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Irradiation Effect on Silo Dry Storage Systems for CANDU Spent Nuclear Fuel

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The 300 concrete silo systems installed and operated at the site of Wolsong nuclear power plant (NPP) have been storing CANDU spent nuclear fuel (SNF) under dry conditions since 1992. The dry storage system must be operated safely until SNF is delivered to an interim storage facility or final repository located outside the NPP in accordance with the SNF management policy of the country. The silo dry storage system consists of a concrete structure, liner steel plate in the inner cavity, and fuel basket. Because the components of the silo system are exposed to high energy radiation owing to the high radioactivity of SNF inside, the effects of irradiation during long-term storage must be analyzed. To this end, material specimens of each component were manufactured and subjected to irradiation and strength tests, and mechanical characteristics before and after irradiation were examined. Notably, the mechanical characteristics of the main components of the silo system were affected by irradiation during the storage of spent fuel. The test results will be used to evaluate the long-term behavior of silo systems in the future.

Keywords: Dry storage system, Concrete silo, Irradiation, Mechanical property, Long-term behavior

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1. Introduction

Since 1992, 162,000 bundles of CANDU SNF have been stored in the storage facility using 300 concrete silo dry storage systems on the site of Wolsong NPP (Fig. 1) [1]. This facility with a 50-year licensing period must be operated safely until SNF is delivered to an interim storage facility or final repository located the outside NPP according to the country's SNF management policy, so the long-term integrity of dry storage system must be maintained [2, 3].

As the concrete silo system at Wolsong NPP has been in operation for more than 30 years, it is necessary to review the aging management in preparation for long-term operation and future license renewal. Because the dry storage system has time constraints on the limited design life, countries that operate the dry storage facilities are making efforts to secure the safety for the long-term operation of storage systems. The IAEA also recommended that SNF dry storage facilities must be evaluated for long-term storage of SNF and proposed technical criteria for aging management programs and integrity assessments to ensure the long-term safety of dry storage facilities [4, 5].

When high-energy radiation particles are irradiated to a material, various types of irradiation defects are formed due to the collision of between incident particles and lattice particles, which changes the physical and mechanical properties of material, and this is called irradiation damage. The defects caused by irradiation are affected by irradiation temperature, irradiation dose, irradiation speed, etc., and are also affected by the composition of material [6]. Consideration of environmental conditions, including irradiation, is also important for aging management to maintain the long-term integrity of material, as the longer the material is used, the more likely it is that irradiation defects accumulate and cause material damages. Nuclear reactor pressure vessel is periodically evaluated for these irradiation defects [7], and reactor containment buildings and shielding walls are also required to evaluate the strength and mechanical properties of concrete due to irradiation when renewing NPP's license [8-9]. The silo dry storage system consists of a concrete structure, a steel liner in the inner cavity, and a fuel basket directly loading SNF (Fig. 2). The components of silo system are exposed to high-energy radiation and are likely to deteriorate due to the irradiation damage because they are in contact with or close to SNF with high radioactivity. In particular, it is of utmost importance to demonstrate the integrity of concrete structure in the long-term operation of silo dry system. Therefore, it is necessary to analyze the aging effects due to irradiation on each component of the silo system in order to ensure the integrity of long-term storage.

Fig. 1. Silo dry storage facility at Wolsong NPP site.

To this end, specimens of concrete, carbon steel and stainless steel, which are the materials of each silo component, were prepared and subjected to irradiation and strength tests, and the mechanical properties before and after irradiation were examined. The effects of irradiation are mainly evaluated using by neutron and gamma rays, but it is difficult to conduct neutron irradiation tests in Korea, so only gamma ray irradiation tests were carried out using the test facility of the Korea Atomic Energy Research Institute. Of course, gamma rays cause less irradiation damage than neutrons of similar size. But previous studies have shown that gamma rays can interact with atoms in metals and cause damage [10], and concrete

