

# Investigation on Weakly Penetrating Radiation and Personal Dose Monitoring for VVER Units

October 2025

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01

# Overview of Weak Penetration Radiation

# 01 Overview of Weak Penetration Radiation

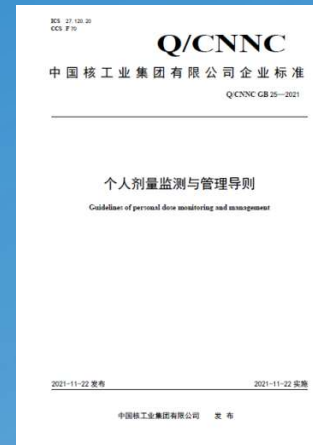
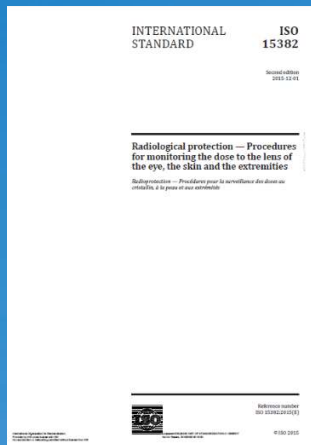


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## Definition of Weak Penetration Radiation

**weakly penetrating radiation**: in a uniform, unidirectional field, the dose equivalent in any small area of the radiosensitive layer of the skin (typically at 0.07 mm depth) **exceeds 10 times** the effective dose equivalent. Examples include photons below 15 keV and electrons below 2 MeV.

- ICRU 39 《Determination of Dose Equivalents Resulting from External Radiation Sources》
- ISO 15382 《Radiological protection — Procedures for monitoring the dose to the lens of the eye, the skin and the extremities》



# 01 Overview of Weak Penetration Radiation

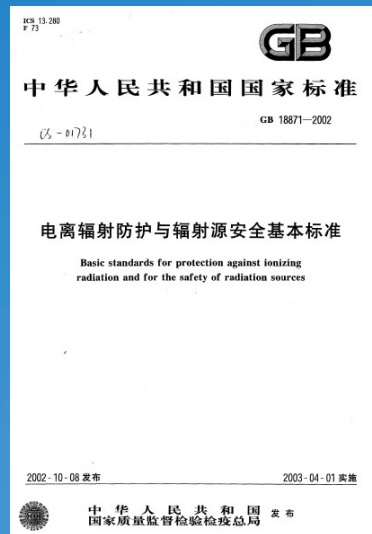
## Weak Penetration Radiation Monitoring Quantity

IAEA Safety Standards 《International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, BSS》 GSP Part 3.

GB18871 《Basic standards for protection against ionizing radiation and for the safety of radiation sources》

$H'(d, \Omega)$  Directional dose equivalent:

$H'(d, \Omega)$  Directional dose equivalent:  
at a point in a radiation field is the dose equivalent at a depth  $d$  on a radius in the specified direction  $\Omega$  in the ICRU sphere for the corresponding expanded field.  
——For weakly penetrating radiation, a reference depth of  $d = 0.07 \text{ mm}$  is recommended.





# 01 Overview of Weak Penetration Radiation

## Weak Penetration Radiation Monitoring Quantity

IAEA Safety Standards 《International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, BSS》 GSP Part 3.

GB18871 《Basic standards for protection against ionizing radiation and for the safety of radiation sources》

$H_p(d)$  Personal dose equivalent:

The personal dose equivalent,  $H_p(d)$ , is the dose equivalent in soft tissue at an appropriate depth,  $d$ , below a specified point on the human body.

—For strongly penetrating radiation, a reference depth of  $d = 10\text{mm}(H_p(10))$  is usually used to assess the stochastic effects on the whole body caused by strongly penetrating radiation (such as high - energy photons, neutrons), and it is a substitute for the effective dose in occupational exposure.

—For weakly penetrating radiation, a depth of  $d = 0.07\text{mm}(H_p(0.07))$  is used to assess the deterministic effects on the skin caused by weakly penetrating radiation (such as low - energy photons, beta rays), corresponding to the monitoring of skin dose limits in BSS. In addition, for the eye lens, a depth of  $d = 3\text{mm}(H_p(3))$  is used.





