E3S Web of Conferences **131**, 01058 (2019) https://doi.org/10.1051/e3sconf/201913101058
ChinaBiofilms 2019

Environmental Monitoring and Evaluation of the X-Ray Field Flaw Inspection Workplace in a Factory Building

Qing Li[1, 2, *], Wei Xie[3, *], Hong You[2,4], Xiaohua Qiu[5], Quan Guo[6], Lingxi Zhao[1], Jing Zhang[1], Wei Liu[1]

[1]Shandong Analysis and Test Center, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250014, China
[2]State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China.
[3]School of Information science and Engineering, Harbin Institute of Technology at WeiHai, WeiHai 264209, China
[4]School of Marine Science and Technology, Harbin Institute of Technology at Weihai, Weihai 264209, China
[5]No. 1 institute of geology and mineral resources of Shandong Province, Jinan 250010, China
[6]Qingdao Institute of Textile Fiber Supervision and Inspection, Qingdao 266000, China

Abstract. The surrounding radiation environment of the field flaw detection workplace has been theoretically calculated and monitored on site when an industrial X-ray flaw detector in a factory building is operated during the field flaw detection. The results show that when 5mA tube current and 250 kV tube voltage penetrate the steel tube at the thickness of 16mm twice, the calculated value of the air kerma rate at the inspection point is basically consistent with the measured value. Additionally, the boundary of the controlled area and the supervised area corresponded to the measured value along the main beam direction belongs to the wall in the east of the workshop. The calculated distances of the leaking beam corresponding to the boundary of the controlled area and the supervised area of the calculated value should be 19m and 58m, respectively. The minimum and maximum distances of the controlled area of the measured value are 13m and 17m, respectively; while the maximum and minimum distances of the supervised area of the measured value are 31m and 36m, respectively, both areas are within the workshop. Meanwhile, annual effective doses that might be accepted by professionals and the public have been estimated.

1 INTRODUCTION

The XXG-2505 industrial X-ray flaw detector is a Class-II ray device being ranked at the middle risk level, which may cause serious radiation damage to the persons exposed to radiation in an accident. What's worse, high-dose radiation might even lead to death. Therefore, great importance must be attached to the protection and management of X-ray flaw detector. The project is to conduct on-site flaw detection in the factory building, which is performed in a fixed factory building. Therefore, the project also has the characteristics of flaw detection in the flaw detection room. On this basis, the division of the controlled area and the supervised area should be emphasized in the project among the main focuses of the influence exerted by the main beam, the leaking beam and its scattering.

Aiming at the practical situation of applying an industrial X-ray flaw detector in a factory building for field flawdetection, the suggestion of dividing the controlled area and the supervised is proposed in this paper based on theoretical calculation and monitoring verification of the radiation level in the workplace. Meanwhile, the likely acceptable annual effective doses of workers and the public are also estimated to comprehensively evaluate the radiation effect on the surrounding environment.

2 Theoretical Calculation and Measurement Methods

2.1. Basic situation of the workplace of field flaw detection

The XXG-2505 X-ray flaw detector produced by Dandong Radiation Instrument Co., Ltd. is adopted in the X-ray field flaw inspection workplace within a factory building. Technical parameters of the device are shown in Table 1.

Table 1. Technical indicators of the industrial X-ray flaw detector.

Model	XXG-2505
Input power	220V/50Hz，AC
Tube voltage	150~250Kv
Tube current	5mA

* Corresponding author: 18660407217@163.com, hitxiewei@163.com

 https://doi.org/10.1051/e3sconf/201913101058

Radiation form	Orientation
X-ray radiation angle	±22.5°
Focus size	2.0x2.0mm

To the east of the factory is the main road; to the east of the road is a gas station; to the north of the gas station is low-rise dwellings; to the north of the low-rise houses is a vegetable greenhouse; the north is a patrol service center of the police station; the west is farmlands; and the south is a wood-based company. The workplace for X-ray field flaw inspection is confined to the wind tower welding workshop that is located in the northeast corner of the factory. It should be noted that the welding workshop was not designed and constructed as a special flaw inspection room. The general layout and the neighboring relationship of the factory are shown in Fig. 1.

