Calculation of Decay Tank Capacity and Minimum Storage Time for Nuclear Medicine Based on Total Emission Control

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Abstract

In recent years, during the accelerated development of nuclear medicine department construction, the storage duration of radioactive wastewater containing iodine-131 and decay tank construction have become matters of great concern to hospitals, environmental assessment agencies, and ecological environment regulatory authorities. The "Basic Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources" (GB 18871), "Radiation Protection and Safety Requirements for Nuclear Medicine" (HJ 1188), and "Reply Letter on Consultation Issues Regarding Relevant Clauses of Nuclear Medicine Standards" specify the compliant discharge methods for radioactive wastewater (with iodine-131 as the main nuclide) in decay tanks. This paper presents, through theoretical derivation, a theoretical calculation formula for the activity of iodine-131 when the decay tank is full under full-load conditions; demonstrates that among the three compliant discharge methods for radioactive wastewater containing iodine-131, discharge according to the method specified in GB 18871 is most advantageous for the operation of hospital nuclear medicine departments; and proposes the RJ equation set, which solves the problem of how to determine the minimum storage time for radioactive wastewater containing iodine-131 and the capacity of decay tanks. Actual monitoring data from four hospitals show that after the storage time of radioactive wastewater containing iodine-131 reaches the minimum storage time calculated by the RJ equation set, the total iodine-131 emissions comply with national ecological environment standards requirements. The above can provide clear and specific guidance for the construction of decay tanks in hospital nuclear medicine departments, wastewater discharge management, and supervision and inspection by regulatory authorities.

Full Text

Preamble

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Calculation of Decay Tank Capacity and Minimum Storage Time for Nuclear Medicine Department Wastewater Based on Total Emission Control

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Abstract

In recent years, as the construction of nuclear medicine departments has accelerated, the storage time of radioactive wastewater containing iodine-131 and the design of decay tanks have become major concerns for hospitals, environmental assessment agencies, and ecological environment regulatory authorities. The *Basic Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources* (GB 18871), *Radiation Protection and Safety Requirements for Nuclear Medicine* (HJ 1188), and the *Reply to Consultation on Relevant Clauses of the Nuclear Medicine Standard* specify compliant discharge methods for radioactive wastewater from decay tanks (primarily containing iodine-131). This paper derives theoretical formulas for calculating the activity of iodine-131 when a decay tank reaches full capacity under full-load conditions. It demonstrates that among the three compliant discharge methods for radioactive wastewater containing iodine-131, the method specified in GB 18871 is most advantageous for hospital operations. The paper proposes the RJ equation group to determine the minimum storage time and appropriate decay tank capacity. Monitoring data from four hospitals show that when the storage time for iodine-131 wastewater reaches the minimum duration calculated by the RJ equations, total iodine-131 emissions comply with national ecological environment standards. These findings provide clear and specific guidance for decay tank construction, wastewater discharge management, and regulatory oversight in hospital nuclear medicine departments.

Keywords: Hospital, Decay Tank, Radioactive Wastewater, Iodine-131

1. Theoretical Derivation

1.1 Total Activity of Iodine-131

The majority of iodine-131 ingested by patients is excreted within the first three days [?]. Assuming a hospitalization period of 3 days, average administered activity per patient of A, number of beds N, and continuous operation with all beds constantly occupied, let P_1, P_2, and P_3 represent the ratios of iodine-131 activity excreted via urine and other pathways on days 1, 2, and 3 relative to the administered activity, respectively, and let λ denote the iodine-131 decay constant. After T days of operation when the decay tank becomes full, the contribution D_1 to the iodine-131 activity in the tank from patients' day-1 excretions is:

$$D_1 = N \cdot P_1 \cdot A \cdot \sum_{i=0}^{n-1} e^{-\lambda(3i)} = N \cdot P_1 \cdot A \cdot \frac{1 - e^{-\lambda T}}{1 - e^{-3\lambda}}$$

where $n = T/3$ represents the number of hospitalization cycles during the tank filling period. For example, if the tank fills in 60 days, $n = 20$. For computational convenience, we first assume $T = 3n$ where n is an integer.

