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Peura, Pauli

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Thin NaI(Tl) crystals to enhance the detection sensitivity for molten ^{241}Am sources

Pauli Peura^{a,1}, Camille Bélanger-Champagne^a, Paula Eerola^{a,b}, Peter Dendooven^a

^a Helsinki Institute of Physics, P.O.B. 64, FI-00014 University of Helsinki, Finland

^b Department of Physics, P.O.B. 64, FI-00014 University of Helsinki, Finland

Eero Huhtalo^c

^c Outokumpu Tornio Works, FI-95490 Tornio, Finland

Abstract

A thin 5-mm NaI(Tl) scintillator detector was tested with the goal of enhancing the detection efficiency of ^{241}Am gamma and X rays for steelworks operations. The performance of a thin (5 mm) NaI(Tl) detector was compared with a standard 76.2-mm thick NaI(Tl) detector. The 5-mm thick detector crystal results in a 55 % smaller background rate at 60 keV compared with the thicker detector, translating into the ability to detect 30 % weaker ^{241}Am sources. For a 5 mm thick and 76.2 mm diameter NaI detector in the ladle car tunnel at Outokumpu Tornio Works, the minimum activity of a molten ^{241}Am source that can be detected in 5 seconds with 95% probability is 9 MBq.

1. Introduction

Recycled metal is widely used for steelworks worldwide. Between 2011 and 2015, about 36 % of all the crude steel produced was made from scrap metal . Unfortunately, scrap metal loads sometimes contain undeclared radioactive sources. Such radioactive sources are outside regulatory control, i.e. orphan sources . In the U.S. alone, hundreds of radioactive sources were found among scrap metal since 1983. Accidental melting of orphan radioactive sources is a major problem for steelworks and foundries. Melting accidents pose a health risk for the workers, and they result in costly production interruptions accompanied by high cleaning costs. Between 1983 and 1998, 49 instances of accidental melting of radioactive sources were reported worldwide . Hence there is a need to improve the performance of the radiation detection systems at steelworks and foundries.

¹ Corresponding author. Email address: pauli.j.peura@gmail.com

While the scrap-metal industry currently employs a wide variety of radiation detectors to detect sources, incidents still occur. Three of the most commonly detected isotopes are ^{137}Cs (48 %), ^{60}Co (26 %) and ^{241}Am (5–6 %). Plastic and inorganic scintillators, e.g. EJ200, NaI(Tl) and CsI(Tl) are commonly used by factory operators. These detectors are often large in volume, as they need to have a high detection efficiency for gamma rays up to 1–2 MeV.

Radioactive sources that emit no or only low-energy gamma rays are a challenge for the radiation detection at steelworks. One such example is ^{241}Am , which is used in e.g. moisture gauges. One possible, though unlikely, source of ^{241}Am is also special nuclear materials, as ^{241}Am is in the decay chain of ^{241}Pu . The alpha decay of ^{241}Am leads often to the emission of a 60-keV gamma ray, as well as lower energy gamma and X ray emissions listed in Table 1. The half-thickness for 60-keV gamma rays in iron is 0.7 mm, making the detection of these gamma rays difficult. In addition, orphan sources still inside their original shielding will not be detected by radiation monitors before the melting process. At Outokumpu Tornio Works, between 2006 and 2014, the accidental melting of an ^{241}Am source occurred about once-a-year. When an ^{241}Am source is melted at a furnace containing molten steel and slag, americium binds completely to the slag. When the melted metal is poured from the furnace into a ladle car, part of the slag from the oven also gets into the ladle car. The slag floats on top of the molten metal and thus the gamma radiation originating from the slag can be detected by a radiation detector above the ladle car. At Outokumpu, all the process lines after the electric arc furnaces have radiation monitors installed.

Table 1. The gamma-ray energies and intensities and the X ray data for the ^{241}Am alpha decay.