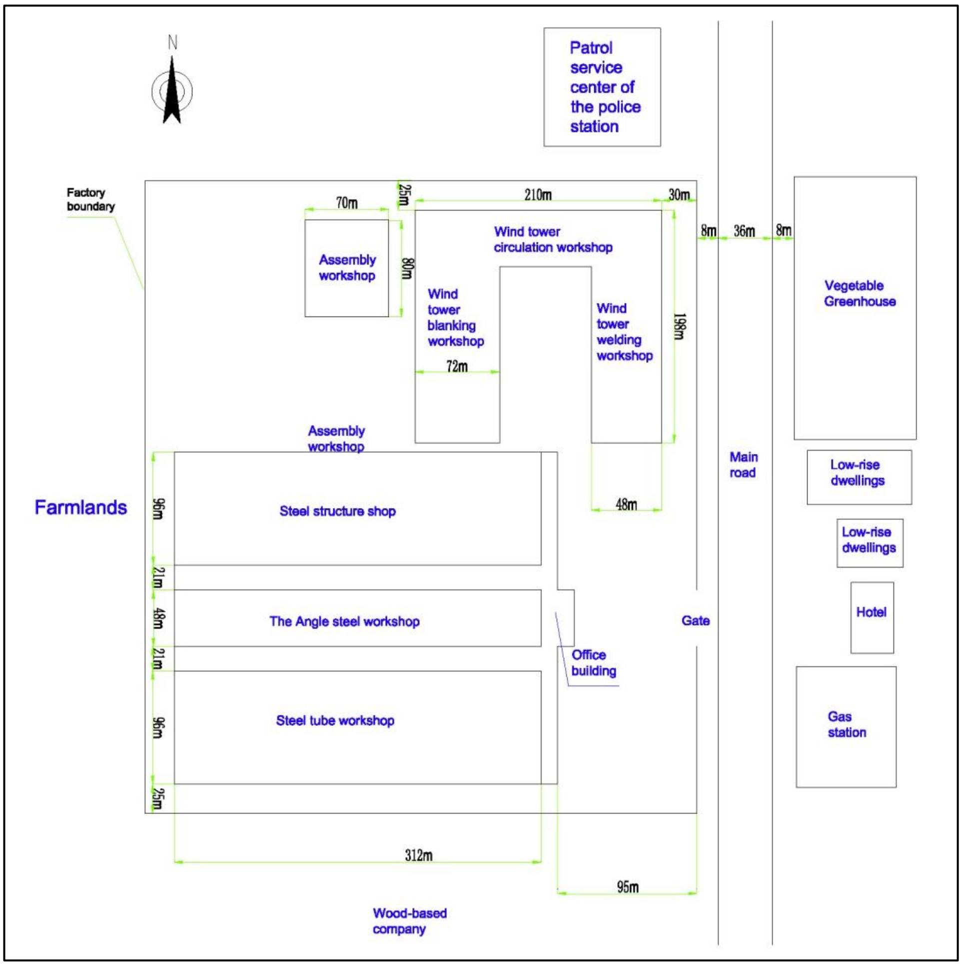

Fig. 1. The general layout and the neighboring relationship of the factory.

The wind tower workshop is composed of a wind tower blanking workshop, a wind tower circulation workshop and a wind tower welding workshop. There are 8 workers who engage in plate rolling and longitudinal seam welding in the day shift in the wind tower welding workshop. The wind tower circulation workshop mainly supplies materials and circulates semi-finished products, which is operated by the remote control vehicle with nobody on duty. There are 20 workers who engage in girth welding in the day shift in the wind tower welding workshop.

The wind tower welding workshop is located at the northeast corner of the factory. The east of the workshop is an open space, 30m away from factory boundary; the west is an open space, 70m away from the wind tower blanking workshop; the south is a large open space where there is no worker; the north is an open space, 25m away from the factory boundary, which is connected to the north of the workshop and the wind tower circulation workshop. The location and the surrounding layout of the field flaw inspection workplace are shown in Fig. 2.

