



Analysis of iodine-126 contamination in the production of iodine-125 at the IEA-R1 reactor for brachytherapy applications

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Received: 12 November 2025 / Accepted: 6 February 2026 / Published online: 5 March 2026
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Abstract

This work developed a method to determine the contamination rates of iodine-126 (^{126}I) in the sodium iodide (NaI) solution used in the production of iodine-125 (^{125}I) seeds for brachytherapy. The production of ^{125}I is carried out at the IEA-R1 Reactor of the Nuclear and Energy Research Institute (IPEN-CNEN/SP) by irradiation with natural xenon. For the radionuclide analysis, a High-Purity Germanium (HPGe) radiation detector (ORTEC model GEM-C5970-B, coaxial detection system and beryllium window, nominal efficiency of 43% at 1333 keV of cobalt-60) was used, in which the activity of ^{125}I was determined by the sum-peak method and the activity of ^{126}I by an efficiency curve using a $^{166\text{m}}\text{Ho}$ calibration source ($A = (1832 \pm 2)$ Bq, $T_{1/2} = 1.20 \times 10^3$ years and reference date: Feb 23rd 2024). The results demonstrated the predictions of ^{125}I production in the IEA-R1 Reactor with ^{126}I contamination levels below 0.005%, meeting the production requirements for clinical use.

Keywords NaI · Iodine-125 · Iodine-126 · Brachytherapy · Sum-peak

Introduction

The radionuclide iodine-125 (^{125}I) is widely used in brachytherapy [1–3], especially for the production of radioactive sources in the form of seeds, which are used, for example,

in the treatment of prostate cancer [4]. Cancer is a global public health problem, and in developing countries like Brazil, there are challenges related to a lack of resources for prevention, diagnosis, and treatment, resulting in higher mortality rates, especially among socioeconomically vulnerable groups [5, 6]. Currently, treatment with ^{125}I seeds in Brazil is only performed in private hospitals, using supplies imported from other countries, which prevents many patients from accessing brachytherapy.

In an attempt to nationalize the production of ^{125}I for the manufacture of seeds and, in the future, make the sources available to the Brazilian Unified Health System (SUS) (public hospitals), the research group at the Laboratory of Radioactive Sources Production (LPFR) of the Radiation Technology Center (CETER-IPEN) is investigating the production parameters of this radionuclide in the IEA-R1 Nuclear Reactor (open pool type, with a power of up to 5 MW), with the objective of producing the raw material for the seeds, which is the sodium iodide solution (Na^{125}I). In the seed production process, it is necessary to ensure that this solution has adequate radioactive activity for use in brachytherapy, in addition to having a contamination index (which will be described later in this work) that is at a safe level for clinical use. This is necessary because, to make

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the seed, silver wires are used to adsorb the ^{125}I from the solution, which are encapsulated in a titanium casing. If the solution is low in terms of contamination, then the ^{125}I seeds will also be safe in those terms when they are produced.

In terms of production in a nuclear reactor, ^{125}I is formed by neutron irradiation of xenon-124 (^{124}Xe), from the reaction $^{124}\text{Xe}(n,\gamma)^{125}\text{Xe}$. The xenon-125 (^{125}Xe), formed in the reaction, decays into ^{125}I . However, this production route presents a challenge: a portion of the generated ^{125}I is also irradiated with neutrons, resulting in the formation of iodine-126 (^{126}I), a radionuclide that is not suitable for use in brachytherapy and is therefore a contaminant in the source production process. The production route of ^{125}I , as well as the half-life ($T_{1/2}$), thermal neutron cross-section (σ), and type of radioactive decay of the radionuclides involved in the process are illustrated in Fig. 1.

^{126}I is considered a contaminant because the ^{125}I seeds used in the treatment of prostate cancer, for example, are permanent Low Dose Rate (LDR) implants, which emit relatively low gamma (γ) energy ($E_{\gamma}^{125}\text{I} = 35.4925 \pm 0.0005$ keV, with $I_{\gamma} = 6.68 \pm 0.13\%$ [7]), while ^{126}I has relatively high characteristic γ energies ($E_{\gamma_1}^{126}\text{I} = 388.633 \pm 0.011$ keV, with $I_{\gamma} = 35.6 \pm 0.6\%$ and $E_{\gamma_2} = 666.331 \pm 0.012$ keV, with $I_{\gamma} = 32.9 \pm 0.5\%$ [7]), unsuitable for the described use. In addition, iodine has the following X-ray energies: $K\alpha = 27.473$ keV and $K\beta = 31.359$ keV [7], which were also considered in the calculation of the source activity, which will be discussed in the materials and methods section.

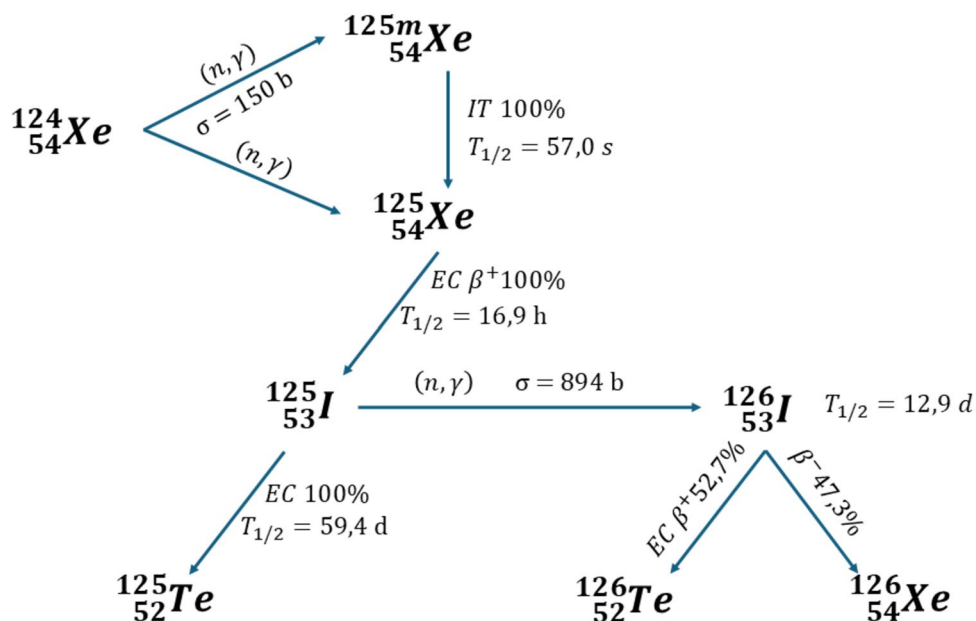
In this sense, this work determined the contamination rates of ^{126}I in ^{125}I by analyzing a sodium iodide (NaI) solution. To obtain the activities of the radioisotopes of interest, γ -spectrometry was performed using a High-Purity

Germanium (HPGe) radiation detector (ORTEC model GEM-C5970-B, coaxial acquisition system and beryllium window, with a nominal efficiency of 43% at 1333 keV of cobalt-60 – ^{60}Co). Due to the characteristics of these radioisotopes, which involve the energies and intensities of the peaks in the acquisition of the γ -spectrum, it was necessary to adopt different methods for calculating the radioactive activity. The activity of ^{125}I was obtained by the peak-sum correction method [8], while the activity of ^{126}I was estimated using an adjusted efficiency curve [9] (with well-defined energies in the intervals of interest of the spectrum) from a holmium-166 m calibration source ($^{166\text{m}}\text{Ho}$ – with $A = (1832 \pm 2)$ Bq, $T_{1/2} = 1.20 \times 10^3$ years and reference date: February 23, 2024).

In this way, it was possible to estimate the ratio between the activities of $^{126}\text{I}/^{125}\text{I}$. The values obtained were directly related to the parameters of ^{125}I production in the IEA-R1 Reactor, such as: amount of xenon gas in the samples sent for neutron irradiation; irradiation time; decay time required for safe handling of the irradiated samples; neutron flux and mathematical model necessary for calculating the activity of each radioisotope. In addition, the data obtained for the $^{126}\text{I}/^{125}\text{I}$ ratio were compared to the contamination indices adopted by international manufacturers that also produce the NaI solution, such as NEN Radiochemicals [10] and the Institute of Isotopes CO. LTD – IZOTOP [11]. Finally, considering that the NaI solution is used for the subsequent manufacture of ^{125}I seeds, it is necessary that the activity of this solution allows the preparation of seeds with 0.2 to 0.8 mCi, suitable for use in prostate cancer treatments.

