Ultrasonic Inspection of CANDU Fuel Bundles for Water Ingress In Defective Fuel Elements

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Presentation Guideline

• Introduction
• Motivation / Previous Works
• Theory of Ultrasound NDT
• Experimentation
• Data Collection/Analysis
• Conclusion/Recommendations
CANDU (CANadian Deuterium Uranium) Reactor

*Courtesy of Dr. Ali El-Jaby.*
37 elements in a fuel bundle (CANDU 6)
- Hold in place by endplates
- Each element contains columns of fuel pellets (~16mm in length) enclosed by Zircaloy sheath
- Outermost ring has high power profile
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Defective Fuel Element

- Breach in the sheath
- Leaking of fission product
- Increase in coolant activity level
- Water ingress
Current Post Irradiation Examination

1. **Coolant activity**

2. Discharge suspect fuel bundles to fuel bay (if possible leaker can be identified)

3. Visual inspection for sheath breach

4. Identified bundles sent for detailed metallographic examination at Chalk River to determine root cause
Previous Work

• Use Ultrasound to detect presence of water
• Designed for Light-water reactors’ vertical fuel assembly
• Ultrasonic wave enters the sheath at normal incidence
  – Careful tuning and equipment setup
How does it work?

Relative signal intensity vs. Relative time delay.

- **Intact Fuel**
  - Sheath
  - Fuel rod interior without water

- **Defective Fuel**
  - Sheath
  - Fuel rod interior with water ingress
What can be improved?

• For CANDU fuel bundle inspection
  – Much tighter gap between fuel elements
  – Horizontal orientation

• Software controlled inspection system
  – Reduce radiation exposure to technician
  – Reliable and repeatable results

• Robust, fast, and accurate
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What is Ultrasound?

• Sound wave greater than 20 kHz
• Propagates in elastic media
  – Speed as a function of Young’s modulus
• Four general wave modes
  – Longitudinal (sound you hear)
  – Shear (slinky)
  – Lamb (plate vibration)
  – Surface wave (elliptical motion)
Generation of Ultrasound

- Ultrasound probe
  - Piezoelectric crystal generates mechanical stress under applied voltage
  - Process is reversible
  - Pulse-echo inspection technique
- Only Longitudinal waves are generated with the ultrasound probe
- Different wave modes are generated at the media boundary or within media
  - Zircaloy sheath
Modes of Wave Propagation

Relative wave magnitude

1st critical angle

Relative incident angles

2nd critical angle

Longitudinal

Shear

Surface

Wavelength \( \lambda \)

Particle motion

Direction of travel

Longitudinal wave

Asymmetric Lamb wave

Symmetrical Lamb wave
Acoustic Impedance

\[ Z = \rho V \]

- Acoustic impedance
- Medium density
- Wave propagation velocity

Minimal difference between media impedance = Maximum acoustic energy through boundary
Transmission and Reflection Coefficients

Transmission Coefficient

\[ T = \frac{I_t}{I_i} = \frac{(4Z_2Z_1)}{(Z_2 + Z_1)^2} \]

Reflection Coefficient

\[ R = \frac{I_r}{I_i} = \left[ \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \right]^2 \]

\[ T + R = 1 \]
Transmission Coefficients for Intact and Defective Fuel

- High reflection (low transmission) coefficient results in stronger received signal
- Zircaloy-Helium transmission coefficient
  \[- = 1.6 \times 10^{-5} \ll 1\%
- Zircaloy-Water transmission coefficient
  \[- = 0.125 \text{ or } 12.5\%

Intact Fuel Element

Medium A: Zircaloy sheath
Medium B: Element interior

Defective Fuel Element

Medium A: Zircaloy sheath
Medium B: Element interior
Principles of Defective Fuel Element Inspection: Intact Fuel

Probe

He-gas

Fuel pellet

Zr-4

Zr-4
Principles of Defective Fuel Element Inspection: Defective Fuel Fuel pellet

Probe

Water ingress

Variation in signal magnitude
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UT Scan System

- Processor/Monitor
- Actuator with X-Y motion
- Ultrasonic probe
- Half-cylinder that contains water and fuel element
- Remote controller
- System amplifier
Fuel Elements

Submerged under-water during ultrasonic scan

Intact (experimental control)  Defective

Holes were drilled to allow water ingress
Scan Setting

- Scan the length of fuel element
- Scan speed during experiment: 1.3 cm/s (or 0.5 Inch/s)
  - Prevent wave generation
- Can go as fast as 5 cm/s (or 2 inch/s) without compromising quality
Data Presentation

- Three A-scan from various location of specimen

Signal magnitude

Ultrasonic wave

Test specimen

B-scan (compilation of many A-scan data)

X-axis

Signal magnitude is represented by color
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Normal Incidence

Intact fuel element

- Bearing pad
- He-gas
- Sheath
- Pellet
- End cap

*Not drawn to scale
Normal Incidence

Defective fuel element

- Bearing pad
- Water
- Sheath
- Pellet
- End cap
Oblique Incidence at 30° with Respect to Normal

Still traverse along the length of the fuel element
Results (30°)

Time delay

Unmodified

Water ingress

16 mm

X- displacement
Why do they look so different?

- Shear wave mode only occurs in the sheath
- Noise and back-wall echoes are reduced significantly
- Long white stripes are results of each “bounce” on the walls of pellet end
Results: Incidence at 50°
Looks even more different?

- Lamb wave region at this angle
  - Axial mode in the sheath
  - Induces longitudinal wave in the interior
- Sheath is no longer visible on the B-scan
- White stripes result in the same way as that of 30°
Which angle is the best?

Compilation of B-scans for defective fuel element for various incident angles (from 30 to 65 degrees with respect to normal)

Shear wave mode: 30 to 35 degrees
Lamb wave mode: 50 to 55 degrees
Induced-Source-Effect

- Slanted stripes that are 16 mm apart (length of fuel pellet)

(Left) Water ingress in a defected fuel rod at a 30 degrees incident angle and (right) blow up of region outlined by the white rectangle.
• Generation of trapped sound between the two concave ends of the fuel pellets
• Secondary wave point sources are induced in which will reach the transducer at times corresponding to their relative distance to the probe
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Conclusion

• Fast (inspection requires less than 10s/element), easy to use (all software controlled) technique for water ingress detection in defective fuel elements were implemented

• Oblique incidence provided a clearer result
  – Characteristic white stripes that are ~16 mm apart

• Possibility to routinely and efficiently inspect CANDU fuel bundles (a capability that currently does not exist!)
  – A gap in the industry that is yet to be filled
Recommendations

• Develop inspection for the inner-ring elements
  – Aim the probe at the gaps near end plate location
  – Scan specific length of an element by tilting probe

• Testing on an irradiated fuel element
Acknowledgement

• Stern Lab where the experiments were done
  – Gordon Hadaller and Ed Ritchie
• Dr Lewis and Dr Krause
• NSERC research fund