Study on the life management of CAP1400 nuclear power plant safety-related coatings

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Abstract. CAP1400 is a generation III NPP type with the independent copyright of China. Under accident conditions, its safety related coating plays an important role in passive containment cooling and core cooling without manual intervention measures within 72 hours. By conducting simulation experiments on inorganic zinc in the basic coating, the changes in its contact angle and thermal conductivity functional characteristics after environmental degradation were systematically studied. By observing the microstructure changes of inorganic zinc before and after aging through scanning electron microscopy, it was found that the water contact angle decreased and the hydrophilicity increased due to the filling of voids in the pore structure and the porosity of the coating before and after aging. Based on RG1.54 guidelines and ASTM coating management standards, the CAP1400 Nuclear Power Plant Safety Related Coating Life Management Guidelines have been proposed, laying a solid foundation for the regulatory guidelines for nuclear power plant safety related coatings and the life management of CAP series nuclear power plant safety related coatings.

Keywords: CAP1400, Safety-related coatings; Life cycle management; Inorganic zinc

1 Introduction

CAP1400 nuclear power technology is independently developed by our country on the basis of the digestion and collection of AP1000 nuclear power technology introduced by Westinghouse of the United States [1-2]. The reactor coolant system, special safety facilities, the main nuclear island auxiliary system and main equipment, and the nuclear island plant layout have been redesigned and systematically optimized, and key equipment has been localized. It is a third-generation passive pressurized water reactor technology with independent intellectual property rights in our country. Its safety, economy and environmental compatibility have reached the world advanced level of generation III NPP. Under the goal of carbon peaking and carbon neutrality, Chinese energy system will continue to accelerate the clean and low-carbon transformation, and

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the CAP1400 nuclear reactor technology will play an important role in Chinese clean and low-carbon transformation.

Protective coatings are widely used on the surfaces of nuclear power plant facilities and equipment to reduce surface corrosion and radioactive contamination. In addition, the failure of the coating affects the safety functions of nuclear power equipment and facilities to a certain extent. The safety-related coating of the CAP1400 nuclear power plant assumes the main heat transfer interface of the passive containment shell cooling system. At the same time, the internal coating of the containment shell also needs to bear the responsibility of not blocking the recirculation of the containment shell pit in the event of failure, thereby affecting the realization of the safety function of the passive core cooling system. Therefore, key attention should be paid to the design, construction and operation supervision of CAP1400 safety-related coatings. Since Chinese nuclear regulatory authority has not yet established the "Guidelines for the Supervision of Safety-related Coatings for Pressurized water reactor Nuclear power Plants", the Lifecycle management system of CAP1400 nuclear power plant safety-related coatings such as design, procurement, construction, and inspection needs to be developed and established on the basis of the US Nuclear Regulatory Commission RG 1.54 and ASTM D5144 framework [3].The CAP1400 nuclear power plant safety-related coating partition is shown in Figure 1.

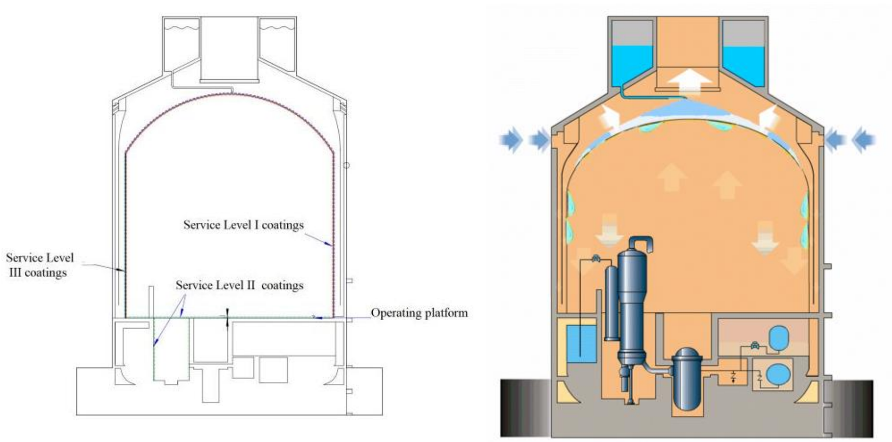


Fig. 1. CAP1400 Nuclear Power Plant Safety Coating Zoning Diagram

Referring to the U.S. Nuclear Regulatory Commission RG1.54-2010, the CAP1400 nuclear power plant divides the coating of the power station into Service Level I, Service Level II, and Service Level III. Among them [4]:

