DOI: 10.5516/NET.2011.43.1.075

EFFECT OF STAINLESS STEEL PLATE POSITION ON NEUTRON MULTIPLICATION FACTOR IN SPENT FUEL STORAGE RACKS

HEE DONG SOHN[1] and JONG KYUNG KIM[2,*]
[1]Doosan Heavy Industries & Construction
555 Gwigok-Dong, Changwon, Gyeongnam 641-792, Korea
[2]Nuclear Engineering Hanyang University
Seoul 133-791, Korea
[*]Corresponding author. E-mail : jkkim1@hanyang.ac.kr

Received November 17, 2010
Accepted for Publication January 17, 2011

The neutron multiplication factor in spent fuel storage racks, in which a stainless steel plate encloses a fuel assembly, was evaluated according to the variation of distance between the fuel assembly and stainless steel plate, as well as the pitch. The stainless steel plate position with the lowest multiplication factor on each pitch consistently appeared as 6mm or 9mm away from the outmost surface of the fuel assembly. Because the stainless steel plate has a thermal neutron absorption cross section, its ability to absorb neutrons can work best only if it is installed at the position where thermal neutrons can be gathered most easily. Therefore, the stainless steel plate position should not be too close or too far away from the fuel assembly, but it should be kept a pertinent distance from the fuel assembly.

KEYWORDS : Spent Fuel Storage Rack, Multiplication Factor, Stainless Steel Plate

1. INTRODUCTION

Spent fuels discharged from a nuclear reactor are temporarily stored in the Spent Fuel Storage Racks (SFSR), which are installed in an on-site spent fuel storage pool filled with boric acid solution. An SFSR is composed mostly of two kinds of material: a stainless steel plate that supports the fuel assembly, and a neutron absorbing material that absorbs neutrons produced in the fuel assembly. In fuel assemblies stored in a SFSR, neutrons are continuously produced by an (α, n) reaction in Actinide series nuclides and spontaneous fission reactions. Thus, SFSR criticality analysis should be performed to optimize conditions for the absorption of neutrons that can restrict the chain reaction and store fuel assemblies safely **[1]**.

Stainless steel with a high corrosion resistance is widely used for SFSR structural material used for the long-term storage of spent fuel in a spent fuel storage pool. Furthermore, stainless steel is a useful material for securing criticality safety because of its capability to absorb thermal neutrons **[2]**. However, stainless steel has been used only as structural material to support the fuel assembly instead of absorbing neutrons. Separate neutron absorbing material including Boron (^{10}B neutron absorption cross section: 3835 $\times$ 10^{-24}cm^2)**[2]** has been used for the sole purpose of neutron absorption, because its neutron absorption ability is greater than that of stainless steel. Thus, when SFSR is designed, the key design factor of deciding the distance between the fuel assembly and stainless steel plate has only been considered for mechanical reason rather than that of criticality.

This study evaluates how the use of a stainless steel plate surrounding the fuel assembly affects the criticality safety, assuming that the SFSR is comprised of a stainless steel plate without neutron absorbing material on the general type of SFSR model **[3]**. We performed analyses to find the optimal stainless steel plate position that can get the lowest multiplication factor while varying the distance between the outmost surface of the fuel assembly and the stainless steel plate. The results can be used to design the spent fuel storage rack model.

2. MATERIAL AND METHODOLOGY

2.1 Stainless Steel

The spent fuel storage pool, in which the spent fuel storage rack is installed, is always filled with boric acid solution to secure criticality safety. Thus, austenitic stainless steel is used as structural material because it is highly resistant to corrosion. In metallurgy, stainless steel is defined as an iron-carbon alloy with a minimum of 11.5 wt% chromium content. Stainless steel does not stain, corrode, or rust as easily as ordinary steel and differs from carbon steel due to the content of chromium. Its resistance to corrosion makes it an ideal base material for the spent fuel storage rack in a boric acid solution.

Among the types of stainless steel, 304L [4] has higher chromium and extra-low-carbon contents and exhibits excellent resistance to a wide range of atmospheric and chemical exposures. Based on the above characteristics and its strength, the stainless steel type 304L is widely used for SFSR. 304L is an extra-low-carbon variation of type 304 with a 0.03 % maximum carbon content that eliminates carbide precipitation due to welding. Besides, stainless steel has an absorption cross section for thermal neutrons, so it is an effective material for criticality safety. Table 1 shows the compositions and absorption cross sections for the thermal neutrons of the austenite stainless steel.