The wind tower workshop is 48m in length from east to west and 198m in length from north to south. Two 8-meter-wide holes in the south are openings for objects (the qualified wind tower is delivered out of the workshop through the opening). Walls in the north and the south are concrete walls with 370mm in thickness and 8m in height in the lower part and color steel walls with 5mm in thickness and 6m in height in the upper part. Walls in the east and the west are concrete walls with 370mm in thickness and 8m in height in the lower part, color steel walls with 5mm in thickness and 6m in height in the upper part, and 5mm color steel tiles on the roof.

The location where the flaw detector is used in this project is about 80 meters away from the walls in the south and in the north, about 6 meters from the wall in the east; and about 42 meters from the wall in the west. Useful beams are adopted to have fixed irradiation on the wall in the east. The area irradiated with useful beams is a cone-shaped area at a coning angle of 45°. The use of the flaw detector, the useful beams irradiating area, and the monitoring (calculation) point setting are shown in Fig. 2 and Fig. 3.

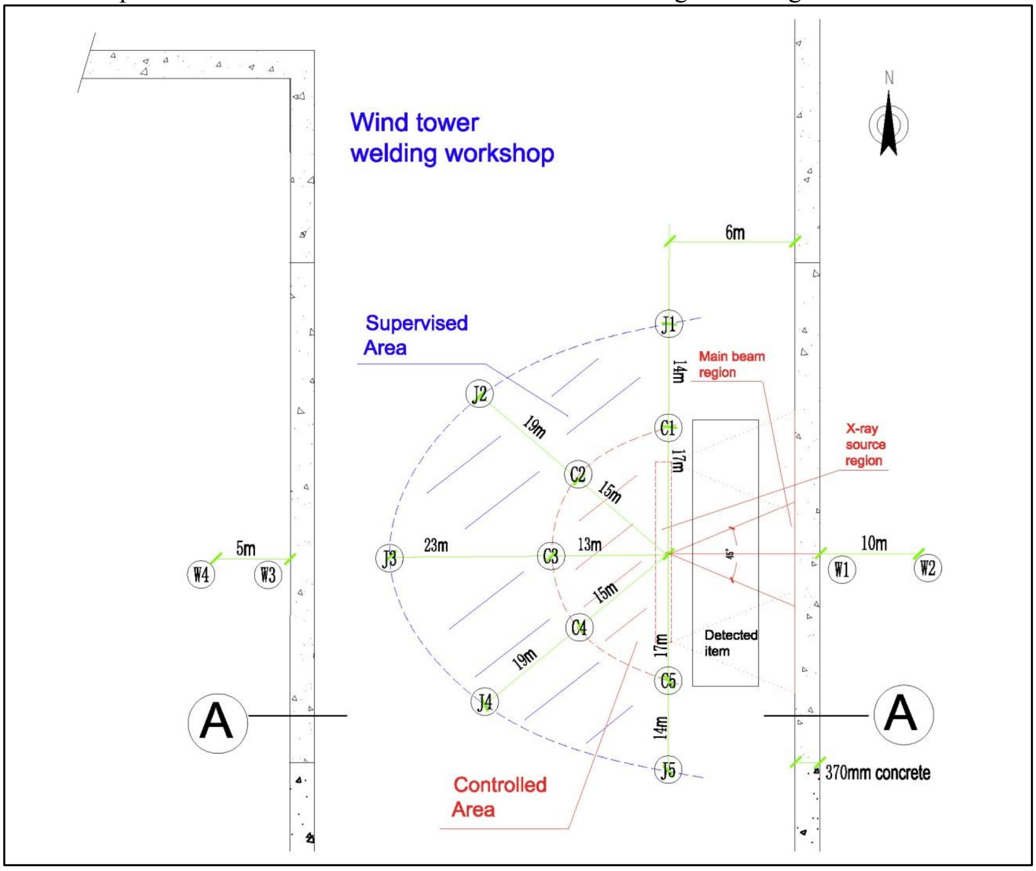

Fig. 2. Radiation monitoring spots-setting in the X-ray field flaw inspection workplace.