Service Level I coating is applied to inner surface of the reactor containment shell. Its failure will seriously affect the operation of the fluid system after the accident, which in turn affects the safe shutdown of the nuclear power plant. The inorganic zinc coating on the surface of the CAP1400 nuclear power plant containment shell and above a certain height of the operating platform needs to support the heat conduction from the atmosphere in the containment shell to the containment shell after the accident. The inorganic zinc coating needs to be tested and analyzed for the cooling system of the passive containment shell. This coating is divided into Service Level I coating. Use an inorganic zinc coating system for the internal equipment of the containment shell (surfaces that exceed the temperature range of the epoxy coating under normal operating environment). This part of the inorganic zinc coating is also coated in the Service Level I to prevent the coating from peeling off during LOCA (because the coating fragments are not easy to settle).

After the failure of Service Level II coating, it will affect but not block the normal operation of the plant. In the area where radiation exposure and radioactivity are received outside the containment shell, the main function of the Service Level II coating is to provide corrosion protection and improve the removal capacity of radioactive contaminants. The internal structure of the containment shell and the coating system used in the equipment are Service Level II. The coating system is mainly a high-solid epoxy coating. The Service Level II coating are not safety-related coatings. Based on the principle of conservative considerations, the design of the CAP1400 nuclear power plant requires that the epoxy density of the concrete and carbon steel surfaces inside the containment shell is large enough (the dry film density is greater than $1600kg/m^3$), and they all need to pass LOCA, irradiation and many other tests to verify. This can limit the migration of debris in the containment shell at low water flow speeds. If the dry film density of the coating for walls, structures, or equipment is less than $1600kg/m^3$, tests and analysis must be carried out to prove that the coating fragments will not be transferred to the filter or enter the core through flooding and rupture.

Reactor Service Level III is the outer coating of the reactor containment shell, and its failure will seriously affect the operation of safety-related structures, systems, and equipment (SSC). The inorganic zinc coating on the outer surface of the shell above the CAP1400 nuclear power plant containment operating platform needs to support the heat conduction of the passive containment cooling system, which is a Service Level III coating.

The functional description of the CAP1400 nuclear power plant safety-related coating is shown in Table 1.

Table 1. CAP1400 Nuclear Power Plant Safety Related Coating Function Description

part	coating type	functional	classification
The outer surface of the safety shell (the elevation of the operating platform is above 12.65m)	Inorganic zinc	1.Increase wetability; 2.Heat conduction under accident; 3.Non-peelable; 4.Corrosion resistance	Service Level III
The inner surface of the containment shell (the elevation of the operating platform is above 12.65m)	Inorganic zinc	1.Increase wetability; 2.Heat conduction under accident; 3.Non-peelable; 4.Corrosion resistance	Service Level I
The surface of the inner body of the safety shell (the elevation of the operating platform is above 12.65m, and the decontamination requirements are required)	Inorganic zinc primer and epoxy topcoat	1.Non-peelable 2.Corrosion resistance 3.Improve radioactive decontamination	Service Level I
Inside the containment shell (concrete walls, ceilings and floors, equipment surfaces, etc.)	Epoxy	No safety function	Service Level II

