Analysis on radiation control and the impact of land pipeline leakage of offshore nuclear power plant on groundwater

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Abstract. Using the groundwater migration and dispersion analytical model, combined with the topography and groundwater characteristics along the land drainage pipeline of an offshore nuclear power plant, the migration and dispersion of six radionuclides (³H, ¹⁴C, ¹³⁷Cs, ¹³⁴Cs, ⁶⁰Co, ⁹⁰Sr, etc.) in groundwater under the condition of pipeline breach accident are predicted. The scope of impact of radionuclides and the annual effective dose caused by drinking water pathways to the public are analyzed. By summarizing the radionuclide concentration and dose index requirements for groundwater at home and abroad, the corresponding environmental impact assessment is given. The prediction results show that the radionuclide concentration and public effective dose at the same distance first increase and then decrease with time, and the peak radionuclide concentration and maximum public effective dose gradually decrease with distance increasing, in other words, the impact of the breach accident on the distance above 30 m is limited.

Keywords: Offshore nuclear power plant; radionuclide; pipeline; breach accident; effective dose.

1. Introduction
At present, the nuclear power plants (NPPs) that have been put into operation and approved for construction in China are all coastal sites. With the continuous development of China's inland economy, the continuous increase of electricity demand and the urgent need of energy conservation and emission reduction, the construction of NPPs will be promoted from coastal to offshore. Compared with the coastal site, the offshore site needs to be connected to the sea area through land water intake and drainage pipelines to meet the water demand and wastewater discharge of NPPs. The groundwater and surface water in offshore areas are closely connected. If the residents around the NPP generally use groundwater as a source of domestic and drinking water, the natural storage conditions of groundwater in the area where the plant site is located will inevitably be affected during the operation of NPPs. Under accident conditions, radionuclides may enter groundwater and threaten the life and health of surrounding residents.

Up till now, there is no offshore NPP has been put into commercial operation in China. The existing research mainly focuses on the environmental impact on groundwater caused by the rupture of radioactive waste storage tank in NPP [1, 2, 3] and the leakage accident in petrochemical industry such as oil and gas transportation pipeline [4, 5, 6], while there is less research on the leakage accident of...
land pipeline in NPP. Abroad, as of 2019, a total of 57 NPPs in the United States were in operation, 40 of the NPPs in operation had $^3$H leakage events, and 26 of the 35 inland NPPs had $^3$H leakage events. Among them, the liquid $^3$H leakage of many NPPs was caused by the rupture of circulating water blowdown pipelines [7, 8, 9]. Therefore, breach accident as a typical leakage accident of land drainage pipeline, the environmental impact caused by radionuclides entering groundwater is more worthy of attention and research.

2. Study Area
The land pipeline of a NPP is about 10 km long. The pipeline passes through orchards, woodlands, farmland and wasteland, crosses roads, highways, railways and rivers, and finally enters the NPP. According to the characteristics of the surrounding environment of the pipeline, the groundwater around the pipeline is mainly Quaternary loose rock pore water, and the water level is shallow. The surrounding residents mainly use water wells for scattered extracting. Some towns and villages are small-scale centralized extracting, which is mainly used for drinking water and domestic water.

At present, there are two main schemes for offshore NPPs to transport liquid effluent through land pipelines: separate discharge scheme and combined discharge scheme. The NPP adopts the combined discharge mode of mixing the liquid effluent directly with the sewage discharged from the seawater cooling tower. The NPP plans to share a DN1600 drainage pipeline for liquid effluent and circulating cooling tower drainage of each 3 units, and 2 drainage pipelines for 6 units, with a single pipe flow rate of 2.2 m/s. The pipeline is directly buried along the whole line, with a buried depth of about 1.5 m, and the height difference between the starting point and the ending point of the drainage pipeline is about 90 m.