	Energy, keV	Intensity, %
Gamma rays	26	2.3
	60	36
X rays	L_{α} , 13.8–14.0	13
	L_{β} , 16.2–18.7	19
	L_{γ} , 20.1–22.4	5

In this work, an effort is made to enhance the detection of ^{241}Am gamma rays. At Outokumpu Tornio Works, an Exploranium AT-140 detector containing a NaI(Tl) crystal of commonly used size (76.2 mm diameter, 76.2 mm thick) is presently used (Huhtalo, 2016). This thickness ensures a close to 100 % intrinsic efficiency for detecting the full energy of gamma rays of 60 keV and lower. Improving the lower limit of detectable ^{241}Am activity can thus not be achieved by increasing the detector intrinsic efficiency. It can however be improved by increasing the geometric efficiency or by decreasing the background in the relevant low-energy part of the gamma ray spectrum. Increasing the geometric efficiency is achieved by placing the detector closer to the ladle car as well as by increasing the surface area of the detector system using multiple detectors and/or detectors with a larger surface area. The gamma ray background spectrum, in a given location, depends on both the diameter and thickness of the detector. In this work, we investigate the gamma ray background around 60 keV for a NaI detector much thinner than the presently used 76.2 mm. A thickness of 5 mm is chosen in order

to maintain a close to 100 % intrinsic efficiency for 60 keV gamma rays. The 76. mm diameter is maintained in order not to lower the geometric efficiency. We thus compare the performance of a 5-mm thick NaI(Tl) detector for detecting the gamma and X rays originating from a ^{241}Am source with that of a 76.2-mm thick NaI(Tl) detector. The sensitivity of these two detection systems is specified according to the critical and detection limits, L_C and L_D , which are calculated following the method of Currie; see also .

2. Experimental methods

At Outokumpu Tornio Works, a ladle car carrying 100 tons of molten metal from the Electric Arc Furnace (EAF) is 3 meters in diameter and moves at a speed of 0.5 m/s past a 76.2-mm diameter and 76.2 mm thick NaI(Tl) radiation detector. The thickness of the slag layer varies between 0.05 and 0.50 m. The distance between the detector and the FeCr slag is about 1 meter, varying according to molten metal and slag volumes present in the ladle car. A simplified schematic of the measurement set up at Outokumpu Tornio Works is shown in Figure 1.

Figure 1. A schematic drawing of the measurement set up at Outokumpu Tornio Works (not to scale).

Performing the comparison between a thick and thin detector at the ladle car tunnel at Outokumpu Tornio Works was not possible as it would represent a too big impact on factory operations. The measurements were therefore performed at the Accelerator Laboratory of the University of Helsinki. As the effect of gamma ray background is the focus of this work, the comparison with a background measurement at Outokumpu Tornio Works is used to establish the relevance of the measurements in Helsinki for the situation at Outokumpu Tornio Works.

Two NaI(Tl) scintillator detectors from Scionix Holland B.V.² were used for the detection of gamma and X rays. Both NaI(Tl) crystals are 76.2-mm in diameter. The thinner crystal has a thickness of 5 mm and the thicker crystal has a thickness of 76.2 mm. The entrance window of each detector is a 0.3-mm thick

² Scionix Holland B.V., P.O. Box 143, 3980 CC Bunnik, The Netherlands

beryllium film and they both are connected to an ETL 9305 type 76.2-mm diameter photomultiplier tube (PMT). A 5.55 kBq ^{241}Am point source was used in the measurements. The source was placed perpendicular to the middle of the detector crystal. A schematic drawing of the measurement setup at the Accelerator Laboratory of the University of Helsinki is shown in Figure 2.

Figure 2. Schematic drawing of the measurement setup at the Accelerator Laboratory of the University of Helsinki. The NaI crystal dimensions are to scale. The location of the fireproof fabric during the attenuation measurements is indicated.

At first, an estimate for the critical limit, L_C , needs to be established. For a chosen false positive probability α , L_C is the number of counts needed for a positive observation of a signal above background. The detection limit, L_D , is the minimum number of counts that need to be observed when a source is present, so that the probability of a false-negative result is β . For radioactivity counting applications, L_C is given by :

$$L_C = k_\alpha \sigma_0 = k_\alpha (\mu_B + \sigma_B^2)^{\frac{1}{2}}, \#(1)$$

where k_α is the abscissa of the standardized normal distribution that corresponds to the probability of $1 - \alpha$, and σ_0 is the standard deviation of the observed counts originating only from the background (no source present). The mean value of the background counts is denoted by μ_B and $\sigma_B^2 = \mu_B/n$ is the variance of the n observations of the background radiation in the case of Poisson statistics. If the background can be assumed to be accurately known, then $\sigma_B^2 = 0$ is assumed, as the number of observations, n , is large.