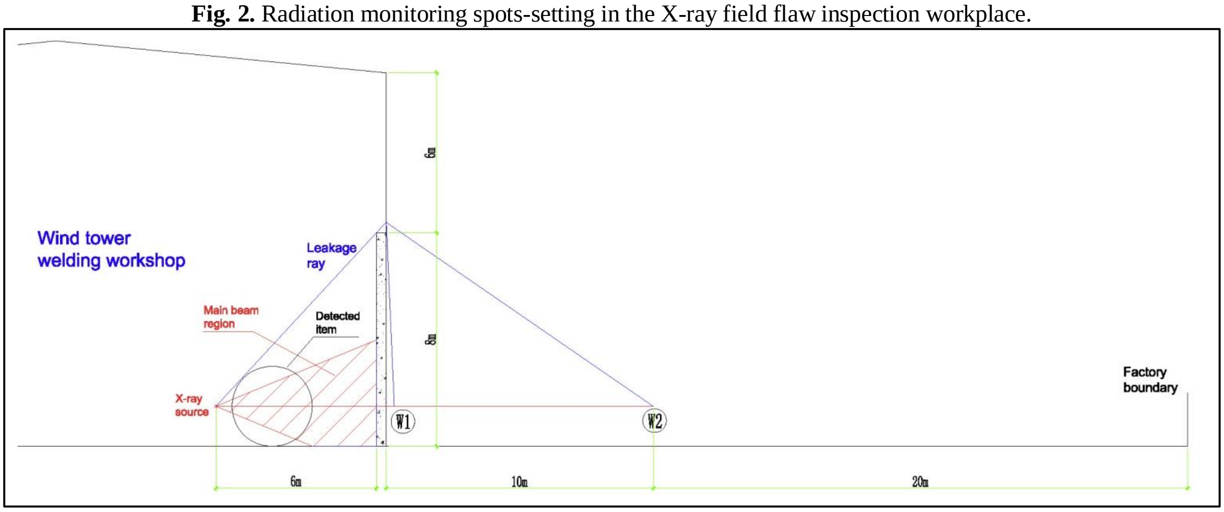

Fig. 3. The layout of the X-ray flaw detection room and radiation monitoring spots-setting in the workplace.

2.2 Calculation methods

The detected target in this project is the wind power tower steel tube with the wall thickness ranging from 10mm to 30mm, the diameter ranging from 2.5m to 4m and the length ranging from 18m to 28m. The thickness of the wind tower steel tube that should be detected by X-ray is larger than or equal to 16mm. In the process of flaw detection, the tube voltage required for exposure curves of the flaw detector is between 150kV and 250 kV due to a variety of uncertainties in the actual situations such as the type and the thickness of the components to be detected. Thus, estimating every situation is difficult.

For safety reasons, the steel tube at the thickness of 16mm is taken as the detected target under the working condition that the tube voltage is 250kV; the tube current is 5mA. By referring to the dividing base of the controlled area (15μGy·h^{-1}) [1] and the supervised area (greater than 1.5μGy·h^{-1}) [2], the calculation and the measurement of the X-ray dose rate in the workplace provide theoretical guidance for the actual radiation protection.

The air kerma rate of the main beam irradiating area [3] can be calculated as the Eq.1.

$$D=0.873\times K^{-1}\times X/r^2 \quad \text{(Eq. 1)}$$

Where: D is the air kerma rate at the inspection point, cGy/h;

X is the X-ray exposure rate at 1m, R/h;

0.873 is the conversion coefficient of exposure rate and dose rate, cGy/h / R/h;

K^{-1} is the attenuation coefficient of X-ray and materials, dimensionless;

r is the distance away from the X-ray machine, m.

The exposure rate of the useful X-ray beams produced by the X-ray machine at the distance of r from the focal spot of the X-ray tube can be approximately calculated by Eq. 2[4].

$$X = IX_0\,(r_0/r)^2 \quad \text{(Eq. 2)}$$

Where: X is the exposure rate of the X-ray machine at r m, R/ min;

I is the tube current, mA;

X_0 is the output of the X-ray machine at r0m, R/mA·min;

r is the distance away from the X-ray machine, m.