# 01 Overview of Weak Penetration Radiation

## Weak Penetration Radiation Dose Limit

In ICRP Publication 60 and IAEA BSS 115, the dose limit for the eye lens is set at 150 mSv per year, and this value is also adopted in China's national standard GB 18871-2002.

B1.1.1.1 The occupational exposure levels of any staff member shall be controlled so as not to exceed the following limits:

- a) The annual average effective dose over a consecutive 5-year period (retrospective averaging is not allowed), which is 20 mSv;
- b) The effective dose in any single year, which is 50 mSv;
- c) The annual equivalent dose to the eye lens, which is 150 mSv;
- d) The annual equivalent dose to the extremities (hands and feet) or skin, which is 500 mSv.

Early Standards:

—It is generally considered that if the specified dose limits are not exceeded, stochastic effects on the skin will not occur, and the primary concern for skin dose is deterministic effects.

—It is generally considered that if the effective dose limit and the skin dose limit are not exceeded, Hp(3) will not exceed the eye lens dose limit either.

# 01 Overview of Weak Penetration Radiation



## Weak Penetration Radiation Dose Limit

In 2011, the International Commission on Radiological Protection (ICRP) revised the eye dose threshold for cataract induction. Compared with the previous thresholds of 5 Gy for visual impairment caused by cataracts from acute exposure and 8 Gy for more severe cases, the revised limit was set at **0.5 Gy**.

ICRP Publication 118, IAEA GSR (General Safety Requirements), and ISO 15832 revised the occupational exposure dose limit for the eye lens: the equivalent dose limit for the eye lens was adjusted from 150 mSv per year to an average of no more than **20 mSv per year** over five consecutive years, with no more than **50 mSv in any single year**.

Based on international standards, the Council of the European Union stipulated in 2013 that the dose should be an average of no more than 20 mSv per year over five consecutive years, with no more than 50 mSv in any single year, or no more than 20

Q/CNNC GB 25—2021

### 5.3 监测计划的确定

根据工作场所辐射水平的高低与变化和潜在照射的可能性与大小，确定个人剂量监测计划与方案。

### 5.4 个人剂量控制与优化

5.4.1 对于计划照射情况，应对任何工作人员的职业照射水平和风险进行控制，使之不超过下述限值：

- a) 连续5年的年平均有效剂量，20 mSv；
- b) 任何一年中的有效剂量，50 mSv；
- c) 眼晶体的年当量剂量，20 mSv；
- d) 四肢（手和足）或皮肤的年当量剂量，500 mSv。

**The new dose limit has not yet been adopted in China:** The updated version of Basic Standards for Ionizing Radiation Protection and Safety of Radiation Sources has not been released. However, CNNC Guidelines for Individual Dose Monitoring and Management – specifies that for occupational exposure of staff, the annual equivalent dose limit for the eye lens shall not exceed **20 mSv**.



# 01 Overview of Weak Penetration Radiation

## The Significance of Investigation and Monitoring

During the maintenance period of nuclear power plants, the on-site radiation is usually a mixed field of  $\beta$  and  $\gamma$  radiation, and weakly penetrating radiation may account for a relatively large proportion in some areas. It has been reported that the directional dose equivalent rate in certain workplaces of nuclear power plants in Germany is as high as 2 Sv/h, and the dose ratio between the directional dose equivalent  $H'(0.07)$  and the ambient dose equivalent  $H^*(10)$  ranges from 1:1 to 10:1, reaching **40:1** in individual locations.

- According to the monitoring and evaluation conclusions of weakly penetrating radiation at a certain Nuclear Power Plant, the dose ratio of  $H'(0.07)$  to  $H^*(10)$  is between 2 and **18 times**.
- Based on the investigation of weakly penetrating radiation from valve-type equipment at a certain Nuclear Power Plant, the  $H'(0.07)/H^*(10)$  ratio is between 1.1 and **28**, and the  $H'(3)/H^*(10)$  ratio is between 1.0 and 2.2. These data indicate that the contribution of weakly penetrating radiation in some places is **not negligible**.