Research aimed at nationalizing the ^{125}I seed production process in Brazil, especially at CETER, began in 2005 [12] and continues to this day. During this period, researchers at

Fig. 1 Diagram of the production and decay pathway of ^{125}I



LPFR-CETER investigated many of the production steps, including the necessary inputs for the manufacture of a novel prototype, systems for inserting xenon gas into a capsule for irradiation and leak testing, dosimetry, and synthesis of the NaI solution [13–18]. There were studies that investigated the radionuclidic purity of ^{125}I , but adopting other methodologies and objectives, although they are also adopted as a reference in this work [19]. In this sense, this work completes the cycle of all stages of production of the NaI solution, aiming to study in detail the levels of contamination by ^{126}I , in the hope that this technology will, in the future, allow prostate cancer patients to have greater access to treatment with ^{125}I seeds in Brazil.

Experimental

Materials and methods

^{125}I was produced at the IEA-R1 Reactor of IPEN through the nuclear reaction $^{124}\text{Xe} (n, \gamma) ^{125}\text{Xe} (T_{1/2} = 16.9 \text{ h}) \rightarrow ^{125}\text{I}$, in which the undesirable contaminant ^{126}I was generated by the nuclear reaction $^{125}\text{I} (n, \gamma) ^{126}\text{I}$. This work discusses two samples [20] that underwent the following production and analysis steps, until the contamination index was obtained:

For the investigation and laboratory-level tests, natural xenon gas was chosen for neutron irradiations. At the commercial production level, enriched ^{124}Xe is expected to be used. It was verified that the other isotopes that constitute natural Xe do not cause significant formations during neutron irradiation, therefore they do not interfere in the ^{125}I production process. In terms of contamination, the use of natural Xe is not a problem, since the proportion of $^{126}\text{I}/^{125}\text{I}$,

which is formed from ^{124}Xe anyway, was investigated. Table 1 presents the characteristics of each isotope of natural Xe and ^{124}Xe -enriched, in addition to the isotopes that could be generated during the irradiation of natural Xe.

To prepare the samples for neutron irradiation, approximately 15 mg of Xe gas was injected into each aluminum (Al) capsule, developed at CETER [15], with dimensions shown in Fig. 2. This capsule has low thermal neutron absorption ($0.231 \pm 0.003 \text{ b}$ [7]), good thermal conductivity and machinability [22], and complies with the ISO 9978 standard for leak testing [23].

The capsule containing Xe was placed in an aluminum cylinder, which is a standard used in long irradiations in the IEA-R1 Reactor. The Neutron Activation Analysis (NAA) method [24, 25] was used to measure the induced radioactivity of the radioisotopes of interest, ^{125}I and ^{126}I . For this purpose, the two samples were subjected to an irradiation time $t_i = 48 \text{ h}$, under a neutron flux $\phi = 4.5 \times 10^{13} \text{ n.cm}^{-2} \text{ s}^{-1}$ in positions 34-A and 34-B of the reactor core, contained in the device called Water-Cooled Irradiation Element (EIRA) [26]. Figure 3 shows the position of the EIRA in relation to the fuel rods in the reactor core.

The waiting time (t_w), which refers to the decay time between irradiation and measurements in the HPGe detector, was one week. This time is necessary for the radioactive activity of the sample to decay to a dose that is safe for handling in experiments. This is verified by the radiological protection sector of the Research Reactor Center (CERPq) of IPEN, which releases the sample to CETER.

After release, the Al cylinder was opened in a hot cell at CETER to remove the capsule containing iodine. This capsule was immersed in liquid nitrogen (LN2) so that the iodine would be adsorbed onto its walls. Using a cutting

Table 1 Natural Xe and enriched xenon in ^{124}Xe

Xe Isotope	Natural (%)	Enriched ^{124}Xe (%)	Half-life ($T_{1/2}$)	Cross-section for thermal neutrons σ [b]
^{124}Xe	0.10	> 99	$\geq 1.6 \times 10^{14} \text{ y}$	150 ± 20
^{125}Xe	–	–	$16.9 \pm 0.2 \text{ h}$	–
^{126}Xe	0.09	0.05	Stable	2.74 ± 0.25
^{127}Xe	–	–	$36.346 \pm 0.003 \text{ d}$	0.01
^{128}Xe	1.91	0.01	Stable	3.5 ± 0.7
^{129}Xe	26.40	0.01	Stable	21 ± 3
^{130}Xe	4.02	0.01	Stable	3.5 ± 0.7
^{131}Xe	21.23	0.01	Stable	93 ± 9
^{132}Xe	26.91	0.01	Stable	0.45 ± 0.06
^{133}Xe	–	–	$5.2475 \pm 0.0005 \text{ d}$	190 ± 90
^{134}Xe	10.44	–	$> 5.8 \times 10^{22} \text{ y}$	0.265 ± 0.002
^{136}Xe	8.86	–	$(2.165 \pm 0.062) \times 10^{21} \text{ y}$	0.26 ± 0.02
^{137}Xe	–	–	$3.818 \pm 0.013 \text{ min}$	–

Source: Encyclopedia of Geochemistry [21], 2018; IAEA (Isotope Browser) [7], 2024

wall thickness = 0.16 cm



Fig. 2 Aluminum capsule for containing Xe gas

tool developed at CETER [19], the capsule was cut into two parts. To remove the iodine from the capsule wall, a NaOH solution was previously prepared, in which 20 mg of NaOH was dissolved in 50 mL of deionized water. The capsule parts were submerged in a glass container containing 12 mL of this NaOH solution. Through the chemical reaction $\text{I}_2 + 2\text{NaOH} \rightarrow 2\text{NaI} + \text{H}_2\text{O} + \text{O}_2$, NaI was generated containing ^{125}I and ^{126}I . 1 μL aliquot of this NaI solution was extracted with a pipette (KASVIPLUS model for volumes from 0.5 to 10 μL) and placed in a glass vial (15 mL penicillin type) to obtain the γ spectra using the HPGe detector. This was necessary because it was not possible to measure the 12 mL directly, since at this volume the radioactive activity causes excessive interactions in the detector, which cannot process it and, consequently, cannot generate the spectrum. Therefore, the results for the 1 μL aliquot were used to estimate the activity in 12 mL. To ensure the reliability of this extrapolation, a homogeneity test of the NaI solution production process was performed, which consisted of analyzing 10 aliquots of 3 μL for a measurement time of 600 s in the HPGe detector, as described in the results section. Furthermore, it is important to emphasize that, at the time of the aliquot measurements in the HPGe detector, the dead time was less than 10%. To perform the calculations, the dead time was corrected for the live time.

The HPGe detector was calibrated with standard sources of cobalt-60 (^{60}Co), barium-133 (^{133}Ba), cesium-137 (^{137}Cs), and europium-152 (^{152}Eu). The acquisition of the γ spectra in the HPGe detector was performed using the Maestro software (version 5.3), which was also used for analysis along with the InterSpec software (version 1.0.9). Both samples were measured at a distance of 0.45 cm from the Be window of the detector (Fig. 4).

Due to the high intensity (in terms of radioactive activity) of ^{125}I , sum-peaks were observed in the spectra (Fig. 5), which occur when two γ photons interact almost simultaneously with the detector and the total energy of these photons is recorded as a single detection signal.