2 Introduction and failure mechanism of safety-related coatings

The inorganic zinc coating is the basic coating of the CAP1400 nuclear power plant containment shell. In order to make the area below the operating platform in the containment shell that can enhance the decontamination effect, the inorganic zinc primer is coated with epoxy topcoat. In the inorganic zinc coating of CAP1400 nuclear power plant safety coating, ethyl silicate is the polymer precursor in the coating. Sufficient water is required during the curing process of the coating, and a suitable environment can ensure that the curing is fully carried out. Hydrolyzed silicate forms the substrate of the dry film of the coating. Zn particles are filled in the voids of the Si-O structure. The strong bond binding of Si-O ensures good performance and is better than organic coatings based on C-C bonds. The inorganic zinc coating matrix is conductive, the electrode potential of the metal Zn is low, and it is more active than the steel containment material SA738 Gr. B grade steel. It plays a cathodic protective role on the surface area of any exposed steel body. The reaction products of the inorganic zinc coating under environmental erosion, zinc carbonate and zinc hydroxide, form a denser protective layer and produce self-healing properties. In addition, the oxidation process of Zn in the inorganic zinc coating is slow, and the corrosion products formed reduce the oxidation rate of the inorganic zinc coating, but when the coating is damaged, the exposed new metal zinc once again enhances the cathodic protection effect. The inorganic zinc coating based on the Si-O bond is dense and strong, which structurally guarantees the stability of the inorganic zinc coating. It is less affected by climate, sunlight, ultraviolet and gamma radiation, rain, dew, bacteria, fungi, or temperature. At present, the service level i and service level III used in the CAP1400 nuclear power plant have been replaced by localization. Its thermal conductivity, coating specific gravity, salt spray resistance test, DBA performance, and decontamination performance all meet the requirements of the design technical specification, breaking the long-term monopoly of foreign companies on nuclear-grade coatings in AP series nuclear power plants.

The EPRI report has shown that the failure of inorganic zinc coatings includes many forms, mainly: stratification, bubbles, cracks and fragments; the main reasons for the failure are poor surface treatment of the base material, insufficient or too thick coating thickness, improper coating composition or incorrect use, improper coating application environment, incorrect deployment of coating components or mass production errors in the production process, etc. Among them, 65% of coating failures are caused by construction defects, including surface treatment defects, insufficient or too thick coating thickness, and insufficient curing of inorganic zinc coating. 35% of coating failures are caused by environmental factors. Only the Service Level I coating, which accounts for 6% of the internal coating of the containment shell, showed a deterioration signal. For safety-related coatings for long-term operation, for safety-related inorganic zinc coatings under working conditions such as irradiation, salt spray, LOCA accidents, and long-term rain erosion and erosion under the action of fouling under natural conditions, changes in their performance indicators, whether they meet the design requirements, it is necessary to carry out performance tests to verify whether the containment shell coating can perform safety functions under long-term operating conditions.

3 Safety-related coating aging test research method

Unlike the AP1000 nuclear power plant, the safety-related coatings of the CAP1400 nuclear power plant use domestic inorganic zinc coatings. Through the production of sample steel plates for the two coatings, a two-month exposure test in the natural environment was carried out to compare the performance differences of the two coatings after two months of fouling to provide support for subsequent life management [5].

In order to verify the performance of the inorganic zinc coating used in the CAP1400 nuclear power plant before and after aging, a neutral salt spray test was used to simulate the marine atmospheric environment in which the outer wall of the containment shell is located, and irradiation tests and LOCA tests were used to simulate the most extreme conditions that the inner wall coating of the containment shell may face. Before and after passing the environmental accelerated aging test, the initial and post-aging heat transfer performance indicators of the sample, including heat conductivity, specific heat, emissivity and water contact angle, were tested, and the measured values were compared with the design values to verify whether the heat transfer performance of the containment shell coating still meets the design requirements [6-10].

The steel plate material used in the test is SA-738 Gr.B, the sample size is 200mm×100mm. The imported coatings use inorganic zinc coatings for steel containment shells of AP1000 nuclear power plants in operation in China and domestic coatings used in CAP1400 nuclear power plants. After the substrate of the specimen is sandblasted in accordance with the requirements of SSPC-SP10, the roughness of the surface of the substrate is 25~75μm and the cleanliness meets the requirements of SSPC-SP10. After the sandblasting treatment is completed, compressed air is used to remove the surface dust. The surface temperature of the steel plate is 5.4℃ relative to the dew point temperature, the ambient temperature is 22.5℃, and the relative humidity is 33%. After the coating is completed, the dry film thickness of the sample is between 60 and 90μm.

3.1 Comparative test of coating exposure in natural environment

A two-month exposure test in a simulated natural environment was carried out, and the surface contact angle, surface roughness, and microscopic morphology changes of the coating were observed under scanning electron microscopy after the first and second months. Compare the performance of localized coatings with imported coatings.

