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Artificial Radioactive Aerosol Continuous Monitor with Low False Alarm Rate Based on DS Evidence Theory

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Abstract

False alarm rate of artificial radioactive aerosol continuous monitor is inevitable. When the standard deviation of artificial radioactive aerosol concentration is determined, the minimum detection limit and false alarm rate are a pair of contradictory relations. This paper proposes the concept of alarm measure, transforms the results obtained by several deduction algorithms into alarm measure, and then uses DS evidence theory to fuse several alarm measures. The fused results are used as the basis for whether to alarm. This method can greatly reduce the false alarm rate while keeping the minimum detection limit unchanged. The experiment proves the effectiveness of this method.

Subject Areas

Industrial Engineering

Keywords

DS Evidence Theory, False Alarm Rate, Aerosol, Alarm Measurement, Detection Limit

1. Introduction

In the production of various nuclear materials, decommissioning of nuclear facilities and storage and treatment of radioactive waste, long-lived radioactive materials may be dispersed in the air to form artificial radioactive aerosols. Radioactive aerosols cause internal radiation damage [1] to the human body mainly through inhalation. A common monitoring method for nuclear radioactivity in the environment is the continuous monitoring of radioactive aerosol in the field with the continuous monitoring [2] [3] [4] [5] instrument. False alarm is the alarm given by the monitoring system when the concentration of artificial radioactive aerosol in the detection site does not reach the minimum detection limit. Due to the statistical fluctuation of aerosol radioactivity itself, false alarms cannot be completely avoided in nuclear monitoring events. The quality of a nuclear monitoring system does not lie in whether there is false alarm, but in the probability of [6] false alarm. When the standard deviation of the concentration of artificial radioactive aerosol is determined, the minimum detection limit and false alarm rate are a pair of contradictory relations. At present, although many artificial radioactive aerosol continuous monitors have a low detection limit, the false alarm rate is high, which brings great inconvenience to on-site monitoring. How to ensure a low detection limit and reduce the false alarm rate is a topic worth studying. This paper puts forward the concept of alarm measure for the first time. The alarm measure obtained by integrating multiple radon daughter deduction algorithms with DS evidence theory, as the final detection result, can ensure the low detection limit and greatly reduce the false alarm rate at the same time.

Minimum Detection Limit and False Alarm Rate

The artificial radioactive aerosol online monitor measures the aerosol collected on the filter paper, and then analyzes the measurement results to determine whether there is artificial radioactive aerosol in the air. In the collected aerosols, due to the existence of a large number of natural radon and thorium daughter aerosols, their α particle energy low-energy trailing will enter the artificial radionuclide α particle energy region, which will interfere with the accurate measurement of artificial radionuclide α particle concentration. Therefore, the influence of radon and thorium daughter trailing must be deducted. After the net count N_0 of α particles produced by artificial aerosols is obtained by using the radon daughter subtraction algorithm, the concentration of artificial radionuclide aerosol can be calculated according to the following formula:

$$C = \frac{N_0}{\varepsilon Q T_2 T_1} \tag{1}$$

Here, C represents the concentration value of artificial *alpha* radioactive aerosol during the sampling period, in unit Bq/m^3, and N_0 represents the net count generated by artificial nuclide, that is, the total number of artificial nuclide energy regions after deducing the radon daughter interference count. ε represents the detection efficiency of the detector, unit: 1/sBq; Q represents the sampling flow rate, in m^3/s; T_1 indicates sampling duration, in unit: s; T_2 represents the measurement duration, in s.

Let the standard deviation of N_0 be σ_0, then the standard deviation of the artificial aerosol concentration C, σ_C is:

$$\sigma_C = \frac{\sigma_0}{\varepsilon Q T_1 T_2} \tag{2}$$

The minimum detection limit of the artificial radioactive aerosol online monitor is

$$L_C = K_\alpha \sigma_C \tag{3}$$

Here, k_α *represents* the expansion coefficient, setting a higher value of k_α can reduce the false alarm rate, but will increase the judgment limit [1]. According to the normal distribution law, if the expansion coefficient $k_\alpha = 1.645$, the false alarm rate is 5%; If the expansion coefficient $k_\alpha = 3.0$, the corresponding false alarm rate is 0.1%, the relationship between the expansion coefficient and the false alarm rate can be queried from the normal distribution table, and the false alarm rate obtained from the table is the theoretical value of the false alarm rate.

The actual value of the instrument's false alarm rate can be calculated by [6] the following formula:

$$\upsilon_{\text{false}} = \left(N_{\text{alarm}} / N_{\text{all}}\right) \times 100\% \tag{4}$$

where N_{alarm} is the number of false alarms monitored and N_{all} is the total number of monitoring.