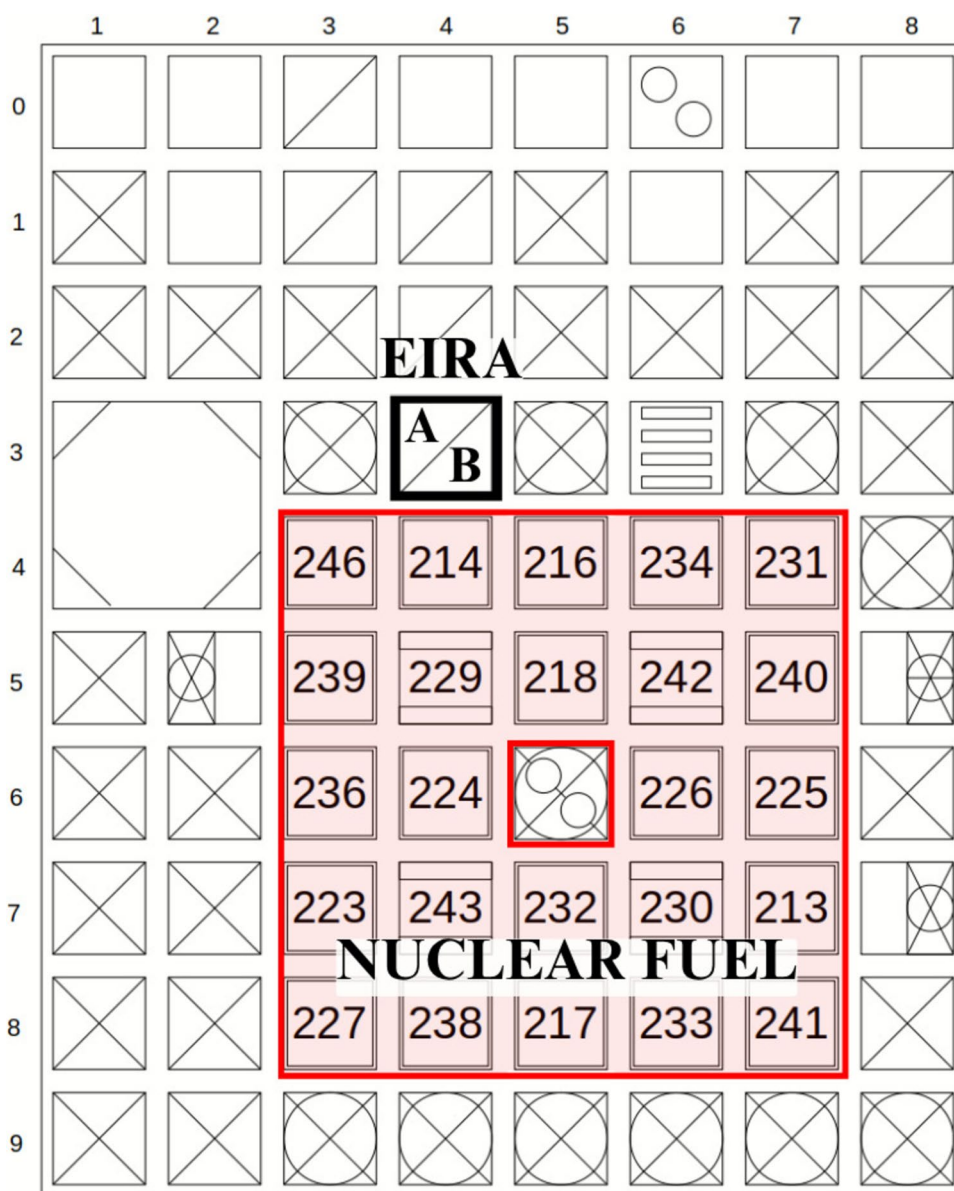
Consequently, to determine the activity of ^{125}I , represented as N_0 , it was necessary to use the following Eq. (1) for the sum-peak correction method [8], which allowed for the correction of the ^{125}I activity by reconsidering the contribution of photons that interacted simultaneously with the detector:

$$N_0 = \frac{P_1 P_2}{(P_1 + P_2)^2} \frac{(A_1 + 2A_2)^2}{A_2} \quad (1)$$

A_1 = Counting rate of the actual areas of gamma transition energies A_2 = Sum of the peak area counts P_1 = Probability of electron capture emission P_2 = Probability of X-ray emission by internal conversion added to the probability of emission of the 35.4925 keV gamma energy from ^{125}I .

We opted not to use absorbers because they only reduce the count in the spectrum and the sum peak does not disappear. Equation 1 uses the areas of the sum peaks, therefore there is no need to reduce them.

Sum-peak generation was not observed in the spectrum for the γ energies of ^{126}I (Fig. 6), therefore another method was adopted for calculating the activity, using an energy efficiency curve obtained from a standard $^{166\text{m}}\text{Ho}$ calibration source. Calibration sources contain a known radioactive activity (the $^{166\text{m}}\text{Ho}$ source used has $A = (1832 \pm 2)$ Bq of activity and reference date = Feb 23rd 2024 at 00:00 h) and well-defined energies, as well as a relatively high $T_{1/2}$

Fig. 3 Reactor core configuration IEA-R1 [26]

($^{166\text{m}}\text{Ho}$ has $T_{1/2} = 1.20 \times 10^3$ (18) y). Furthermore, the $^{166\text{m}}\text{Ho}$ source is made of collodion deposited on polyethylene, with a 0.01 cm aluminum cover.

An efficiency curve of $^{166\text{m}}\text{Ho}$ was fitted to the region of interest, that is, the region encompassing the energies of ^{126}I . Thus, the relationship used to calculate the activity of ^{126}I was the following Eq. (2) [9]:

$$A = C / (\varepsilon_i I_\gamma T) \quad (2)$$

where: A = Radioactive source activity C = Total Count Obtained (Net Area Under Peak Total Energy Absorption) ε_i = Counting efficiency for the energy of interest I_γ = Absolute gamma intensity of the energy of interest T = Measurement time.

To refine the efficiency curve adjustment, the SUMCOR code [27] was used to obtain cascade sum correction factors for the energies of the $^{166\text{m}}\text{Ho}$ source. The execution process follows several steps, according to the methodology described in [27], in order to obtain the necessary parameters for calculating these factors, obtained for each energy by the Eq. 3:

$$\bar{F}_S = \frac{\sum_{i=1}^{N_p} F_{Si} \varepsilon_{pi}}{\sum_{i=1}^{N_p} \varepsilon_{pi}} \quad (3)$$

where: N_p = Total number of random points within the source volume ε_{pi} = Efficiency of the total energy absorption peak (FEP) for each random point, for the corresponding



Fig. 4 - Geometry used for analysis in the detector HPGe

transition in the cascade. F_{Si} = Summation correction factor for each random point, for the corresponding transition in the cascade.

For this purpose, the MCNP 4C code was initially used for Monte Carlo simulation, where a point source of ^{166m}Ho was placed 0.45 cm away from the Be window of the HPGe detector (maintaining the geometry of the measurements with the NaI sample). Figure 7, obtained using the VISED software, shows the geometric model used in the simulation, in which the HPGe detector was created based on the dimensions of the ORTEC GEM-C5970-B model, used in the experimental measurements.

The dimensions of the HPGe detector were obtained from the ORTEC manual and are shown in Fig. 8.

In MCNP, the geometric model of the PMMA protective casing (which protects the detector) was also simulated, as it is part of the experimental setup. Figure 9 shows an illustrative diagram of this casing, with dimensions given in millimeters.

Table 2 describes the parameters used in MCNP for this work.

Results and discussion

Using the Neutron Activation Analysis (NAA) method, with the parameters determined as: $t_i = 48$ h, $\phi = 4.5 \times 10^{13}$ n.cm $^{-2}$ s $^{-1}$, positions 34-A and 34-B in the reactor core and $t_w = 1$ week, two ampoules (referring to samples A and B) containing approximately 15 mg each of natural Xe in Al capsules were irradiated, in order to form ^{125}I which, consequently, ends up forming ^{126}I . After irradiation, the content inside the capsule, containing ^{125}I and ^{126}I , was used to produce the NaI solution following the methodology described. 1 μL of the NaI solution from samples A and B were analyzed by γ -spectrometry.

For the analysis of ^{125}I by the sum-peak method, as an example, the raw spectrum of the first measurement of sample A is shown in Fig. 10, along with the background spectrum (ambient radiation—Bg) used. Both measurements (sample A and Bg) had a counting time $t_c = 3600$ s.