3.2 Salt spray test

In order to verify the performance of the CAP1400 nuclear power plant containment shell coating after accelerated aging, ten steel plate samples were evenly placed in the salt spray corrosion test chamber. Conduct a neutral salt spray test for 3000 hours in accordance with ASTM B117, the test temperature is 35°C, and the test solution is 5% NaCl solution [11].

3.3 Irradiation test and LOCA test

The most extreme conditions that the inner wall coating of the containment shell of the CAP1400 nuclear power plant may face are simulated by using irradiation tests and LOCA tests. The nine samples after the 3.2 section 3000-hour salt spray test were placed in the γ irradiation device and the irradiation test was carried out in accordance with ASTM D4082. For every 2500KGy, one piece of samples of different specifications is taken for heat transfer performance testing. The nine samples after the salt spray and irradiation tests were placed in the LOCA test platform, and the LOCA test was carried out in accordance with ASTM D3911. The time-temperature curve in the simulated LOCA environment is shown in Figure 2.

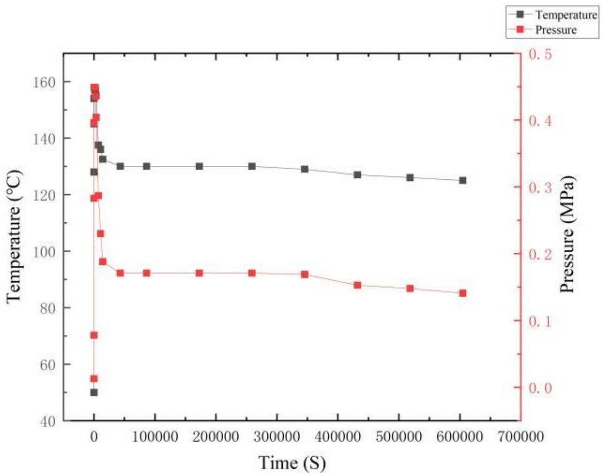
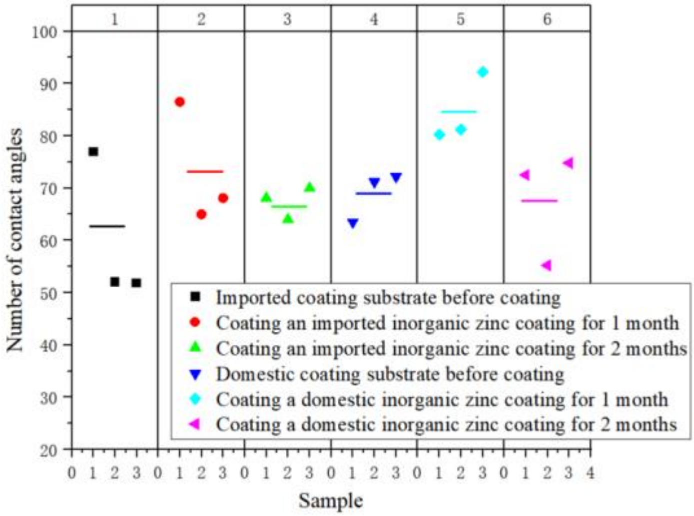


Fig. 2. Time temperature curve under simulated LOCA environment

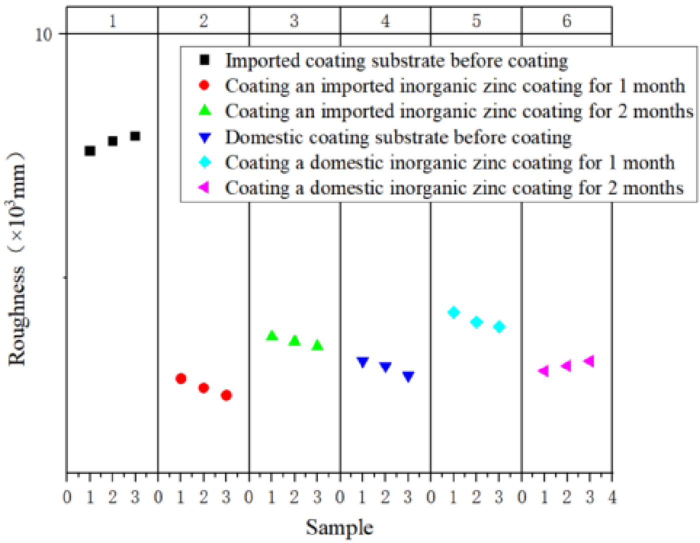
4 Research analysis and discussion on coating aging test