3. Data and Methods

3.1. Radionuclide selection
The NPP plans to use the Hualong One unit, and the radioactive waste liquid during the operation of the NPP will be discharged into the sea through the discharge pipeline after the treatment reaches the standard. Since there are many types of radionuclides involved in the liquid effluent in the pipeline, up to dozens of them, the half-life of each radionuclide is different, the influence factors in the migration process are different, and the dose conversion factors of each radionuclide are also different, therefore, the impact of different radionuclides on the environment varies greatly.

Up till now, there are no relevant guidelines and specifications in China to give the radionuclides that need to be considered in the process of migration in groundwater under accident conditions. The American Nuclear Society (ANS) and the Nuclear Regulatory Commission (NRC) have given the radionuclides that need to be considered according to the relative abundance, activity and migration characteristics of radionuclides in the liquid effluent discharged from American NPPs [10, 11], as shown in Table 1. Combined with the liquid radioactive effluent source items of Hualong One unit and years of experience in the operation of NPPs in the United States, $^3$H, $^{14}$C, $^{137}$Cs, $^{134}$Cs, $^{60}$Co and $^{90}$Sr are considered as the critical radionuclides for radiation impact assessment.

| Guideline and specification | ANSI/ANS-2.17-2010 [10] | NRC RG4.25-2017 [11] |
|----------------------------|---------------------------|---------------------|
| Nuclide                    | $^{90}$Sr, $^{137}$Cs, $^{60}$Co, $^3$H, $^{134}$Cs, $^{129}$I, $^{65}$Ni, $^{14}$C, $^{238}$Pu and $^{241}$Am | $^3$H, $^{90}$Sr, $^{137}$Cs, $^{65}$Ni, $^{60}$Co and $^{125}$Sb |

3.2. Leakage of liquid effluent
Considering the impact of a breach accident on groundwater, the following assumptions are made for the breach accident:
(1) The pipeline is ruptured. It is assumed that the leakage accident can be found within 30 min and measures shall be taken to prevent the leakage;

(2) The size of the breach, the aperture of the breach is assumed to be 50 mm [12].

According to Technical specification for investigation and evaluation to external human-induced events of nuclear power plants (NB/T20200-2013, China’s guideline) Appendix H.2.1.1 recommended pipeline liquid leakage formula [13]:

\[
Q_0 = C_v \rho (2gH_1)^{\frac{1}{2}}
\]  

Where:
- \(Q_0\) is the liquid leakage speed, kg/s;
- \(C_v\) is the flow velocity coefficient (0.97 to 0.98 in the case of perfect shrinkage), which is related to the Reynolds number of the fluid, take 0.98; and
- \(V_1\) is the flow velocity on the cross section of the inner wall of the leakage orifice, m/s, Using 6 units to run single pipe flow velocity 2.2 m/s; 
- \(A\) is the Breach area, m\(^2\);
- \(\rho\) is the leakage liquid density, kg/m\(^3\), using the density of water 1000 kg/m\(^3\);
- \(P\) is the pressure of medium in the container, Pa;
- \(P_0\) is the ambient pressure, Pa;
- \(g\) is gravitational acceleration, take 9.8 m/s\(^2\);
- \(H_1\) is the pressure head of the liquid at the leakage orifice, m. Calculated as follows:

\[
H_1 = \frac{P - P_0}{\rho g} + \frac{V_1^2}{2g}
\]  

Calculated by formula (1), the leakage velocity of liquid effluent is 4.231 kg/s, and the total leakage in 30 min is 7616 L.

The above concentration of radionuclides in the pipeline can be calculated according to the design parameters such as the discharge of liquid radioactive effluent of a single unit under the design conditions of Hualong One unit, the annual discharge of nuclear island waste liquid discharge system (TER) (the annual discharge of TER of a single unit is 17500 m\(^3\)), the maximum discharge flow velocity of TER (0.069 m\(^3\)/s) and the discharge flow velocity of other effluents such as circulating cooling tower drainage (8.4 m\(^3\)/s). According to the radionuclide concentration in the pipeline and the leakage amount of breach accident, the activity of each radionuclide entering the groundwater environment after leakage can be obtained. The calculation results are shown in Table 2.

