Research Article

Radiation Protection Practices during the Helium Circulator Maintenance of the 10 MW High Temperature Gas-Cooled Reactor-Test Module (HTR-10)

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Current radiation protection methodology offers abundant experiences on light-water reactors, but very few studies on high temperature gas-cooled reactor (HTR). To fill this gap, a comprehensive investigation was performed to the radiation protection practices in the helium circulator maintenance of the Chinese 10 MW HTR test module (HTR-10) in this paper. The investigation reveals the unique behaviour of HTR-10's radiation sources in the maintenance as well as its radionuclide species and presents the radiation protection methods that were tailored to these features. Owing to these practices, the radioactivity level was kept low throughout the maintenance and only low-level radioactive waste was generated. The quantitative analysis further demonstrates that the decontamination efficiency was over 89% for surface contamination and over 34% for γ dose rate and the occupational exposure was much lower than both the limits of regulatory and the exposure levels in comparable literature. These results demonstrate the effectiveness of the reported radiation protection practices, which directly provides hands-on experience for the future HTR-PM reactor and adds to the completeness of the radiation protection methodology.

1. Introduction

Radiation protection practices protect people from harmful effects of exposure to ionizing radiation [1], which is a key issue throughout the life-cycle of a nuclear reactor. Because the radiation sources and hazards can vary significantly between different types of reactors, the corresponding radiation protection strategies and practices have to adapt to these changes as well. Therefore, it is important to build up a complete radiation protection methodology that covers most nuclear reactor types.

Up to now, most researches on radiation protection practices of nuclear reactors are focused on the commercial light-water reactors. For those light-water nuclear reactors in operation, there has been a continuous effort to reduce the annual collective dose [2–7]. For recently developed Generation III light-water reactors, various radiation protection methods have been proposed in the design stage and the

collective dose has been estimated to be lower than existing commercial light-water reactors [8, 9].

Compared to abundant radiation protection resources for light-water reactor, there are much fewer reports on the radiation protection of pebble-bed high temperature gas-cooled nuclear reactors (HTR). The pioneer 15 MWe AVR experimental reactor has achieved an average collective dose between 0.5 and 0.6 Sv per year during its 21 years of successful operation [10]. For the 300 MWe thorium high temperature reactor (THTR-300), considerable efforts have been made to reduce the occupational exposure [11] and the maximal annual collective dose of both operation and decommission stages was 0.12 Sv [12]. For the Chinese 10 MW high temperature gas-cooled reactor (HTR-10) [13, 14], which is the only one in operation, a study report that the annual collective doses at different power stage was between 2.36 and 7.64 man * mSv, but this study does not include radiation practices information [15].

Therefore, current radiation protection methodology lacks systematic studies on radiation protection practices for HTR. This gap can be a potential disadvantage for future HTR deployment and operation, such as the latest 200 MWe High Temperature Reactor-Pebble-Bed Module (HTR-PM) which will be connected to electrical grid system in 2017.

In order to fill the above gap and add to the completeness of radiation protection methodology, the helium circulator maintenance of HTR-10 is investigated both qualitatively and quantitatively in this paper. The investigation reveals the unconventional features and preliminary radionuclide species of the radiation sources in the maintenance and presented radiation protection practices that are tailored to these features, which includes radiation source control, decontamination, radioactivity measurement, and individual protection. The radiation data shows that the radiation level was kept low throughout the work process and only low-level radioactive waste was generated. The quantitative analysis further demonstrates that the decontamination efficiency was over 89% for surface contamination and over 34% for γ dose rate and the occupational exposure was much lower than both the limits of regulatory and the exposure levels in comparable literature. As far as we know, this is the first systematic report on these topics of HTR maintenance, which is valuable for the future practices on HTR-PM and adds to the completeness of the radiation protection methodology.

2. Materials and Methods

2.1. Layout of the Work Area. The helium circulator is installed in the helium circulator cavity, which is under the reactor maintenance hall (Figure 1(a)). In the maintenance, the helium circulator was moved from its cavity to the reactor maintenance hall, maintained, and reinstalled back into its cavity. The layout of the hall during the maintenance is displayed in Figure 1(b). The top caps of the reactor cavity and the helium circulator are close to the center of the hall. In the maintenance, the cap of the helium circulator cavity was opened and staffs entered the cavity to remove the helium circulator. The removed cap was placed in the southwest of the hall.