Table 1. Total gamma and neutron flux

Cooling time (years)	6	26	56
Gamma (#/sec-bundle)	4.645×10^{13}	2.046×10^{13}	1.015×10^{13}
Neutron (#/sec-bundle)	7.209×10^{4}	5.701×10^{4}	4.672×10^{4}

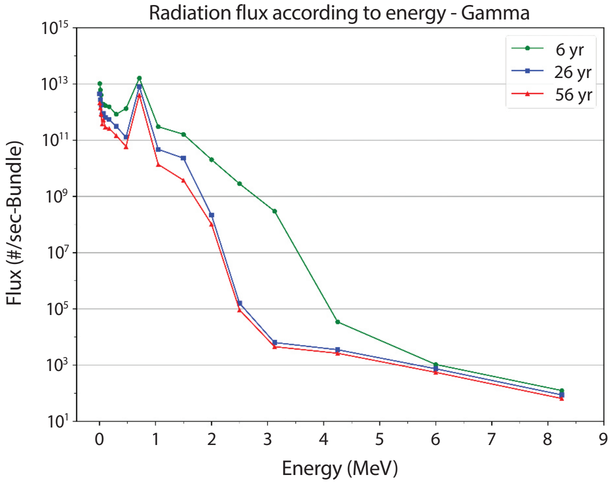
also affects the material properties by causing voids due to moisture loss in the cement paste [11], so it is possible to examine the effects of irradiation on each material of components through a gamma ray irradiation tests alone. The results of analyzing the irradiation effects can be used to evaluate the long-term behavior of silo dry storage systems in the future.

2. Calculation of Source Term and Irradiation Dose

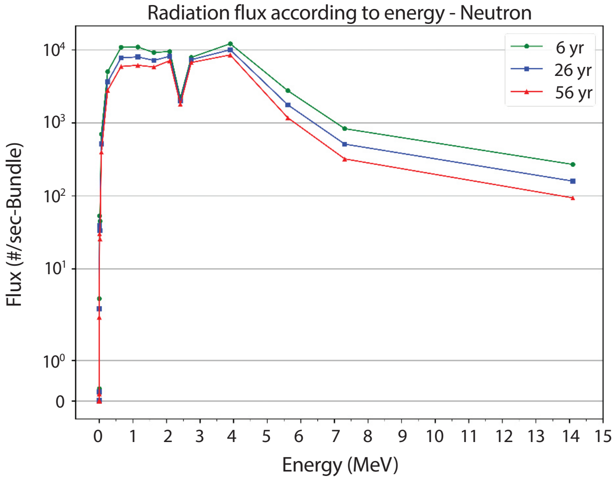
2.1 Source Term

In general, source term calculations are determined by the design data of SNF (^{235}U enrichment, pellet/aggregate specifications), operation history (specific power, cooling time), fuel burnout characteristics (period, burnup), etc. Based on the intact CANDU SNF with an average burnup of 7,800 MWd·MTU^{-1} and a minimum cooling time of 6 years, which is the design basis fuel that can be loaded into the silo dry storage system, the source term according to the cooling time was calculated using the ORIGIN-ARP module of SCALE 6.0. Cooling time of 26 years (20 years of dry storage after 6 years of wet storage) and 56 years (50 years of dry storage after 6 years of wet storage, i.e., licensing period) were considered starting from the minimum cooling time of 6 years (6 years of wet storage).

The gamma flux and neutron flux due to the decay of fission products and actinides per fuel bundle at each of the 6-year, 26-year, and 56-year cooling times were calculated for the energy range and are shown in Table 1 and Fig. 2.



(a) Gamma



(b) Neutron

Fig. 2. Radiation flux according to energy.

2.2 Irradiation Dose

The components of silo system were modeled as shown in Fig. 3, and the irradiation energy and dose to the specimen were calculated using the average value of silo's gamma flux (Fig. 4) by year from 6 to 56 years of dry storage based on the release from the reactor.

