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HW/4

Performance test of non-metallic liner materials to be used inside reactor building

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ABSTRACT

Because of the cracks caused by creep, shrinkage and seismic displacement etc., the Reactor Containment Structure has always a possibility of leakage under accidental conditions. So, in order to minimize the potential leakage of radioactive material through the Containment structure, CANDU type Nuclear Power Plant use slip-form to eliminate construction joints and adopt non-metallic liner. This paper presents the performance tests of the non-metallic liner system developed to be used inside Reactor Building and Spent Fuel Pool.

1. Introduction

Non-metallic Liner has become a widely used material that replaces the metallic liner of tanks, pools and also Reactor Building Containment Liner. Due to the low price, fast construction and the ease of application and maintenance, the non-metallic liner material might be a good material if well developed, qualified and applied.

In CANDU type nuclear power plants, as there is no steel liner inside the Reactor Building and the Spent Fuel Storage Pool, the non-metallic liner plays a very important role in preventing leakage of radioactive materials to the surrounding environment. So, before the start of non-metallic liner application in Wolsong Nuclear Power Plants 2, 3 and 4 Units, AECL(Atomic Energy Canada Limited -Designer), KEPCO(Korea Electric Power Corporation - Owner) and KINS(Korea Institute of Nuclear Safety - Regulatory Bureau) have set up a test specification and procedure to assure that the performance of lining materials meet the design and safety requirements.

Because test had not been performed since the Canada National Standard (CSA/CAN3-N287.2)[1] was established in 1982, the test conditions have been newly fixed through discussions between the above three organizations and the manufacturers of the lining materials.

2. Test Items and Conditions

A. Test Items Selection

Basically eight test items were selected by AECL according to the Canadian National Standard CSA/CAN3-N287.2 clause 7.5[1]. These are Radiation Resistance Test, Air Leakage Rate Test, Elasticity Test, Decontamination Test, Impact Resistance Test, Adhesion Test, Fire Resistance Test and Abrasion Resistance Test. Detailed test requirements and the acceptance criteria are shown on paragraph 2.B.

Three additional test items were selected based on previous experience in the paint qualification in nuclear industries. These can supplement the standard and are helpful to determine the acceptance of liner materials to be used inside reactor building. These are Chemical Resistance Test, Heat Aging Test and Hardness Test.

By the way, in order to assure the identity of liner materials between one in qualification test and others in mass production process, three tests - Weight per Gallon, Non-volatile Contents and Ash Contents - were selected and requested to the liner material manufacturers before starting the qualification tests. Other tests such as Viscosity, Fineness of grind, Sagging, Drying Time, Flash Point, etc. are done by the manufacturers for their own quality control. These are based on 'Manual of Coating Work for Light-water Nuclear Power Plant Primary Containment and other Safety-Related Facilities[2]' published by ASTM sub-committee.

B. Test Conditions and Acceptance Base of the Test

As stated in previous paragraphs, the non-metallic liner in CANDU type nuclear power plants is essential for preventing the leakage of radioactive materials through the concrete structure. So, the characteristics of liner materials should be maintained through the lifetime of nuclear power plant in any harsh environmental conditions inside Reactor Building. To do so and to verify the characteristics of liner materials following test conditions and the acceptance criteria are given :

1) Radiation Resistance Test
   - Accumulate maximum Dose Level in CANDU : 1×10^7 Rad
   - Accumulated minimum Test Dose : 2×10^8 Rad
   - Accumulated reference Test Dose : 3×10^9 Rad

2) Air Leakage Rate Test
   - Test Pressure : 124 kPa (18psi)
   - Temperature : 125 ℃
   - Relative Humidity : 100 %
   - Permissible Leakage Rate※ : 1.6 cc / min.m²

※ calculated by following formula : see reference 3.

ℓ = (Containment Vol. x total allow. leak rate x expected liner leak ratio) / (total liner area x safety factor)
= (48,480 m³ x 0.5 % C.V./day x 20 %) / (5,541 m² x 4) / (24 x 60 min)
= 1.6 cc / min. m²

3) Elasticity Test

- Elongation (reference)	: continuous loading with film strip
- Crack Bridging	: ① constant loading
	: ② step loading (0.08 mm step / 12 h)
- Min. crack bridge width	: 0.25 mm (0.01 inch) - 2 times bigger than the max. predicted crack width [3]

4) Chemical Resistance Test

- Chemical solution	: Nitric Acid, Sulfuric Acid, Caustic Soda
- Test duration	: 24 hours

5) Decontamination Test

- Test method	: BSI 4247 Part 1
- Decontamination Factor	: min. 3 x 10^2 (99.7 % removal)

6) Impact Resistance

- Min. Impact	: 2.3 N.m

7) Adhesion Test

- Minimum Adhesion	: 550 kPa - After Radiation or Impact
	: 700 kPa - Other conditions