The rest of the hall was partitioned into several functional areas. Electricity power as well as small tool preparation and storage areas were surrounding the two cavities for convenience. The air supplier was installed in the northwest of the hall, which filtered the air and pumped it into the respiratory protection apparatus.

The only entrance/exit channel to the whole work place during the maintenance was set in the southeast of the hall, where staffs changed their clothes and received examination of radiation and contamination. In the south of the hall, a maintenance area was set to accommodate the removed helium circulator. Tasks such as the decontamination, inspection, sampling, and repair were all performed in this area. After these tasks, the helium circulator was reinstalled back onto SG in the helium circulator cavity.

The temporary storage area of waste was set close to the maintenance area of the helium circulator, so that the waste

transport path was reduced and the risk of waste disperse was decreased as well.

The three shaded areas in Figure 1(b) (the helium circulator cavity, the maintenance area of helium circulator, and the waste storage) were the places where most radioactive work took place.

2.2. Work Flow. The on-site work of the helium circulator maintenance started on May 27 and ended on July 5, which lasted 39 days. This period can be roughly divided into three phases: the preparation phase, the work phase, and the test phase.

A brief flow chart of the on-site work process is shown in Figure 2, including the critical time points and the work content information.

In the preparation phase, the facilities such as scaffolding were installed and the cables to the helium circulator were disconnected. Instrument and equipment were validated through a series of tests. Meanwhile, the γ dose rate, surface contamination level, and radioactive aerosol were measured at representative positions such as the reactor maintenance hall, the helium circulator cavity, and the vicinity of SG flange. These data provide the background information for quantifying the radioactivity level changes due to the maintenance, which help evaluate the effectiveness of radiation protection practices.

For the work phase, an important date was May 31, when the helium circulator was removed from its cavity and transferred to the maintenance place. The radiation dose was measured throughout the removal process of the helium circulator on May 31. The aerosol in the helium circulator was also measured when the helium circulator was lifted away from SG.

From June 4 to June 13, the helium circulator was under decontamination and maintenance. During this period, the radioactivity measurement covered several places, which were the surroundings of the helium circulator, the helium circulator cavity, and the helium circulator maintenance area. At each place, both γ dose rate and surface contamination level were measured. Meanwhile, the specific activity of aerosol was also measured for the reactor maintenance hall and the gas insulation tent that wrapped the bottom of the helium circulator.

From June 14 to June 17, the helium circulator was reinstalled back onto SG in the helium circulator cavity. And the radioactive aerosol was monitored online for the helium circulator cavity.

The test phase started on June 18. In this phase, cables were reconnected to the helium circulator for testing. Meanwhile, the work place was cleaned. The radiation field and the surface contamination was measured again to compare with the measurement before maintenance.

2.3. Dose Limit. The individual effective dose limit for occupational exposure is 20 mSv per year according to the Chinese radiation protection regulatory [16]. The Institute of Nuclear and New Energy Technology (INET), which operates HTR-10, uses an even stricter dose limit, which is 5 mSv per year for an individual. For the maintenance task, specific dose

FIGURE 1: Schematic layout of the work place. (a) Vertical view of the work place. (b) Horizontal layout of the reactor maintenance hall. The three shaded areas were the places where most radioactive work took place.

limits have been established by INET, which are 1.25 mSv for individual dose and 40 mSv for collective dose.

2.4. Radiation Sources. There were two possible sources of radiation in the maintenance. The first one was the fission product in the helium coolant of the primary loop. However, its activity might be extremely low because it was consecutively removed by the helium purification system.

The other possible radiation source is the radioactivity that deposited on the surface of the helium circulator. This includes the contribution of both direct deposition of fission products and the deposition of graphite dust that carries radionuclides. Because the fission product in the HTR-10's

coolant is very few, the graphite dust becomes the most concerned radiation source. The graphite dust might have several layers. The inner layer might stick strongly to the surface of helium circulator components and might stay still during the removal and transfer of the helium circulator. Therefore, it mainly contributed to the surface dose rate of the helium circulator. But the outer-layer dust could be loose, which might fall off the surface and be transferred to other places during the maintenance. This could result in surface contamination problem and radioactive aerosol in the work place. This mobility of the graphite dust makes the radiation protection practices significantly different from that of the light-water reactor whose radiation sources are usually unmoveable.

FIGURE 2: Work flow and radioactivity measurement of the helium circulator maintenance for HTR-10.