The annual gamma energy to be irradiated to the concrete specimen from the average gamma flux for a storage

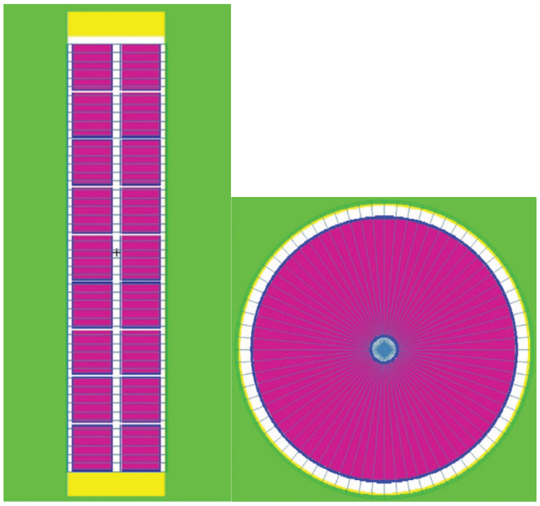


Fig. 3. Source term analysis model.

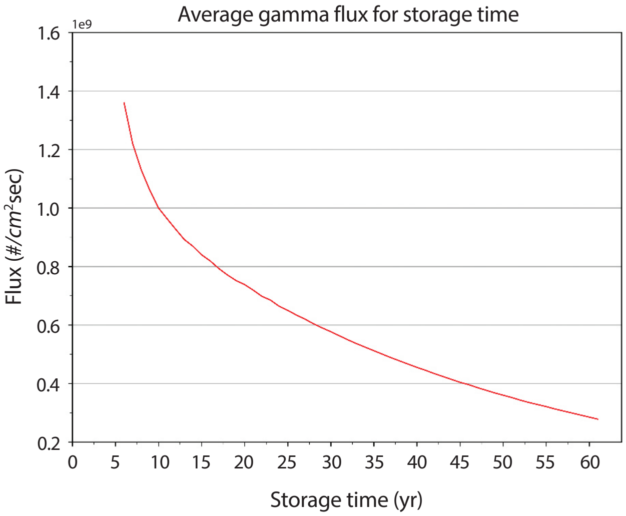


Fig. 4. Average gamma flux for storage time.

Table 2. Irradiation energy

Storage time (yr)	Avg. gamma flux (#/cm^{2}sec)	Avg. gamma energy (J/#)	Gamma energy flux per area (J·cm^{-2}·sec^{-1})	Annual gamma energy (J)	Total gamma energy(J)	
6	1.356×10^{9}	4.821×10^{-14}	6.536×10^{-5}	4.122×10^{5}	5.6×10^{6}	9.9×10^{6}
16	8.192×10^{8}	5.072×10^{-14}	4.155×10^{-5}	2.621×10^{5}		
26	6.341×10^{8}	5.057×10^{-14}	3.207×10^{-5}	2.023×10^{5}		
36	4.998×10^{8}	5.054×10^{-14}	2.526×10^{-5}	1.593×10^{5}		
46	3.956×10^{8}	5.051×10^{-14}	1.998×10^{-5}	1.260×10^{5}		
56	3.132×10^{8}	5.041×10^{-14}	1.579×10^{-5}	9.959×10^{4}		

period of 6 years was calculated as follows:

Average gamma flux = $1.356\times10^{9}\times\#/\text{cm}^2$ sec

Average gamma energy per gamma ray (total energy of gamma spectrum / total number of gamma rays in each period) = $(0.2996\ \text{MeV}/\#)\times(1.609\times10^{-13}\ \text{J}\cdot\text{MeV}^{-1}) = 4.821\times10^{-14}\ \text{J}/\#$

Average gamma energy flux per area $=(1.356\times10^{9}\ \#/\text{cm}^2\ \text{sec})\times(4.821\times10^{-14}\ \text{J}/\#) = 6.536\times10^{-5}\ \text{J}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$