4.1 Results of exposure test in natural environment

Referring to ASTM D7334, an optical contact angle meter is used to measure the contact angle of the coating. The research results show that: 1) The number of contact angles of imported and localized coatings, the contact angle of the test surface of the two-month fouling has not decreased; 2) After two months of natural fouling, the surface coating contact degree of the coating is basically less than 90°, which still meets the design requirements.3) The surface roughness of the coating has not changed significantly within two months. Measure the changes that may occur on the surface of the coating after the test. The changes in contact angle and surface roughness after the exposure test in the natural environment are shown in Figure 3.



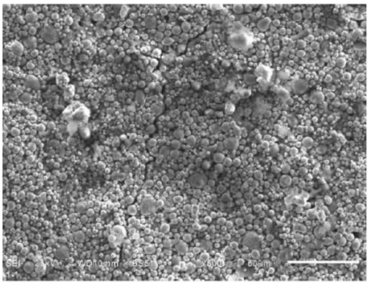
(a)Changes in contact angle



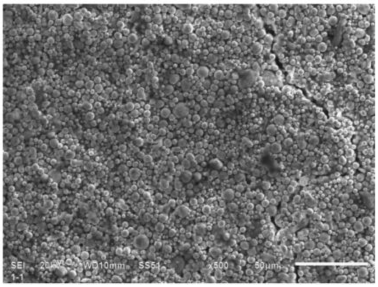
(b)Changes in surface roughness

Fig. 3. Changes in contact angle and surface roughness after exposure to sunlight in natural environments

The results of 500 times microscopic electron microscopy showed that the microscopic morphology of the surface before and after the sample test had fine cracks in the sample after two months of fouling, and the cracks could not be observed with the naked eye. The surface microscopic morphology of the coating is shown in Figure 4.



(a) Imported coating 500 ×

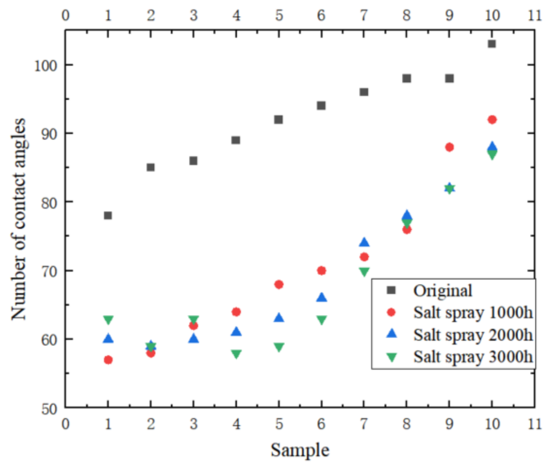


(b) Domestic coating 500 ×

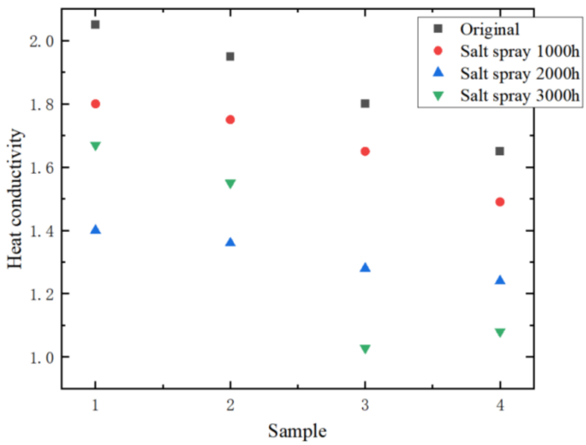
Fig. 4. Surface Micromorphology of the Coating 500×

4.2 Salt spray test results

With the advancement of the salt spray test, the surface color of the sample is getting whiter and whiter, and the white range is getting wider and wider, indicating that the thickness of the zinc salt layer is gradually deepening and the zinc powder is further oxidized. By the end of the 3000h salt spray test, there were no signs of matrix corrosion on the surface of the sample. The angle measuring method is used to measure the original, salt spray 1000h, salt spray 2000h, salt spray 3000h, and inorganic zinc coatings with a large initial water contact angle. With the salt spray test, the water contact angle decreases sharply and tends to stabilize. Judging from the heat conductivity test results, the inorganic zinc coating has a large initial heat conductivity. With the salt spray test, the heat conductivity continues to decrease, and with the salt spray test, the heat conductivity continues to decrease. The changes in contact and thermal conductivity after the coating salt spray test are shown in Figure 5.