2.5. Practices for Collective Dose Reduction. Based on the mobility feature of the potential radiation source, a corresponding radiation protection scheme was conducted to reduce the radioactivity level and the collective dose of the maintenance, which involved various practices.

2.5.1. Radiation Source Control. The containment of radioactive graphite dust during the helium circulator removal is one major radiation protection challenge of the maintenance, for which no similar practices have been reported as far as we know. In this study, a gas insulation tent was used to wrap the flange connected area between the helium circulator and SG (Figure 3(b)), in order to keep the radioactive dust isolated from the environment.

During the lifting-up process, both the helium circulator and SG were kept in this tent, so that the dispersion of the graphite dust into the environment was prohibited (Figure 3(c)). When the helium circulator was about to be moved away, the tent was tied at its middle part (Figure 3(d)). Then the tent was separated into two from its middle and the helium circulator was being moved away (Figure 3(e)). In this way, both the helium circulator and SG were kept insulated from the air, which avoided the dispersion of radioactive graphite dust.

After the removal, an air bag was plugged into the open side of SG. And a seal cap was put on it to further ensure the leakproofness.

Figure 4 shows the removed helium circulator wrapped in the gas insulation tent, which had been moved from its cavity to its maintenance area. Because persons needed to enter the helium circulator, the gas insulation tent had to be opened. After the opening, an equipment was used to keep

the pressure in the tent lower than that outside the tent, so that no air inside the tent could escape out and the airborne radioactivity was kept inside.

In order to ensure successful implementation, the gas insulation operation was rehearsed intensively with a model of the SG flange before the removal and reinstallation of the helium circulator.

2.5.2. Radioactivity Measurement. The radioactivity measurement was performed at different phases of the maintenance, as shown in Figure 2.

For the γ dose rate, the measurement serves two purposes, which are area monitoring and item monitoring. For area monitoring, the γ dose rate was measured at potential working positions, in order to evaluate the radiation hazard of the working crew. This type of dose measurement depended on the working requirement and could be quite different for each work. In the case of large areas such as the helium circulator maintenance area, a dose rate monitoring survey was performed at representative positions and the average value of the 10 maximal survey data was used to represent the general radiation level at that area. As for specific tasks, such as the helium circulator maintenance, the dose rate was measured at the places where the task was performed. With respect to the item monitoring, the dosimeter was placed at a distance of 30 cm away from the measured object, in order to provide comparable data between different items.

For surface contamination, degreased cotton was used to take samples. And the activity of the sample was measured, which represented the surface contamination level.

For the airborne radioactivity, the aerosol in several work positions was sampled and measured offline in a laboratory, before the helium circulator reinstallation. During the reinstallation, the radioactivity of the aerosol was monitored continuously online.

The radioactivity measuring instrument used in the maintenance was as follows.

The γ dose rate was measured using RM2030 portable dosimeters, which covers a measurement range of 0.01 μSv/h~200 μSv/h. The uncertainty at 95% confidence was below 5% for the interval between 0.50 μSv/h and 50 μSv/h and 10% for the interval between 50 μSv/h and 200 μSv/h.

The offline aerosol sample analysis was performed using the low-background CLB-101 α/β measuring instrument in a laboratory, whose lower limit of detection (LLD) is 1.6×10^{-3} Bq/m³.

The online aerosol monitoring was implemented using a LB 6500-4T H10 continuous monitor with a Si-HLD detector. The measurement range of this instrument is 5×10^{-3} Bq/m³ ~ 1.8×10^3 Bq/m³ for the specific activity of α aerosol and 4.1×10^{-2} Bq/m³ ~ 1.8×10^3 Bq/m³ for the specific activity of β aerosol.

For the surface contamination, it is measured by CoMo 170. Its LLD is 0.01 Bq/cm² for both α and β contamination.

The individual dose was monitored by the thermoluminescence dosimeter TLD2000, whose lower limit of detection was about 10^{-7} Sv.

FIGURE 3: The gas insulation during the removal of the helium circulator.

FIGURE 4: The removed helium circulator wrapped with the gas insulation tent.

2.5.3. Radiation Zoning. In the three shaded areas in Figure 1(b), the floor was covered with PE plastic carpet to avoid contamination. Meanwhile, fences and isolation belts were used to separate these areas from nonradioactive work areas. A signboard was set at the entrance of these areas with radioactivity type and radiation level on it.

