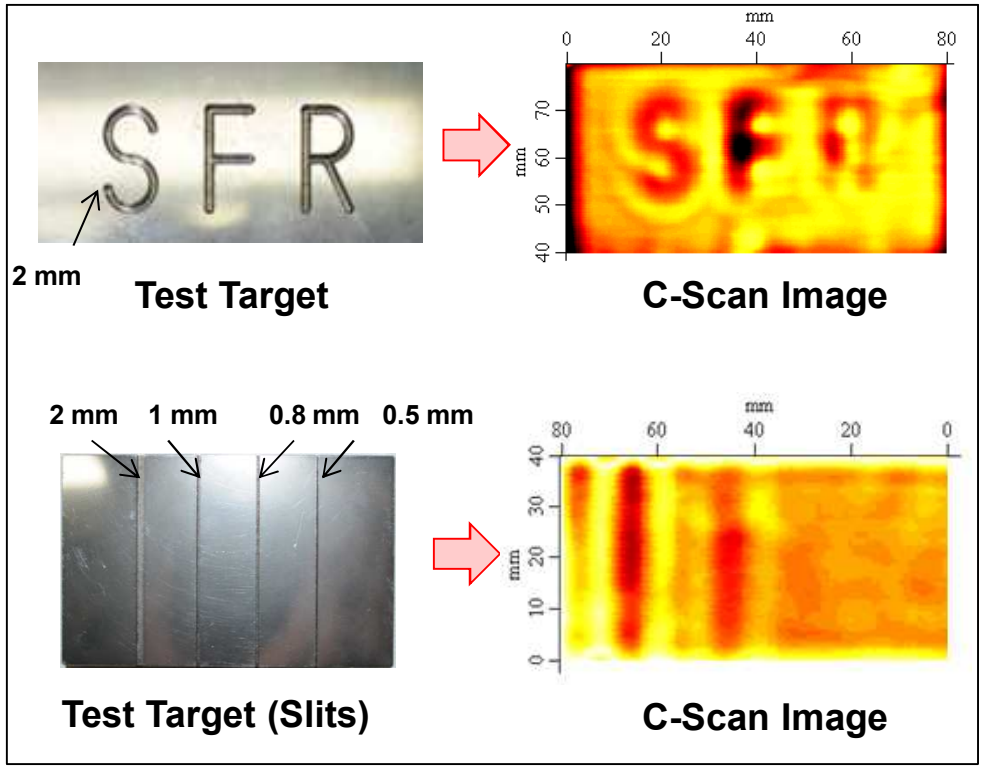
Performance Test of Under-Sodium WG Sensor in Sodium

❑ C-Scan Imaging Test in Sodium (10 m Long Distance)

- 10 m long under-sodium waveguide sensor
  - 1.5t SS304 Plate (L : 10m)
  - Teflon wedge, 1MHz Transducer
- Excitation Freq. : 0.94MHz, Pulse : 8 cycles
- Sodium temperature : 250 °C



Protrude Defects



Engrave Defects

Summary

- A new idea and concept of plate-type ultrasonic waveguide sensor and inspection technique have been suggested for under-sodium viewing
- Development of 10m long waveguide sensor modules and visualization software program
- Feasibility verification of 10 m waveguide sensor modules in water
- Development of under-sodium ultrasonic waveguide sensor with Be and Ni coating layers
- Setup of sodium test facility and performance demonstration of under-sodium waveguide sensor in sodium

Thank You for Attention !