2.2 Fuel Assembly

The fuel assembly used in this study is ^{235}U enrichment 5.0 w/o Plus-7 [5] new fuel. In spite of the burned conditions of the fuel assembly in the reactor, new fuel with maximum reactivity is applied instead of the spent fuel because in the spent fuel storage rack, both spent fuel and new fuel are stored together. Thus, the most conservative condition is chosen.

Plus-7 is composed of 236 fuel rods and 5 zirconium guide thimbles and each guide thimble is assumed to be filled with water. Including the upper and lower parts of the stainless steel structure in Plus-7, the total length is 4528mm. In this study, however, only the active fuel assembly length of 3810mm is considered, and other parts are assumed to be filled with water. The detailed specification of Plus-7 is shown in Table 2, and the cross-sectional view is shown in Figure 1.

2.3 Spent Fuel Storage Rack

Spent fuel storage racks are divided into two regions according to the characteristics of the fuel assembly: Region I and Region II. The role of Region I is to store new fuels temporarily before they are loaded into the reactor and to store spent fuels with high reactivity discharged from the reactor. Region II is used to store spent fuels with reduced reactivity while they are stored in Region I until they are transported to the intermediate storage facility or permanent disposal area for spent fuels.

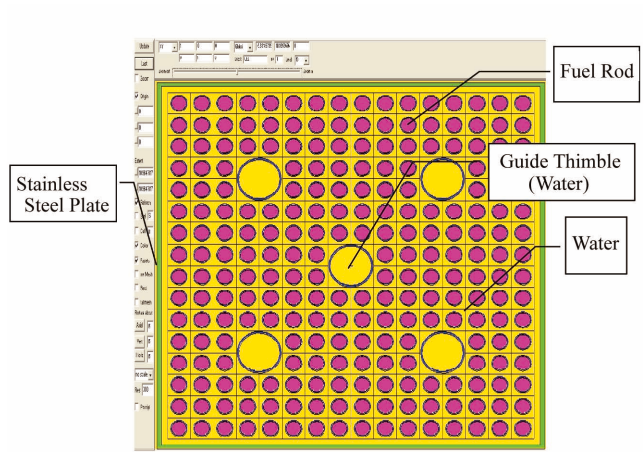

Fig. 1. Cross-Section View of Plus-7 Fuel Assembly

Table 1. Composition Abundance and Absorption Cross Section of Austenite Stainless Steel

Composition	Abundance (%)	Absorption Cross Section for 2200ms^{-1} neutrons (barn=1×10^{-24}cm^2)
Carbon	0.03	0.0035
Sulfur	0.03	0.53
Phosphorus	0.045	0.172
Nitrogen	0.10	1.9
Silicon	0.75	0.171
Manganese	2.00	13.3
Chromium	18.0~20.0	3.05
Nickel	8.0~12.0	4.49
Iron	Balance	2.56

Table 2. Fuel Specifications for Plus-7

Description	Specification
FA Overall Length (cm)	452.8
Active Fuel Length (cm)	381.0
Pellet Diameter (cm)	0.81915
Fuel Rod Clad O.D. (cm)	0.94996
Fuel Rod Clad I.D. (cm)	0.83566
Guide Tube O.D. (cm)	2.489
Guide Tube I.D. (cm)	2.2860
Number of Fuel Rods	236
Pitch (cm)	1.28524
Rod Array	16 x 16
Number of Guide Thimble	5
FA Weight (kg)	616
Clad Material	Zr-4

The basic unit constituting a spent fuel storage rack is a structure called a cell, which is a square pillar of a stainless steel plate that encloses a fuel assembly with neutron absorbing material attached to each outer surface of a stainless steel plate, as shown in Figure 2. In other words, the stainless steel plate completely surrounds the whole length of the fuel assembly. Though the inner dimensions of the cell differ according to the type of fuel assembly, the normal width is 210mm to 220mm × 210mm to 220mm and the normal length is 4000mm to 4600mm. Lots of cells arrayed with constant distance compose a complete SFSR called a module, as shown in Figure 3.