2.5.4. Surface Decontamination. Decontamination was performed before major radioactive work began. From June 4 to July 6, the decontamination was conducted to the entrance, the end closure dome, and the internal of the removed helium circulator, before the work on the circulator started. Cloth and degreased cotton were used to decontaminate the surface of the helium circulator components with alkaline

HAKAUPUR detergent (HAKA Kunz GmbH, 71111 Waldenbuch). Meanwhile, the radiation protection items to be reused were carefully decontaminated after work.

2.5.5. Cleaning and Preparation. The work area was cleaned to reduce the hazard of radioactivity, before radioactive tasks were performed. And the facilities required by the task were installed in advance. For example, the helium circulator cavity was cleaned and platforms were installed ahead of both the removal and the reinstallation of the helium circulator.

Besides the contamination, the airborne radioactivity was also taken into consideration. Before the crew entered the removed helium circulator for decontamination and sampling, the inside of the helium circulator was cleaned by a vacuum which was equipped with four HEPA (high-efficiency particulate arrestance) filters in order to remove radioactive aerosol and dust in the air.

2.5.6. Individual Radiation Protection. The individual radiation protection depended on the specific radiation risk of tasks.

When a person was working in the vicinity of the helium circulator, he/she was required to wear an additional disposable cloth outside his/her work clothes as well as socks, hat, glove, and shoe cover which were all disposable.

In order to avoid radionuclide inhalation, a Honeywell GRIDEL respiratory protection apparatus (product number CC8527X39) was equipped with the person, which was transparent and gas-tight. The GRIDEL apparatus covered both head and neck, which avoided contamination at these two parts. Purified air was fed into the GRIDEL apparatus by the air supplier through a long tube, so that the person wearing the GRIDEL apparatus was breathing clean and nonradioactive air.

When working far away from the helium circulator, a person wore the 3M 8210 N95 Particulate Respirator for respiratory protection.

After the maintenance, the crew received whole body counterexamination to measure the radioactivity within the human body.

2.5.7. Waste Classification. The surface dose rate of waste was monitored in the waste storage area. The criterion for radioactive and nonradioactive waste separation was set to be the measured dose rate of a 1×10^4 Bq standard source. Because the weight of each bag is about 1 kg, this criterion actually requires the specific activity of each waste bag to be lower than 1×10^4 Bq/kg. And this criterion is even stricter than the 4×10^6 Bq/kg limit for low-level radioactive waste in the Chinese National Standard GB9133 [17].

2.5.8. Other Daily Practices. The maintenance work involves 47 persons of different technical backgrounds, including operation, instrument, radiation protection, and soldering. Daily meetings were held to optimize the work flow and radiation protection schemes. The entrance/exit of the maintenance area was strictly controlled with respect to both persons and tools. There were also safety supervisors in the reactor maintenance hall, who inspected the measures of safety and radiation protection and corrected nonstandard practices during the work every day.

3. Results and Discussion

3.1. γ Dose Rate. Figure 5 compares the average γ dose rates for primary work places and positions, which were generally quite low and are on the level of the radiation background at the site.

In the preparation phase, the γ dose rate of both the reactor maintenance hall and the helium circulator cavity remained $0.1 \mu\text{Sv/h}$. The γ dose rate of the helium circulator maintenance area was slightly higher than that of the other two areas, which was $0.11 \mu\text{Sv/h}$.

In the work phase, the γ dose rate remained the same for the helium circulator maintenance area and the reactor maintenance hall. For the helium circulator cavity, there were some fluctuations between measurements at different positions. The highest γ dose rate was close to $0.12 \mu\text{Sv/h}$, while the lowest one was about $0.09 \mu\text{Sv/h}$.

In the test phase, the γ dose rate of the reactor maintenance hall was slightly higher than that before the maintenance. For the helium circulator maintenance area, the γ dose rate remained constant at three phases. In contrast, the γ dose rates at different positions of the helium circulator cavity showed mild variation in the test phase, which ranged from $0.08 \mu\text{Sv/h}$ to $0.11 \mu\text{Sv/h}$.

The temporal γ dose rate changes between the three phases were also quite limited for all the measured areas, which were between $-0.02 \mu\text{Sv/h}$ and $+0.01 \mu\text{Sv/h}$. Because the measured γ dose rates were close to the LLD of the dosimeter, the above γ dose rate changes might have the contribution of the background statistical fluctuations of the

FIGURE 5: Average γ dose rate levels of primary work places in the preparation, work, and test phases.