(a)Changes in contact angle



(b)Changes in thermal conductivity

Fig. 5. Changes in contact angle and thermal conductivity of coatings after salt spray testing

4.3 Irradiation test and LOCA test results

The samples after irradiation of 2500KGy, irradiation of 5000KGy, irradiation of 7500KGy and LOCA were tested for water contact angle. With the development of the irradiation test, the water contact angle was further reduced, and the final water contact angle of the coating was <90°, which still meets the design requirements. The irradiation test was carried out, and the heat conductivity was further reduced. This is due to the continuous generation of zinc salt, and the thermal conductivity of zinc salt is worse than that of metal zinc powder. The mean heat conductivity of the test temperature of 120°C is 1.276W/m·K. The LOCA test has little effect on the water contact angle. The change in contact degree after the coating irradiation test is shown in Figure 6.

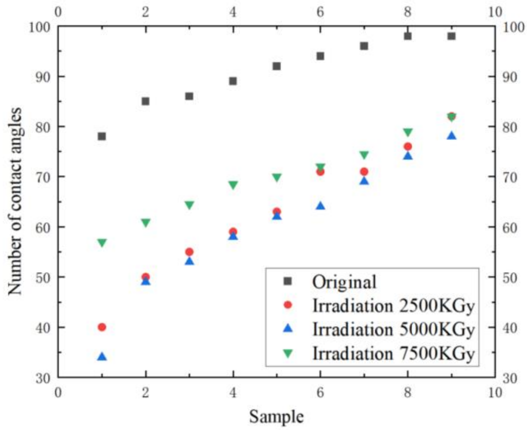


Fig. 6. Changes in contact angle after coating irradiation test

4.4 Inorganic zinc coating test summary

From the microscopic morphology point of view, the particle size of the original inorganic zinc coating is 2~8μm, it is coated with a binder, and the surface of the coating is a porous structure. As the coating ages, zinc salts with higher surface energy are generated on the surface of the coating. On the other hand, the zinc salts generated fill the voids in the porous structure, reducing the porosity of the coating, reducing the water contact angle and increasing the hydrophilicity. For the outer wall coating of the containment shell, its working conditions and environment are simulated by salt spray test. After the neutral salt spray test after 3000h, the water contact angle of the inorganic zinc coating continues to decrease, showing hydrophilicity and good wetting properties. The water contact angle is less than 90°, and the heat conductivity of the inorganic zinc coating decreases. After the LOCA test, the heat conductivity of the coating increased, which was due to the impact of high-speed water flow to remove part of the loose zinc salt on the surface of the coating.

The main purpose of passing the coating exposure test, salt spray aging acceleration test, radiation aging acceleration test, and LOCA test is to verify whether the safety-related coating performance can still perform the safety-related functions of the CAP1400 nuclear power plant after 60 years of service life (including increased wetability, heat conduction under accidents, etc.)

The research shows that the simulated aging test shows that the performance of the safety-related coating of the CAP1400 nuclear power plant containment shell can still meet the design requirements, and it also provides a technical basis for the follow-up safety-related coating life management [12-14].

5 Coating lifecycle management system

The reliability evaluation system of safety-related coatings runs through all stages of the Lifecycle management of nuclear safety coatings in power stations. The system model to ensure the Lifecycle safety includes the production stage of nuclear safety coatings, the engineering construction stage, and the operation stage of power stations [15-16]. The evaluation items at each stage are different. See Figure 7 for the specific evaluation content.