The structure of the spent fuel storage rack Region I used in this study is a stainless steel plate with a thickness of 3mm and a length of 3810mm, which is a square pillar enclosing the spent fuel assembly (cell). These cells are arrayed with a pitch of 277mm along the X-Y direction. In reality, there are many stainless steel structures between the cells and on the upper and bottom parts of the fuel assembly to support the fuel assembly. However, in this study, these structures are replaced by water to minimize the neutron absorbing effect of stainless steel. Figure 4 shows the spent fuel storage rack region I module with 9 (3 × 3) fuel assemblies.

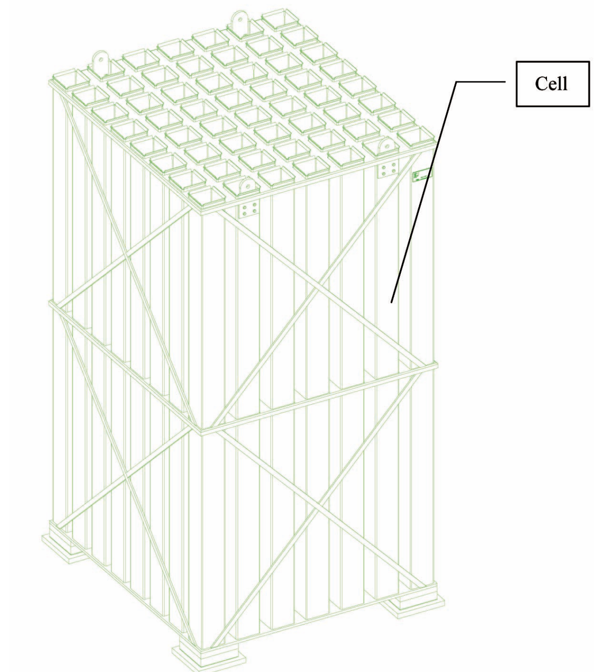

Fig. 3. Spent Fuel Storage Rack Module

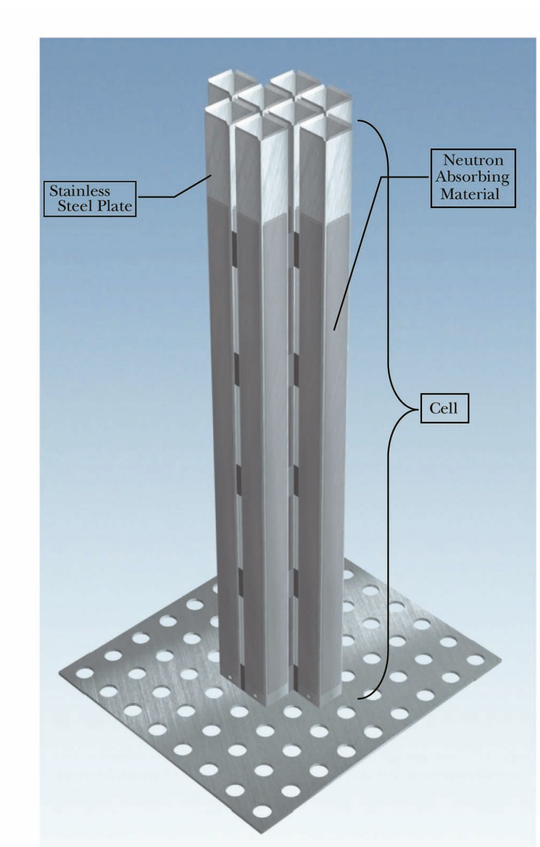

Fig. 2. Cell Structure (Stainless Steel Plate + Neutron Absorbing Material)