In practical application, under the condition that the standard deviation σ of concentration C is certain, how to further reduce the false alarm rate is a concern of people. If the alarm is given after 2 to 3 times exceeding the limit, although this method can reduce the false alarm rate, it will cause a long insufficient alarm time, especially in some sudden emergencies, which will delay the handling of the accident. Secondly, at present, the radon thorium subtracting algorithm of the artificial radioactive aerosol continuous monitor basically adopts a single algorithm, and judges according to the results obtained by the algorithm, which is also a reason for the high false alarm rate. In this paper, DS evidence theory is adopted and a variety of radon thorium daughter subtraction algorithms are integrated, which can greatly reduce the low false alarm rate while keeping the minimum detection limit unchanged, and the alarm time is not extended.

2. Introduction of Radon Thorium Daughter Subtraction Algorithm

At present, the main deduction algorithms for radon thorium daughter bodies are: α/β ratio method; Pseudo-β coincidence method, the proportional coefficient deduction method of fixed energy region and energy spectrum fitting stripping method [7] [8] [9]. At present, the energy spectrum fitting stripping method is mainly used in the air chamber measurement, and the fixed energy region proportional coefficient deduction method is mainly used in the vacuum chamber measurement. In order to further reduce the detection limit, the vacuum chamber is used to measure more. The ratio coefficient deduction method of fixed energy zone is mainly divided into two energy zone methods and multiple energy zone methods. The multi-energy zone method has a better deduction effect than the two-energy zone method, so it is widely used.

The multi-energy region method divides the aerosol measurement spectrum line into two energy regions: artificial energy region and radon daughter energy region. For example, 3.0 - 5.57 MeV can be set as artificial energy region, and 5.58 - 10 MeV can be set as radon daughter energy region, and then radon daughter energy region can be divided into several sub-regions according to the difference in the interference degree of α particles of radon daughter with different energies. Energy scale formula is used to convert the energy region into the trace number range.

The count of particles falling into the artificial energy zone α is set as N_1, and the count of particles falling into the radon daughter energy zone α is set as $N_2, N_3, \cdots, N_m$, then the count of α particles of artificial radioactive aerosol is

$$N_0 = N_1 - K_{12} \times N_2 - \cdots - K_{1m} \times N_m \tag{5}$$

where $K_{12}, K_{13}, \cdots, K_{1m}$ is the ratio of the count of each subregion falling into the artificial energy region to the count of that subregion. These ratios should be determined when there is no artificial nuclide and can be determined by the least square method or other methods.

Different subdivision methods for the energy region of radon daughter bodies will form different algorithms. In this paper, the following three subdivision methods are adopted to form three different subdivision algorithms.

The first partitioning method is the universal peak partitioning method, that is, the 5.58 - 10 MeV radon daughter energy region is divided into three regions, of which the energy range of the second zone is 5.58 - 6.14 MeV, the third zone is 6.14 - 7.83 MeV, and the fourth zone is 7.83 - 10 MeV. In this way, each region contains the main energy peak and tail of the region, and the zoning diagram is shown in Figure 1.

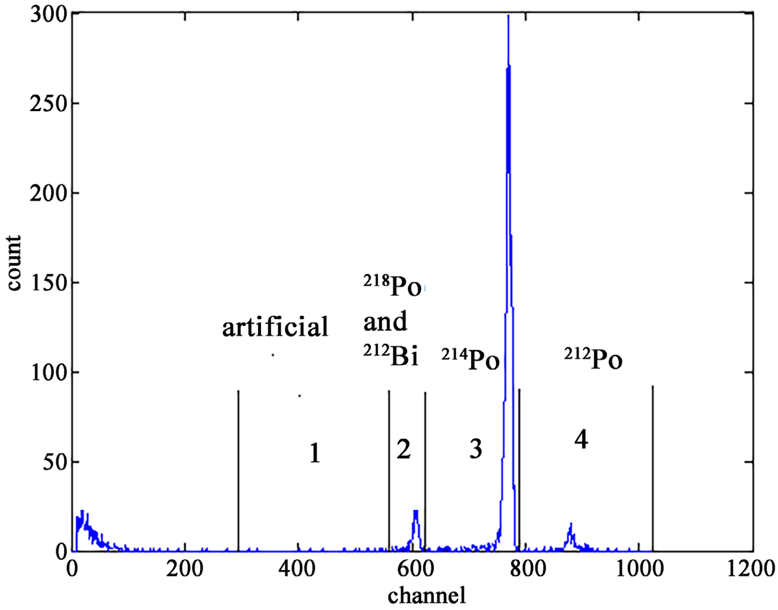

Figure 1. Schematic diagram of the universal partition method.