The detection limit is given by:

$$L_D = L_C + k_\beta \sigma_D, \#(2)$$

where σ_D is the standard deviation of the total number of counts when a source is present. When $k_\alpha = k_\beta = k$, a simple expression:

$$L_D = k^2 + 2L_C, \#(3)$$

is obtained. In this work, the false positive and false negative probabilities were taken to be reasonably low at $\alpha = \beta = 0.05$, which results in $k = 1.65$. In this way, a measured value above the calculated L_C limit results 95 % of the time in a positive detection of a source.

The minimum detectable activities (MDAs) can be estimated from the L_C and L_D values for each measurement geometry. The MDA is calculated in this work as:

$$MDA = \frac{N}{\varepsilon_g \times \varepsilon_i \times b_\gamma}, \#(4)$$

where N is the number of counts observed, ε_g and ε_i are the geometric and intrinsic efficiencies of the detection system, respectively, and b_γ is the gamma-ray branching ratio for the decaying nucleus. The MDA depends on the gamma ray energy through the energy-dependent intrinsic efficiency.

The current NaI(Tl) detector system at Outokumpu Tornio Works is shielded from the heat that originates from the metal in the ladle car using three layers of 1.0 mm-thick heat resistant silica fabric. The fabric layers in front of the detector are held in place by a diamond-shaped mesh made of 3-mm thick metal wire. The attenuation of low-energy electromagnetic radiation by the heat-shielding fabric used at Outokumpu was also measured in this work. Such pieces of fabric were placed approximately 50 mm in front of the detector crystal.

3. Results

At 60 keV gamma-ray energy, the measured energy resolutions were 11.3 ± 0.2 % and 11.7 ± 0.2 % for the thin and thick detectors, respectively (the corresponding values at 662 keV are 7.09 ± 0.01 % and 7.43 ± 0.05 %).

The attenuation of the 60-keV gamma rays and the ^{237}Np X rays was measured using 0, 1, 3 and 5 layers of 1.0 mm-thick fireproof fabric. The ^{241}Am source was positioned 100 mm from the thin detector's beryllium window during the measurements. Each of these measurements lasted 300 seconds. The measured energy spectra are shown in Figure 3. Two regions of interest (ROI) were defined, covering the energy regions 9–37 keV and 45–68 keV for the X rays and gamma rays, respectively. The background level at the ROIs was obtained from a 300-second measurement without the ^{241}Am source. The attenuation is calculated relative to the net counts in the given ROI when the source is present, but no fireproof fabric is placed between the source and the detector. The results are shown in Table 2. The attenuation of the 60 keV peak by 5.0 mm of fireproof fabric is 10 ± 2 %. The attenuation is much stronger in the X ray ROI, where the attenuation by 5.0 mm of fabric is 84.1 ± 0.4 %.

Figure 3. The gamma and X ray energy spectra of a ^{241}Am source measured using the thick NaI(Tl) detector various layers of fireproof fabric between the source and the detector.

Table 2. Total counts within the region of interest (ROI) around the ^{241}Am 60 keV gamma-ray peak and the ^{237}Np X-ray region within the 300-second measurement time.

	Fabric thickness, mm	Total counts within ROI, 60 keV	Total counts within ROI, X rays	Attenuation at 60-keV region, %	Attenuation at X-ray region, %
Background	0	3169	1260	-	-
^{241}Am	0	16941	18392	-	-
^{241}Am	1.0	16396	11202	4.0 ± 1.4	42.0 ± 0.8
^{241}Am	3.0	16082	5768	6.2 ± 1.4	73.7 ± 0.5
^{241}Am	5.0	15597	3988	9.8 ± 1.4	84.1 ± 0.4

For the determination of the critical limit, the count rate due to the background radiation was determined separately for the thin and thick detectors from a 10-minute measurement without a source. The resulting energy spectra within the 0–150 keV region are shown in Figure 4. In Figure 3 and Figure 4, there is a peak visible at 75 keV, which is due to the K X rays from a lead layer used for shielding to ensure personnel safety. The inset in Figure 4 shows the ^{241}Am energy spectrum from both detectors for a 15 minute measurement time. The intrinsic detection efficiencies at and below 60 keV are practically the same for both detectors, considering the lower background for the thin detector in the inset spectrum. As before, the region of interest (ROI) for the 60 keV gamma ray was defined to range from 45 keV to 68 keV. The total number of counts was integrated for the spectra of Figure 4, giving 13,763 and 6,184 counts for the thick and thin detector background spectra, respectively. These background data were taken to define the well-known background radiation rate for the calculation of the limits L_C and L_D using Equations (1) and (3), respectively. The background was assumed to be well known for these calculations ($\sigma_B^2 = 0$ in Equation (1)) and the results for the calculated limits are shown in Table 3.