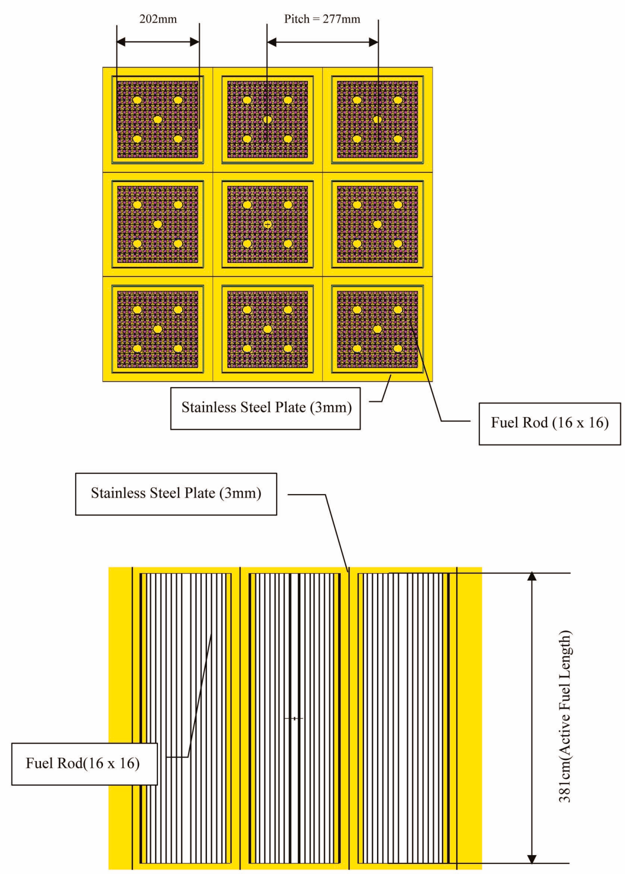

Fig. 4. Spent Fuel Storage Rack Region I Module (9 Fuel Assemblies)

2.4 Analysis Conditions

To calculate multiplication factors according to the distance between the fuel assembly and stainless steel plate in the spent fuel storage rack, a cell (one fuel assembly and the enclosing stainless steel plate) is spread infinitely along the X-Y direction. In order to conserve more, the reflective boundary condition is added in the +/- Z directions. Thus, fuel assemblies are arrayed infinitely in the X, Y and Z directions. Boric acid solution in the spent fuel storage pool is replaced by water to eliminate the neutron absorbing effect of Boron, while the temperature and density of the water are set to 20ºC and 1g·cm^{-3}, respectively.

The multiplication factor is calculated with distance variation between the fuel assembly and stainless steel plate from 0mm (stainless steel plate is attached on the outmost surface of the fuel assembly) to 24mm with 3mm intervals. The multiplication factor is also calculated with the variation of pitch to investigate the stainless steel plate position that appears as the lowest multiplication factor.

2.5 Computer Code and Cross Section Library

The Monte Carlo N-Particle transport code, MCNPX [6], developed at Los Alamos National Laboratory (LANL) and ENDF/B-VI cross section library, are employed to calculate the multiplication factor of the spent fuel storage rack. MCNP is a general purpose Monte Carlo code used for calculating the time-dependent continuous energy transport of neutrons, photons, and/or electrons in three-dimensional geometries. It is also most widely used in the field of criticality, shielding analysis, and the verification evaluation, not only because of its high confidence, but also because of its high variance reduction techniques that can improve the efficiency of difficult calculations.

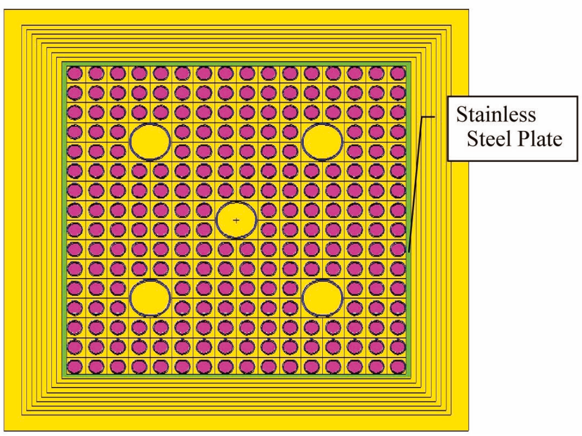

Fig. 5. Stainless Steel Plate Contact to the Outmost Surface of Fuel Assembly (10.1125cm from the Center of Fuel Assembly)

3. RESULTS AND DISCUSSION

3.1 Neutron Multiplication Factors According to the Stainless Steel Plate Position

The neutron multiplication factor in the spent fuel storage rack is calculated for two cases. For Case 1, as shown in Figure 5 and Figure 6, the stainless steel plate is installed from the outmost surface of the fuel assembly of 0mm to 24mm with 3mm intervals. For Case 2, as shown in Figure 7, there is just water around the fuel assembly without any stainless steel plate.