# 01 Overview of Weak Penetration Radiation

## The Significance of Investigation and Monitoring

Regarding the on-site radiation source terms and on-site radiation conditions of nuclear power plants, there may be significant differences between **different types of units**. Meanwhile, these conditions also change with the plant's operating conditions and years of operation. Conducting investigation work on weakly penetrating radiation during the maintenance period of nuclear power plants can provide basic data for understanding the contribution of weakly penetrating radiation during the overhaul, evaluating the radiation exposure of workers' skin and eye lenses, and reviewing or formulating corresponding dose monitoring procedures. This is of positive significance for improving the on-site radiation protection level of nuclear power plants and ensuring the safety of workers.

The harm of weakly penetrating radiation to the human body mainly affects tissues and organs such as the skin, limbs, and eye lenses. Although the current national standards have not yet adopted the international dose limit for eye lenses, to ensure that dose limits are not exceeded and to protect the health of workers, it is necessary to conduct **investigations** into the status of weakly penetrating radiation at the power plant work sites. This will further help **understand the relevant risks and formulate corresponding monitoring and protective measures**.

02

Investigation on Weakly  
Penetrating Radiation Of  
VVER

## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Investigation Content

- Investigation Time: During the overhaul of the nuclear power plant, three overhauls of Units 1 and 2 were selected.
- Investigated Nuclides: According to the results of the radiation source term investigation at Tianwan Nuclear Power Plant, the main radiation source terms of Tianwan Units 1 and 2 include nuclides such as  $^{60}\text{Co}$ ,  $^{58}\text{Co}$ ,  $^{110\text{m}}\text{Ag}$ ,  $^{124}\text{Sb}$ ,  $^{59}\text{Fe}$ ,  $^{54}\text{Mn}$ , and  $^{95}\text{Zr}$ .
- Investigation Locations: Referring to the experience of peer pressurized water reactors, focus on areas and maintenance work in the plant's radiation-controlled area that may have a high risk of weakly penetrating radiation, including **main pumps, steam generators, reactor pool-related equipment, pumps, valves, borated water storage system tools, and waste barrels**.
- Investigation Content: Monitor the radiation dose rate levels in the area ( $H^*(10)$ ,  $H'(0.07)$ ,  $H'(3)$ ) and the personal doses of weakly penetrating radiation ( $H_p(3)$ ,  $H_p(0.07)$ ) received by workers participating in maintenance. Identify **work or areas** that may cause workers' weakly penetrating radiation doses to exceed the limits. At the same time, test **the protective effect** of protective equipment and provide suggestions for personal protection and monitoring.