Gamma energy absorbed by the specimen (concrete cross-sectional area 10×20 cm=200 cm^2) in one year = $(6.536\times10^{-5}\ \text{J}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1})\times(200\ \text{cm}^2)\times(3.154\times10^{7}\ \text{sec}) = 4.122\times10^{5}\text{J}$

Irradiated dose to the concrete specimen (concrete density 2 g·cm^{-3}) = $(4.122\times10^{5}\text{J})\ /\ [\pi\times(5\ \text{cm})^2\times(20\ \text{cm})\times(2\times10^{-3})\ \text{kg}\cdot\text{cm}^{-3}] = 1.312\times10^{5}\ \text{J}\cdot\text{kg}^{-1} = 1.312\times10^{5}\ \text{Gy}$

According to this method, the annual irradiation energy to the specimen was conservatively calculated, and Table 2 summarizes the average gamma flux, gamma energy, and annual irradiation energy to the specimen for 6 to 56 years of storage time at 10-year intervals.

Based on these calculations, the 20-year irradiation energy with the storage time of 6 to 26 years is 5.6×10^{6}J, corresponding to the specimen irradiation dose of 1.78 MGy, and the 50-year irradiation energy with the storage time of 6 to 56 years is 9.9×10^{6}J, corresponding to the specimen irradiation dose of 3.18 MGy.

Table 3. Specification of test specimens

Specimen		Test	Specification	Dimension
Concrete	Irradiation	Compressive	ASTM C39/C KS F2405	D100 × 200 mmH
		Tensile	ASTM C496/C KS F2423	D100 × 200 mmH
		Flexible	ASTM C78 KS F2408	150×150×450 mmL
Carbon steel	Irradiation	Tensile/yield/elongation/ elastic modulus	KS B0802 KS D1652	10×400×400 mmL
Stainless steel	Irradiation	Tensile/yield/elongation/ elastic modulus	KS B0802 KS D1652	10×400×400 mmL

(a) Concrete (tensile/compressive) (b) Concrete (flexible) (c) Carbon steel (d) Stainless steel

Fig. 5. Test specimens.

3. Irradiation and Strength Tests

3.1 Test Specimens

The specimens for each material of silo components for the irradiation test and the strength test were in accordance with the technical standards. The specification is summarized in Table 3 and shown in Fig. 5. In particular, the concrete mix design used in the construction of silo dry storage facility the was applied to the concrete specimens. Each test specimen was made in 20 sets, taking spares into account.

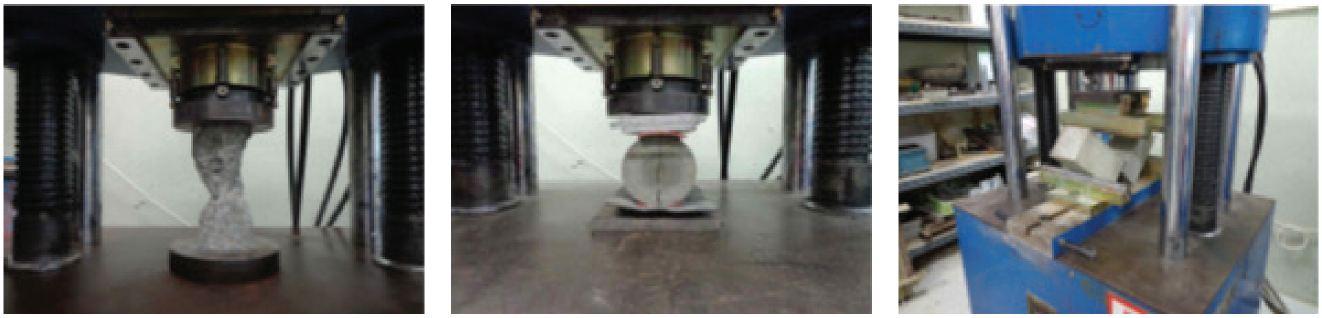
3.2 Irradiation Test

The irradiation test uses a ^{60}Co gamma ray source (average energy spectrum is 1.25 MeV), a sealed encapsulated source (Fig. 6), which is pencil-shaped and rotates to irradiate the specimen with gamma rays. However, due to unavoidable conditions and schedule of the test institute, only an irradiation dose of 1.8 MGy for a 20-year storage time was possible. At this dose, each specimen was irradiated for approximately 8 days (178.66 hours for concrete specimens, 193 hours for carbon steel and stainless steel specimens).