Measurements with the ^{241}Am source were made using source-to-detector distances of 100 mm, 200 mm and 400 mm. At each distance, measurements lasting 5 s, 10 s, 20 s and 40 s were repeated 10 times. All the measurements were performed with both detectors. The observed net counts are shown in

Table 4. The 5 second measurement represents the typical time the moving ladle car is in the field of view of the radiation detector after the EAF at Outokumpu. The number of background counts during each measurement was calculated from the 10-minute background measurement. The net counts in the 60 keV peak ROI were determined by subtracting the background counts in the ROI during the measurement time, from the total number of counts in the 60 keV ROI.

The minimum detectable ^{241}Am source activities were calculated based on the limits L_C and L_D of Table 3 according to Equation (4) and using $b_\gamma = 0.36$ in the calculations. The calculated MDAs are shown in Table 5. The intrinsic detection efficiency ε_i for 60 keV gamma rays was taken to be 100 % for both the thick and thin NaI(Tl) detectors used in this work. The results in Table 4 also support the assumption of using the same intrinsic efficiency for both detectors. The geometric efficiency ε_g was estimated by calculating the average solid angle of a point source that moves across the 3-meter-wide ladle car that is centred on the detector's symmetry axis. The source-to-detector distance d was taken to be 1 meter at the centre of the ladle car. As in this setup the detector radius r_D is much smaller than d , a parallel gamma-ray beam from the source towards the detector was assumed in the calculation. The solid angle, Ω , is then given by $\Omega = \pi r_D^2 \cos \theta / r^2(\theta)$, where $r(\theta)$ is the distance between the source and the detector, and θ is the angle between the line perpendicular to detector's front face and the line from the source to the centre of the detector. Integrating Ω over θ results in an average ε_g of 0.016 ± 0.002 %. The uncertainty in the distance between the detector and centre of the ladle car is the main source of uncertainty in the solid angle in these calculations. The variation of the distance d was assumed to be ± 200 mm, representing the variation in the fill level of the ladle car. The attenuation of the gamma and X rays in the slag was not considered in the calculation of the MDAs.

Figure 4. The background energy spectrum of the thick (black) and thin (blue) NaI(Tl) detectors.

Table 3. The critical limits L_C and detection limits L_D for the thick and thin detectors. False-positive and false-negative probabilities were chosen to be 0.05, resulting in $k_\alpha = k_\beta = 1.65$.

Meas. Time, s	Thick detector		Thin Detector	
	L_C , counts	L_D , counts	L_C , counts	L_D , counts

5	17.7	38.1	11.8	26.4
10	25.0	52.7	16.8	36.2
20	35.3	73.4	23.7	50.1
40	50.0	102.7	33.5	69.7

Table 4. The net counts in the 60 keV peak ROI, N_{thick} and N_{thin} , for the thick and thin detectors, respectively, for a given measurement distance d and measurement time t .

d , cm	t , s	N_{thick}	N_{thin}
10	5	240±20	240±20
	10	440±30	460±30
	20	920±50	930±40
	40	1820±90	1840±60
20	5	61±13	65±13
	10	130±20	131±11
	20	260±30	260±30
	40	520±50	540±30
40	5	21±11	19±8
	10	50±20	39±10
	20	80±30	72±13
	40	160±30	150±30

Table 5. The calculated point-source MDAs using Equation (4). The limits L_C and L_D are from Table 3.

Meas. Time, s	Thick detector		Thin Detector	
	MDA , kBq $N = L_C$	MDA , kBq $N = L_D$	MDA , kBq $N = L_C$	MDA , kBq $N = L_D$
5	63±7	140±20	42±5	94±10
10	44±5	94±10	30±4	64±7
20	31±4	65±7	21±3	44±5
40	22±3	46±5	15±2	31±4

Figure 5. Background radiation spectrum at Outokumpu measured at the ladle car tunnel. The measurement time was 52 seconds. The background spectrum measured at the Accelerator laboratory of the University of Helsinki is a 10-minute measurement scaled by a factor of 0.05 to overlay the spectra above 150 keV and thus allow for visual comparison of the spectra.