## 02 Investigation on Weakly Penetrating Radiation of VVER Units

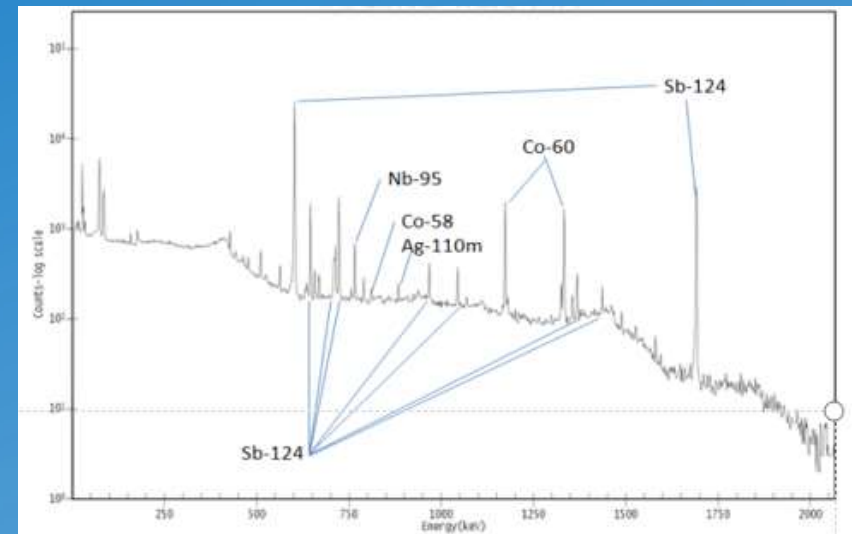
### Investigation Methods

- **Measurement of ambient radiation dose rate:** Select representative workplaces and equipment. Use a portable X and  $\gamma$  dose rate meter to directly measure  $H^*(10)$ . Use a  $\beta$  spectrometer to measure workplaces, equipment, and wipe samples, and calculate  $H'(0.07)$  and  $H'(3)$  from the measured  $\beta$  spectra.
- **Test of protective effect of protective equipment:** Place different combinations of protective equipment in front of the wipe samples from the main pump extractable components and reactor pool, and measure the ratio of  $H'(0.07)$  before and after placing the protective equipment.
- **Measurement of workers' personal dose:** Select representative positions, use ring dosimeters and eye lens dosimeters to monitor workers' skin dose  $H_p(0.07)$  and eye lens dose  $H_p(3)$  during the overhaul, and compare them with the personal dose equivalent  $H_p(10)$  measured by electronic dosimeters in the same period.



### Investigation on Weakly Penetrating Radiation in the Workplace (Main Pump)

- **Before decontamination of the main pump**, After decontamination, the maximum values of directly measured  $H'(3)/H * (10)$  and  $H'(0.07)/H * (10)$  were 1.41 and **9.08**, which were significantly lower than those before decontamination.
- Analysis of wipe samples using an HPGe spectrometer showed that the nuclide composition of the wipe samples was consistent before and after decontamination, mainly including  $^{58}\text{Co}$ ,  $^{60}\text{Co}$ ,  $^{95}\text{Nb}$ ,  $^{124}\text{Sb}$ ,  $^{110\text{m}}\text{Ag}$ , etc. The accompanying  $\beta$ -rays of these nuclides are mainly below 600 keV, and the  $\beta$ -ray energy actually measured by the  $\beta$  spectrometer is also mainly concentrated **below 600 keV**.
- The content of  $^{124}\text{Sb}$  was relatively high **before decontamination**, and the  $\beta$ -rays with a maximum energy of 2.3 MeV emitted by  $^{124}\text{Sb}$  resulted in a significant high-energy component in the  $\beta$  spectrum, which also made an obvious contribution to  $H'(3)$  and  $H'(0.07)$ .

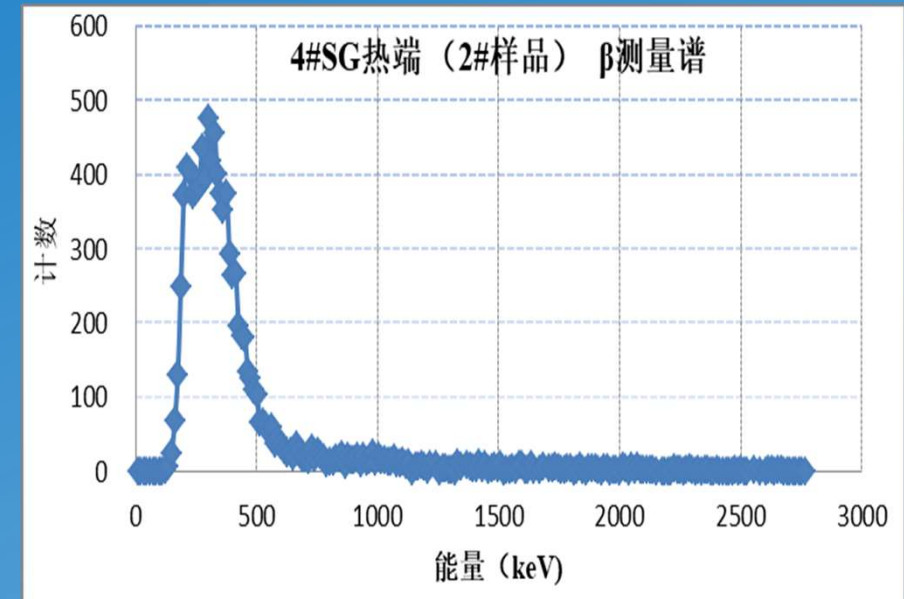


$\gamma$  Measurement Spectrum of a Wipe Sample from the Main Pump Thermal Shield

## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Investigation on Weakly Penetrating Radiation in the Workplace (Steam Generator)