8) Fire Resistance Test

- Test standard	: ANSI/ASTM E84
- Acceptance Criteria	: F.S.C. < 40

9) Abrasion Resistance Test

- Test Condition	: Taber abrator H-18 wheel and 100 g weight
- Acceptance criteria	: more than 50 cycles to remove 0.25 mm of liner material

10) Heat Aging Test

- Test Condition	: Max. temperature - 125 ℃
	: Max. Pressure - 125 kPa

11) Hardness Test

- Test Condition	: ASTM D2240 Portable Shore 'A'
- Acceptance Criteria	: Hardness Change < 15 %

3. Performance of the Test

It took 8 to 18 months to complete the tests from the preparation of concrete test specimens to submit the test reports depending upon each paint manufacturers' conditions.

There were certain problems during the test performance. Some were related to the test code, standard, conditions and/or the test procedure and others were related to the evaluations of the test results.

All problems were resolved by immediate discussion during the test between AECL, KEPCO, KINS, Testing Laboratory and Manufacturers of lining materials. Based on the conclusion of the discussion, related code, technical specifications and test procedure have been revised.

A. Specimen preparation

Each manufacturer of the liner materials prepares liner samples to test and fabricates the specimens as shown on Table 3-1. Some specimens are prepared by the testing laboratory depending upon the tests to be performed.

Table 3-1 Number of Test Specimens

Substrate	Samples	Non-irradiated	Irradiated	Remarks
Concrete Block	2 x 6	HA + A	HA + A	2 x 10^8 Rad
	1 x 3	-	R	3 x 10^8 Rad
	2 x 2	C1 + H + A	C1 + H + A	
	2 x 2	C2 + H + A	C2 + H + A	
	2 x 2	C3 + H + A	C3 + H + A	
	2 x 2	D	D	
	2 x 3	I + A	I + A	
	2 x 3	H + HA + A	H + HA + A	
	2 x 6	E(CB)	E(CB)	
Liner Film	2 x 2	E(S)	E(S)	by Testing Lab.
	2 x 6	L	L	by Testing Lab.
Cement Asbestos	2 x 3	F	F	by Testing Lab.
	1 x 3	AB	-	

A : Adhesion
D : Decontamination
F : Fire Resistance
H : Heat Aging
HA : Hardness Test
R : Radiation Resistance

AB : Abrasion Resistance
E : Elasticity
(CB) - Crack Bridging
(S) - Stress strain Curve
I : Impact Resistance

C : Chemical Resistance
C1 - Nitric Acid
C2 - Sulfuric Acid
C3 - Sodium Hydroxide
L : Air Leakage Rate Test

B. List of Tested Non-metallic Liner Materials

Qualified liner materials are as shown on Table 3-2.

Table 3-2 List of Liner Materials for each Manufacturer

Manufacturer	non-metallic liner for Containment Structure	fiber-glass reinforced epoxy liner for Spent Fuel Pool	Remarks
KCC	Nukopox EP 1120 Nukopox EP 5140	Nukopox EP1120 Nukopox EH2340	
Carboline	Carboline 195 Carboline 890	Same as left	
Semo	Senupon primer 4363 Senupon HB 3334	Same as left	

C. Problems found during the Tests

1) Decontamination Test

The dimension of test specimen required in the standard BSI 4247 Part 1 is 140 x 50 x 13㎜. On the other hand, that of technical specification[4] requires 150 x 150 x 35㎜ because of the 20㎜ of maximum aggregate size used in the Reactor Building Containment Structure. In the real test done in the laboratory - Corrosion JJL and Warnock-Hersh in CANADA - the specimens are cut out to 150 x 50 x 35㎜ (for KCC and Carboline) and 150 x 50 x 10㎜ (for Semo) in order to be submerged into the decontamination solution in testing bowl and to obtain reasonable results.

The Decontamination Factor(DF) obtained by the result of the test is lower than the acceptance criteria as predicted. The reasons are thought that : ① the selected and tested epoxy materials are elastic and soft thus coherent and, ② the vortex required to clean the contaminated surface is not sufficient because of the disturbance by the thicker specimen than the thickness specified in the test standard.

But the resulted DF is bigger than that of owner's operation requirements of 20 (95 % of contamination removal) as shown on paragraph 4 of this paper and, as a result, was considered acceptable with no further test.

2) Abrasion Resistance Test

Cement asbestos plate used to make the abrasion resistance test specimens tends to be distorted when epoxy liner materials are applied on one side and, as the epoxy profile applied onto the specimens is not perfectly flat the measurement of coating material removal shows big differences in one plate. So, one group of test was re-performed after making the surface with flat condition by rotating the 'Taber Abrator' 150 cycles and the other groups of test were performed with steel plate specimens.