To compare the background spectra at the Accelerator laboratory of the University of Helsinki and at the ladle car tunnel at the Outokumpu factory site, Outokumpu provided a background spectrum that was measured using a ruggedized Exploranium GR 135 38.1 mm×55.9 mm (diameter×thickness) NaI(Tl) detector. This background spectrum is shown in Figure 5, together with the 10-minute background spectrum that was measured at the Accelerator laboratory using the 76.2 mm×76.2 mm NaI(Tl) detector with a Be window. The two background spectra are very similar in shape down to 120 keV, below which the Outokumpu background spectrum has less counts, possibly due to a smaller crystal size and higher photon absorption in the rugged casing of the GR 135 detector. The shapes of these two spectra are nevertheless similar in the region of the 60-keV ^{241}Am peak, as are also the thin and thick detector background energy spectra compared in Figure 4.

4. Discussion

The results obtained from the spectra shown in Figure 4 clearly show that the detection limits for the 60 keV gamma rays are improved by using the thinner NaI(Tl) crystal. This is due to the 55 % smaller background count rate at the 60 keV ROI in the thin crystal (see Figure 4). The lower background rate in turn translates into a 30 % improvement in the critical limit L_C and the detection limit L_D , compared with the thick detector results. This follows directly from Equation (1) where L_C is proportional to the square root of the observed counts. Comparing the calculated L_C and L_D values in Table 3 with the measured counts from the 5.55 kBq ^{241}Am source in Table 4, one can see that both detectors clearly detect the source from 100 and 200 mm distances, for all the measurement times. The results in Table 4, together with spectra of the inset in Figure 4, also show both detectors to have practically the same intrinsic detection efficiency for 60 keV gamma rays. The improved detection limits of the thinner detector make it possible to detect the Am source in a shorter time, compared with the thick detector, from a 400-mm distance: For a 20 second measurement time, $L_D^{thick} = 73.4$ and $N_{thick} = 80 \pm 30$, thus the observed counts

are not above the detection limit for the thick detector. However, for the thin detector $N_{thin} = 72 \pm 13$ which is above L_D^{thin} of 50.1 within uncertainties for the same 20 second measurement time.

The improvement in the detection limits is translated directly into improved MDAs, as shown in Table 5. Going from the thick detector to the thin detector improves the MDA by 30 % for a fixed measurement time. On the other hand, the MDAs can also be improved by measuring for a longer time. If the measurement time for either detector is doubled, the resulting MDA is 30 % lower compared with the shorter measurement's MDA. Hence, if the ladle car can be slowed down when it passes by underneath the radiation detector, the detection sensitivity is increased, and a lower MDA is obtained. The possibility to increase the measurement time may be limited due to the impact this has on the production process. The best way to increase the number of counts and thus decrease the MDA is to increase the solid-angle coverage of the detection system. This can be achieved by placing the detector closer to the slag layer or by using a detector with a larger surface, either a single detector with larger diameter or multiple detectors. Substantially increasing the detector surface from what was used in this work (4600 mm²) should be straightforward.

The attenuation of the 60-keV gamma rays and the X rays in the slag was estimated assuming a homogeneous distribution of the ²⁴¹Am nuclei with the slag volume in the ladle car. The height of the slag layer was taken to be 200 mm and the ²⁴¹Am activity was assumed to be 10 MBq, yielding a vertical activity distribution of 5 kBq/0.1 mm. The total activity emitted upwards from the slag was then calculated in 0.1-mm steps from the top to the bottom of the slag layer. The following FeCr slag composition, from, was used as input to the NIST XCOM database for the calculation of the mass attenuation coefficient: SiO₂ (30%), Al₂O₃ (26%), MgO (23%), CaO (2%), Cr (8%) and Fe (4%). The density of the FeCr slag is 2500 kg/m³. At each depth, the number of the 60 keV gamma rays that reaches the top of the slag layer without interactions was calculated using the linear attenuation coefficient of 0.0792 /mm. For an upper limit estimate for the attenuation, half of the radiation available at each step was assumed to be emitted in the upwards direction, and the calculation assumes that all these gamma rays travel straight up. The total 60 keV gamma ray flux at the surface of the slag layer was calculated to be 114 000 per second, which is only 1 % of the original ²⁴¹Am activity. Assuming an average photon energy of 20 keV for the ²³⁷Np X rays results in a linear-attenuation coefficient of 1.25 /mm. The branching ratio for the X rays was taken to be 24 % in the calculation. For the ²³⁷Np X rays, the activity at the top surface of the slag slab was calculated to be only 5 kBq for the same initial 10 MBq ²⁴¹Am activity.