As shown in Figure 8, the neutron multiplication factor for Case 1 is less than that of Case 2 with a difference of as much as 0.0701 to 0.0851 caused by the neutron absorption effect of the stainless steel plate. For Case 2, the neutron multiplication factor on all positions is almost the same, however for Case 1, the multiplication factor

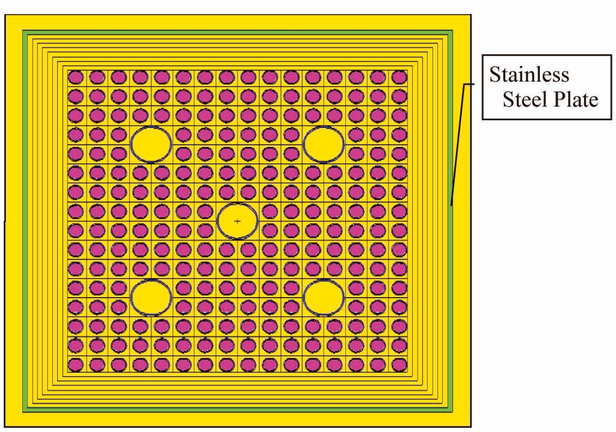

Fig. 6. Stainless Steel Plate Positioned 24mm from the Outmost Surface of Fuel Assembly (12.5125cm from the Center of Fuel Assembly)

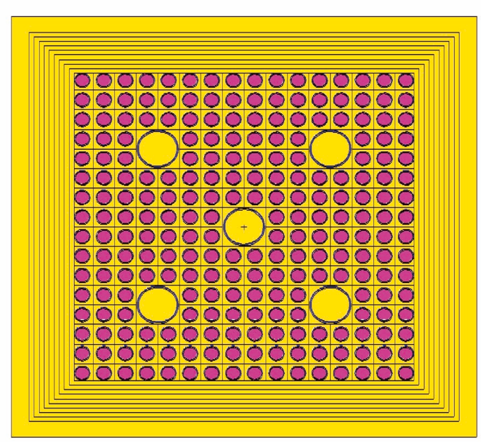

Fig. 7. Without Stainless Steel Plate around Fuel Assembly

decreases gradually from 0mm to 9mm. and then it increases abruptly. The highest multiplication factor is 1.10408 at 24mm, while the lowest one is 1.08905 at 9mm with a difference of 0.01503. In other words, the stainless steel plate position with the lowest multiplication factor is 9mm apart from the outmost surface of the fuel assembly.

3.2 Fluence Variation according to the Stainless Steel Plate Position and Neutron Energy

Figure 9 shows the neutron fluence at a specified position around the fuel assembly for both cases of Section 3.1 with a pitch of 277mm. The neutron fluence for Case 1 is less than that of Case 2 at the same position because of the thermal neutron absorption ability of the stainless steel plate. As the distance between the fuel assembly and stainless steel plate increases, the neutron fluence increases gradually for Case 2. However, for Case 1, it decreases instantaneously around the stainless steel plate, and after the stainless steel plate, it increases gradually, as in Case 2.

For Case 2, the thermal neutron fluence does not decrease as the distance between the fuel assembly and stainless steel plate increases. This is not only because of the moderation of fast neutrons to thermal neutrons, but also because of the effect of neutrons transferred from neighboring fuel assemblies.

Figure 10 to Figure 13 show the variation of fluence in accordance with the neutron energy. For neutrons below 0.001 MeV, the neutron fluence for Case 1 is less than that of Case 2. However, for neutrons above 0.001 MeV, the neutron fluence appears to decrease, regardless

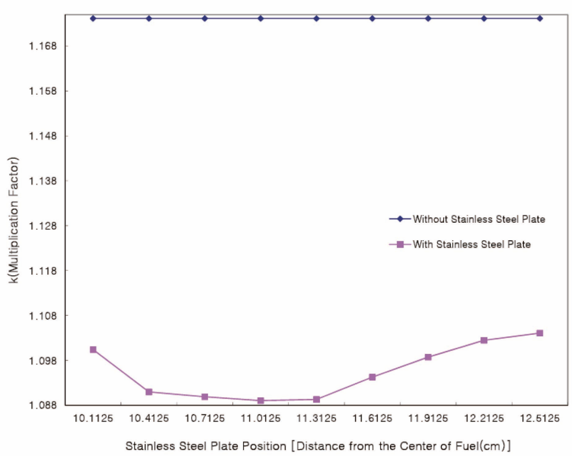

Fig. 8. Variation of Neutron Multiplication Factor according to the Distance between Fuel Assembly and Stainless Steel Plate