Fig. 6. ^{60}Co source in wet storage.

3.3 Strength Test

The strength and quality tests were carried out in accordance with the relevant technical standards using the KOLAS certified agency that meets the standards of KS and National Standards Act. The specimens were tested before and after irradiation. The concrete specimens were tested to determine the compressive strength, tensile strength and bending strength, respectively (Fig. 7), and the carbon steel and stainless steel were tested to determine the tensile strength, yield strength, elongation and elastic modulus, respectively (Fig. 8).



(a) Compressive (b) Tensile (c) Flexible

Fig. 7. Strength tests for concrete specimens.

(a) Tensile (b) Elastic modulus (c) Elongation

Fig. 8. Strength tests for metal specimens.

Table 4. Test result for concrete specimens

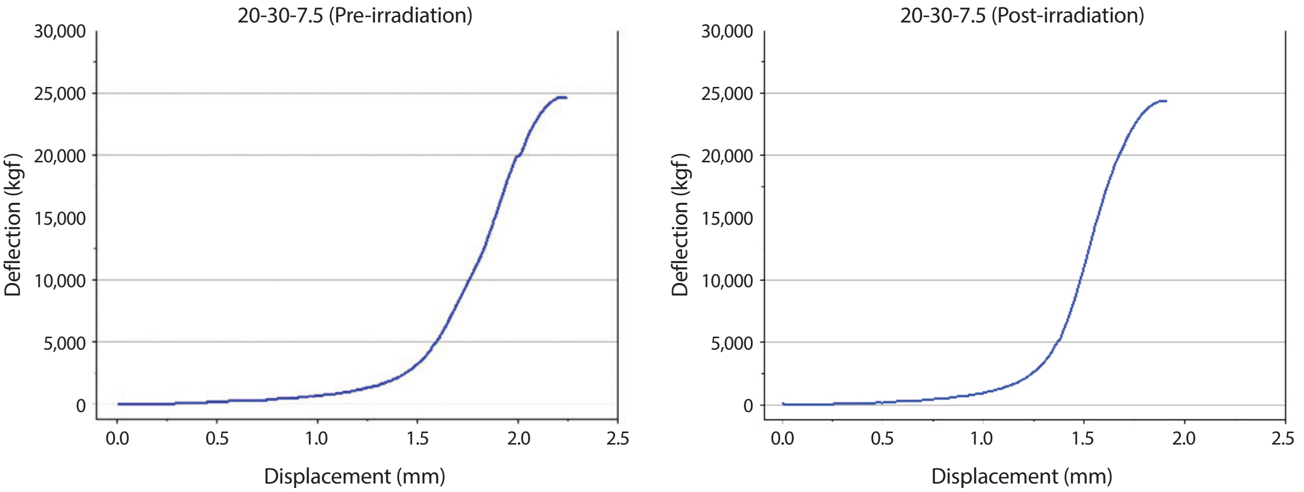
Test	Specimen	Pre-irradiation	Post-irradiation	Variation	
				Test (20 years)	Estimate (50 years)
Compressive strength ($kg\cdot cm^{-2}$)	1	312	310		
	2	327	293		
	3	316	315		
	4	343	309		
	Average	324.5	306.8	−5.45%	−9.72%
Tensile strength ($kg\cdot cm^{-2}$)	1	28.2	25.3		
	2	26.7	24.7		
	3	27.7	24.1		
	4	29.4	21.6		
	Average	28.0	23.9	−14.6%	−25.87%
Flexible strength ($kg\cdot cm^{-2}$)	1	45.8	43.6		
	2	48.7	47.5		
	3	42.7	44.8		
	Average	45.7	45.3	−0.88%	−1.68%