FIGURE 6: γ dose rates near the SG flange at different times.

dosimeter as well. Thus, the actual γ dose rate changes due to the radiation source could be even less, which demonstrated that the radiation level was kept low throughout the process.

Figure 6 displays the γ dose rates near the flange that connects the helium circulator and SG, which was a potential hot spot during the maintenance. Before the maintenance started, the mean value of γ dose rate was $0.26 \mu\text{Sv/h}$, which was higher than the general γ dose rate level of the helium circulator cavity (Figure 5). When the helium circulator was lifted up by about five meters, the maximal dose rate in the cavity increased to $2.9 \mu\text{Sv/h}$. This increment might result from the weakening of the shielding effect after the helium

circulator was lifted up, which also implied that the radiation from the inside of the helium circulator dominated the γ dose rate near the SG flange. When the removed helium circulator was under inspection and decontamination, the γ dose rate near the flange dropped to about $1.2 \mu\text{Sv/h}$. Thus, the flange connected area was worth particular attention in the radiation protection scheme design. After the maintenance, the γ dose rate reduced to $0.11 \mu\text{Sv/h}$ owing to the decontamination.

When the helium circulator was placed in the maintenance area, the γ dose rates near its top, middle, and bottom parts were measured. As shown in Figure 7(a), the γ dose rates remained fairly uniform for all measuring positions near the top parts of the helium circulator, which were all below $0.1 \mu\text{Sv/h}$ at a distance of 0.1 meters. As the measurements moved down to the middle part, the γ dose rates increased by 2~4-fold and there were more differences between data at each position (Figure 7(a)).

At the bottom part of the helium circulator, the maximal surface γ dose rate reached $1.2 \mu\text{Sv/h}$ at a distance of 0.1 meters. This is possibly because there was no shadow shielding effect of the helium circulator vessel near the bottom of the helium circulator. The dose rate reduced to $0.13 \mu\text{Sv/h}$ (Figure 7(a)), as the measurement position moved farther away from the bottom of the helium circulator. However, the γ dose rates around the helium circulator were still higher than that of the helium circulator maintenance area (Figure 5) in the work phase, which indicated that the helium circulator was the main radiation source.

3.2. Surface Contamination. Before the maintenance started, both α and β surface contamination levels were below LLD for the reactor maintenance hall, the helium circulator cavity, and the maintenance area of the helium circulator.

After the removal of the helium circulator, the surface contamination level was still below LLD for the helium circulator cavity and the entrance of the helium circulator maintenance area. However, there were mild increases in the surface contamination level near the middle part of the helium circulator (Figure 8). Because the γ dose rate level was relatively high at this place, the γ radiation might have contributed to the surface contamination level in Figure 8 as well.

Therefore, the vicinity of the helium circulator was the only area that showed both high γ dose rate and surface contamination level above LLD. This localized distribution suggested that there was no detectable dispersion of radiation sources in the work process.

When the whole maintenance was finished, both the α and the β surface contamination levels were below LLD for the reactor maintenance hall, the helium circulator cavity, and the maintenance area of helium circulator.

3.3. Radioactive Aerosol

3.3.1. Sample Measurement. The aerosol sample measurement revealed that the α and β specific activities of the helium circulator cavity were 0.004 Bq/m^3 and 0.003 Bq/m^3 , respectively, in the preparation phase.

During the lifting-up of the helium circulator, the sample measurement showed that the β specific activity of aerosol in the helium circulator cavity was 0.003 Bq/m^3 , which was similar to that in the preparation phase.

When the helium circulator was under maintenance, the average α and β specific activities of aerosol in the reactor maintenance hall were 0.017 Bq/m^3 and 0.018 Bq/m^3 , respectively, according to the sample measurement. Compared to the specific activity in the preparation phase, there were over 4-fold increases of the radioactive aerosol measurements in the work phase for the reactor maintenance hall. Inside the gas insulation tent of the helium circulator, the average α and β specific activities were even higher for aerosol, which reached 0.058 Bq/m^3 and 0.059 Bq/m^3 , respectively.

3.3.2. Online Monitoring. The above sample measurement showed that the aerosol introduced both obvious global increase of radioactivity and local hot spot in the work phase, which was the primary concern of radiation safety in the maintenance process. For this reason, the α and β specific activities were continuously monitored online, when the helium circulator was being reinstalled back onto SG.