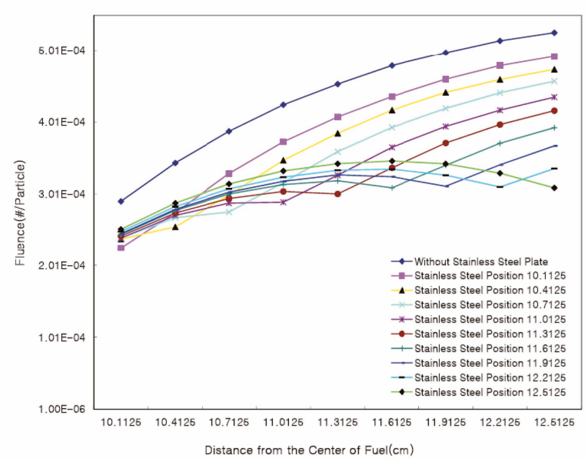

Fig. 10. Neutron Fluence according to the Position of the Stainless Steel Plate (Neutron Energy: Below 0.001 MeV)

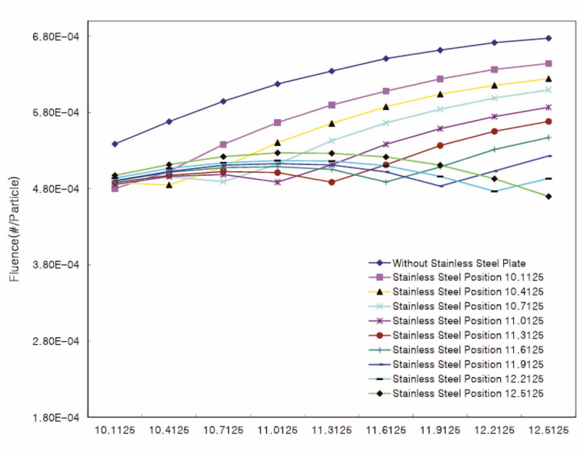

Fig. 9. Neutron Fluence according to the Position of the Stainless Steel Plate (Total Neutron Energy)

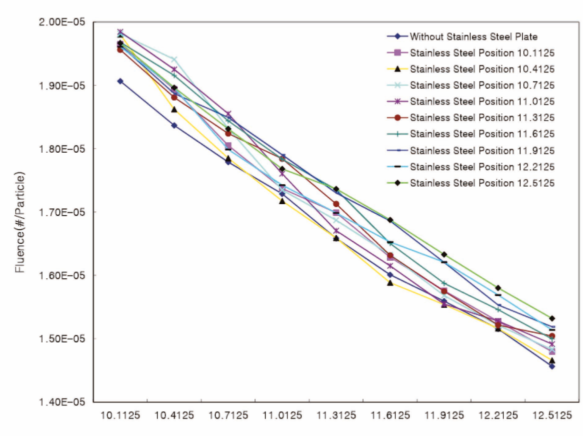

Fig. 11. Neutron Fluence according to the Position of the Stainless Steel Plate (Neutron Energy: Between 0.001 MeV and 0.005 MeV)

of the existence of a stainless steel plate. That is, the stainless steel plate can absorb epithermal neutrons below 0.001 MeV.

3.3 Neutron Mean Free Path (MFP) Variation According to the Stainless Steel Plate Position

Table 3 shows the neutron mean free path at each position around the fuel assembly for Cases 1 and 2. As shown in Table 3, the MFP gradually decreases for both cases as the position moves farther away from the fuel assembly. At all positions, regardless of the distance from the fuel assembly, the MFP for Case 1 is 1.5 to 1.8 times longer than that of Case 2, and the neutron collision number in Case 2 is about 2.9 to 4.5 times greater than in Case 1. That is, most neutrons (except for some thermal neutrons) pass through the stainless steel plate, rather than collide with it.

