Research on biological sealing for openings in nuclear power plant

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Abstract. Civil opening sealing is an important work during the construction stage of nuclear power projects, which directly affects the follow-up nuclear cleaning and system transferred to commissioning. The sealing of biological shielding openings mainly exists in the walls and floors across the boundary of the nuclear island buildings, which is with great significance to ensure the integrity of the boundary function of the radiation zone. The configurations for openings in concrete shield walls shall provide adequate attenuation to reduce the exposure of the workers. Through the research of the biological sealing for civil opening and the investigation of good practice for foreign nuclear facilities, the purpose of this paper is to optimize the opening sealing scheme based on construction and operation experience, and give the guidance for the construction application and save the cost for the nuclear project.

1. Introduction
During the civil engineering design and construction of nuclear power plant, a large number of openings are reserved in the concrete structure to ensure the passage of various installation items, such as pipeline, ventilation ducts, cables, etc. According to the installation items in the openings, it can be divided into mechanical openings and electrical openings. According to the function of the zones, it can be also divided into air tightness, water tightness, fire proof and biological shielding, which mainly exists in the civil walls and floors of different functional zone boundaries [1-2]. Among them, the biological shielding opening sealing is mainly concentrated in the control areas of nuclear island, which is important to ensure the functional management of radiation zone boundary in the nuclear buildings.

According to radiation protection requirements, all penetration configurations for openings in concrete shield walls shall be shown to provide adequate attenuation. The configuration should be similar to one that is functioning properly under comparable conditions in an operating nuclear facility, or similar to one that has been evaluated experimental and found to be effective for the radiation level under consideration. The configuration for openings can also be similar to the one that has already been shown by analysis to be effective [3]. The biological shielding sealing materials are normally used to reduce the radiation dose of the staff during the operation and maintenance period of the power station. But this kind of sealing is more difficult than other types of openings for construction and the material price is much higher than others. By studying the design requirements, materials, construction technology of biological shielding opening sealing, analyzing the statistics for biological sealing openings for typical nuclear power project in domestic and investigating the good practices of foreign
nuclear facilities, this paper summarizes and puts forward some suggestions and concerns, so as to guide the design and construction application of various nuclear projects.

2. Sealing principle and requirements for biological shielding openings

The radiation protection design principle of nuclear power plant is to ensure the safety of personnel and to take reasonable measures to control the risks. In order to facilitate radiation management and occupational exposure control, nuclear island building is divided into control area and supervision area according to radiation level. The control area is divided into sub areas according to different radiation doses, such as green area, yellow area, orange area and red area. Biological shielding opening sealing is mainly through special sealing materials or facilities to avoid radiation hazards to the workers in the low radiation dose area caused by the radiation in the high radiation dose area during the operation and maintenance activities.

During the design process of nuclear power plants, the following principles are usually required for the sealing of biological shielding openings.

a). According to the anthropometric size, 95% of Chinese men aged from 18 to 60 years old are below 1775mm in height [4]. Therefore, the openings below 2 meters away from the floor of the radiation protection wall are generally sealed. The openings above 2 meters should be analyzed according to the actual situation by different radiation protection requirements.

b). The civil openings to be sealed by biological shielding are mainly based on the radiation zones. Normally, opening sealing should be considered combine with whether there is radioactive equipment in the room, the period of personnel work activities, etc. The basic principle is that the two rooms with openings are divided into different zones, if one of which is red zone or orange zone and the other is yellow zone or green zone, the opening should be sealed with biological shielding. Besides, if the two zones of the connecting opening are different, one of which is in normal operation and has a long time of operation work or is main passage for personnel during operation and maintenance, the openings are better to be sealed with biological shielding materials. After that, if the two rooms connected with opening are the same red zone or orange zone, it is better to seal the opening with biological shielding materials.

c). According to the design requirements of biological shielding and sealing, the density of sealing materials and the ability to resist gamma rays should be equal to or higher than that of the concrete. Therefore, the thickness of concrete in two radiation zones is an important index to measure whether it can resist corresponding gamma rays. When calculating the thickness of sealing materials, the formula $e^{-\mu x} = e^{-\mu' x'}$ can be used, in which $e^{-\mu x}$ and $e^{-\mu' x'}$ represent the attenuation of radiation from wall or floor and sealing material respectively; $\mu$ and $\mu'$ are the linear attenuation coefficient of radiation from wall or floor and sealing material respectively; $X$ and $X'$ are the thickness of wall or floor and sealing material respectively. When the calculated thickness of sealing material is less than 150 mm, at least 150 mm shall be taken into consideration.