3.4 Strength Test Results

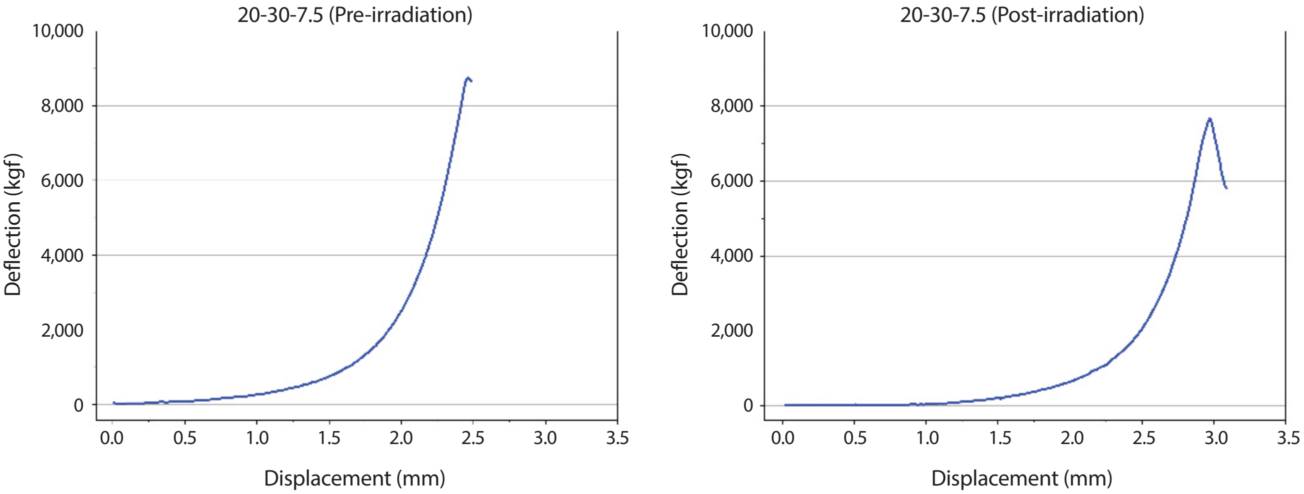
The test results of concrete specimens before and after irradiation of dose 1.8 MGy are summarized in Table 4, and each average strength of concrete specimens after irradiation is 5.45% lower in compression, 14.6% lower in tension, and 0.88% lower in bending, respectively. The force-displacement curves of specimen-1 before and after irradiation are shown in Fig. 9.

The test results of metal specimens before and after irradiation of dose 1.8 MGy are summarized in Tables 5 and 6, and the force-displacement curves before and after irradiation for specimen-1 are shown in Fig. 10. For carbon steel after irradiation, the average values of tensile strength and elastic modulus increased by 1.51% and 6.45%, respectively, and the average values of yield strength and elongation decreased by about 2.67% and 3.70%, respectively. For stainless steel after irradiation, only the average tensile strength increased by 2.47%, while the average yield strength, elongation, and modulus of elasticity decreased by 1.79%, 0.72%, and 1.42%, respectively.

Using the results obtained by irradiating with the dose equivalent to the storage time of 20 years, the increase-decrease rate was estimated by extrapolation for the irradiation dose to 3.18 MGy, which corresponds to the licensed storage time of 50 years for the silo system (see the rightmost columns of Tables 4, 5, and 6). The strength of concrete after irradiation decreased by 9.72% in compression, 25.87% in tension, and 3.13% in bending. After irradiation, the tensile strength and elastic modulus of carbon steel increased by 2.69% and 11.79%, respectively, and the yield strength and elongation decreased by 4.86% and 6.60%, respectively, while the tensile strength of stainless steel increased by 4.29% and the yield strength, elongation, and elastic modulus decreased by 3.16%, 1.40%, and 3.38%, respectively.



(a) Compressive strength



(b) Tensile strength

Fig. 9. Force-deflection curves of concrete specimen (for specimen 1).

