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Effects of Acoustic Impedance on Spent Nuclear Fuel Ultrasonic Inspection

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1. Introduction

Currently, Visual inspection Test (VT), In-Mast Sipping test (IMS) and Ultrasonic fuel inspection test (UT) Methods are used to find defective fuel rods in domestic PWR. Visual inspection can mainly find defects in the structure of the fuel assembly, defects in the spacer grid and defects in the outer fuel rod of the fuel assembly, but there are limitations in finding defects in the inner fuel rod of the fuel assembly and defects in the fuel rod inside the spacer grid. The In-Mast Sipping test can determine whether the fuel assembly is defective, but it cannot find defective fuel rods. For this reason, Ultrasonic Test is used as a practical method of finding defective fuel rods.

In the reported studies, fuel rod burn-up, oxide thickness of the fuel rod surface, alignment of UT probe and fuel rod, and location of fuel defects are factors influencing the reliability of UT, and statistically derived UT reliability is about 80~90% [1]. KHNP also conducted UT demonstration test on fuel assembly with various fuel types, cooling periods and burn-up histories to confirm the reliability of UT [2]. In the test, we realized that the acoustic impedance affects the determination of fuel rod defects using UT. In this paper, we introduce the mechanism by which acoustic impedance affects the determination of fuel rod defects in UT and propose a method to increase the reliability of UT.

2. Determination of defective fuel rod by UT

If signs of fuel defects in the reactor are identified, the defective fuel rods will be found and repaired during the plant overhaul, and the cause of the fuel rod defects will be determined. Since the ultrasonic fuel inspection is performed one to two weeks after the reactor is shut down, the pressure inside the fuel rod decreases as the fuel rod cools, and water enters the defective point. Water entering the defective part is collected by moving to the lower part of the fuel rod by the spent fuel pool water pressure and gravity. Ultrasonic inspection is performed on the lower side of the fuel assembly, and when the ultrasonic probe is inserted in a direction perpendicular to the fuel rod and comes into contact with each fuel rod cladding, ultrasonic waves are transmitted from the emitter of the probe and received by the receiver. At this time, the ultrasonic wave transmitted from the probe emitter is reflected from the inner and outer boundary surfaces of the cladding, and proceeds along the circumferential direction of the cladding and is received by the receiver. When the transmitted ultrasonic waves are reflected on the inner and outer boundary surfaces of the cladding, they pass through the boundary surface or are reflected at the boundary surface, and are scattered and attenuated by deposits of cladding material. If received ultrasonic wave level exceeds the set signal level, it is determined to be a normal fuel rod without water. (see Fig.1 (a)) When water is present inside the fuel rod, ultrasonic waves reaching the inner boundary surface of the cladding are attenuated by water, so that the received ultrasonic signal level does not exceed the gate level, so it is determined as a defective fuel rod. (see Fig.1 (b))

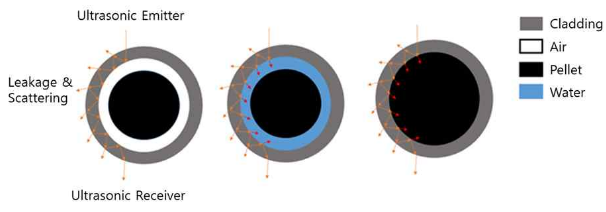

Fig. 1 Progress of ultrasonic waves in cladding

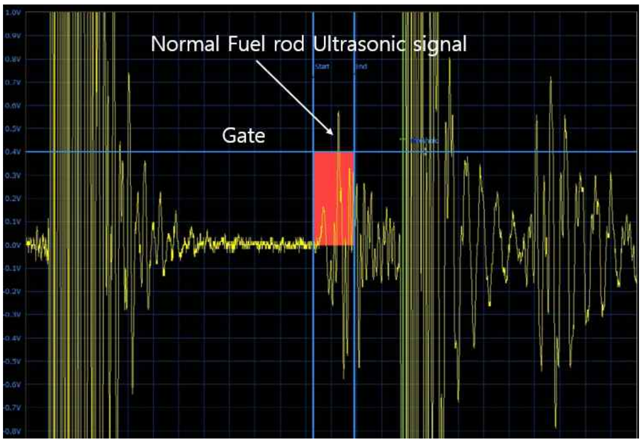

Fig. 2 UT signal of normal fuel rod

3. Acoustic Impedance effects of defective fuel rod determination

3.1. Acoustic Impedance

Acoustic impedance is calculated by multiplying the density(ρ) of material and the speed(V) of the waves in the material. Table 1 shows the acoustic impedance of air, water, uranium oxide and zircaloy.