| Nuclide | Single unit discharge, GBq (Units*year)\(^{-1}\) | Pipeline radionuclide concentration, Bq L\(^{-1}\) | Leakage amount, L | Activity of entering groundwater, Bq |
|---------|---------------------------------------------|---------------------------------------------|----------------|-----------------------------------|
| \(^3\)H | 4.48E+04 | 2.12E+04 | 7616 | 1.61E+08 |
| \(^{14}\)C | 1.85E+01 | 8.74E+00 | | 6.66E+04 |
| \(^{137}\)Cs | 7.29E-01 | 3.44E-01 | | 2.62E+03 |
| \(^{134}\)Cs | 4.98E-00 | 2.35E-01 | | 1.79E+03 |
| \(^{60}\)Co | 5.01E-02 | 2.37E-02 | | 1.80E+02 |
| \(^{90}\)Sr | 6.40E-05 | 3.02E-05 | | 2.30E-01 |

### 3.3. Migration models and parameters

In the case of pipeline rupture that can be found and prevented in a short time, the point source instantaneous one-dimensional dispersion model in the analytical method of Technical guidelines for environmental impact assessment-groundwater environment (HJ 610-2016, China’s guideline) can be used for prediction [14]. The calculation conditions are now assumed as follows:

(1) The aquifer is generalized as a single phreatic aquifer, the initial concentration of pollutants is 0, and the pollutants directly enter the aquifer, regardless of the vertical infiltration process in the aeration zone;
(2) The degradation and retardation of pollutants by soil and rock stratum are not considered, but the influence of radionuclide decay is considered;

(3) The instantaneous point source one-dimensional dispersion model assumes that when \( t = 0 \), pollutants are generated at the source point (\( x = 0 \)) and disperse in one direction along the groundwater.

The analytical formula of dispersion model is:

\[
C(x, t) = \frac{m/W}{2n_e(D_L t)^{3/2}} e^{-\left(\frac{x-ut}{4D_L}\right)^2-\lambda t}
\]  \( \text{(3)} \)

Where: \( x \) is the distance from the breach point, m; \( t \) is time, d; \( C(x,t) \) is the contaminants concentration of distance \( x \) at time \( t \), Bq/m³; \( m \) is the activity of the radionuclide entering groundwater, Bq; \( W \) is cross-sectional area, m²; \( u \) is groundwater flow velocity, m/d; \( n_e \) is valid porosity, no scale; \( D_L \) is longitudinal dispersion coefficient, m²/d; and \( \lambda \) is the radionuclide decay constant.

According to the hydrogeological survey results of land water intake and drainage pipelines, the cross-sectional area is taken as 20 m² (the thickness of the aquifer is taken as 5 m), and the longitudinal dispersion coefficient is taken as 0.5 m²/d. The hydraulic slope is taken as 0.015, the permeability coefficient \( K \) is taken as 1.5 m/d, and the effective porosity is taken as 0.3, so the groundwater flow velocity is 0.075 m/d.

After the radionuclides migrate in the aquifer and enter the biosphere, they will eventually have radiation impact on the public through various irradiated ways. According to the characteristics of the surrounding environment of the pipeline, the radiation dose generated by the public drinking mainly through the groundwater well is considered, that is, the internal radiation dose caused by the drinking water is considered. The model and parameter values of the irradiation path are as follows:

\[
D_{EW} = 365 \cdot \sum Q_w \cdot C_{Ki} \cdot D_{FEi}
\]  \( \text{(4)} \)

Where: \( D_{EW} \) is the effective dose caused by the public's personal drinking water, Sv/a; \( Q_w \) is the public's personal drinking water, 730 L/a; \( C_{Ki} \) is the concentration of radionuclide \( i \) in the water, Bq/L; \( D_{FEi} \) is the effective dose conversion factor of radionuclide \( i \) to human body, Sv/Bq. The decay constants and effective dose conversion factors of the selected 6 typical radionuclides are shown in Table 3 [15].