The output and the exposure of the X-ray machine are related to the X-tube type, voltage and voltage waveform, target material and shape, as well as material and thickness of the filter plate. The maximum tube voltage of the flaw detector in this project is 250KV. According to the Volume I of the *Radiation Protection Manual*, the output X_0 of a typical X-ray machine with such a tube voltage (3.0mm copper is the filter plate) at the distance of 1m from the target is approximately 0.7 R/mA·min. The operating current of the flaw detector is considered in accordance with the maximum current of 5 mA.

Radiation attenuation [5] of the 32mm steel and the 370mm concrete is calculated with TVT:

$$K^{-1}=10^{-(h/TVT)} \quad \text{(Eq. 3)}$$

Where: K^{-1} is the attenuation coefficient of shielding radiation;

h is the thickness of the shielding layer, mm;

TVT is the thickness value of one tenth layer.

By referring to ICRP No.33 publication [6], when 250kV tube voltage and 32mm steel are equivalent to 3.0mm lead, and the shielding material is lead; the TVT of the X-ray of 250 kV tube voltage is 2.9mm, the radiation attenuation K^{-1} will be 0.092. The TVT of 370mm concrete is 9cm. The dose rate after the main beam passing through the concrete wall can be calculated as Eq. 4[5]:

$$D_m=D_0\times K_1^{-1}\times K_2^{-1}/r^2 \quad \text{(Eq. 4)}$$

Where: D_0 is the air kerma rate of the main beam at 1m (D_0=0.873X), cGy/h.

The leaking beam will scatter after passing through the side wall of the color plate (above the concrete wall). The scattering radiation is characterized by cosine distribution [5], which can be estimated by Eq. 5:

$$D_l=D_0'\times K_1^{-1}\cos\theta/r_1^2 r_2^2 \quad \text{(Eq. 5)}$$

Where: D_0' is the air kerma rate of the leak beam at 1 m, cGy/ h;

r_1—leaking distance, m;

r_2—scattering distance, m.

Hence, the air kerma rate D at the inspection point outside of the wall in the east is estimated with Eq. 6:

$$D= D_m+ D_l \quad \text{(Eq. 6)}$$

2.3 Monitoring instruments and methods

The X-ray field flaw detection workplace is tested with the 451P pressurized ionization chamber survey meter produced by the INOVISION Company in America. The meter performance is shown in Table 2. The meter has been verified as qualified by the Shanghai Institute of Measurement and Testing Technology and is within the validity period.

Table 2. Main parameters of the 451P pressurized ionization chamber survey meter.

No.	Project	Main parameters
1	Detecting radiations	β-ray that is greater than 1 MeV, γ and X-ray that are greater than 25 KeV
2	Operating range	There are 5 grades; the lowest grade is ranged from 0 to 5μSv/ h; the highest grade is ranged from 0 to 50mSv/ h.
3	Accuracy	The accuracy between 10% and 100% of the full scale indication at any range should be within 10%, except for energy response. The calibration source is 137Cs.
4	Working conditions	-20℃~ +50℃

As stipulated in *Requirements for Radio-logical Protection in Industrial X-ray Radiography (GBZ117-2015)* [1], monitoring points should be set in the workplace of X-ray field flaw detection. And the controlled area and the supervised area are divided through patrol.

3 Results and Discussions

3.1. X-ray dose rate in the useful beams irradiating area

When the flaw detection is conducted on a steel tube at the thickness of 16mm, the useful beam will pass through the tube at the thickness of 16mm (or steel at 32mm) twice and pass through the concrete wall of 370mm to emit out of the workshop, as shown in Fig. 2 and Fig. 3. Calculation results and measured results are shown in Table 3.

Table 3. X-ray dose rate at the useful beam direction of different distances with detection components (Tube voltage:250kV)

Position	Calculated value		Measured value	
	6m from the flaw detector and 30cm behind the concrete wall	10m from the flaw detector and 4m behind the concrete wall	6m from the flaw detector and 30cm behind the concrete wall (W1)	10m from the flaw detector and 4m behind the concrete wall (W2)
Dose rate	0.39μGy/h	0.29μGy/h	0.44μGy/h	0.27μGy/h

Note: The natural γ radiation background is not deducted from test data in the table.