Table 1. Acoustic impedance

Material	Density (kgm^{-3})	Speed of sound (ms^{-1})	Acoustic Impedance ($kgm^{-2}s^{-1}\times10^6$)
Air	1.204	340	0.000409
Water	998.2	1482	1.479
Zircaloy	6560	4724	30.989
UO2	18700	3370	63.019

When the waves are incident on the interface of two materials, the ratio of reflection is determined by the acoustic impedance of the materials. The ratio of the reflected intensity *r* is given by;

$$\gamma = \frac{I_r}{I_0} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Where I_r: the intensity of the reflected wave
I_0: the intensity of the incident wave
Z ($= \rho V$): Acoustic impedance

When sound waves meet the interface of two material with a large impedance difference, they are reflected from the interface, and when they meet the interface of two material similar impedance differences, they pass through the interface.

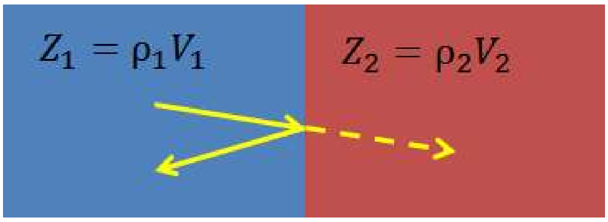

Fig. 3 Reflection and pass-through of the wave due to acoustic impedance difference

3.2 HBS and Pellet cladding bonding

In the outermost region of the UO_2 pellet, fissile plutonium concentration is increased due to high neutron capture of U-238. The number of fissions increases further due to locally increased Pu, resulting in increased fission gases. As a result, numerous fission gas bubbles are formed, and this bubble rich region, High Burn-up Structure (HBS), is well-known [3,4]. The formation of HBS is known to begin at around 50 GWD/MTU and above, and the bubble-rich HBS region has a lower density than the fresh pellet density [3,4].

When the pellet is burned, the pellet swells due to fission gas and contacts the cladding. As fission continues, the interface between the pellet periphery and the cladding forms a strong bonding.

3.3 Effects of Acoustic Impedance on high burn-up fuel rod

For high burn-up fuel rods, the difference in acoustic impedance between the pellet and the cladding is reduced due to the reduced density at the outermost part of the pellet. As the acoustic impedance difference decreased, the signal received from the ultrasonic test becomes lower than the gate level, and the fuel rod is determined to be defected. (see Fig1. (c)) However, even in high burn-up fuel rods, the blanket region loaded with pellets of 2% U-235 enrichment shows relatively low burn-up. Therefore, performing ultrasonic inspection in non-HBS locations below 40,000MWD/MTU will improve the reliability of the inspection.

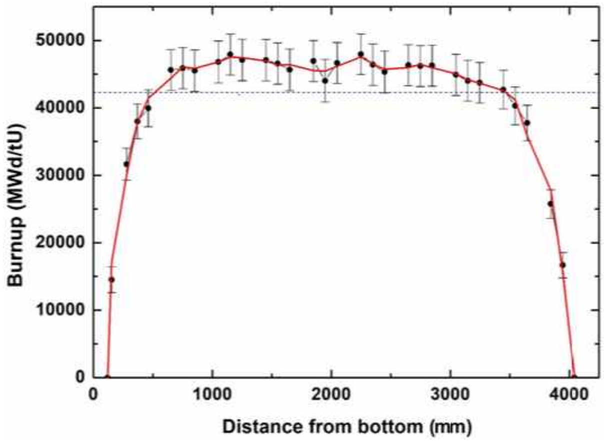

Fig. 4 Fuel rod Axial burn-up distribution

5. Summary and Conclusion

Ultrasonic inspection of nuclear fuel rods is the most practical way to determine rod-level defects. HBS and pellet cladding bonding of fuel pellets reduces the acoustic impedance difference between the pellet and the cladding, making it difficult to identify fuel rod defects, which reduces the reliability of ultrasonic inspection. From an ultrasonic inspection reliability perspective, it is preferable to perform ultrasonic inspections in non-HBS locations to minimize acoustic impedance effects.

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