| Nuclide | Decay constant, d⁻¹ | Effective dose conversion factor, Sv Bq⁻¹ |
|---------|---------------------|-------------------------------------|
| \(^3\)H | 1.54E-04            | 1.80E-11                            |
| \(^{14}\)C | 3.32E-07            | 5.80E-10                            |
| \(^{137}\)Cs | 6.30E-05           | 1.30E-08                            |
| \(^{134}\)Cs | 9.21E-04           | 1.90E-08                            |
| \(^{60}\)Co | 3.59E-04           | 3.40E-09                            |
| \(^{90}\)Sr | 6.54E-05           | 2.80E-08                            |

4. Results and Analysis

4.1. Groundwater forecast results

The point source instantaneous one-dimensional dispersion model is used to predict the radionuclide dispersion within 200 m of the pipeline breach. The prediction results of radionuclide concentration are shown in Figure 1. It is assumed that adults consume 730 L of drinking water per year. According to the effective dose conversion factor of each radionuclide, the changes of \(^3\)H and total public effective dose at different distances with time are shown in Figure 2. The peak concentration of each radionuclide, the maximum public effective dose of multi-nuclide and the corresponding time are shown in Table 4.
Figure 1. Variation of radionuclide concentration with time at different distances

Figure 2. Variation of public effective dose with time at different distances
Table 4. Peak concentrations of each radionuclide and the maximum public dose of multi-nuclides at different distances

| Distance, m | $^3$H  | $^{14}$C  | $^{137}$Cs | $^{134}$Cs | $^{60}$Co | $^{90}$Sr | Maximum public dose, Sv.a$^{-1}$ | Time, d |
|------------|--------|--------|--------|--------|--------|--------|-------------------------------|-------|
| 10         | 1.08E+03 | 4.50E-01 | 1.77E-02 | 1.14E-02 | 1.19E-03 | 1.55E-06 | 1.47E-05 | 70     |
| 30         | 5.38E+02 | 2.33E-01 | 9.00E-03 | 4.75E-03 | 5.66E-04 | 7.89E-07 | 7.32E-06 | 300    |
| 50         | 3.91E+02 | 1.77E-01 | 6.72E-03 | 2.88E-03 | 3.86E-04 | 5.89E-07 | 5.31E-06 | 600    |
| 80         | 2.87E+02 | 1.38E-01 | 5.12E-03 | 1.59E-03 | 2.65E-04 | 4.48E-07 | 3.90E-06 | 1000   |
| 100        | 2.13E+02 | 1.08E-01 | 3.89E-03 | 1.10E-03 | 1.94E-04 | 3.40E-07 | 2.89E-06 | 1000   |
| 200        | 1.42E+02 | 8.57E-02 | 2.89E-03 | 2.31E-03 | 9.47E-05 | 2.52E-07 | 1.93E-06 | 2500   |

It can be seen from the prediction results of Figure 1 and Figure 2 that the concentration of each radionuclide and the public effective dose at the same distance increase first and then decrease over time. The peak concentration of the radionuclide and the maximum public dose gradually increase with the increase of distance. As the $^3$H discharge of a single unit under design conditions far exceeds that of other radionuclides, $^3$H plays a leading role in both concentration and public effective dose in the prediction results. It can be seen from Figure 2 that the public effective dose of $^3$H accounts for more than 95% of the total public effective dose, and the two curves basically overlap, indicating that $^3$H is the most important source of radiation impact and can be used as the most critical evaluation index of environmental impact under breach accident conditions.

4.2. Environmental impact assessment and analysis

In China, Standard for ground water quality (GB/T 14848-2017, China’s guideline) and Standards for drinking water quality (GB 5749-2006, China’s guideline) only specify the total $\alpha$ radioactive and total $\beta$ radioactive concentration limits (0.5 Bq/L and 1 Bq/L, respectively) [16, 17], and there are no specific radionuclide concentration index requirements for groundwater. Regulations for environmental radiation protection of nuclear power plant (GB 6249-2011, China’s guideline) requires, "The effective dose of radioactive substances released to the environment by all nuclear power reactors at any plant site to any individual in the public must be less than the dose constraint value of 0.25 mSv per year" [18]. However, the dose constraint value is the total dose caused by various irradiated ways, not just the dose caused by drinking water.