Figure 9 presents the corresponding real-time and the temporally averaged specific activity data of aerosol during and after the reinstallation of the helium circulator. Before the helium circulator was put back onto SG, the maximal α and β specific activities for the real-time measurement were about 5 Bq/m^3 and 30 Bq/m^3 , respectively (Figure 9(a)). For the corresponding averaged data, the maximal α specific activity was 5 Bq/m^3 , while the maximal β specific activity was 15 Bq/m^3 (Figure 9(b)).

After the helium circulator was put back onto SG, the maximal β specific activity was nearly 10 Bq/m^3 , which was still higher than the α activity (Figure 9(c)). Compared to the data in Figure 9(a), there were significant decreases in the real-time data after the reinstallation. The peak value of the α specific activity in Figure 9(c) was about 40% of that in Figure 9(a), while the peak value of the β aerosol was less than 30% of that in Figure 9(a). With respect to the temporally averaged data, there were fewer oscillations than the real-time data (Figure 9(d)). The maximal average α and β specific activities were 0.7 and 2 Bq/m^3 , respectively (Figure 9(d)), which were only 1/7 of those before the helium circulator was put back onto SG (Figure 9(b)). This decrease might imply that the radioactive aerosol mainly came from the inside of the helium circulator. Meanwhile, the peak values in Figure 9(d) were still higher than the aerosol measurement (0.058 Bq/m^3 and 0.059 Bq/m^3 for α and β , resp.) during the maintenance of the removed helium circulator. This showed that the radioactive aerosol problem was more severe in the reinstallation process than in other maintenance work processes.

3.4. Decontamination. Figure 10 compares the γ dose rates and the surface contamination levels for different helium circulator components before and after the decontamination.

FIGURE 7: γ dose rates near the top, the middle, and the bottom parts of the removed helium circulator during the maintenance. (a) The dose rates measured at 0.1 meters away from the top and middle parts of the helium circulator; (b) the dose rates measured at different distances away from the bottom part of the helium circulator.

FIGURE 8: Surface contamination level near the middle part of the removed helium circulator during the maintenance.

Before the decontamination was performed, the γ dose rates were all below $5 \mu\text{Sv/h}$ for the four measured components (Figure 10(a)). The impeller showed the highest γ dose rates, which was more than $4.5 \mu\text{Sv/h}$. The γ dose rate levels for the inlet and the bottom of the helium circulator were the

same, which were close to $3 \mu\text{Sv/h}$. And the O-ring showed the lowest dose rates, which was less than $1 \mu\text{Sv/h}$.

The γ dose rate differences between these components depended on the deposition of radioactive graphite dust. The inlet, the impeller, and the bottom part of the helium circulator were directly exposed to the radioactive graphite dust, so there were large chances that the graphite dust could adhere and accumulate on their surface. Consequently, the γ dose rates of these components were high. In contrast, the O-ring was positioned inside the flange and was much less exposed to the graphite dust, so the deposition of graphite dust on it was quite limited. For this reason, the γ dose rate of the O-ring was the least among the measurements. After the decontamination, the γ dose rates of the bottom and the inlet dropped by more than 50% and the γ dose rate at the impeller decreased by nearly 30%. For the O-ring, the γ dose rate was below LLD of the instrument after the decontamination.

With respect to the surface contamination, there were only limited α pollutions at the bottom and the inlet of the helium circulator before the decontamination. These pollutions were removed by the decontamination work, after which the measured α specific activity decreased below LLD correspondingly (Figure 10(b)). For the impeller and the O-ring, the α contamination was below LLD before the decontamination.

FIGURE 9: The specific activity of aerosol during and after the reinstallation of the helium circulator. (a) The online monitoring data during the reinstallation; (b) the temporally averaged data during the reinstallation; (c) the online monitoring data after the reinstallation.

In comparison, the β contamination was relatively severe. Before the decontamination, the measured β specific activities were significantly higher than the corresponding α specific activities for all the measured components. The inlet showed the highest β specific activity, which was nearly 8 Bq/cm^2 . For the bottom part, the β specific activity was slightly lower than the inlet. And the β specific activity of the impeller was less than a half of that of the inlet. As for the O-ring, it showed the least β specific activity among the four components. After the decontamination, the specific activities of the β contamination dropped below 0.2 Bq/cm^2 for the bottom and the inlet of the helium circulator and the impeller. For the O-ring, the β contamination was even lower, which was 0.06 Bq/cm^2 .