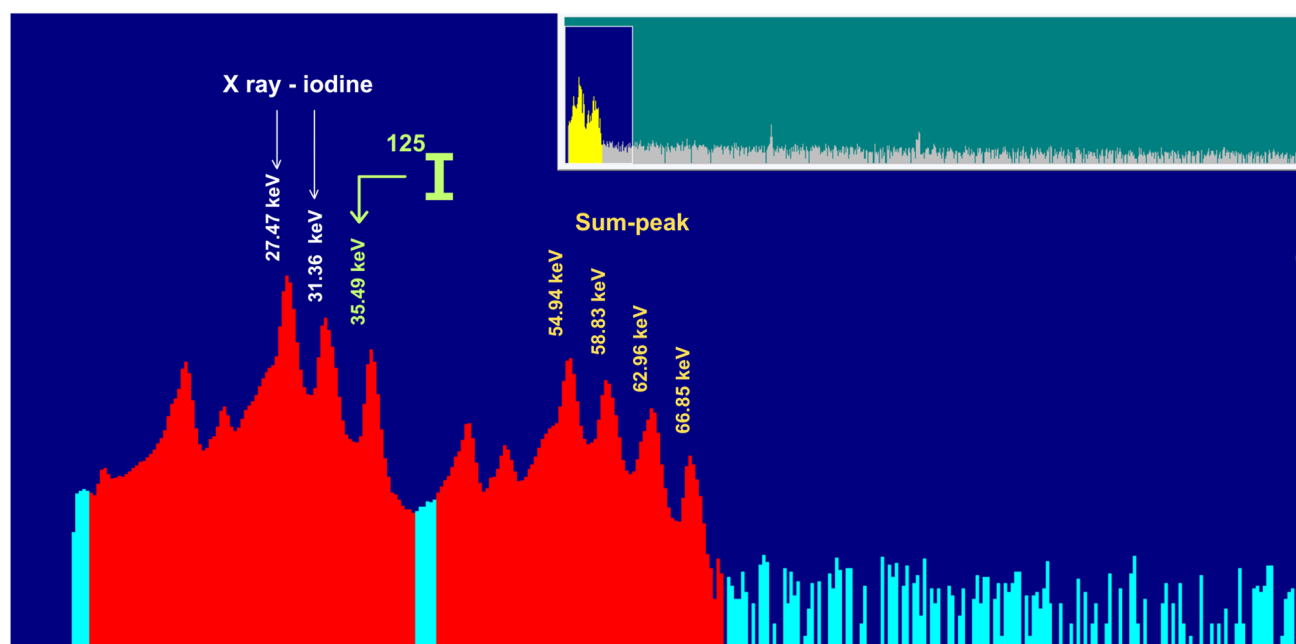


Fig. 5 Example of ^{125}I spectrum with sum-peaks, with irradiated sample for 48 h and measurement time of 3600 s

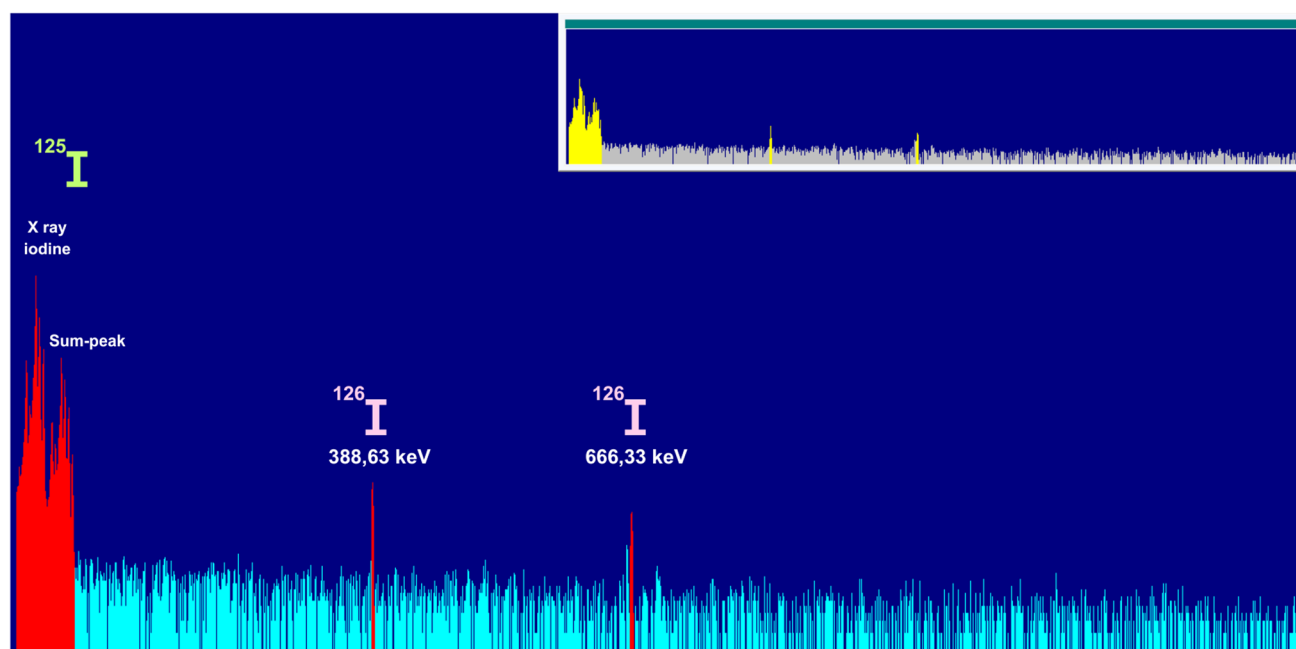


Fig. 6 Example of a ^{126}I spectrum, with a sample irradiated for 48 h and a measurement time of 3600 s

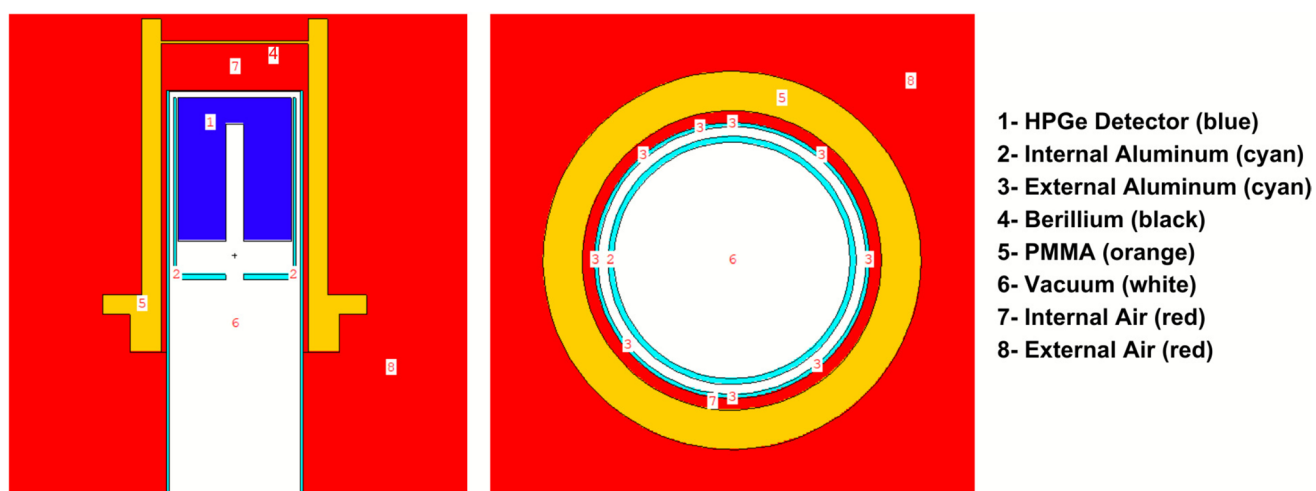
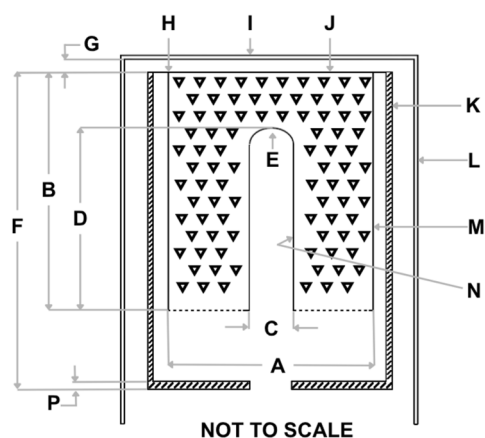


Fig. 7 Geometric model of the HPGe detector model GEM-C5970 ORTEC in MCNP

In the spectrum of sample A, the background was subtracted and two Regions of Interest (ROIs) were selected: the first between channel 36 (12.24 keV) and 119 (40.44 keV) is area 1, a region that comprises the count rate of the actual areas of the gamma transition energies, and the second between channels 125 (42.48 keV) and 198 (67.29 keV) is area 2, referring to the count rate of the areas of the sum-peaks. In this way, it was possible to extract the value of the net areas corresponding to each ROI, as shown in Fig. 11.