d). For the concrete structure, the density of biological shielding sealing material should not be less than 2.3g/cm³. For the high density concrete civil structures, the density of biological sealing materials shall not be less than that of high density concrete, which is special aggregate or mixtures of special aggregate with the nature mineral aggregates used, such as iron shot, steel punchings and so on [5]. At the same time, the biological shielding sealing material should also be able to ensure the fire resistance of the fire barrier at the sealing position [6].

e). In order to protect the health and safety of personnel during construction stage, the use of lead and asbestos containing products including packaging materials or asbestos fibers mixed with adhesive materials shall be prohibited.

f). The measurement or assessment of concentrations of radioactivity for quantify workers' exposure need to be monitored in the workspace, especially for biological shielding area [7].
3. Sealing material for biological shielding

Different types of silicone are widely used for industry building constructions. In nuclear power plants, high density silicone or ultra-high density silicone is generally used as opening sealing materials for biological shielding. Flexible fire-resistant silicone can be used for openings with large displacement of special pipes, which can also resist biological shielding. These materials need to also have high water tightness, fire resistance, decontamination and seismic performance. Partial parameter comparison for them can be seen in Table 1 [8-9].

Because of the difficulty of construction and high price of biological shielding materials, in order to reduce the waste and unnecessary consumption of radiologic shielding materials in the nuclear island, some approaches can be considered to optimize the sealing scheme according to the boundary function of radiation zone during the design process. For example, the management requirements for personnel maintenance activities of two adjacent radiation zones are the same during normal operation and maintenance, the biological shielding sealing between these zones can be considered to be cancelled. After that, the shielding of different radiation zones can be converted into the minimum thickness required for isolation of concrete according to the management requirements during the operation and maintenance period. The greater difference is between the two adjacent radiation zones, the higher the shielding requirements will be applied and the more materials will be consumed. Otherwise, the smaller the difference is between the two adjacent radiation zones, the lower the shielding requirements will be applied and the less materials will be used.

| Product                        | Water tight (m) | Fire resistant (min) | Density (g/cm³) | Cleaning | Sesmic Displacement (mm) |
|-------------------------------|----------------|----------------------|-----------------|----------|--------------------------|
| High density silicone         | 10             | 140                  | 2.3             | ✓        | ✓                       | 5mm |
| Ultra-high density silicone   | 2              | 140                  | 3.5             | ✓        | ×                        |     |
| Flexible fire-resistant silicone | 10           | 140                  | 2.3             | ✓        | ✓                       | 30mm|

4. Construction process of biological shielding openings

The construction process of biological shielding opening mainly includes the following steps: surface cleaning, formwork erection, sealing material construction, formwork removal, surface decoration, completion acceptance [10-12]. The main concerns in the construction process include the following.

a). During surface cleaning, it is necessary to clean up the loose slag, dust, oil and water on the surface of the sealing opening to avoid residue.

b). For the openings through mechanical pipes, if the casings or sleeves are embedded during the concrete pouring, the high density silicone shall be used for sealing space around the pipes after the pipes installation. For the openings through ventilation ducts, the concrete shall be used for shrinkage first between the ventilation ducts and the reserved openings, and then the high density silicone shall be used for sealing. When pipes, ventilation ducts and cables pass through opening at the same time, steel plates shall be used to separate the sealing of different functions, and then sealing shall be carried out according to different methods.

c). When sealing the electrical openings, the floor openings shall be embedded with 8mm diameter steel mesh, with the spacing less than or equal to 80mm. The location of the steel bars shall be arranged at the bottom of the sealing material or 150 mm from the floor surface to the bottom of the sealing material. The sealing method is shown in Figure 1.

d). When the thickness of floor or wall is greater than or equal to 200mm, plywood or foam board should be used to seal and make reinforcement on both sides of floor or wall. When the thickness of
floor or wall is less than 200 mm, steel frame and formwork shall be used to supplement the thickness of 200 mm. Figure 2 shows this kind of the sealing method.

e). Attention shall be paid to check whether the adhesive of silica gel fiber cloth is tight. If there is any doubt about the effect of biological shielding protection after sealing, γ ray source can be used for inspection. The radiation at the sealing place shall not exceed 1.4 times of that at the adjacent concrete wall.