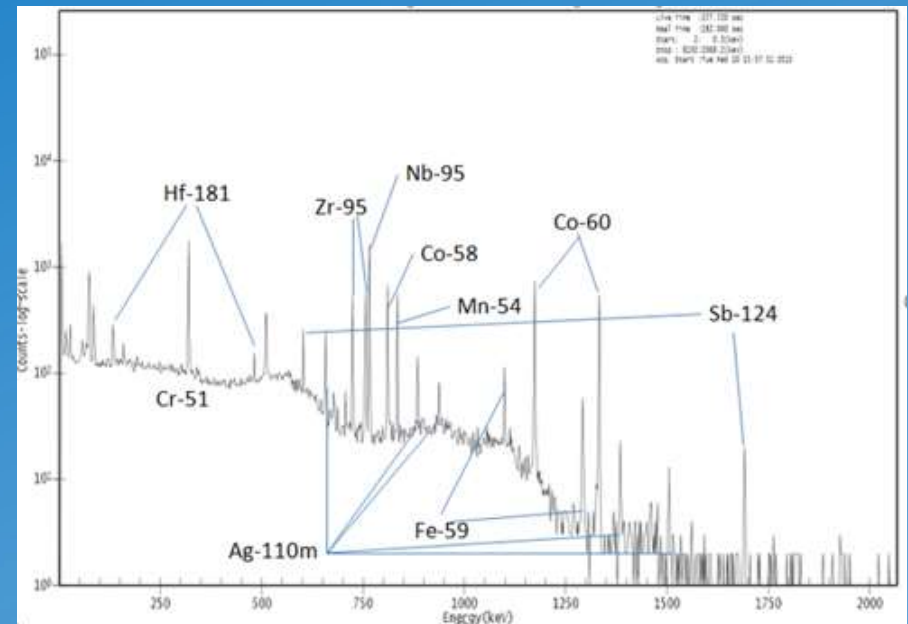
- Analysis of wipe samples from the steam generator using an HPGe spectrometer revealed that the types of nuclides were basically the same as those in the wipe samples from the main pump, with the corresponding  $\beta$  spectra mainly consisting of low-energy components **below 500 keV**.
- The maximum  $H'(3)/H^*(10)$  ratio of the eddy current inspection equipment and probes for the steam generator was 2.58, and the  $H^*(10)$  reached approximately 1 mSv/h, indicating that there was relatively serious contamination and the presence of **high-energy  $\beta$**  components. However, the directly measured  $H'(3)/H^*(10)$  ratio of the eddy current inspection equipment during the overhaul was low and the dose rate contribution was **mainly from  $\gamma$  radiation**.



$\beta$  Measurement Spectrum of a Wipe Sample from the Hot End of the Steam Generator

### Investigation on Weakly Penetrating Radiation in the Workplace (Reactor)

- The values of  $H'(3)/H^*(10)$  and  $H'(0.07)/H^*(10)$  of the position indicators measured during several overhauls were relatively high, while the measured ratios of the control rod drive mechanisms **decreased after cleaning** compared with those before cleaning.
- The  $H'(3)/H^*(10)$  values of the reactor pool and the protective tube assembly are all around 1. Analysis of the wipe samples by HPGe spectrometer showed that the types of nuclides were consistent with those of the wipe samples from the main pump and steam generator.