Based on the information extracted from Fig. 11, the other parameters used for calculating the ^{125}I activity and an example of the use of Eq. (1) are available in Table 3, below:

Using the parameters from Table 3, through Eq. 1, an activity N_0 of (2739 ± 10) Bq was obtained in the first measurement (of a series of measurements presented below) of sample A. This activity value was extrapolated to 12 mL (i.e., the 1 μL value was multiplied by 12,000) and converted to mCi (where $1 \text{ Bq} \approx 2.7 \times 10^{-8} \text{ mCi}$). Therefore, in the first activity measurement, the 12 mL



$$A = \frac{58.7}{\text{CrystalDiameter}} \text{ mm}$$

$$B = \frac{74.1}{\text{CrystalLength}} \text{ mm}$$

$$C = \frac{9}{\text{HoleDiameter}} \text{ mm}$$

$$D = \frac{60.4}{\text{HoleDepth}} \text{ mm}$$

E: NOMINAL 5 mm RADIUS
 F: 94 mm CUP LENGTH
 G: 3 mm SPACE
 H: 0.03 mm/0.03 mm Al/Mylar
 I: 0.5 MM BERYLLIUM
 J: < 0.010 mm Ge DEAD LAYER
 K: 1.5 mm Al
 L: 1 mm Al
 M: 0.7 mm Ge/Li DEAD LAYER
 N: 0.3 micron Ge/B DEAD LAYER
 P: 3 mm

Fig. 8 HPGe model GEM-C5970 ORTEC

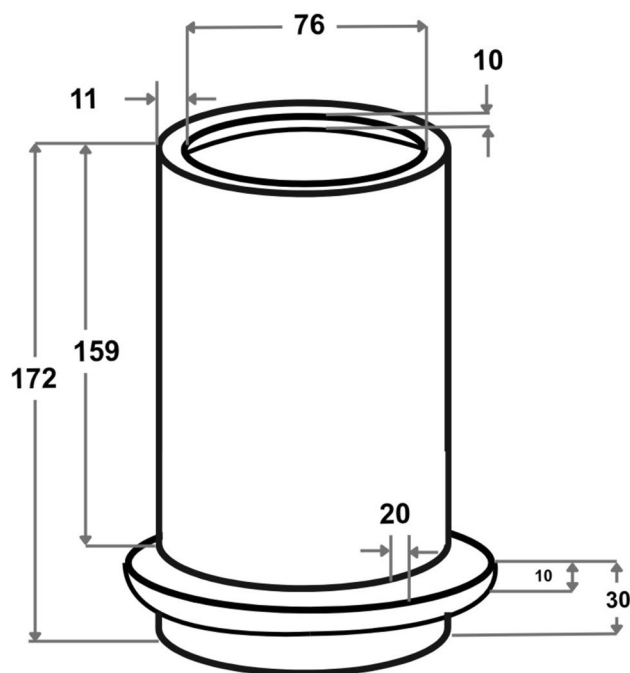


Fig. 9 PMMA protective casing for the HPGe detector (measurements in millimeters)

NaI solution would have an activity of (0.8865 ± 0.0033) mCi. The activity estimate for the total volume of the solution was necessary to obtain values close to the reference values for the production of ^{125}I seeds (0.2 to 0.8 mCi). To verify the reliability of this estimate, a homogeneity test of the solution production process was performed, in which 10 samples containing 3 μL of the NaI solution were prepared and measured in the HPGe detector for 600 s. The activity results (which were determined by the same process as the sum-peak method [8]) are presented in Table 4:

To calculate the activity of ^{126}I , the efficiency curve of $^{166\text{m}}\text{Ho}$ was fitted by the polynomial $y = 0.35(0.02)x^2 - 5.1(0.2)x + 14.6(0.6)$, where y is the efficiency value at the peak of the energy of interest (in ln) and x is the γ energy of interest (in ln). Figure 12 shows the plotted efficiency curve, between the regions of 180 and 840 keV (which covers the γ energies of ^{126}I).

In this way, the calculation of the ^{126}I activity was performed through the following steps:

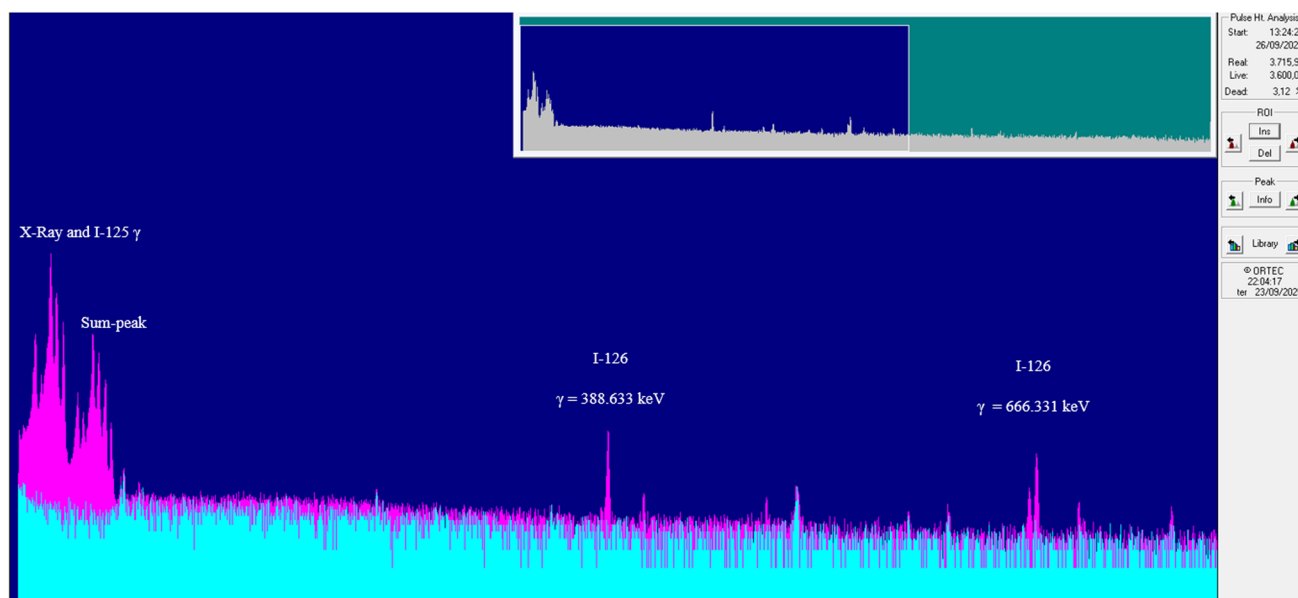
- I. The natural logarithm of the γ -ray energy of 388.633 keV was calculated (chosen because it has the highest $I_\gamma = 35.6 \pm 0.6\%$);
- II. The value of the natural logarithm of 388.633 keV, which is equal to 5.963, was substituted for x in the polynomial that fits the efficiency curve of $^{166\text{m}}\text{Ho}$. This results in the value of the natural logarithm of the efficiency for this same energy (in this case, -3.112).
- III. The exponential of the natural logarithm of the efficiency for the energy of 388.633 keV was calculated to obtain the efficiency value ($\text{EXP}(-3.112) = 0.044$).
- IV. The efficiency value at the peak for the energy of 388.633 keV ($\epsilon_i = 0.044$) was used in Equation $A = C/(\epsilon_i \cdot I_\gamma \cdot T)$ to calculate the activity of ^{126}I .

As an example, Fig. 13 shows the energy peaks of ^{126}I adjusted by the Interspec software (the background was subtracted from the spectrum). The net area count for the 388.633 keV peak was $C = 2590$. In addition, the counting time of the measurement was $T_c = 3600$ s. With this information, we have that the activity of ^{126}I , using Eq. (2), is $A = 2590 / (0.0435 \times 0.35 \times 3600)$, so $A \cong 49$ Bq.