U.S. Environmental Protection Agency (EPA) uses the reference dose level (RDL) of 0.04 mSv/a to guide the maximum concentration levels (MCLs) in public drinking water, and proposes that the $^3$H concentration guidance value in drinking water is 740 Bq/L, which is a non-mandatory concentration limit [19]. U.S. Code of Federal Regulations 10 CFR Part 20 requires, "The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 1 mSv in a year" [20].

In addition, the World Health Organization (WHO) requirements for radionuclides in drinking water stipulate that the dose caused by human drinking water within one year should be less than 0.1 mSv/a. In the standard, it is assumed that adults consume 730 L of drinking water each year, and the guideline level of a single radionuclide in drinking water is derived, and the guideline value of $^3$H concentration is 10000 Bq/L [21].
Based on the above-mentioned domestic and foreign radionuclide concentration limits in groundwater and annual public effective dose limits, in accordance with the most stringent selection principles of $^3$H concentration and total public effective dose, the guiding value of $^3$H concentration level in drinking water 740 Bq/L given by EPA and the dose constraint value of 0.1 mSv specified by the WHO are adopted as the standard of environmental assessment.

According to the radionuclide concentration and annual public effective dose prediction results at different distances, the peak concentration of $^3$H at 10 m is 1.08E+03 Bq/L (day 70), and the maximum public dose at this distance is 1.47E-02 mSv/a (day 70), higher than the EPA's 740 Bq/L drinking water $^3$H concentration guideline value, lower than the WHO's 0.1 mSv limit, the peak concentration at 30 m and the maximum public dose are respectively 5.38E+02 Bq/L (day 300) and 7.32E-03 mSv/a (day 300), which are lower than the EPA's 740 Bq/L drinking water $^3$H concentration guideline level and lower than the WHO's 0.1 mSv limit, that is, the impact of the breach accident on the distance beyond 30 m is limited.

5. Conclusions and Prospects

5.1. Conclusions
(1) Among the six radionuclides predicted for the breach accident of the land drainage pipeline of NPPs, $^3$H plays a leading role in both the concentration and the public effective dose. It is the most important source of radiation impact. The monitoring of $^3$H shall be strengthened during the operation of land pipeline, and the radiation impact on $^3$H after leakage accident shall be mainly controlled and managed.

(2) $^3$H is the most critical evaluation indicator for the environmental impact of a breach accident, the peak concentration at a distance of 10 m from the breach is higher than the EPA's 740 Bq/L drinking water $^3$H guideline value level, and the peak concentration at 30 m is lower than concentration guideline level, the annual public effective dose at 10 m and 30 m is lower than the 0.1 mSv limit specified by WHO, and 30 m can be used as the safety distance for a breach accident.

5.2. Prospects
With the continuous advancement of "peak carbon dioxide emissions" and "carbon neutrality" in China, nuclear power, as an important part of clean energy, is bound to be further promoted and developed. However, in terms of the design and radioactivity monitoring requirements of the land drainage pipelines of offshore NNP, China is still in its infancy, and national standards have not yet put forward requirements for the specific radionuclide concentration indicators of groundwater. Therefore, research should be carried out from the following aspects in the future.

(1) Statistics on radionuclide leakage accidents in domestic NPP and land drainage pipelines in the surrounding area, carry out investigation and research on radionuclides in groundwater after the leakage accident, find out the main types of radionuclides in groundwater and their pollution sources, analyze pollution status, and discuss the potential pollution threat of radionuclides to underground aquifers to provide a basis for the formulation of specific radionuclide concentration indicators in groundwater and public effective dose standards of drinking water in China.

(2) Establish a groundwater radionuclide pollution database, promote the development of radioactive monitoring and treatment technology, combined with relevant environmental standards and advanced experience in the operation of NPPs in Europe and the United States, provide guidance for the design and radioactive monitoring of land drainage pipelines of NPPs, reasonably predict the possible accident environmental risks during the operation period of pipelines and carry out effective control.

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