Quantitatively, the total removal efficiency of γ dose rate was between 34.0% and 58.6% for the four components. For α surface contamination, the total decontamination efficiency was above 98%. For β surface contamination, the total decontamination efficiency was between 89.3% and 97.9%. On average, about 3 decontamination cycles were performed during the maintenance, so the corresponding decontamination factors per cycle could be calculated using cube root, which were 12.9%~25.4% for γ dose rate, 72.8% for α , and 52.5%~72.6% for β .

The reduction of the surface contamination level was more noticeable than that of the γ dose rates. This difference suggested that the decontamination was more effective on the surface dust layer. For the inner dust layer which sticks

FIGURE 10: The radiation and contamination level of four helium circulator components before and after the decontamination. (a) γ dose rate; (b) α and β specific activities.

strongly, the effect of the decontamination was somewhat limited. There could be several reasons for this phenomenon. First, the detergent appeared to be more effective on the surface dust layout than the inner layer that sticks strongly. Such phenomenon has also been reported in a previous study, which used a second chemical decontamination detergent to remove the residual radioactivity [18]. Second, during the maintenance, it was impossible to enhance the dissolution of the dust in the detergent by long-time immersion or ultrasonic bath as performed in the literature [18]. Therefore, the performance of the detergent might not be as well as it was in the laboratory.

3.5. Preliminary Radionuclide Specification. Figure 11 qualitatively compares the background γ spectrum and the dust sample's γ spectrum. For the background spectrum (Figure 11(a)), K-40 is the most predominant radionuclide, which is a common background radionuclide in the environment. Meanwhile, Pb-214 and Bi-214 are also noticeable contributors, which are daughters of Ra-226. For the dust sample, the spectrum also shows the peaks of some background radionuclides, such as the 1.461 MeV peak of K-40 (Figure 11(b)). Except background radionuclides, Co-60 dominates more than 99% of the total counts of the dust sample spectrum, whose peak area exceeds 1×10^5 counts. One potential source of Co-60 in the dust sample spectrum could be the activation of impurities in the graphite matrix of the fuel elements. However, this preliminary inference needs to be confirmed with further investigation. Another important radionuclide in the dust sample's spectrum is Cs-137. But its peak area is

only 124 counts, which only contributes 0.12% to the total account. Because Cs-137 is a common fission product, there might be the possibility that it is leaked from the particles in the fuel element. Similar to Co-60, this guess requires the support of further studies, especially the quantitative study.

Both Co-60 and Cs-137 contributed to the β radioactivity, which could explain the predomination of the β radioactivity over the α radioactivity in Figures 9 and 10(b). However, for accurate radioactive source identification, it is necessary to simultaneously measure the specific activity of the aerosol and the corresponding γ spectra during the reinstallation for joint analysis, which shall be our future work for similar radiation protection case.

3.6. Radioactive Waste. The entire maintenance process generated 45 bags of waste. Among these bags, there were 31 bags of radioactive waste and 14 bags of nonradioactive waste. All the radioactive waste was of low level according to the classification criteria in the Chinese National Standard GB9133-1995.

The radioactive waste was categorized into 9 types and the surface dose rates of each type were compared in Figure 12.

Generally, no surface γ dose rate exceeded $20 \mu\text{Sv/h}$. The γ dose rate of the vacuum filter was highest among all types of radioactive waste, which exceeded the sum of the γ dose rates of all other wastes. This is because that the vacuum was used to purify the inside of the helium circulator, where the airborne radioactivity was considerably high due to the aerosol and graphite dust. This indicated that the airborne radioactivity was an important radiation

FIGURE 11: The qualitative γ spectrum measurement. (a) Background; (b) dust sample.

FIGURE 12: The surface γ dose rate of radioactive waste generated in the maintenance.

source during the maintenance. The duster cloth that was used to clean the inside of the helium circulator showed the second highest γ dose rate, which was close to $4 \mu\text{Sv/h}$. The duster cloth used for impeller cleaning showed the third highest γ dose rate, which was a little more than $2 \mu\text{Sv/h}$. In comparison, the surface γ dose rate of the dust cloth used for the O-ring cleaning was much lower. This also suggested that the contamination level of the O-ring was much lower than that of the inside and the impeller of the helium circulator. For other types of waste, those tools used for isolating the radiation sources also showed mild surface γ dose rates, such as the plastic wrapper and the rubber sealer (Figure 10).