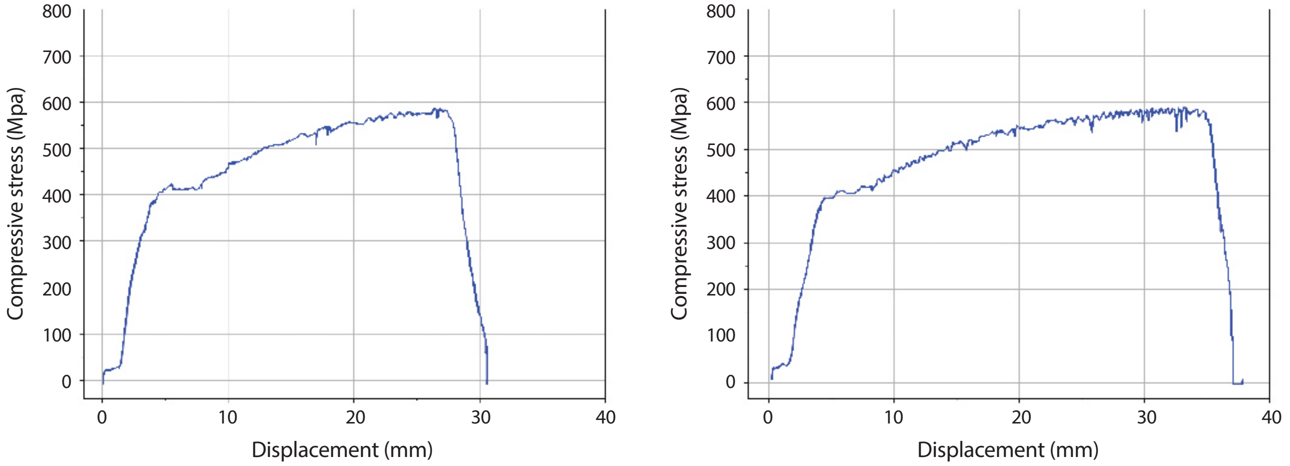
Table 5. Test result for carbon steel specimens

Test	Specimen	Pre-irradiation	Post-irradiation	Variation	
				Test (20 years)	Estimate (50 years)
Tensile strength (MPa)	1	591	595		
	2	599	613		
	3	595	604		
	Average	595.0	604.0	+1.51%	+2.69%

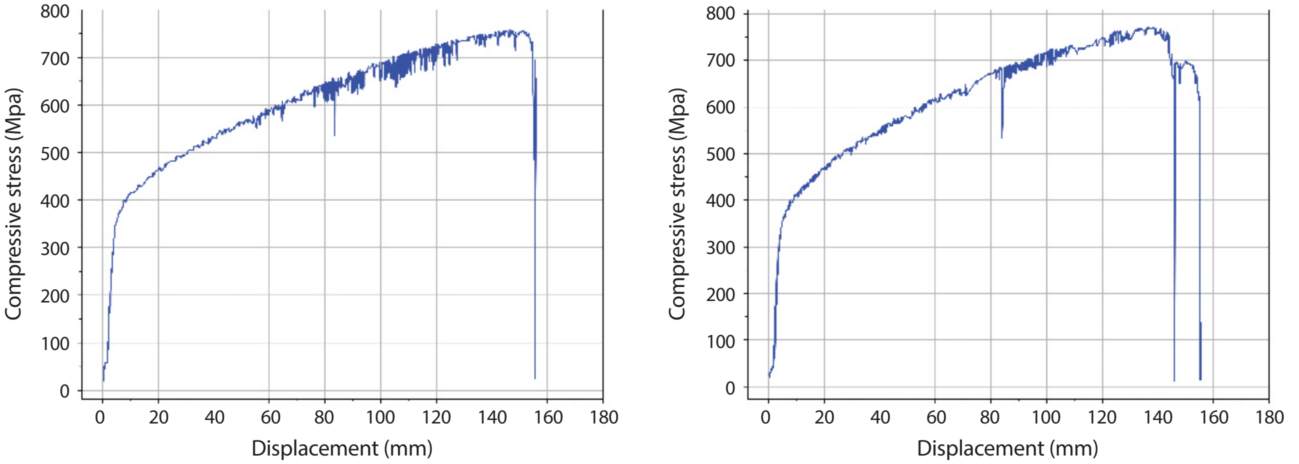
Test	Specimen	Pre-irradiation	Post-irradiation	Variation	
				Test (20 years)	Estimate (50 years)
Yield strength (MPa)	1	427	411		
	2	427	419		
	3	426	415		
	Average	426.7	415.0	−2.67%	−4.86%
Elongation (%)	1	18.5	17.3		
	2	191.1	18.5		
	3	19.0	18.7		
	Average	18.9	18.2	−3.70%	−6.60%
Elastic modulus (MPa)	1	1.86×10^5	1.93×10^5		
	2	1.80×10^5	2.07×10^5		
	3	1.92×10^5	1.95×10^5		
	Average	1.86×10^5	1.98×10^5	+6.45%	+11.79%