3.4 Stainless Steel Plate Position with Lowest Multiplication Factor According to the Variation of Pitch

In cases where other conditions, except for pitch, are the same as in 3.1, the stainless steel plate position with the lowest multiplication factor is evaluated. Including the results for a pitch of 277mm, the multiplication factor for various pitches ranging from 260mm to 300mm with

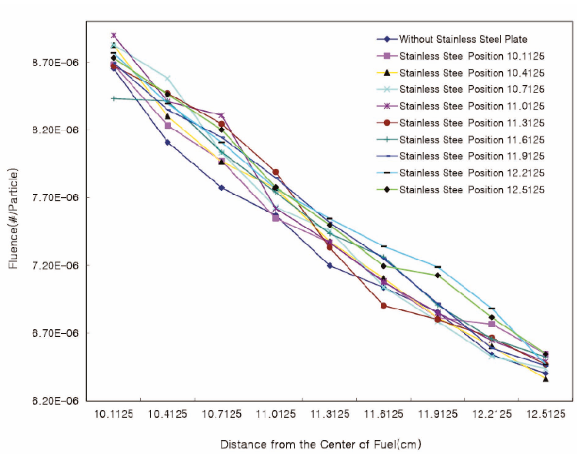

Fig. 12. Neutron Fluence according to the Position of the Stainless Steel Plate (Neutron Energy: Between 0.005 MeV and 0.01 MeV)

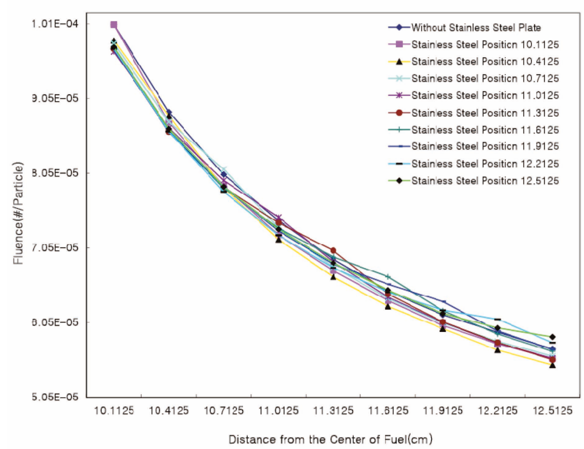

Fig. 13. Neutron Fluence according to the Position of the Stainless Steel Plate (Neutron Energy: Between 1 MeV and 10 MeV)

Table 3. Neutron Mean Free Path in Stainless Steel and Water according to the Distance from the Outmost Surface of Fuel

Distance from the Outmost Surface of Fuel (mm)	Fuel Type		Neutron Mean Free Path (cm)	
	Without Stainless Steel Plate	With Stainless Steel Plate	Without Stainless Steel Plate	With Stainless Steel Plate
0	1,000,444	346,173	1.41E+00	2.25E+00
3	1,260,384	397,483	1.25E+00	2.09E+00
6	1,496,868	438,880	1.13E+00	1.98E+00
9	1,717,139	473,374	1.05E+00	1.91E+00
12	1,916,086	503,613	9.83E-01	1.84E+00
15	2,106,103	528,547	9.30E-01	1.80E+00
18	2,263,335	544,070	8.95E-01	1.77E+00
21	2,429,935	555,324	8.65E-01	1.75E+00
24	2,563,771	565,186	8.42E-01	1.73E+00

10mm intervals is calculated. As shown in Figure 14, the multiplication factor decreases gradually as the pitch increases, however the stainless steel plate position with the lowest multiplication factor on each pitch appears to be consistently 6mm or 9mm from the outmost surface of the fuel assembly. That is, the stainless steel plate position with the lowest multiplication factor is almost constant, regardless of pitch.

As the pitch increases, the multiplication factor decreases because the multiplication factor can be affected not only by the neutrons produced in the fuel assembly, but also from neighboring fuel assemblies. However, the stainless steel plate position with the lowest multiplication factor for each pitch is mostly affected by the neutrons around the fuel assembly itself than by the neutrons produced from neighboring fuel assemblies.

Considering the neutron MFP in water and the stainless steel plate, as well as the thermal neutron absorption cross section of the stainless steel plate, the lowest multiplication factor in the spent fuel storage rack is decided by the position of the stainless steel plate that surrounds the fuel assembly.

If a stainless steel plate contacts the outmost surface of the fuel assembly, the possibility that fast neutrons produced in the fuel assembly pass through the stainless steel plate is much greater than being absorbed by the stainless steel plate because of the long MFP and small absorption cross section for fast neutrons present in the stainless steel plate. After neutrons that have passed through the stainless steel plate are reflected by water, some thermalized neutrons are absorbed by the stainless steel plate, while others return to the fuel assembly. That is, if the stainless steel plate is positioned too close to the fuel assembly, neutrons from the fuel assembly are unlikely to be directly absorbed by the stainless steel plate. However, some of the reflected neutrons will be absorbed by the stainless steel plate, and those contribute to reducing the multiplication factor.