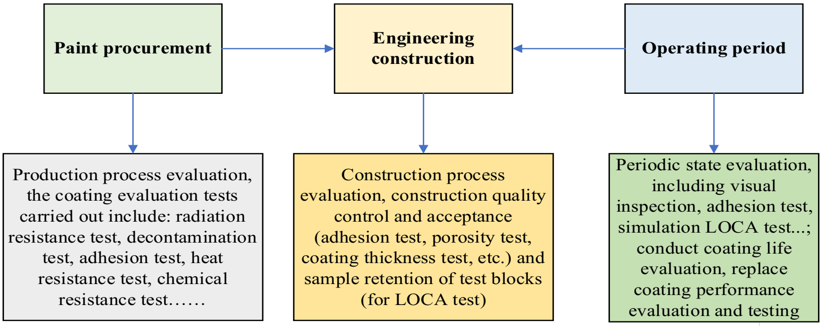


Fig. 7. Safety related coating full life assessment system diagram

In the coating procurement stage, manufacturers need to conduct the necessary coating performance evaluation tests in accordance with the procurement specifications before supplying, and provide satisfactory test data. According to the different parts of the coating application, the required test content is not exactly the same, and the tests carried out need to be entrusted to a testing agency independent of the coating production plant. The specific test methods and acceptance standards are carried out in accordance with the acceptance specifications of the coating, including LOCA test, radiation resistance test, decontamination test, adhesion test, salt spray resistance test, artificial aging test, etc.

The coating construction is carried out after the coating has completed the acceptance of the power station. On the one hand, the reliability of this process is evaluated through the reliability of the construction process, specifically through the pretreatment of the substrate surface, the coating primer, the coating thickness and quality of the topcoat, the coating adhesion test and other evaluation of different construction processes. On the other hand, reliability is achieved by controlling the quality of the construction process and testing the coating thickness, adhesion, porosity, etc. The above two tasks need to be entrusted to a third-party unit with relevant experience to implement. At this stage, the power station should require the construction contractor to prepare and number the test blocks, and it has been prepared for regular LOCA tests.

During the operation of the power plant, the coating reliability evaluation is carried out through regular series of inspections, including visual inspections, adhesion tests, LOCA tests and other tests. Visual inspection of appearance mainly refers to whether the coating has cracked, layered, flaked, bulged, cracked, chalked, and discolored after a period of operation. Adhesion refers to the adhesion between the coating and the substrate, which can determine whether the coating will fall off in a large area under normal working conditions and accident conditions. The simulated LOCA test is to check the ability of the coating to resist LOCA operating conditions by simulating LOCA operating conditions. The visual inspection cycle is checked during each material change and overhaul; the adhesion testing cycle should be tested once during the construction period of the nuclear power plant, once after 5 years of operation, once after 10 years of operation, and once after 10 years of operation. The LOCA test cycle can be selected every 5 years.

Through periodic inspections and evaluations, it is possible to grasp the aging of various types of nuclear safety coatings in different cycles of power station operation, and through the accumulation of data in several cycles, the coating condition monitoring and remaining life assessment can be carried out. For alternative coatings, procurement-related regulations and quality control should also be carried out.

5.1 Coating procurement management

The procurement and use of service-level I and Level III coatings, as well as the procurement of service-level II coatings in the containment shell according to the principle of conservative decision-making, are listed as safety-related activities. The evaluation should include two parts: 1) Whether the product performance meets the requirements for use, and determine its scope of application; 2) The technical verification of power plant chemicals, the potential hazards caused by the chemicals to power plant personnel, equipment and the environment, in order to meet the requirements of power plant chemical management. Before purchasing, manufacturers should provide the following information for evaluation, including: product instruction manual, used to evaluate product performance. The evaluation content includes, but is not limited to, product use, main ingredients, theoretical coating rate, typical film thickness, method of use, drying time, surface treatment requirements, system compatibility, packaging specifications, storage requirements, etc. The composition analysis report assesses whether its composition meets the requirements of on-site use restrictions and whether it is harmful to structures, equipment and components.

5.2 Inspection and evaluation of safety-related coatings

Nuclear power plants should formulate safety-related coating evaluation and inspection plans in accordance with ASTM D5163 and ASTM D7167 to better protect the integrity and service performance of the coating. The monitoring and evaluation of the coating shall be carried out in accordance with the cycle and content determined by the preventive anticorrosion outline, the civil anticorrosion outline, the in-service inspection outline, the preventive maintenance outline, etc., and the defects found shall be evaluated. During the implementation process, the inspection technical procedures and construction technical procedures shall be used as the requirements, and the work order shall be used as the carrier to carry out relevant inspection work. The specific process is shown in Figure 8, the coating status evaluation process.