Using the same method, the contributions from patients' day-2 and day-3 excretions, D_2 and D_3, are:

$$D_2 = N \cdot P_2 \cdot A \cdot \sum_{i=0}^{n-1} e^{-\lambda(3i+1)} = N \cdot P_2 \cdot A \cdot e^{-\lambda} \cdot \frac{1 - e^{-\lambda T}}{1 - e^{-3\lambda}}$$

$$D_3 = N \cdot P_3 \cdot A \cdot \sum_{i=0}^{n-1} e^{-\lambda(3i+2)} = N \cdot P_3 \cdot A \cdot e^{-2\lambda} \cdot \frac{1 - e^{-\lambda T}}{1 - e^{-3\lambda}}$$

The proportion of iodine-131 retained in cells correlates with cellular metabolic activity [?]. Typically, 30% of iodine-131 is assumed to remain in the body while 70% is excreted in urine [?][?]. However, conservative values should be used for radiation protection calculations. Referencing ICRP Publication 94, P_1, P_2, and P_3 are taken as 55%, 22%, and 6%, respectively [?][?]. The iodine-131 decay constant is 0.0864/d. Based on these parameters, the theoretical activity D of iodine-131 when the decay tank is full is:

$$D = D_1 + D_2 + D_3 = k \cdot N \cdot A \cdot (1 - e^{-\lambda T})$$

where the coefficient k depends on the hospitalization period and tank filling duration. For a 3-day hospitalization period and $T = 3n$, $k = 3.16$. In most practical cases where $T \geq 30$ days, $1 - e^{-\lambda T}$ can be approximated as 1, simplifying the theoretical activity to approximately kNA.

If the tank filling time $T = 3n+1$, the total iodine-131 activity can be considered as the sum of: (1) the remaining activity after one day of decay from the activity at $3n$ days, and (2) the iodine-131 excreted on the day of administration. This yields:

$$D = k \cdot N \cdot A \cdot (1 - e^{-\lambda T}) + N \cdot P_1 \cdot A \cdot e^{-\lambda T}$$

For $T = 3n + 1$, $k = 3.55$. Table 1 provides k values for different hospitalization periods and tank filling durations. The combined excretion on days 4 and 5 accounts for approximately 85% of the administered activity. When calculating k for a 4-day hospitalization period, day-4 excretion is conservatively assumed to be 2% of the administered activity.

1.2 Theoretical Minimum Decay Days (Considering Annual Limits)

According to GB 18871 Section 8.6.2, the annual emission limit E for iodine-131 is:

$$E = 10\mathrm{ALI}_{\mathrm{min}} \times 12 = 1.08 \times 10^{8}\ \mathrm{Bq}$$

Per GB 18871 Appendix B1.3.4 and 1.3.5, $\mathrm{ALI}_{\mathrm{min}}$ is calculated as:

$$\mathrm{ALI}_{\mathrm{min}} = \frac{DL}{e_j} \times \frac{1}{20} = \frac{0.02}{e_j}$$

where DL is the annual effective dose limit of 20 mSv, and e_j is the committed effective dose per unit intake for radionuclide j. From GB 18871 Table B3, e_j for iodine-131 is 2.2×10^{-8} Sv/Bq, yielding $\mathrm{ALI}_{\mathrm{min}} = 9 \times 10^{5}$ Bq and an annual emission limit of 1.08×10^{8} Bq (3 mCi).

Based on the derivation in Section 1.1, the annual cumulative total activity A_t of iodine-131 in the decay tank can be expressed as:

$$A_t = \left\lfloor \frac{365 \cdot W_1}{V} \right\rfloor \cdot k \cdot N \cdot A$$

where W_1 is the daily wastewater volume discharged into the decay tank, $\lfloor\cdot\rfloor$ denotes the floor function, and V is the capacity of a single decay tank. At year-end, the tank is unlikely to be exactly full, and the actual iodine-131 activity in a partially filled tank is less than kNA. Following the conservative principle of radiation protection, the number of tank fillings per year is represented as $\left\lfloor \frac{365 \cdot W_1}{V} \right\rfloor + 1$.