As mentioned earlier, the MDAs given in Table 5 do not consider the attenuation of the 60 keV gamma rays in the slag. With the estimated self-absorption of the 60 keV gamma rays in the slag, more realistic MDAs for a 5 second measurement are 14 ± 2 MBq and 9 ± 1 MBq for the thick and thin detector, respectively. Due to the high absorption of the gamma and X rays from ²⁴¹Am in the slag, and the rather small geometric efficiency of the measurement setup, the estimated MDAs

are above 3 MBq even for the longest measurement times considered in this work.

It is also worth emphasizing that the observed gain in the detection sensitivity is due to the NaI(Tl)-crystal thickness, not caused by the thin entrance windows in the detectors used in this work. Similar performance gain could be obtained with conventional NaI(Tl) detectors that have, for example, an aluminium window. The attenuation of 60-keV gamma rays is about 20 % by a 3-mm aluminium entrance window, which would degrade the MDA equally for both the thin and thick-detector based systems.

The three layers of fireproof fabric used at Outokumpu attenuate the 60 keV peak by about 10 %. There is not much to be gained by optimizing the heat shield, especially as the heat shielding provided by the fabric is essential to protect the detector from the heat from the molten metal. As shown in Figure 3 and Table 2, the counts in the X-ray ROI are attenuated 74 % by the currently used heat shielding. However, for all practical purposes, the X rays are completely absorbed in the slag itself. Thus, optimization of the heat shield to be more transparent to the X rays is not useful in the case of such a thick volumetric source. However, it would be worthwhile to investigate if the detection limits could be further improved by adding shielding and collimation to the current detector system. By reducing the intensity of the background radiation reaching the detector crystal it should be possible to reduce the detection limits compared with the current set up.

To implement a system that could perform similarly to these laboratory measurements, the system needs to be able to record and save the background spectrum in between the pourings of the molten metal from the furnace. The detection limits will be higher if the background radiation rate is not constant or the measurement time for the background data is short. When the background rate is not well known, σ_B^2 equals μ_B in Equation (1), which results in a critical limit that is $\sqrt{2}$ higher than $L_C(\sigma_B^2 = 0)$. Another problem for the background measurement arises from the change in the background rate due to the size of the objects that enter the radiation measurement sites at industrial facilities. A large ladle car or a truck that transports the metal, can shield the natural background radiation that reaches the detector(s) by 10–30 %.

It would be desirable to have a consistent way of detecting ^{241}Am sources within scrap metal loads, so that a radioactive source could be detected already before the melting process. The contamination of the furnaces and the melted metal could be then avoided. Detection before the melting process would also provide better radiation protection of the personnel at steelworks. If a ^{241}Am source contains AmO_2 , neutrons are produced via (α, n) reactions on oxygen. The neutron yield for a 1 Ci ^{241}Am source can be estimated to be about 2000 n/s, based on the tabulated neutron yield for 5.4-MeV alpha particles. A polypropylene moderated ^3He detector was tested for the neutron detection in this scenario. Then, at least the most active orphaned ^{241}Am sources might be detected using neutron detectors.

5. Conclusions

For the detection of low-energy gamma rays from a ^{241}Am source, a thin 5-mm NaI(Tl) crystal is thick enough for almost a 100 % intrinsic detector efficiency. It was shown that the use of such a dedicated detector improves both the critical limit and the detection limit by 30 % at 60 keV, as compared with a 76.2 mm thick detector. This improvement is due to the lower background radiation absorption rate in the thin crystal. The same 30 % improvement is translated directly into the minimum detectable activities. For a 5-mm thick and 76.2-mm diameter NaI detector in the ladle car tunnel at Outokumpu Tornio Works, the minimum activity of a molten ^{241}Am source that can be detected in 5 seconds with 95% probability is 9 MBq. Low geometric efficiency and high source self-absorption are the two largest factors that limit the minimum detectable activities of the current method for the detection of a ^{241}Am contamination in the slag.

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Highlights

- 1) A thin (5 mm thick) NaI detector is developed to detect molten ^{241}Am (60 keV) sources in slag at steel works.
- 2) The detector has a lower background count rate at 60 keV than a standard sized NaI detector.
- 3) It is shown that a molten ^{241}Am source with an activity as low as 9 MBq can be detected within 5 s.