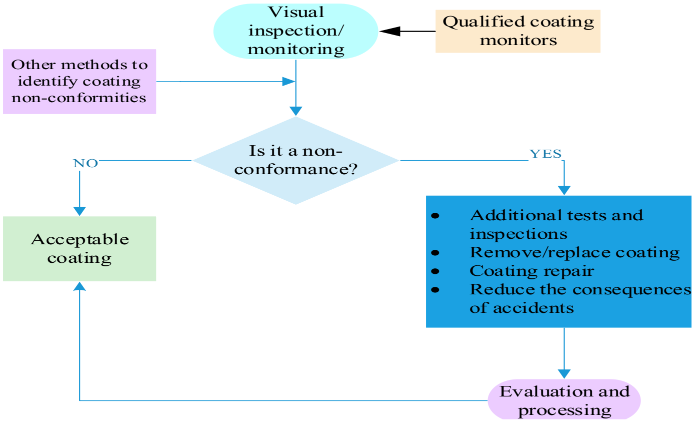


Fig. 8. the process of Coating status evaluation

5.3 Paint construction management

The damaged coating should be repaired, and the repair process should comply with the manufacturer's construction instructions. In principle, the same coating should be used for repairing Level I, Level II, and Level III coatings. If the original coating cannot be used, the item replacement changes should be made. The coatings used in the containment shell and the interior of the containment shell are carefully considered in practical applications. They are tested and identified in accordance with the requirements of RG1.54 and ASTM D5144, and they have passed the assessments of LOCA, radiation resistance, easy decontamination, and high density. Only coated products that meet the requirements can be replaced by items. The quality assurance of the coating operation process should meet the requirements of HAF003 and ASTM NQA-1, or be consistent with the requirements of the quality assurance level of the item to be coated. Coating construction personnel should obey and follow qualified procedures to control surface pretreatment, coating coating and coating inspection. Coating construction personnel inside the containment shell, on the inner and outer surfaces of the containment shell, and in the irradiation control area outside the containment shell shall pass the assessment and training of the coating supplier, and issue a certificate of assessment of the coating supplier.

6 Conclusions and recommendations

Chapter 9 of HAF102 “Safety Regulations for Nuclear Power Plant Design” Containment System, 9.11 Cover Layers and Coatings" clearly states: "In order to ensure the safety functions of the cover layers and coatings of structures and components in the containment system, and to minimize the impact of other safety functions when they deteriorate, the materials for the cover layers and coatings must be carefully selected, and special regulations must be made on the methods of their construction.” A large number of cases and public empirical feedback show that during the entire life of nuclear power plants, safety-related coatings of nuclear power plants must have failure behavior. Because these coatings will affect the safety-related systems, equipment, and components to perform their safety functions, it is necessary to effectively manage the safety-related coatings of nuclear power plants to ensure that the initial design requirements of the coating system are continuously met during the operating life. The CAP1400 nuclear power plant is one of our country's major national science and technology projects, and the world's first CAP1400 nuclear power plant is about to be put into operation. On the basis of the successful replacement of localized safety-related coatings, judging from previous evaluation practices, the initial design requirements of the coating system are continuously met. The CAP1400 nuclear power plant is one of China's major national science and technology projects. The world's first reactor is about to be put into operation. On the basis of the successful replacement of localized safety-related coatings, The nuclear safety coating management outline and maintenance strategy of domestic nuclear power plants in operation have a satisfactory state of use. How to effectively extend the accumulation of existing experience and technology to CAP1400 nuclear power units, and establish a safety-related Lifecycle management system applicable to CAP1400 nuclear power units as soon as possible, so that the safety functions of safety-related coatings, including anticorrosion, wetting, and heat conduction, will not be implemented under the design benchmark accident conditions, and the heat conduction and infiltration properties of the coating will not be adversely affected. It is recommended that on the basis of absorbing domestic nuclear safety coating management technology, the regulatory department of nuclear power plants in my country has not issued a nuclear power plant safety-related coating management system. Before the guidelines, drawing on the U.S. nuclear safety regulations and the safety life management system of the AP1000 nuclear power plant that has been put into operation in China, a life management system applicable to the CAP1400 nuclear power safety coating is established.

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