The minimum required decay storage time T_{min} should satisfy:

$$\left(\left\lfloor \frac{365 \cdot W_1}{V} \right\rfloor + 1 \right) \cdot k \cdot N \cdot A \cdot e^{-\lambda T_{\mathrm{min}}} \leq E \quad (1)$$

Assuming M decay tanks are installed, the tank capacity V should satisfy:

$$T_{\mathrm{min}} \geq \frac{V}{M \cdot W_1} \quad (2)$$

Since equation (1) contains V, solving equation (2) with equality yields the minimum tank capacity. Equations (1) and (2) constitute the RJ equation group for determining decay tank capacity and minimum storage time under annual emission limits.

For existing nuclear medicine departments where W_1 and V are fixed, $\frac{W_1}{V}$ is constant, allowing calculation of the required wastewater storage time to meet regulatory requirements using equation (1). For planned departments, the RJ equation group can determine the required decay tank capacity and minimum storage time to satisfy annual emission limits.

1.3 Theoretical Minimum Decay Days (Considering Monthly Limits)

Per GB 18871 Section 8.6.2, monthly iodine-131 emissions must not exceed $10\text{ALI}_{\min}$ (0.25 mCi). Denoting monthly emissions as E_m, the minimum storage time for iodine-131 wastewater should satisfy:

$$\left(\left\lfloor \frac{30 \cdot W_1}{V} \right\rfloor + 1\right) \cdot k \cdot N \cdot A \cdot e^{-\lambda T_{\min}} \leq E_m \quad (4)$$

The decay tank capacity V should satisfy:

$$T_{\min} \geq \frac{V}{M \cdot W_1} \quad (5)$$

Considering the annual emission limit, the capacity must also satisfy:

$$\left(\left\lfloor \frac{365 \cdot W_1}{V} \right\rfloor + 1\right) \cdot k \cdot N \cdot A \cdot e^{-\lambda T_{\min}} \leq E \quad (6)$$

Equations (4), (5), and (6) constitute the RJ equation group for determining tank capacity and minimum storage time under monthly emission limits. Since annual emission limits are more commonly applied in radionuclide radiation safety management, subsequent calculations and analyses in this paper primarily focus on annual limits.

1.4 Optimality of GB 18871-Based Discharge

Besides the discharge method specified in GB 18871 Section 8.6.2, wastewater may also be discharged when the iodine-131 activity concentration decays to 10 Bq/L. At this concentration, discharging 1.08×10^8 Bq (3 mCi) would require:

$$\frac{1.08 \times 10^8 \text{ Bq}}{10 \text{ Bq/L}} = 1.08 \times 10^7 \text{ L} = 1.08 \times 10^4 \text{ m}^3$$

Annual wastewater generation from hospital iodine-131 therapy wards is far below 1.11×10^4 m^3, making GB 18871-based discharge superior to discharge at 10 Bq/L.

If hospitals choose to store wastewater for 180 days before discharge, assuming total discharged iodine-131 activity of 1.08×10^8 Bq (3 mCi), the annual cumulative activity in the decay tank would be:

$$A_t = \frac{1.08 \times 10^8}{e^{-\lambda \cdot 180}} = 1.70 \times 10^{14} \text{ Bq} = 1.70 \times 10^4 \text{ Ci}$$

Annual iodine-131 usage in a single hospital nuclear medicine department is far below 1.70×10^4 Ci, and considering decay factors, the cumulative activity A_t when the tank is full is even lower. Therefore, GB 18871-based discharge is also superior to 180-day storage discharge.