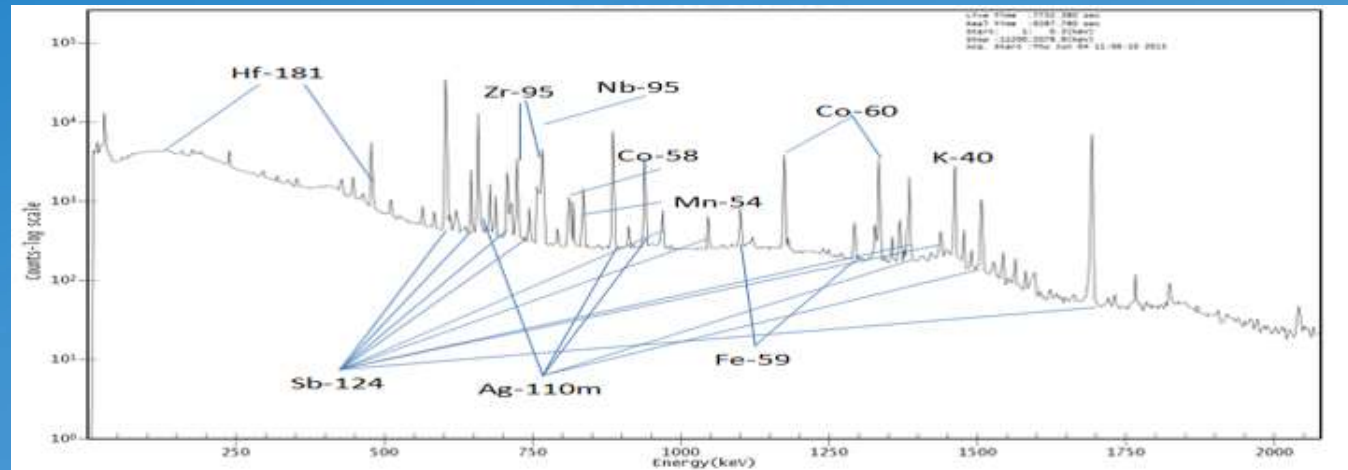
$\gamma$  Measurement Spectrum of a Wipe Sample from the Control Rod Drive Mechanism

## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Investigation on Weakly Penetrating Radiation in the Workplace (Other Pumps and Valves)

Among the various pumps directly measured during several overhauls, except for the small-flow charging pump of the volume and boron control system, the values of the other pumps were relatively low.

- According to the spectrum analysis results of the wipe samples, in addition to low-energy  $\beta$  components, the wipe samples of the small-flow charging pump of the volume and boron control system also contained some high-energy components, whose main contribution came from  $^{124}\text{Sb}$ .
- The values of  $H'(3)/H^*(10)$  and  $H'(0.07)/H^*(10)$  of the relevant valves measured during several overhauls were all low, mostly around 1, and the dose rate contribution was mainly from  $\gamma$  radiation.

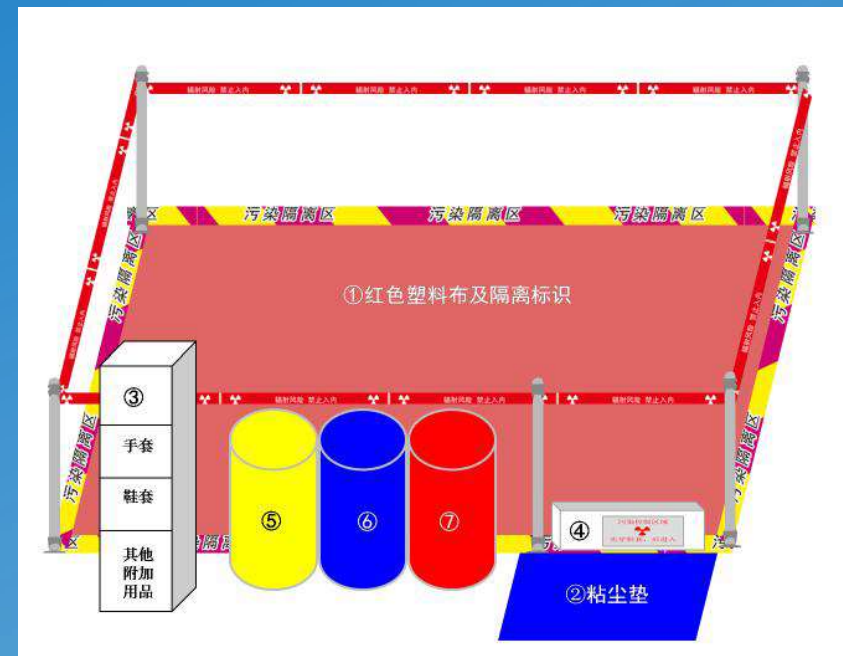


$\gamma$  Measurement Spectrum of a Wipe Sample from a Certain Pump

## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Investigation on Weakly Penetrating Radiation in the Workplace (Other Items)

- During several overhauls, the measured  $H^*(10)$  values of items related to Borated water storage system maintenance were all relatively low.
- The  $H'(3)/H^*(10)$  and  $H'(0.07)/H^*(10)$  ratios of radioactive waste bags were all around 1, with the dose rate contribution **mainly from  $\gamma$  radiation**.
- The experiment on the protective effect of protective equipment focuses on the personnel's skin dose  $H_p(0.07)$ . the protective effects of the minimum standard configuration for contaminated work—including "cotton gloves plus single-layer rubber gloves" and "T-shirt plus single-layer coverall"—are **all more than 4 times**.





## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Conclusion

- In the investigation, the maximum directly measured value of  $H'(3)/H^*(10)$ , which was found in **the small-flow charging pump of the volume and boron control system**. Due to its low surface dose rate  $H'(3)$  of approximately 0.1 mSv/h, and considering the personal dose from the maintenance work (the maximum personal dose in historical maintenance was within 0.2 mSv), the eye lens dose of the maintenance personnel for this upward flushing pump should not exceed 20 mSv/a under normal circumstances.
- Based on the results of the dose monitoring for maintenance personnel, where the maximum value of  $H_p(3)/H_p(10)$  was 1.77, and combined with the results of the workplace dose rate investigation, it can be concluded that under normal circumstances, if the external exposure personal dose  $H_p(10)$  of workers does not exceed **the management target value**(12mSv) of the power plant, the eye lens equivalent dose will not exceed the new IAEA limit.



## 02 Investigation on Weakly Penetrating Radiation of VVER Units

### Conclusion

- For equipment with relatively high surface dose rates and large directly measured  $H'(3)/H^*(10)$  values (such as main pumps that have not been decontaminated, eddy current inspection equipment for steam generators, etc.), in order to prevent workers' eye lenses from being exposed to large doses of weakly penetrating radiation, **the working hours** of maintenance personnel for such equipment should be strictly controlled.
- Considering that the surface dose rate of the extractable components of the main pump is relatively high, the  $H'(3)/H^*(10)$  and  $H'(0.07)/H^*(10)$  values before decontamination are relatively large, and the relevant maintenance personnel need to contact **the extractable components of the main pump** at close range, close attention should be paid to the weakly penetrating radiation doses received by personnel engaged in this work.

# 03

## Weakly Penetrating Personal Dose Monitoring for VVER Units



## 03 Weakly Penetrating Personal Dose Monitoring for VVER Units

### Investigation on Weakly Penetrating Personal Dose of Staff

During several overhauls, the monitoring results of the eye lens dose  $H_p(3)$  and extremity dose  $H_p(0.07)$  for personnel engaged in relevant work showed that the average value of  $H_p(3)/H_p(10)$  was around 1.1, with the maximum  $H_p(3)$  being 0.226 mSv. The average value of  $H_p(0.07)/H_p(10)$  was below 2.0, and the maximum  $H_p(0.07)$  was 0.316 mSv. The personal dose equivalent  $H_p(10)$  of workers under weakly penetrating radiation monitoring during the monitoring period was all below 0.2 mSv, while the personal dose equivalent  $H_p(10)$  of all personnel in the two overhauls was **less than 2 mSv**. The conclusions of each special personal dose investigation are consistent with those of the workplace weakly penetrating radiation investigation.

During the subsequent two overhauls, the monitoring results of the extremity dose  $H_p(0.07)$  for personnel engaged in relevant work showed that the average value of  $H_p(0.07)/H_p(10)$  was below 3.0. The personal dose equivalent  $H_p(10)$  of workers under weakly penetrating radiation monitoring during the monitoring period was all below 0.35 mSv, while the personal dose equivalent  $H_p(10)$  of all personnel in these overhauls was **less than 2 mSv**.



## 03 Weakly Penetrating Personal Dose Monitoring for VVER Units

### Weakly Penetrating Personal Dose Monitoring for Staff

In the recent five years, focused attention has been paid to special continuous monitoring. The maximum value of skin dose Hp(0.07) was **4.61 mSv**, with the corresponding Hp(10) being **2.747 mSv**. The maximum value of eye lens dose Hp(3) was 4.40 mSv, with the corresponding Hp(10) being 1.629 mSv. These values are far below the personal dose limits specified by the national standard (500 mSv/a) and the new IAEA limit (20 mSv/a) respectively.