FIGURE 13: The daily on-site collective dose that occurred in the reactor maintenance hall during the primary work process (the number of on-site workers was about 10~20 every day).

3.7. Occupational Exposure. Figure 13 shows the daily on-site collective dose that occurred in the reactor maintenance hall during the primary work process. Because the specific tasks were different every day, the work group in the reactor maintenance hall was also changing. As a result, the data in Figure 13 do not represent the collective dose of all the staffs involved in the maintenance. Instead, it should be viewed as an incomplete statistics. However, the relative temporal variation in Figure 13 provides an insight into the contribution of each task to the occupational exposure that occurred in the reactor maintenance hall, which was useful for dose distribution investigation and radiation protection methods optimization.

On May 31, the on-site collective dose in Figure 13 reached its peak, when the helium circulator was being moved from its cavity to the helium circulator maintenance area. After May 31, the on-site collective dose decreased by more than 50%. On June 7, the on-site collective dose reached the second peak, which was much lower than the first one. On that day, the staffs entered the helium circulator from its bottom and performed the internal inspection. The minimum of the on-site collective dose in Figure 13 occurred on June 13, when only visual inspection and evaluation were performed in a distance away from the helium circulator.

Another more complete individual external dose record, which involved all the crew and covered the whole three phases of maintenance, showed that the maximal individual dose was 0.45 mSv, while the average individual dose was 0.05 mSv. These data are far below the dose limits stipulated by the maintenance plan, INET, and the Chinese radiation protection regulatory, which proves the efficiency of the radiation protection scheme.

The collective dose for the whole maintenance was 2.33 man * mSv. Because there are no other reports on the dose of helium circulator maintenance for HTR, it is difficult to perform a direct comparison between this study and the same practice on other HTR reactors.

Except HTR, the circulator of the British advanced gas-cooled reactor (AGR) could be the most similar one to the helium circulator in this study because AGR also uses gas as coolant and the circulator also acts as a primary pump. The collective dose of AGR's circulator maintenance is 14 man * mSv [19], which is higher than the 2.33 man * mSv in this study.

The collective dose of HTR-10 for the whole 2013 was 3.47 man * mSv, which is close to the lower bound of the collective dose range (2.36~7.64 man * mSv) [15] of HTR-10's power operation stage. Meanwhile, the 3.47 man * mSv is also much lower than the AVR's annual collective dose level (0.5~0.6 man * Sv) [10].

However, the comparison with AGR and AVR does not indicate the superiority of HTR-10's radiation protection practices over AGR or AVR because the operation status of these three reactors is quite different. But it demonstrates that the radiation protection practices successfully kept the occupational dose of the crew at a very low level.

For internal dose, the online aerosol concentration measurement value was lower than the derived air concentration (DAC) value of the corresponding radionuclides. According to the whole body countermeasurement, the individual committed effective dose for all the crew was lower than 5 μ Sv. For concerned radionuclides such as Cs-137 and Co-60, the measurement revealed that their internal activities were lower than the lower limit of detection of instrument (101 Bq for Cs-137 and 43 Bq for Co-60).

From the perspective of optimization, the occupational exposure dose has the potential to be further reduced, if tailored tools could be developed to facilitate the tasks and shorten the work time. This maintenance also provides the demand and information for developing these tools, which shall be our focus in the next work stage.

4. Conclusions

The radiation protection practices and radiation data in the maintenance of HTR-10's helium circulator were investigated thoroughly in this study. This investigation reveals that the graphite dust was the most concerned radiation sources during the maintenance, in which Co-60 and Cs-137 were qualitatively identified as the primary radionuclides. The graphite dust can either deposit on surfaces or suspend with aerosol in the air, which is significantly different from the radiation source behaviour of light-water reactors. Thus, gas insulation and air flow control are important to prevent the dispersion of the dust and to reduce the radioactivity of the aerosol, while chemical decontamination is essential for surface dose reduction. The measurement data shows that the decontamination efficiency was over 89% for surface contamination and over 34% for γ dose rate. And the maintenance only generated low-level radioactive waste. As for the occupational radiation exposure, both individual and collective dose of the maintenance were not only much lower than the limits of regulatory, but also lower than the exposure levels in comparable literature. These results prove the effectiveness of the radiation protection practice in the maintenance, which enriches the radiation protection methodology.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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