For example, with 10 patients, average administered activity of 200 mCi per patient, 3-day hospitalization period, 20 m^3 decay tank capacity, and average daily water usage of 0.08 m^3 per patient, the RJ equations yield: (1) minimum storage time $T_{\text{min}} = 120$ days (less than the 180 days required by the second method), and (2) discharge activity concentration of 370 Bq/L (higher than the 10 Bq/L required by the third method). This analysis confirms that the GB 18871-specified discharge method is most favorable for hospital operations, and decay tank capacity should be determined using the RJ equation group presented in Sections 1.1-1.3.

2. Actual Measurement Results

Four hospitals were selected for monitoring iodine-131 activity concentration when decay tanks reached full capacity, following the method specified in *Analysis Method for Iodine-131 in Water, Milk, Plants, and Animal Thyroid* (HJ 841-2017). Results are shown in Table 2 . The data demonstrate that: (1) actual iodine-131 activity in full tanks is lower than theoretical calculations; (2) under full-load operation (e.g., Hospital No. 3), measured values closely approach theoretical values; and (3) after verification using the decay times provided by the RJ equations, annual iodine-131 emissions from all four hospitals remain below regulatory limits.

3. Analysis and Discussion

Based on the above analysis and calculations, the following conclusions can be drawn:

1. According to the theoretical activity formula for iodine-131 in full decay tanks, total activity is proportional to patient numbers and administered activity per patient. When the tank operates for more than 50 days, the total iodine-131 activity stabilizes. The theoretical activity represents an

upper limit, calculated under conservative assumptions of full-load operation, continuous patient turnover, and excretion fractions [**?**].

2. If daily wastewater discharge W_1 doubles and tank capacity V doubles correspondingly, the annual cumulative activity A_t and minimum decay time T_{min} remain unchanged, maintaining equality in equation (2). Therefore, under constant other conditions, the required decay tank capacity V calculated using the RJ equation group is directly proportional to W_1.
3. From conclusion (2), since V is proportional to W_1, the ratio W_1/V is constant, making annual cumulative activity A_t proportional to patient number N. From equation (1), the minimum storage time T_{min} is proportional to $\ln(N)$.
4. Assuming constant per-patient water usage W_0, daily wastewater discharge W_1 is proportional to N, while T_{min} has a logarithmic relationship with N. Consequently, required decay tank capacity V is approximately proportional to $N\ln(N)$.

Currently, environmental impact assessments and construction projects typically calculate decay tank capacity based on 180-day storage:

$$V = 180 \cdot W_0 \cdot N$$

Per-patient water usage varies significantly across hospitals and seasons. Table 3 presents measured daily water usage per bed for eight hospitals. Assuming $W_0 = 0.11\ \text{m}^3/\text{bed}$ and three decay tanks, with thyroid cancer patients receiving no more than 150 mCi (conservatively assumed as 200 mCi for calculations), Table 4 compares capacities calculated using the RJ equation group versus current methods, showing the RJ method yields significantly smaller tank requirements.

This paper provides a theoretical formula for iodine-131 activity in full decay tanks, demonstrates the optimality of GB 18871 Section 8.6.2-based discharge, and introduces the RJ equation group for determining tank capacity and minimum storage time. The RJ method substantially reduces capacity requirements compared to the current 180-day approach, decreasing land use, construction costs, and investment barriers while promoting compliant and orderly development of nuclear medicine departments.

For regulatory authorities, after determining patient numbers, hospitalization periods, average administered activity, daily wastewater discharge, and tank capacity, the RJ equation group can verify whether proposed tank capacities meet requirements in environmental impact assessments and calculate minimum storage times. Since theoretical activities represent upper limits and actual activities are typically much lower, emissions can be theoretically proven compliant without monitoring data when storage times exceed calculated minima. Monitoring results from four hospitals confirm that emissions meet GB 18871 requirements when storage times reach RJ-calculated minima.

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Author Contributions

Zhang Qi was primarily responsible for manuscript writing and theoretical formula derivation; Ge Yunwen was primarily responsible for programming, numerical calculations, and investigation of daily water usage in hospital nuclear medicine departments.

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