Following these methodologies for each radionuclide, the activity of the NaI solution was monitored weekly over 140 days. The aim was to obtain the activity values

Table 2 Description of the parameters used in MCNP

Item	Description and Reference
Software	MCNP Version 4C
Hardware	12th generation Intel®Core™ i9 processor with 16 cores, 24 threads and 64 GB of RAM (3.2 GHz clock speed)
Time	Simulation time for efficiency curve calculation: 28.36 h ($\cong$ 1.18 d)
Geometry	The geometric model consisted of reproducing the HPGe detector (Model GEM-C5970-B, Coaxial Detector System), constructed from the ORTEC manual and illustrated in Fig. 7
Materials	The materials used in the simulation were germanium, aluminum, beryllium, polymethyl methacrylate (PMMA), and air, with composition taken from the literature. [28]
Source	The Source Definition (SDEF) card was used to represent the ^{166m}Ho calibration source as a point source, 0.45 cm above the Be window. The gamma spectrum was obtained from the Live Chart of Nuclides, International Atomic Energy Agency (IAEA) – Nuclear Data Services library [29]
Transport	The cross-section data were obtained from MCPLIB84 for photons and EL03 for electrons [30, 31]. The secondary particles (photons and electrons) were transported
Tally	The F8 tally was used to obtain the energy distribution of pulses created in the HPGe detector. The pulse height counting is analogous to a physical detector. The F8 energy bins correspond to the total energy deposited in a detector in the channels specified by each computational particle (history). The E8 supplementary card was used to indicate the division into 4096 channels (bins), consistent with the quantity adopted in the experimental measurements. 10^7 particles (histories) were simulated
Procedures	For each energy level of ^{166m}Ho , the input was processed individually. The distribution of energy pulses was obtained using the F8 tally, from which the following information was extracted from the output: total sum of energy pulses, waste disposal value, and peak value. With this, it was possible to obtain the total efficiency and the efficiency at the specific energy peak
Post-processing	The results of the energy pulse distribution obtained by the F8 tally made it possible to obtain the total efficiency and the efficiency of each peak of ^{166m}Ho . The data were used in SUMCOR, where the correction factor for cascade summation was obtained for the experimental measurements of the ^{166m}Ho efficiency curve. The refined efficiency curve was used to calculate the activity of ^{126}I
Uncertainty	Uncertainty for each parameter: Total sum of energy pulses (0.0008) Waste disposal value (0.0011 to 0.0194) Peak value (0.0009 to 0.0027)

**Fig. 10** Spectrum of the first measurement of Sample A (pink), irradiated for 48 h and measurement time of 3600 s + Background (cyan)

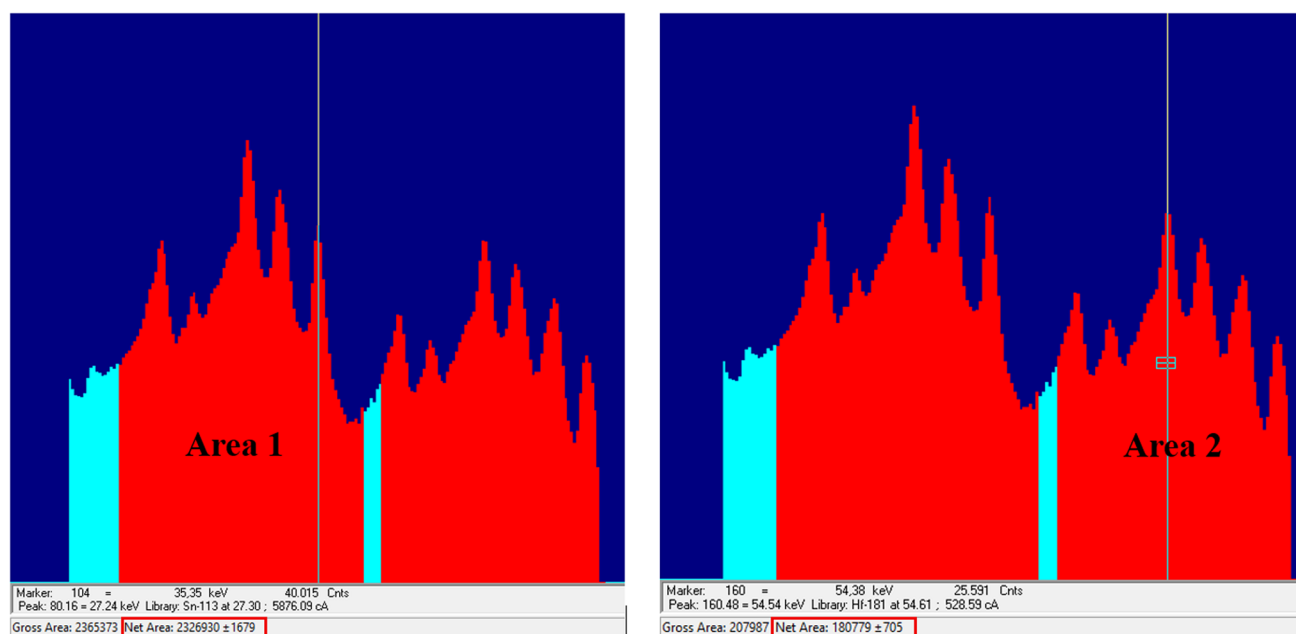


Fig. 11 Determination of the net area of the ROI for application in the sum-peak method in the calculation of iodine-125 activity, in the Maestro software

Table 3 Parameters used in the sum-peak method for calculating the activity of iodine-125

Equation [8]	$N_0 = \frac{P_1 P_2}{(P_1 + P_2)^2} \frac{(A_1 + 2A_2)^2}{A_2}$
Parameter	Value ± SD
Area of region 1 Channel [36–119]	2,326,930 ± 1701
Area of region 2 Channel [125–198]	180,779 ± 705
A1 (counts per second—cps)	646.37 ± 0.47
A ₂ (cps)	50.22 ± 0.20
P ₁ = P _k · ω _k	0.7010 ± 0.0035
P ₂ = (1 + α _k · ω _k) / (1 + α _t)	0.8848 ± 0.0037
P _k *	0.8011 ± 0.0017
ω _k *	0.875 ± 0.004
α _k *	11.7 ± 0.17
α _t *	14.08 ± 0.22

*Constant parameters for ¹²⁵I, whose values were taken from [32]; Source: Dias MS, Koskinas MF, 1995 [8]

experimentally, so that it would be possible to calculate the ¹²⁶I/¹²⁵I ratio and, in this way, obtain the contamination index of the solution by ¹²⁶I. In addition, the decay curve of ¹²⁵I was plotted to determine its T_{1/2} and verify that the sum-peak correction method did indeed work adequately for determining the activity of ¹²⁵I. The slope of the function is equivalent to the decay constant (λ) of the radionuclide. Therefore, using the relationship T_{1/2} = (ln 2)/λ, it was possible to calculate the experimental T_{1/2} and

Table 4 Homogeneity test of the NaI solution

Sample	Activity (Bq)	Standard deviation (Bq)
1	3025	21
2	3195	22
3	3153	22
4	3095	21
5	3137	21
6	3482	28
7	3037	22
8	2616	17
9	3148	21
10	3014	21
Mean ± SD	3228 ± 215	(SD/Mean) × 100 ≈ 7%

Source: Author, 2025

compare it with the theoretical value, which is 59.407 days [7]. Table 5 presents the activity values of ¹²⁵I and ¹²⁶I, as well as the ratio between them and the estimate for 12 mL in sample A.

The decay of ¹²⁵I, corresponding to sample A, is shown in Fig. 14 for up to 140 days. The parameter "days" refers to the time interval after the first measurement date on the HPGe detector.

Similarly, the activity values and the ratio of ¹²⁵I and ¹²⁶I for Sample B are shown (Table 6), as well as the decay graph of ¹²⁵I (Fig. 15).