According to China Nuclear Power 《Guidelines for Personal Dose Monitoring and Management》, the investigation level **for eye lenses is 15 mSv and for skin is 50 mSv**. The historical monitoring data of Tianwan Nuclear Power Plant are all below the above reference levels.

Q/CNNP RP. G 1—2024

全身	连续 5 年的年平均有效剂量（但不可作任何追溯性平均）不超过 <b>20mSv</b> ，其中任何一年中的有效剂量不超过 <b>50 mSv</b>
眼晶体	当量剂量 <b>150 mSv/年</b>
皮肤	当量剂量 <b>500 mSv/年</b>
四肢（手和足）	当量剂量 <b>500 mSv/年</b>

#### 7.1.4 外照射监测参考水平

外照射监测参考水平见表3所示。

表3 外照射监测参考水平

监测项目	监测周期	记录水平	调查水平	行政管理干涉水平
EPD	天	0.001mSv	2mSv	10mSv
	月度		5mSv	
	年度		8mSv	
TLD	按测读周期	MDL	5mSv	10mSv
	年度		8mSv	
弱贯穿TLD（皮肤）	按测读周期	MDL	10mSv	150mSv
	年度		50mSv	
弱贯穿TLD（肢端）	按测读周期	MDL	10mSv	150mSv
	年度		50mSv	
弱贯穿TLD（眼晶体）	按测读周期	MDL	5mSv	50mSv
	年度		15mSv	

04

Summary

# 04 Summary



## Summary

- According to the survey results, the composition of weakly penetrating nuclides in various maintenance equipment at Tianwan Nuclear Power Plant is basically consistent, including  $^{58}\text{Co}$ 、 $^{60}\text{Co}$ 、 $^{95}\text{Nb}$ 、 $^{95}\text{Zr}$ 、 $^{51}\text{Cr}$ 、 $^{124}\text{Sb}$ 、 $^{54}\text{Mn}$ 、 $^{110\text{m}}\text{Ag}$ 、 $^{59}\text{Fe}$ , etc. The  $\beta$ -ray energy is mainly concentrated below 600 keV, and the high-energy  $\beta$  nuclides are mainly  $^{124}\text{Sb}$ .
- Based on the survey and monitoring results, if the external exposure personal dose  $\text{Hp}(10)$  of workers does not exceed **the management target value** of the power plant, the possibility that their weakly penetrating doses  $\text{Hp}(0.07)$  and  $\text{Hp}(3)$  will exceed the personal dose limits specified in the national standard (500 mSv/a) and the new IAEA limit (20 mSv/a) respectively is **relatively low**. According to the protective effect test of protective articles, after considering the use of protective articles, the possibility that the corresponding skin dose exceeds the limit specified in the national standard is even smaller. The  $\text{H}'(3)/\text{H}^*(10)$  ratios of the main pump and steam generator eddy current equipment before decontamination are relatively high. Methods such as optimizing operations and configuring additional protective articles like protective glasses can be considered for dose control.

# 04 Summary

## Summary

- Tianwan Nuclear Power Plant will need to carry out personal dose monitoring of weakly penetrating radiation in the future, including maintenance of extractable components of main pumps, cleaning of reactor pools, disassembly and maintenance of pumps and valves in radioactive systems (especially the volume and boron control systems), sorting of radioactive waste, etc. In addition, for work where source term surveys show a high proportion of high-energy beta nuclides (such as  $^{124}\text{Sb}$ ), personal monitoring of weakly penetrating radiation should also be conducted.
- The power plant will continuously improve protective measures based on the survey results and carry out continuous monitoring of weakly penetrating radiation doses for relevant work. At the same time, it will conduct regular source term surveys to obtain source term information in a timely manner, review the effectiveness of protective measures in combination with personal monitoring results, and ensure that workers' personal doses meet the requirements of national standards, even when national standards adopt new IAEA recommendations.



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**Leaders and experts, your comments  
and corrections are warmly  
welcome!**

**For further information, please  
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**Thank you all!**



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# 中国核电 国家名片