Table 6. Test result for stainless steel specimens

Test	Specimen	Pre-irradiation	Post-irradiation	Variation	
				Test (20 years)	Estimate (50 years)
Tensile strength (MPa)	1	762	771		
	2	763	788		
	3	755	776		
	Average	760.0	778.3	+2.47%	+4.29%
Yield strength (MPa)	1	358	350		
	2	360	348		
	3	352	353		
	Average	356.7	350.3	−1.79%	−3.16%
Elongation (%)	1	55.9	55.2		
	2	54.7	54.4		
	3	550	54.7		
	Average	55.2	54.8	−0.72%	−1.40%
Elastic modulus (MPa)	1	1.47×10^5	1.32×10^5		
	2	1.40×10^5	1.42×10^5		
	3	1.34×10^5	1.39×10^5		
	Average	1.40×10^5	1.38×10^5	−1.42%	−3.38%



(a) Carbon steel



(b) Stainless steel

Fig. 10. Force-deflection curves of metal specimen (for each specimen 1).

4. Conclusion

Because the components of silo dry storage system are exposed to radiation of SNF with high radioactivity, it is necessary to analyze the effects of long-term storage. For this purpose, material specimens of the concrete structure, inner liner, and fuel basket were subjected to the irradiation and strength tests to examine changes in their properties. The irradiation dose caused by the direct and proximity to SNF was calculated, the irradiation tests were carried out using the irradiation dose for the storage time of 20 years. The strength tests were performed on each specimen before and after irradiation. The mechanical properties of each material were determined to analyze the differences due to irradiation. It was found that the mechanical characteristics of the main components of silo system were affected by irradiation during the storage of SFF, although they were not that significant. This can be seen as an aging effect of irradiation damage in which the irradiation defects were formed by the high energy irradiation and then the material properties changed.

Among the mechanical characteristics of these components, the compressive strength of concrete and yield strength of metals, which can affect the structural integrity of the silo system, tended to decrease over the storage time. Previous studies have shown that the compressive strength of concrete is affected by gamma ray irradiation of more than 100 MGy [12-13], and that 1 MeV of gamma rays must be irradiated at more than 5.9 $\mathrm{MGy \cdot yr^{-1}}$ to affect the material properties [14]. The cumulative irradiation dose of 1.8 MGy over 20 years and 3.18 MGy over 50 years are relatively small, so it is unlikely that these gamma ray irradiations will have a significant impact on the long-term integrity of current silo system.

Although the test results were not sufficient due to the test conditions of test institute, the small number of specimens and the concrete specimens that did not take into account the rebar, it was possible to get some insight into the aging characteristics of the components of silo system due to irradiation. It is desirable to take into account the aging characteristics due to irradiation when assessing the long-term integrity of silo system in the future, as the decrease in material strength over the storage time is unfavorable to the structural integrity of silo system.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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