The surface profile gives a small influence as shown on paragraph 4 and both test results are within the acceptance criteria. But for this type of testing it is recommended steel plate specimens be used with the coated surface abraded by performing about 150 cycles in order to minimize the influence of surface profile to the results.

3) Hardness Test

The technical specification (reference 4) calls for ASTM D2240-75 as a test standard and it requires thickness 6㎜ of test specimens to perform the 'Shore A' hardness test. But the liner thickness applied on the concrete specimens is 0.6㎜ for Epoxy Liner applied on Reactor Containment Structure and 0.8㎜ for Fiber-glass Reinforced Epoxy Liner used inside the Spent Fuel Storage Bay Pool.

The epoxy material is so hard that the hardness is about 95, and the newly revised test standard ASTM D2240-91[5] permit to use thinner specimens when the materials having hardness values at the upper end of the scale. This means that the thickness of the specimens is dependent on the extent of penetration of the 'Indentor' into the specimen and the test results are acceptable.

In the future when this kind of test is needed, it would be preferable to use 'Shore C' or 'Shore D' hardness test rather than 'Shore A' for hard materials. To do so would require a revision of the related codes and/or standards.

4. Comparison of the Results of Tests

Major test results that are the most important in CANDU type nuclear power plant - Decontamination, Elasticity (Elongation, Crack Bridging), Air Leakage - and those mentioned above for each liner materials are as follows :

A. Decontamination Test

In general, it is understood that the decontamination factors of non-metallic liner material tend to increase after radiation exposure because the liner material become harder when exposed to the radiation. But, the test results show big deviation in one group of test and not the same tendency before and after irradiation.

The results of decontamination test are shown on Table 4-A-1.

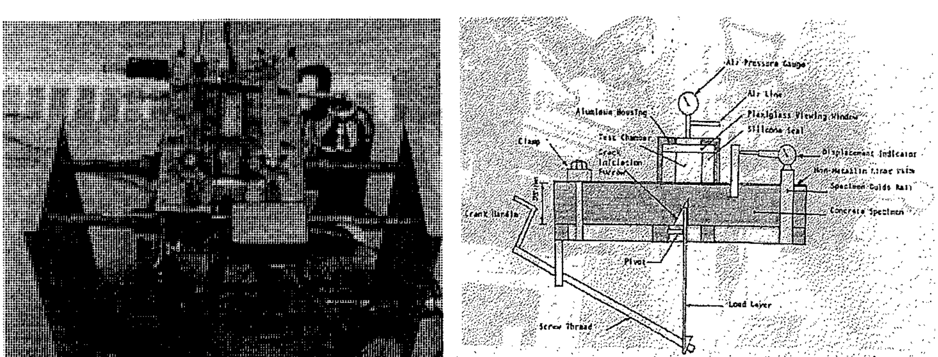
Table 4-A-1 Decontamination Test Results

Manufacturer		Before Radiation	After 200 MRad	Remarks
KCC	Liner	26,28,36,28 (29)	108,97,96,96 (99)	
	Fiber-glass	37,28,34,25 (31)	24,23,27,25 (25)	
Carboline		248,397,360,346,410 (352)	84,105,99,267,144 (140)	
Semo	Liner	151,66,85,46,89 (87)	34,39,38,64,51 (45)	
	Fiber-glass	66,50,67,57,45 (57)	204,98,43,43,85 (94)	

B. Elasticity Test

Epoxy liner specimens coated on concrete block 150 x 150 x 35mm were used to perform the crack bridging test. Two kinds of tests were made with concrete block. One was done with constant loading while the other was done with step loading as stated before.
To perform the test a special test equipment as shown on Figure 4-B-1 is used and the results of the test are shown on Table 4-B-2.

Figure 4-B-1 Crack Bridging Test Equipment



Epoxy film strips were also used to determine the elongation for reference and to demonstrate that the crack bridging results were reasonable. The thickness of the film sample is the same as the epoxy liner to be applied and the film is cut by 100 x 15㎜ and the free span that can be extended between film holders is 1inch (25.4㎜). The test results are as shown on Table 4-B-1.

Epoxy liner is elastic when first made but becomes rigid after several months. More tests are being made to know the change of elasticity in certain time span. The test will be continued for 2 years and the interim test results are shown below at Table 4-B-3 for reference.