As can be seen from the above table, when the flaw detection is conducted on a steel tube at the thickness of 16mm, and the flaw detecting condition is the tube voltage of 250kV and the tube current of 5mA, the measured value of the calculation value of the X-ray dose rate in the useful beam direction are at the same radiation level. Moreover, the wall in the east of the workshop should be the boundaries of the controlled area and the monitoring area along the useful radiation direction.

The calculated value and the measured value of the X-ray dose rate in the main beam radiating area are almost at the same radiation level, but not completely consistent. Main causes are as follows: 1. There are errors between the actual exposure rate and the theoretical value; 2. Air decay in the X-ray is not considered [7] during calculation, resulting in the high calculated value; 3. The density of the wall concrete is lower than that used for calculation, leading to the high calculated value.

3.2 The dose rate of X-ray in the leaking ray radiating area

When the tube voltage is greater than 200KV, the air kerma rate of the leaking ray at 1m is less than $5mGy \cdot h^{-1}$[1]. In this way, dose rates of leaking rays at different distances can be estimated, as shown in Table 4.

Table 4. Calculated values of X-ray dose rates of leaking rays at different distances (Tube voltage:250kV).

Distance	1m	5m	10m	20m	Corresponding distance of 15μGy/h	Corresponding distance of 1.5μGy/h
Dose rate	<5000μGy/h	<200μGy/h	<50μGy/h	<12.5μGy/h	18.3m	57.7m

It can be seen from the above table that the distances of the controlled area and the monitoring area corresponding to the 250KV tube voltage in calculation should be 19m and 58m, respectively.

The flaw detector is used for flaw detection in the wind tower welding workshop. A controlled area at the distance of 19m can be divided in line with the length and width of the workshop (as shown in Fig.1 and Fig.2) at the tube voltage of 250KV. Also, the north and the south of the supervised area can satisfy the requirement of 58m, while the width of the east and the west of the workshop cannot divide a controlled area at the distance of 58m. Based on the thickness of the workshop wall (370mm concrete), the air kerma rate of 5cm outside of the concrete wall in the west of the workshop is less than 2.2×10^{-4} μGy / h. Therefore, the theoretical boundary of regarding the wall in the west of the workshop as the supervised area at 58m away from the supervised area cannot be satisfied in this workshop.

The actual field measurement point settings are shown in Fig. 2 and Fig. 3. The measured results are shown in Table 5.

Table 5. Measured values of X-ray dose rates of leaking rays at different distances.

No.	Code of the measuring point	Dose rate (μGy/h)	Point of the measuring point
1	C1	15.1	Form an angle of about 90° with 17m away from the flaw detector
2	C2	15.1	Form an angle of about 135° with the irradiating direction and 15m away from the flaw detector
3	C3	15.2	Form an angle of about 180° with the irradiating direction and 13m away from the flaw detector
4	C4	15.2	Form an angle of about 225° with the irradiating direction and 15m away from the flaw detector
5	C5	15.1	Form an angle of about 270° with the irradiating direction and 17m away from the flaw detector
6	J1	1.53	Form an angle of about 90° with the irradiating direction and 31m away from the flaw detector

7	J2	1.51	Form an angle of about 135° with the irradiating direction and 34m away from the flaw detector
8	J3	1.52	Form an angle of about 180° with the irradiating direction and 36m away from the flaw detector
9	J4	1.51	Form an angle of about 225° with the irradiating direction and 34m away from the flaw detector
10	J5	1.52	Form an angle of about 270° with the irradiating direction and 31m away from the flaw detector
11	W3	0.22	Form an angle of about 180° with the irradiating direction and 30m away from the concrete wall
12	W4	0.16	Form an angle of about 180° with the irradiating direction and 5m away from the concrete wall

Note: The natural γ radiation background is not deducted from data in the table.