Figure 1. Sealing schematic for cable through floors. Figure 2. Sealing schematic for concrete wall less than 200mm.

5. Analysis for biological sealing of openings in nuclear island buildings

Tens of thousands of openings are included in buildings of nuclear project and biological sealing for openings are normally concentrated in nuclear buildings. The following Table 2 shows the number of shielding opening for a typical nuclear power project in China, mainly including the reactor building, fuel building, safeguard building and auxiliary building. The openings are distinguished according to mechanical and electrical.

Table 2. Statistics for biological sealing openings for nuclear buildings.

| Content                                | Category       | Reactor building | Fuel building | Safeguard building | Auxiliary building |
|----------------------------------------|----------------|------------------|---------------|--------------------|--------------------|
| Biological sealing for mechanical      | Displacement≤5mm | 357              | 364           | 257                | 1671               |
| openings                               | 5mm<Displacement≤20mm | 285             | 262           | 111                | 745                |
|                                        | Displacement>20mm  | 36              | 20            | 6                  | 25                 |
| Biological sealing for electrical      | 241             | 183              | 132           | 826                |
| openings                               | Total biological sealing openings | 919             | 829           | 506                | 3267               |
| Total openings                         | 2210            | 4090             | 9827          | 7805               |
| Percentage                             | 41.6%           | 20.3%            | 5.1%          | 41.9%              |

It can be found from the above table that the number of biological shielding openings in the reactor building and auxiliary building accounts for more than 40%, as the reactor building is mainly concentrated in the nuclear reactor, fuel during operation and related facilities, while the auxiliary building mainly house the waste treatment and disposal related facilities. At the same time, for mechanical openings that needs biological sealing, we can find that the larger the displacement and the less the corresponding number of openings, which means that the materials of ultra-high density
silicone and flexible fireproof silicone needed for plugging are much less than high density silicone. Especially, the amount of flexible fireproof silicone used for radiation shielding is usually much less, which even can be eliminated by design optimizing of displacement, for example, add fix point or support which can limit the displacement near the openings. After that, some principles and requirements for biological shielding openings described in chapter 2 can be also negotiated with plant owners to reduce the number of the openings and save the cost for the project.

6. Good practice for reducing the biological sealing opening
Because the radioactive source mainly travels along the fluid pipeline, the gamma ray propagates along the straight line in the process of propagation. In foreign nuclear facilities, in addition to the high density silicone material plugging, the steel frame connection box type device as shown in Figure 3 is also used as good practices for reducing the biological sealing openings, which is also called as joggle box [13]. The joggle box is embedded in the concrete wall of different radiation zones, and the box is fixed with the embedded pipes connected by elbows or bend pipes. A connection box can include one or more embedded pipes of different diameters and materials. The connection box is directly embedded in the concrete of different radiation zones in the civil construction stage. In the subsequent pipeline installation, it can be directly welded with the reserved interface of the embedded pipes on the box. The pipes with fluid radioactivity and non-radioactive pipes both can be applied for joggle box. Through the design of joggle box device, the subsequent sealing construction of biological shielding openings is avoided, and the construction difficulty and cost are effectively reduced.

![Figure 3. Schematic for joggle box.](image)

7. Conclusions
The opening sealing design of nuclear power plant is related to different design function zones, which is related to the safety and reliability of power plant during operation and maintenance. Based on the investigation of the technical requirements and construction technology of sealing for biological shielding opening in domestic nuclear power projects and the joggle box device in foreign nuclear facilities, the following concerns are proposed for reference during the design stage of nuclear facilities.

a). The pipeline, ventilation duct and cable trays should avoid crossing different radiation zone boundaries as much as possible during the design process, so as to reduce the openings on different shielding zone boundaries. If it is necessary to cross, it should be arranged at a position of more than 2 meters as far as possible.
b). For pipelines crossing different radiation zone boundaries, the performance of shielding and sealing materials should be considered in advance during the design, especially the displacement value of for pipeline.

c). Joggle box has corresponding good practice in foreign nuclear power facilities, which can effectively reduce the difficulty and cost of later plugging construction, which can be used in combination with specific wall conditions.

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