The second partitioning method is the principal energy peak partitioning method, that is, the 5.58 - 10 MeV radon daughter energy region is also divided into three regions, but each region only contains the principal energy peak, the energy range of the second region is 5.80 - 6.14 MeV, the energy range of the third region is 7.49 - 7.83 MeV, and the energy range of the fourth region is 8.55 - 9.20 MeV.

The third partitioning method is based on the partitioning method given in reference 1. Due to the large difference between the energy of radon and that of artificial radioactive particles, the influence of the peak on the artificial energy region can be ignored. Therefore, the 5.58 - 10 MeV daughter energy region is divided into two regions according to the principle of principal energy peak, and the energy range of zone 2 is 5.80 - 6.14 MeV. The energy range of zone 3 is 7.49 - 7.83 MeV.

The first zone of the above three partitioning methods is the artificial energy range of 3.0 - 5.57 MeV. Because these three partitioning methods seem to be very close, when the sampling and testing time is short, because the statistical fluctuations of aerosol particles emitted by the three methods are obvious, the results obtained by these three methods are not exactly the same.

3. Alarm Fusion Based on DS Evidence Theory

3.1. Basic Principles of DS Evidence Theory

The evidence theory, also known as the trust function theory, was proposed by Dempster and then improved by Shafer, so it is also known as Dempster-Shafer theory, or DS theory for short. The core of the evidence theory is Dempster's evidence synthesis rule. The evidence theory can effectively choose the most supported scheme according to the tendency of different strategies expressed by various information sources, and has the ability to directly express "uncertainty" and "don't know".

Definition 1: Let Θ be the recognition frame, and the power set of Θ forms the set of propositions if the function satisfies: $m:2^{\Theta}\rightarrow[0,1]$

$$m(\Phi)=0; \tag{6}$$

$$\sum_{A\subseteq\Theta} m(A)=1 \tag{7}$$

Then m is called the basic probability assignment function on Θ or the mass function. $\forall A\subseteq\Theta$ $m(A)$ is called the fundamental confidence of A.

Definition 2: Let Θ be the identification frame, function, and call the function the reliability function on Θ if it satisfies $m:2^{\Theta}\rightarrow[0,1]$ $Bel:2^{\Theta}\rightarrow[0,1]$

$$Bel(A)=\sum_{B\subset A} m(B)\quad(\forall A\subset\Theta) \tag{8}$$

$Bel(A)$ represents the total confidence in A. By definition, $Bel(\Phi)=0$ $Bel(\Theta)=1$

Definition 3: Let Bel_{21}, Bel is the reliability function on the same identification frame Θ, m_1, m_2 is its corresponding basic confidence assignment, and the corresponding focal elements are $A_1, A_2, \ldots, A_m, B_1, B_2, \ldots, B_N$ $\sum_{A_i \cap B_j} m_1(A_i) m_2(B_j) < 1$

Then, the fundamental reliability distribution rule synthesized from the basic reliability functions of two different evidences is:

$$m(A) = \begin{cases} 0 & X \cap Y = \Phi \\ \dfrac{\sum\limits_{\substack{X \cap Y = A \\ \forall X, Y \subseteq U}} m_i(X) \cdot m_j(Y)}{1 - \sum\limits_{\substack{X \cap Y = \Phi \\ \forall X, Y \subseteq U}} m_i(X) \cdot m_j(Y)} & X \cap Y \neq \Phi \end{cases} \tag{9}$$

The calculation of the combination of multiple evidences can be obtained by recursion of the calculation of the combination of two evidences.

The problem of synthesis paradox may occur when DS rules synthesize conflicting evidence. At present, a large number of improved algorithms have emerged, and this paper adopts the improved algorithm in literature [10] for synthesis.

3.2. Alarm Measure

At present, the alarm output adopts simple criteria for alarm, which is not conducive to the comprehensive use of various criteria. Therefore, this paper puts forward the concept of alarm measurement. For each criterion, the result of alarm or no alarm is not simply given, but the degree of alarm symptom is quantitatively measured according to the value of each criterion, and then a comprehensive decision is made by the fusion decision link to give the alarm result. The alarm measure is a real variable defined on (0, 1), and the suspected measure under a criterion is the obvious degree of alarm characteristics. The larger the alarm measure, the more likely it is that the artificial radioactivity concentration is over limit under the criterion.