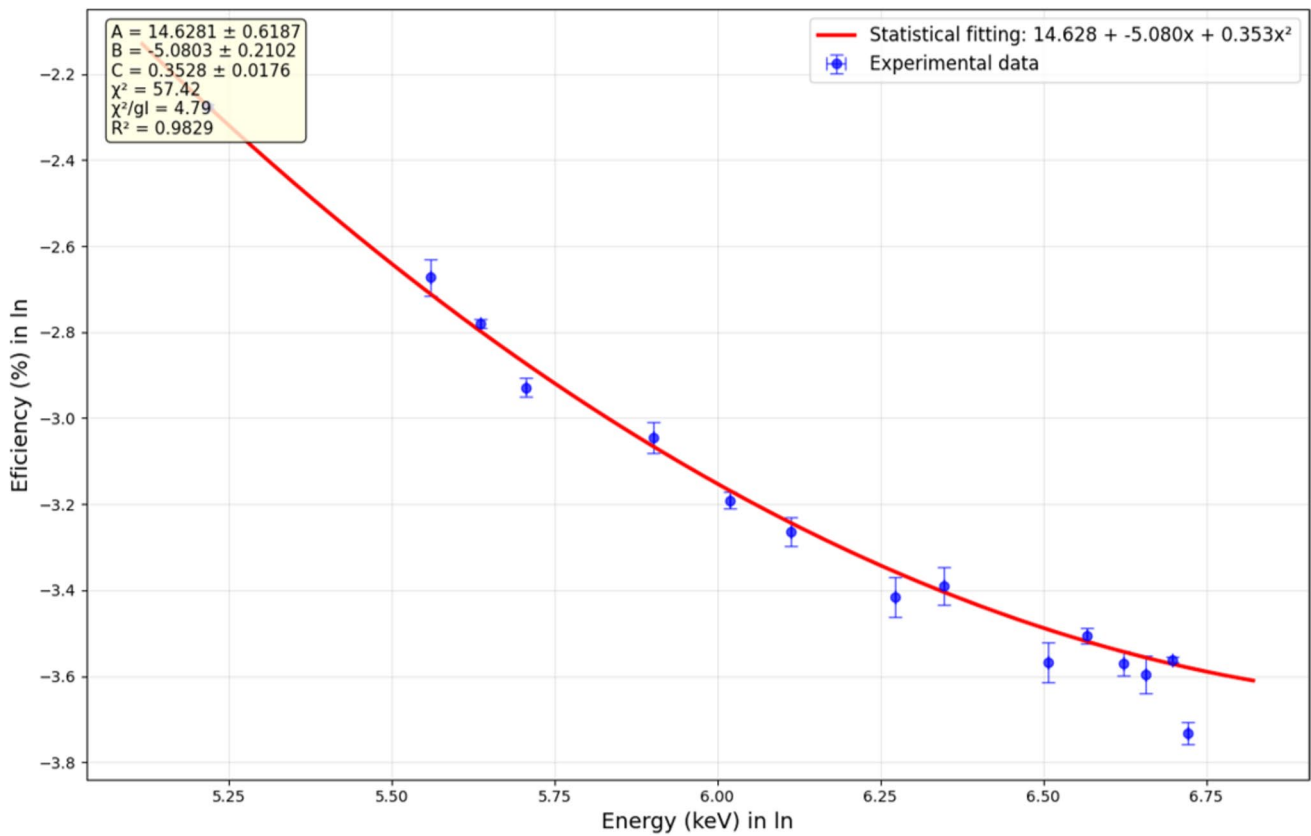


Fig. 12 Efficiency curve of Ho-166 m

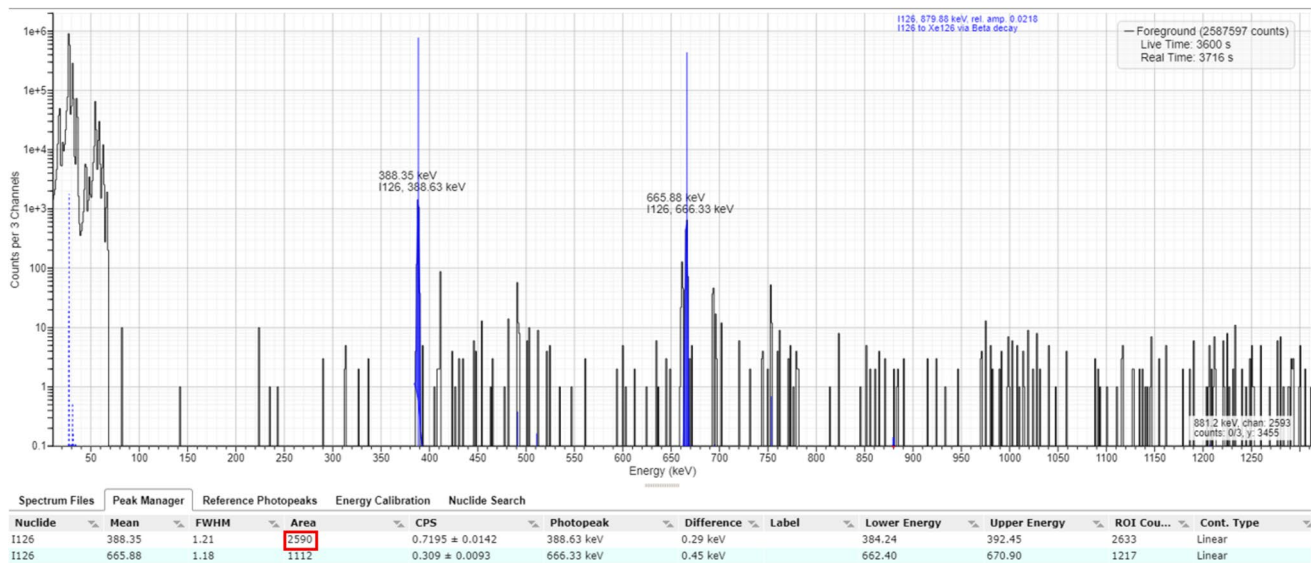
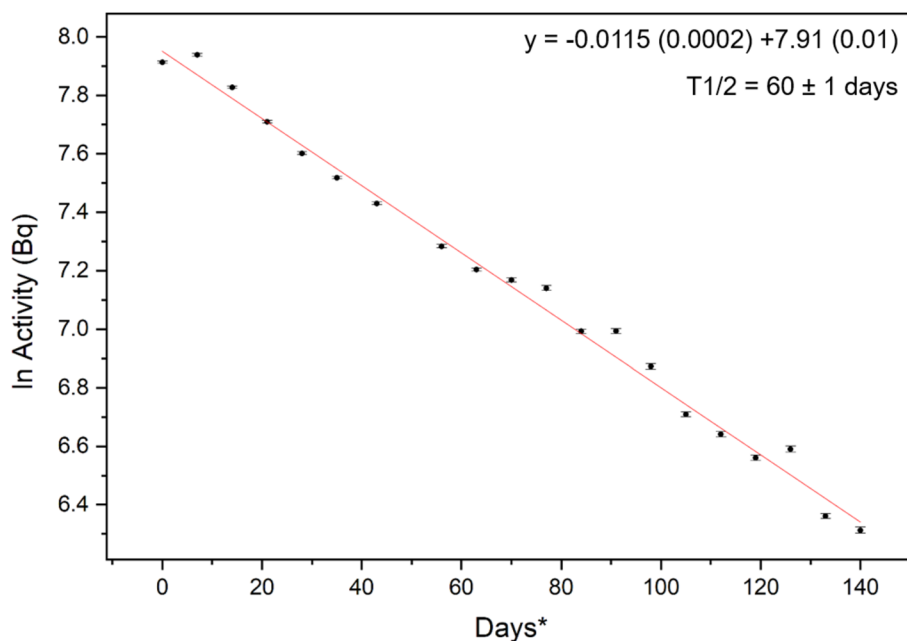


Fig. 13 Determination of the net area of the ROIs for calculating the activity of iodine-126 using the InterSpec software

Table 5 Ratio between the activities of ^{126}I and ^{125}I for Sample A and estimate for 12 mL of the NaI solution (first 5 values corresponding to Fig. 13)

Time interval after the 1st measurement (days)	Activity at 1 μL (Bq)		$\frac{A_{\text{iodine-126}}}{A_{\text{iodine-125}}}$ (%)	Activity 12 mL for ^{125}I (mCi)
	^{125}I ($E_{\gamma} = 35.49 \text{ keV}$)	^{126}I ($E_{\gamma} = 388.63 \text{ keV}$)		
0	2733 ± 10	48 ± 4	0.017 ± 0.003	0.8865 ± 0.0033
7	2705 ± 13	38 ± 3	0.013 ± 0.003	0.8773 ± 0.0041
14	2509 ± 11	25 ± 2	0.010 ± 0.003	0.8136 ± 0.0035
21	2230 ± 10	16 ± 1	0.007 ± 0.004	0.7231 ± 0.0034
28	2001 ± 9	10 ± 1	0.005 ± 0.003	0.6491 ± 0.0030