The controlled area and the supervised area can be divided in accordance with the measured values. The minimum and maximum distances of the controlled area of the measured value are 13m and 17m, respectively; while the maximum and minimum distances of the supervised area of the measured value are 31m and 36m, respectively, which are irregular sector areas, as shown in Fig.2. The controlled area and the supervised area of the measured value are within the workshop. The measured values are smaller than the theoretically calculated values. It's mainly because the actual value of the air kerma rate of the leaking ray is lower than the reference value provided by the standard. Also, air attenuation in the X-ray is not considered in the calculation [7]. What's more, the X-ray dose rate out of the wall in the west is basically consistent with the background level.

3.3 Estimation of annual effective dose

The X-ray flaw detector using in this project is operated discontinuously in the field with 2 workers who work for flaw inspection. The workload is as follows. Each piece is exposed for 3 minutes; 20 pieces are exposed daily. If it's worked 120 days annually, the annual exposure time will be about 3min/ piece × 20 pieces/ d × 120d/ a = 120h / a. If zoning is performed for 15 minutes daily and work for 72 days annually, the zoning working time will be 30h/a. Occupancy factors are selected by referring to the revised ICRP No. 15 Publication [8], as shown in Table 6.

Table 6. Selection of occupancy factors.

Occupancy factor	Occupancy position
Frequent occupancy, T=1	Control room, office, waiting room, operating room, dormitory, ward, and children's playground
Partial occupancy, T=1/4	Utility room, and staff lounge
Temporary occupancy, T=1/16	Toilet, stairs, escalator, parking lot, and sidewalk

Personal dose can be estimated as Eq. 7[9].

$$H = 0.7\times Dr\times T \quad \text{(Eq. 7)}$$

Where: H is the equivalent of annual effective dose, Sv/a Dr is the air kerma rate, Gy/ h 0.7 is the conversion factor of absorbed dose to the equivalent of effective dose [9], Sv /Gy T is the annual exposure time

3.3.1 Annual effective doses of employees

When field flaw detection is performed, one worker is responsible for operating the machine, while another worker is responsible for zoning. The worker who is responsible for operating the machine should stand at the leaking area, 25m behind the machine, outside the controlled area and within the supervised area; while the zoning worker's range of activities is the area between the boundary of the controlled area and the boundary of the supervised area. For safety reasons, the X-ray dose rate of 15μSv/h in the boundary of the controlled area is taken as both workers' dose rates; T=1 is taken as the occupancy factor; and the exposed time and the zoning time are 150h/a. That is to say, the annual effective dose rate of a worker is 15μSv/h×150h/a×1×0.7=1575μSv/a=1.58mSv/a. It is lower than the value constrained by the annual management dose (1/10 of the annual dose limit [10], [11]), 2mSv/a used in this paper.

The title is set in bold 16-point Arial, justified. The first letter of the title should be capitalised with the rest in lower case. You should leave 35 mm of space above the title and 6 mm after the title.

3.3.2 Annual effective doses of members of the public

The public is not allowed to stay near the boundary of the supervised area frequently. Meanwhile, unrelated personnel should keep away from the workplace for flaw detection by taking measures such as cleaning the field, and setting up warnings, etc. For safety reasons, T=1/4 is taken as the occupancy factor; and the occupancy in the boundary of the supervised area is 150h/a. As the X-ray dose rate in the boundary of the supervised area is 1.5μSv/h, the annual effective dose rate of the public is 1.5μSv/h×150h/a×1/4×0.7=39.375μSv/a≈0.04mSv/a, which is lower than the value constrained by the annual management dose, 0.3mSv/a used in this paper[2].