According to the above definition, this paper gives the calculation formula of alarm measure in the form of sigmoid function. Set the alarm threshold as S and the actual measured artificial aerosol concentration as x, then the alarm measure is as follows:

$$A = \frac{1}{1 + \mathrm{e}^{\frac{x - 0.5S}{0.05S}}} \tag{10}$$

The alarm measure curve is a gradual curve from 0 to 1. When the artificial aerosol concentration is zero, the alarm threshold is close to zero; when the concentration is greater than or equal to the alarm threshold, the alarm measure is close to 1, which better describes the relationship between concentration and alarm.

3.3. Fusion of Alarm Measure Based on DS Evidence Theory

In the artificial radioactivity continuous monitor, alarm and non-alarm constitute the identification framework, and the criterion obtained by each deduction algorithm is taken as an evidence body. For the artificial radioactivity aerosol concentration obtained by each deduction algorithm, its alarm measure is calculated to obtain the basic probability assigned function of the target, and then the improved evidence theory is used for fusion. Finally, decisions are made according to the fusion results. The fusion process is shown in Figure 2.

4. Experimental Verification

In order to verify the algorithm, an artificial radioactive aerosol continuous monitor was used to measure radon concentrations in different environments. The radioactive aerosol continuous monitor adopted PIPS detector, sampling pump flow rate of 5 m^3/h, polytetrafluoroethylene filter paper with 0.8 micron aperture, measuring energy range of 0 - 10 MeV, and tested in vacuum environment. An aerosol measurement spectral line is formed every hour, and a total of 800 spectral line data are measured for verification. In the calculation of false alarm rate, the expansion coefficient $k_\alpha = 1.645$, the theoretical false alarm rate is 5%, and the three minimum detection limits are 0.0476 Bq/m^3, 0.0481 Bq/m^3, 0.0472 Bq/m^3, respectively. Table 1 shows the actual false alarm rate directly

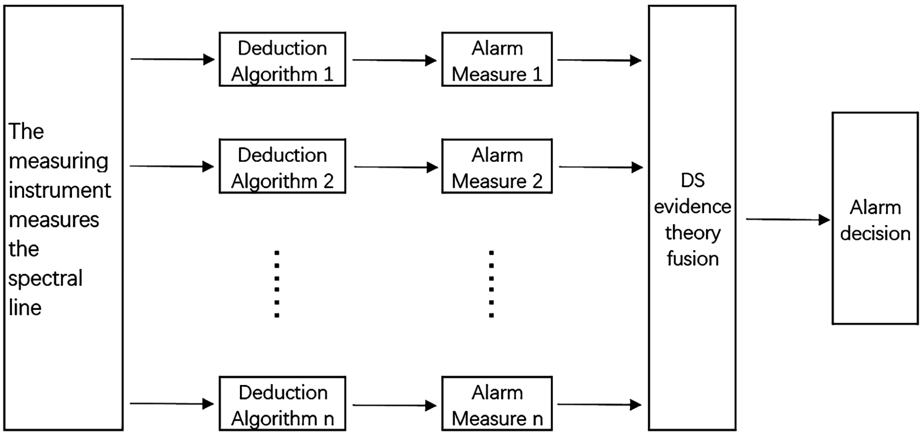

Figure 2. Schematic diagram of DS evidence theory fusion process.

Table 1. Comparison of false alarm rates of the four methods.

Number of Groups	The first partitioning method false alarm rate	The second partition method false alarm rate	The third partition method false alarm rate	DS evidence theory fuses false alarm rate
1	4.87%	5.04%	5.03%	1.80%
2	4.93%	4.98%	5.04%	1.67%
3	5.12%	4.89%	4.97%	1.76%
4	4.96%	5.18%	5.12%	1.83%
5	4.85%	4.94%	4.97%	1.64%
6	5.03%	4.82%	4.87%	1.74%
7	5.09%	5.02%	5.00%	1.77%
8	4.83%	5.03%	5.05%	1.85%

judged by the three deduction algorithms and the false alarm rate obtained by DS fusion. Each group in the table has 100 test data.

As can be seen from Table 1, after adopting the algorithm in this paper, the false alarm rate is greatly reduced while keeping the minimum detection limit unchanged.

5. Conclusion

The minimum detection limit and false alarm rate are both important indicators to measure the performance of the artificial radioactive aerosol online monitor, and they are a pair of contradictory relations. This paper proposes the concept of alarm measure, transforms the artificial aerosol concentration obtained by several radon thorium subdivision algorithms into alarm measure, and then uses DS evidence theory to fuse the fusion results as the basis for alarm. Through a large number of measured data, it is verified that this method can greatly reduce the false alarm rate while maintaining the minimum detection limit.

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Conflicts of Interest

The authors declare no conflicts of interest.

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