Evaluation of radiation safety for ionization chamber smoke detectors containing Am-241

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Abstract. The safety assessment was carried out for ionization chamber smoke detectors (ICSDs) containing $^{241}\text{Am}$ under normal use and accident scenarios. The internal and external doses were estimated using dose coefficients and associated calculations. In normal use of the ICSDs with the activity in a range of 0.002–1 MBq per ICSD, the external doses to an individual for installation, use and maintenance were found to lie in the range of $(0.01-4.17)\times10^{-3}$ $(0.017-6.76)\times10^{-1}$ and $(0.006-2.5)\times10^{-2} \mu\text{Sv/y}$ respectively. The activity of $^{241}\text{Am}$ for domestic smoke detectors contains approximately 40 kBq per ICSD. The corresponding committed effective doses to a fire fighter during a fire and for cleanup operation after a fire via inhalation were found to be $6.1\times10^{-5}$ and $0.024 \mu\text{Sv/y}$ respectively. The committed effective dose equivalent to an infant via ingestion would be 148 $\mu\text{Sv/y}$. The doses arising from normal use and incidents of ICSDs are less than 10 $\mu\text{Sv/y}$ and 1 mSv/y respectively which do not exceed the dose criteria for exemption from regulatory control. It could be concluded that the resultant radiological risk are estimated to be very low and lower than 1 mSv which is the annual dose limit to a member of the public for the safe use.

1. Introduction

The ionization chamber smoke detectors (ICSDs) have been used widely in industries, office buildings, hotels and homes. Since the use of $^{241}\text{Am}$ in the ICSDs is justified, the main benefit of the ICSDs is that the potential saving of lives significantly outweighs the radiation risk involved in their use [1]. In Thailand, the possession or use of radioactive materials in the ICSDs needs to apply for a license regarding to the Atomic Energy for Peace Act B.E. 2504 (1961). At present, the Thai Nuclear Energy for Peace Act B.E. 2559 (2016) has been applied and the use of radioactive materials in the ICSDs could be exempted depending on the activity concentration or total activity of an individual radionuclide or requested for notification regarding to the ratio of radioactivity and dangerous value (A/D). However, in case of both activity concentration and total activity exceeding the exemption level, the dose criteria of 10 $\mu\text{Sv/y}$ and 1 mSv/y in normal and accident situations respectively are suggested to be applied for exemption the use of radioactive materials in the ICSDs from regulatory control. The evaluation of radiation safety of the ICSDs is also necessary for manufacturers, exporters, importers, dealers and members of the public who involved in normal use and accident scenarios to ensure the safety use. In addition, the radiation safety assessment from this study could be used as the reference data to fulfill the requirements of the new updated national regulations.
2. Methodology

The external radiation hazard from $^{241}\text{Am}$ is primary due to the presence of the 59 keV gamma ray emitted in 36 percent of all disintegrations (See Figure 1).

\[ \text{Dext} = \frac{RAk}{d^2} \]  

Figure 1. Radioactive decay scheme of $^{241}\text{Am}$ [2].

In the current work, the exposure rate and estimated dosed arising from normal use of ICSDs i.e. installation, use and maintenance limited to those due to external exposure to gamma radiation were calculated by using the following equations [3]:

\[ R = K \Omega E \left( \frac{\mu_{em}}{\rho} \right) \]  

where

- $R$ is the exposure rate (R/hr)
- $K$ is the correction factor for unit conversions from ergs to MeV, seconds to hours, and ergs per gram to roentgens ($6.58 \times 10^{-5} \text{ R-s-g/MeV-hr}$)
- $E$ is the gamma-ray energy (MeV/\(\gamma\))
- $\mu_{em}/\rho$ is the mass-energy attenuation coefficient in air (cm\(^2\)/g)
- $\Omega$ is the photon flux (\(\gamma\) /cm\(^2\)/s)

The radiological assessment assumes the following:
- The ICSD containing an $^{241}\text{Am}$ point source with the activity in the range of 0.07-28 $\mu$Ci (0.002–1 MBq) per ICSD
- For installation, an average installation time takes one-half hour with the body to source distance is 50 cm.
- For normal use, the ICSD is installed in a bedroom, exposing the individual for 8 hours each day and the body to source distance is 3 m.
For maintenance, the ICSD must be periodically checked for proper operation, cleaning and having the batteries replacement, exposing the individual for 3 hours per year at the distance of 50 cm.

The possible internal exposure arises from alpha emission during accident scenarios i.e. fires, and misusage. Using the associated dose commitment conversion factors for ingestion and inhalation, the 50-year dose commitments to firefighters involved in the extinguishment and cleanup operation were assessed according to the following equation:

\[ E = \frac{ABR_f k t}{a} \tag{3} \]

where 
- \( E \) is the committed effective dose (Sv/hr)
- \( A \) is the source activity inhaled by an individual (Bq)
- \( B \) is the breathing rate of an individual (m³ s⁻¹)
- \( R_f \) is the resuspension factor (m⁻¹)
- \( k \) is the committed effective dose equivalent per unit intake (Sv Bq⁻¹)
- \( t \) is the exposure time (hour)
- \( a \) is the residential area (m²)

The internal exposure bases on the following assumptions [4]:
- The ICSD containing 40 kBq of ²⁴¹Am will release not more than 200 Bq during an accident
- The ICSD is protecting an area of 30 m²
- During a fire, 10⁻³ of the airborne activity is inhaled by a firefighter
- After a fire, the activity of ²⁴¹Am is mixed with the rubble and dust, and 1% of the activity is resuspendable and respirable
- The firefighter attends 20 fires involving ICSD each year
- The extinguishment takes 1 hour
- The clean-up takes 8 hours
- The breathing rate of an adult is \( 3.33 \times 10^{-4} \) m³ s⁻¹
- The resuspension factor is \( 2 \times 10^{-6} \) m⁻¹
- The committed effective dose equivalent per unit intake to an adult via inhalation is \( 9.6 \times 10^{-5} \) Sv Bq⁻¹