Table 4-B-1 Elasticity Test (with film strip)

Manufacturer		Before Radiation		After 200 Mrad		Remarks
		㎜	%	㎜	%	
KCC	Epoxy	24.7	96.7	11.3	44.5	Average
	Fiber-glass	3.1	11.4	2.5	9.9	
Carboline	Epoxy	4.7	18.6	4.2	16.4	
	Fiber-glass	3.6	14.3	3.8	14.8	
Semo	Epoxy	2.2	8.7	2.1	8.0	
	Fiber-glass	2.9	11.5	2.7	10.7	

Table 4-B-2 Crack Bridging Test

Manufacturer		Continuous Loading		Step Loading		Remarks
		Before Rad	After Rad	Before Rad	After Rad	
KCC	Epoxy	0.97	0.55	0.51	0.38	Average (㎜)
	Fiber-glass	0.53	0.44	0.54	0.50	
Carboline	Epoxy	0.56	0.50	0.59	0.51	
	Fiber-glass	0.88	0.96	0.67	0.72	
Semo	Epoxy	0.42	0.45	0.46	0.36	
	Fiber-glass	0.67	0.64	0.73	0.82	

Table 4-B-3 Change of Elasticity

Manufacturer				Time after application (Months)							Remarks
				2	3	5	8	12	18	24	
KCC	ET 5140	Liner	Pour	20.6	5.7	16.1	3.65				Average
			Spray	15.1	5.7	18.3	3.25				
		Block	Cont.	0.39	0.36	0.36	0.40				
			Step	0.33	0.35	0.35	0.39				
	EH 2340	Liner		3.6	3.0	3.4	2.36				
		Block	Cont.	0.55	0.59	0.68	0.72				
			Step	0.63	0.58	0.63	0.60				
Carboline	C890	Liner	Pour	6.1	3.5	4.4	3.75				
			Spray	6.1	3.1	2.8	3.49				
		Block	Cont.	0.41	0.43	0.40	0.44				
			Step	0.38	0.40	0.41	0.40				

C. Air Leakage Rate

Test is performed in the most severe environmental conditions during LOCA event mentioned in paragraph 2.B.2) - 125℃, 18psi (124㎪) and 100% R/H. Some reference tests were made at the first test under manufacturer's help at higher pressure (29psi, 200㎪) and found that the leak rate increases as the pressure rise. It is generally thought that thicker liner reduce the leakage rate; but this is not always true. This is thought, because of the pinholes inside liner caused by worker's application skill.

Table 4-C-1 Air Leakage Rate (unit : cc/m².hr)

Manufacturer		18psi (125㎪)		29psi (200㎪)		Remarks
		Before Rad	After Rad	Before Rad	After Rad	
KCC	Epoxy	0.78	0.59	1.15	0.35	Average
	Fiber-glass	0.49	0.29	0.34	0.21	
Carboline	Epoxy	0.34	0.46	-	-	
	Fiber-glass	0.18	0.56	-	-	
Semo	Epoxy	0.53	0.47	-	-	
	Fiber-glass	0.55	0.37	-	-	

D. Abrasion Resistance

The test have been performed for two times as mentioned in paragraph 3.D.2). The first one was done counting the cycles to remove 25㎛ and the second one was done measuring the thickness removed after 50 cycles.

Table 4-D-1 Abrasion Resistance

Manufacturer		Cycles to remove 25㎛		THK(㎛) Rem'd at 50 c		Remarks
		Before Rad	After Rad	Before Rad	After Rad	
KCC	Epoxy	72	83	17.5	13.3	Average
	Fiber-glass	83	86	10.3	9.3	
Carboline		70	-	15	-	
Semo		58	-	21.9	-	

E. Hardness Test

This test was done for evaluation purpose only and should be read in conjunction with other qualification tests.

Table 4-E-1 Hardness

Manufacturer	Epoxy Liner		Fiber-glass Epoxy		Remarks
	Before Rad	After Rad	Before Rad	After Rad	
KCC	98.3	99.0	97.3	98.1	Average
Carboline	99.1	98.7	98.7	98.2	
Semo	97.0	99.0	97.9	99.8	

5. Conclusion

The epoxy non-metallic liner material has a good characteristics for radiation resistance, for durability and for bridging the crack width. The test for determining elastic change depending upon the age after liner application is not finished yet but, it is believed that the change will be negligible during the lifetime of power plant as shown on the test results.

Both the epoxy and fiber-glass reinforced epoxy liner have sufficient capability to lower the air leakage through the Reactor Containment Structure. But, the application is very important. Without the applicator qualification and checking the environmental conditions - moisture content in concrete, humidity and temperature, due point etc. - we cannot assure the correct functioning of the liner. Leakage can pass through pinholes, cracks or any defects created during the application of liner. A well written procedure and systematic control of work on site is as important as the material qualification.

The fiber-glass reinforced epoxy liner is good and widely used in a pool and a portable water reservoir, nevertheless it will be preferable to use metallic liner inside spent fuel storage pool. The reason is that it is almost impossible to repair the liner when the radioactive spent fuel exist inside the pool and, the liner can be damaged if there are mistakes in handling the spent fuel storage racks and spent fuel.

References

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