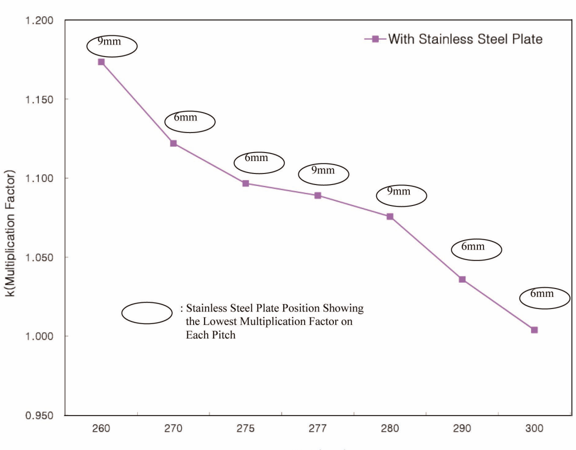

Fig. 14. The Lowest Multiplication Factor According to the Pitch Variation

If the stainless steel plate is positioned far from the fuel assembly, most of the neutrons lose their energy through collisions with water before they arrive at the stainless steel plate. The possibility for neutrons to be absorbed in the stainless steel plate is also small.

Therefore, if the stainless steel plate is installed at the position where thermalized neutrons (through the reaction with water inside the stainless steel plate) and reflected thermal neutrons (caused by the collision with water outside the stainless steel plate) occur the most, then the neutron absorption capability of the stainless steel plate will be the best. That is, the optimal stainless steel plate position to reduce the multiplication factor is neither too close to nor too far from the fuel assembly, but is located at a constant distance of 6mm or 9mm apart from the fuel assembly.

4. CONCLUSIONS

For a spent fuel storage rack with a pitch of 277mm and composed of a stainless steel plate enclosing a fuel assembly without any neutron absorbing material, the neutron multiplication factor according to the variation of distance between the fuel assembly and stainless steel plate ranges from 1.08905 to 1.10408 with a difference of 0.01503. The stainless steel plate position with the lowest multiplication factor is 9mm apart from the outmost surface of the fuel assembly.

The most critical point for reducing the multiplication factor in the spent fuel storage rack is the absorption of thermalized neutrons, not only thermal neutrons inside the stainless steel plate, but also the reflected neutrons from the outside the plate. Thus, if the stainless steel plate is installed at the most suitable position where it encounters the thermalized neutrons, the lowest multiplication factor can be obtained. The optimal stainless steel plate position is not too close to or too far away from the fuel assembly, but is maintained at a constant distance from the fuel assembly.

The stainless steel plate position with the lowest multiplication factor is also identified as the pitch changes from 260mm to 300mm at an interval of 10mm. The lowest multiplication factor appeared at a constant distance of 6mm or 9mm from the outmost surface of the fuel assembly as the result of a pitch of 277mm. This position is the best for absorbing thermal neutrons around the fuel assembly.

Using the above result, if the spent fuel storage rack is only composed of the stainless steel plate, we can decide what the optimized distance is between the fuel assembly and stainless steel plate when designing the spent fuel storage rack.

ACKNOWLEDGMENTS

This study was supported by the Ministry of Knowledge Economy (2008-P-EP-HM-E-06-0000).

REFERENCES

[1] Guidance on the Regulatory Requirements for Criticality Analysis of Fuel assembly Storage at Light Water Reactor Power Plant, Laurence I. Kopp, U.S. Nuclear Regulatory Commission Office of Nuclear Reactor Regulation, February 1998.

[2] NIST(National Institute of Standard and Technology) Center for Neutron Research, Neutron Scattering Lengths and Cross Sections of the Elements and Their Isotopes, October 2003.

[3] Drawing, Spent Fuel Assembly Storage Racks Region I Details, D-HC-95200-D02, Rev.1, Doosan, July 2009.

[4] Product Data Sheet, 304/304L Stainless Steel, AK Steel Corporation, 2007.

[5] Attachment 4-1 of Technical Specification in KHNP ITT, New & Spent Fuel Assembly Storage Racks, V10-N224-000PLUS-7 Fuel Assembly by KNF, April 2010.

[6] MCNP-A General Monte Carlo N-Particle Transport Code, Version X, LA-12625-M, Los Alamos National Laboratory, 2003.