The most significant possible misuse is dismantling of the ICSDs by a member of public. An estimate of the possible dose from accidentally swallowed by an infant who manage to break open the chamber and damage the source was made using the following assumptions:
- The ICSD containing 40 kBq of ²⁴¹Am
- 1% of the source activity is release owing to damage
- 10% of this activity is transferred to the fingers and ingested
- The committed effective dose equivalent per unit intake to a three month old infant via ingestion is \( 3.7 \times 10^{-6} \) Sv/Bq

In this study, some assumptions have been modified comparing to the previous study documented by NUREG/CR-1156 to ensure that the resultant doses were derived under the circumstances with closer to real situations, for example, the ²¹⁴Am activity, the exposure time, the distance between body and source, the numbers of the ICSD installed in the house, the size of the protecting area, etc. The authors of the journal article also assumed two foils being accidentally swallowed by a woman working with the sources but in this study, ingestion of one source by a three month old infant is more concerned since an infant could manage to break open the chamber and damage the source and leading to significant radiation health effects to an infant.

3. Results and discussions

Base on equations and assumptions mentioned above, the resultant effective dose equivalent rates for installation, use and maintenance to an individual per ICSD containing 0.07-28 µCi (0.002-1 MBq) of
and 241\textsuperscript{Am} by using unit conversion from roentgen to sievert would be lie in the range of (0.01-4.17)×10\textsuperscript{-3} (0.01-6.76)×10\textsuperscript{-1} and (0.006-2.5)×10\textsuperscript{-2} \(\mu\text{Sv/yr}\) respectively (See Table 1).

**Table 1.** Effective dose equivalent rates for installation, use and maintenance to an individual.

| Activity\(^a\) (\(\mu\text{Ci}\)) | Effective dose equivalent rate (\(\mu\text{Sv/yr}\)) |
|----------------------------------|-----------------------------------------------|
|                                  | installation | use      | maintenance |
| 0.07                             | 1.04E-05     | 1.69E-03 | 6.25E-05    |
| 0.1                              | 1.49E-05     | 2.41E-03 | 8.93E-05    |
| 0.4                              | 5.95E-05     | 9.66E-03 | 3.57E-04    |
| 0.5                              | 7.44E-05     | 1.21E-02 | 4.46E-04    |
| 0.7                              | 1.04E-04     | 1.69E-02 | 6.25E-04    |
| 0.8                              | 1.19E-04     | 1.93E-02 | 7.14E-04    |
| 0.9                              | 1.34E-04     | 2.17E-02 | 8.04E-04    |
| 1                                | 1.49E-04     | 2.41E-02 | 8.93E-04    |
| 1.6                              | 2.38E-04     | 3.86E-02 | 1.43E-03    |
| 4.6                              | 6.84E-04     | 1.11E-01 | 4.11E-03    |
| 5                                | 7.44E-04     | 1.21E-01 | 4.46E-03    |
| 28                               | 4.17E-03     | 6.76E-01 | 2.50E-02    |

\(^a\) activity per each ICSD.

The maximum annual committed effective doses from inhalation to a firefighter as result of firefighting and cleanup operation were 6.1×10\textsuperscript{5} \(\mu\text{Sv/yr}\) during a fire and 0.024 \(\mu\text{Sv/yr}\) after a fire. It should be noted that credit must be taken for the degree of protection afforded the involved persons by ventilation or the use of respiratory protection. The protection features could significantly reduce the amount of 241\textsuperscript{Am} inhaled by the firefighters during a firefighting operation comparing to those who enter the involved buildings for cleanup operations without the use of respiratory protection. The careless and unsuspecting manner of salvage and cleanup operations following a fire may cause major internal deposition. The committed effective dose equivalent to an infant via ingestion arising from anticipated misusage would be 148 \(\mu\text{Sv/yr}\). The estimated dose obtained in this study was found to be lower than the dose criteria for exemption of 10 \(\mu\text{Sv/yr}\) and 1 mSv/yr in normal and accident situations respectively as reported by IAEA Safety Standards Series No. GSR Part 3 (2014) [5]. It can be concluded that the individual radiological risk resulting from the normal use, incident, and misuse of the ICSDs are estimated to be very low and lower than 1 mSv which is the annual dose limit to a member of the public for the safe use.

According to the Thai Nuclear Energy for Peace Act B.E. 2559 (2016), the exemption levels for 241\textsuperscript{Am} activity concentration and total activity are 10 Bq/g and 10\textsuperscript{4} Bq respectively. If both of 241\textsuperscript{Am} activity concentration and total activity contained in the ICSDs exceeding the exemption level, the radiation dose assessment from this study could be suggested to use for further consideration owing to exemption the use of radioactive materials in the ICSDs from regulatory control.

**4. Conclusions**

In summary, the estimated doses arising from external and internal exposure with the 241\textsuperscript{Am} sealed source contained in the ICSD do not exceed the criteria for exemption from regulatory control both for the normal use and accident scenarios reported by IAEA standards. It can be concluded that the individual radiological risk assessments resulting from the normal use, incidents and misuse of the ICSDs are estimated to be very low and lower than 1 mSv which is the annual dose limit to a member of the public for the safe use. A high-efficiency respiratory protection or well ventilation leading to the
significant reduction in the amount of $^{241}\text{Am}$ inhaled. However, the ICSDs need to conform to the relevant requirements of ISO standard relating the ICSD design and construction stage to ensure that the activity removed from the source is less than 200 Bq for the effects of fire.

References
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