Source: Author, 2025

Fig. 14 Graph of iodine-125 activity in sample A * Time interval after the 1st measurement (days)

* Time interval after the 1st measurement (days)

Table 6 Ratio between the activities of iodine-126 and iodine-125 for Sample B and estimate for 12 mL of the NaI solution (first 5 values corresponding to Fig. 15)

Time interval after the 1st measurement (days)	Activity at 1 μL (Bq)		$\frac{A_{\text{iodine-126}}}{A_{\text{iodine-125}}}$ (%)	Activity 12 mL for ^{125}I (mCi)
	^{125}I ($E_{\gamma} = 35.49 \text{ keV}$)	^{126}I ($E_{\gamma} = 388.63 \text{ keV}$)		
0	5207 ± 13	117 ± 10	0.022 ± 0.003	1.6887 ± 0.0047
7	4780 ± 12	80 ± 7	0.017 ± 0.003	1.5501 ± 0.0040
14	4537 ± 13	55 ± 5	0.012 ± 0.003	1.4715 ± 0.0041
21	3967 ± 11	37 ± 3	0.009 ± 0.003	1.2866 ± 0.0036
28	3652 ± 10	26 ± 2	0.007 ± 0.003	1.1846 ± 0.0034

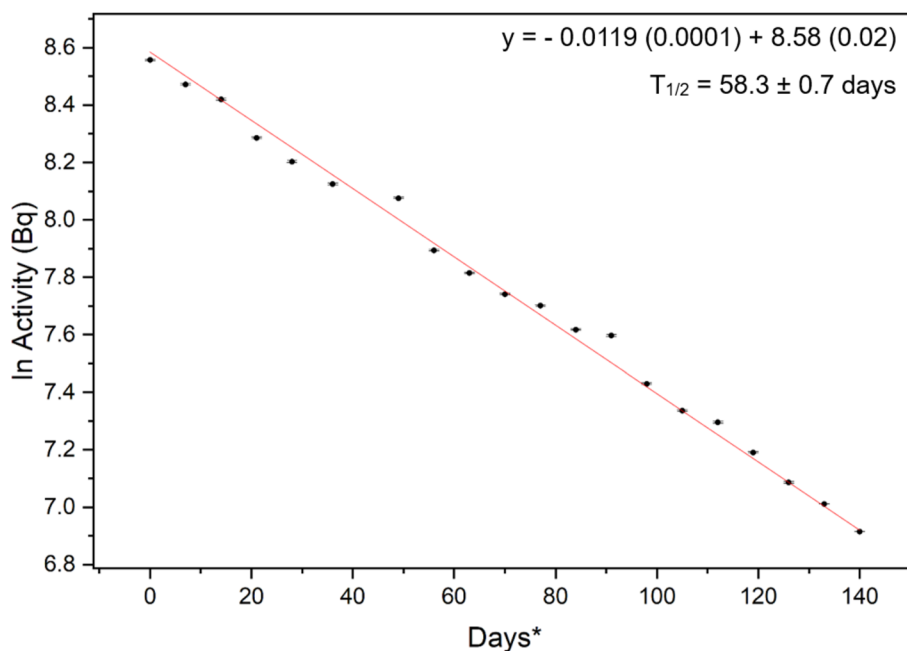
Fonte: Autora, 2025

For both samples, within the uncertainty, the experimental value of the $T_{1/2}$ of ^{125}I is consistent; therefore, the activities were correctly calculated using the sum-peak method. Regarding the contamination levels presented in Tables 5 and 6, for comparison purposes, acceptable contamination

values from international manufacturers of NaI solution were consulted in the literature.

According to NEN Radiochemicals, the concentration of ^{126}I should be less than 0.04% [10], while IZOTOP indicates a value less than or equal to 0.005% [11]. According to previous research conducted at CETER by [19],

Fig. 15 Graph of iodine-125 activity in sample B * Time interval after the 1st measurement (days)



* Time interval after the 1st measurement (days)

the acceptable contamination level for ^{126}I should be less than 0.9% [19]. Considering the contamination levels of 0.9% and 0.04% [10, 19], both samples of the NaI solution showed values below this index, which indicates, according to these references, that they are suitable for use in the production of seeds. However, for the reference index of 0.005% [11], it would be necessary to wait a longer decay time before the solution could be used.

In terms of activity, both solutions showed initial activity values higher than those of interest for the manufacture of seeds for prostate cancer (0.2 to 0.8 mCi). It is possible to dilute this solution or use part of it to make the seeds. Furthermore, considering the manufacturing time for the ^{125}I seeds, in which the solution must be adhered to a silver wire and encapsulated with titanium, and the time for arrival at hospitals and clinics, the logistics can be adjusted to these parameters so that the activity of the seed decays to the correct level upon arrival at its destination.

Conclusion

Cancer is a public health problem in Brazil and worldwide; therefore, research that contributes to the development of treatments, such as brachytherapy, is extremely necessary. The ^{125}I seed, especially for prostate cancer, is being developed nationally at CETER-IPEN, made possible thanks to the availability of the IEA-R1 Nuclear Reactor.

This work produced and analyzed the NaI solution used in the seed production process, determining the levels of ^{126}I contamination in the ^{125}I . The following parameters and conclusions were established:

- After one week following the end of neutron irradiation, it is possible to perform the first measurement of the sample without significant interference from the xenon-125 isotope and with ^{126}I contamination in ^{125}I less than 0.005%, a reference index adopted by one of the international manufacturers of NaI.
- To determine the activity of ^{125}I and ^{126}I in the NaI solution, using data obtained with the HPGe detector, different analysis methods were established due to the particularities of each radioisotope (depending on energy, γ intensity, and the presence or absence of a sum-peak in the spectra). For ^{125}I , the sum-peak correction method was used, verified by plotting the decay curve and calculating the experimental $T_{1/2}$, while for ^{126}I , an efficiency curve of $^{166\text{m}}\text{Ho}$ was used to calculate the activity. Both methods proved suitable for these applications, considering a 1 μL aliquot of NaI.
- Using the defined parameters: irradiation time (t_i) = 48 h; decay time (t_w) = 1 week, neutron flux (ϕ) = $4.5 \times 10^{13} \text{ n. cm}^{-2} \text{ s}^{-1}$ and the injection of approximately 15 mg of xenon gas into the irradiation capsule, a NaI solution with known ^{126}I contamination was obtained which, according to two references [10, 19], has an acceptable

contamination level for the solution to be used in the production of ^{125}I seeds.

Acknowledgements The authors thank the Nuclear and Energy Research Institute (IPEN), the funding agencies São Paulo Research Foundation (FAPESP) 2017/50332-0, the Coordination for the Improvement of Higher Education Personnel (CAPES) 88887.667254/2022-00, the National Nuclear Energy Commission (CNEN), and the International Atomic Energy Agency (IAEA) BRA-6062 for funding this project. We also thank Dr. Mauro Dias for his contributions to the sum-peak correction method.

Author contributions All authors contributed to the study conception and design. Ilca M. M. A. Medeiros: Writing—original draft, conceptualization, investigation, data curation, formal analysis, visualization, validation and methodology; João A. Moura: Methodology and investigation; José A. G. Medeiros: Formal Analysis, writing—review & editing, data curation; Ana C. S. S. Koka: Software, writing—review & editing, data curation; Lucas V. Angelocci: Software and writing—review & editing; Maria E. C. M. Rostelato: Resources and funding acquisition; Carlos A. Zeituni: Methodology, project administration, conceptualization, resources, writing—review & editing, supervision and funding acquisition. All authors read and approved the final manuscript.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614). Coordination for the Improvement of Higher Education Personnel (CAPES), 88887.667254/2022-00

Data availability The Ungdata surveys that support the findings of this study are available from Nuclear and Energy Research Institute (IPEN), but restrictions apply to the availability of these data, which were used under licence for the current study and so are not publicly available. The data are, however, available upon request and with the permission of Nuclear and Energy Research Institute (IPEN).

Declarations

Conflict of interest Coordination for the Improvement of Higher Education Personnel (CAPES): 88887.667254/2022-00—Scholarship and funding National Nuclear Energy Commission (CEN)—BDT-IPEN/CNEN—Scholarship São Paulo Research Foundation (FAPESP) 2017/50332-0 and International Atomic Energy Agency (IAEA) BRA-6062—Funding.

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