4 Conclusions and Suggestions

It can be found that the calculated value of the air kerma rate at the inspection point is basically consistent with the measured value when 5mA tube current and 250 kV tube voltage penetrate the steel tube at the thickness of 16mm twice upon calculation and measurement in the project. The boundary of the controlled area and the supervised area corresponded to the measured value along the main beam direction belongs to the wall in the east of the workshop. The calculated distances of the leaking beam corresponding to the boundary of the controlled area and the supervised area should be 19m and 58m, respectively. Since the flaw detector is operated in a fixed workshop, a controlled area at the distance of 19m can be divided in the workshop when the tube voltage is 250KV. And the supervised area of 58m can satisfy in the south and the north and cannot be satisfied in the east and the west due to the width limit in the workshop. Thus, the wall in the west of the workshop is defined as the boundary of the supervised area. The actual measurement shows that the minimum and maximum distances of the controlled area are 13m and 17m, respectively; while the maximum and minimum distances of the supervised area are 31m and 36m, respectively. All the areas are within the workshop. However, in practical work, the dose rate of X-ray around the workplace is also influenced by scattered rays, which is related to various factors such as the flaw detector, the object to be measured, the surrounding objects and the topography. The specific zoning management should be subject to the values measured by the field inspection device.

When the annual exposure time is 120h, the annual effective dose of a worker responsible for flaw detection and of the public are 1.58mSv/a and 0.04mSv/a, respectively, satisfying the management requirement of “the annual management dose constraints of 2mSv/a for workers who perform flaw detection and of 0.3mSv/a for the public".

Furthermore, the construction unit must be equipped with protective equipment and radiation monitors such as warning signs, warning ropes, lead clothing, and personal alarm dosimeters, etc. All the objects that can be used for shielding and protection on site should be fully utilized during the field flaw detection. Steel plates equipped should be utilized as shielding materials. Workers should take full advantage of the cable length and operate in the controlled area. The cable length can be extended if necessary, so as to avoid that the cable is not long enough. Unrelated personnel should keep away from the workplace for flaw detection by taking measures such as cleaning the field, and setting up warnings, etc.

Acknowledgments

This study was jointly sponsored by the Key Research and Development Plan of Shandong Province (2018GGX101034), the National Natural Science Foundation of China (No.21703125), the Shandong Provincial Natural Science Foundation of China (ZR2016DQ17).

References

1. Institute of Radiation Medicine, Shandong Academy of Medical Sciences. GBZ117-2015 Requirements for Radio-logical Protection in Industrial X-ray Radiography [S]. Beijing: Standards Press of China, 1-7(2015).
2. China Institute of Atomic Energy. DB11/T 1033-2013 Requirements for Radiation Safety and Protection Classification Management of Industrial X-ray Flaw Detection [S]. Beijing Municipal Bureau of Quality and Technical Supervision, 1-10 (2013).
3. D F Zhang. Volume I of Ionizing Radiation Protection Technology and Management [M]. Nanning: Guangxi Nationalities Publishing House, 27-28(2003).
4. D P Li, Z Q Pan. Volume 1 Radiation Sources and Shielding of Radiation Protection Manual [M], Beijing: Atomic Energy Press, 233-237(1987).
5. S J Wang. Shielding Design and Evaluation of Radiation Source Storing Room [R]. National Continuing Education Project Information No. 2002-12-07-044, 6-26(2002).
6. ICRP. Protection against Ionizing Radiation from External Sources Used in Medicine ICRP Publication 33. [M]. Oxford: Pergamon Press, (1982).
7. S Zhu et al. Discussion on Industrial X Ray Flaw Detection Machine Radiation Protection Distance at the Operation Site Flaw Detection [J]. HUNAN NONFERROUS METALS, **31**, 65-67(2015).
8. ICRP. Protection against Ionizing Radiation from External Sources ICRP 15 [M]. Oxford: Pergamon Press, (1970).
9. UNSCEAR. SOURCES AND EFFECTS OF IONIZING RADIATION—UNSCEAR 2000 Report to the General Assembly, with scientific annexes, Annex A: Dose assessment methodologies [M]. New York: UNITED NATIONS PUBLICATION, (2000).
10. Liaoning Instrument Research Institute. GB 22448-2008 Protection Rules for Industrial X-Ray Radiographic Equipment up to 500kV [S]. Beijing: Standards Press of China, 1-2(2008).
11. Nuclear Industry Standardization Institute. GB18871-2002 Basic Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources [S]. Beijing: Standards Press of China, 35-36(2002).