# METHOD FOR DETERMINING $^{14}C$ FROM RADIOACTIVE WASTE GENERATED BY THE TRIGA REACTOR

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*Abstract*

Two methods for $^{14}C$ determination in the radioactive waste generated by the TRIGA reactor operation, namely combustion and acid stripping were studied. Combustion is used to separate $^{14}C$ from other radionuclides present in the radioactive waste. The analytical method used for inorganic and organic $^{14}C$ measurement is based on the acid dissolution and wet oxidation processes. The results obtained represent preliminary data for determining $^{14}C$ in different waste streams generated by TRIGA reactor operation. They also are used as support in selecting the treatment and conditioning methods in accordance with the waste acceptance criteria for their disposal in National Repository Băița-Bihor.

***Keywords:*** *Liquid scintillation counting, Combustion, Activity, Acid stripper, Radioactive waste*

## Introduction

The low-level waste (LLW) generated by nuclear power plants, medical laboratories, and academic institutions contain the long-lived radionuclide $^{14}C$. Disposing of $^{14}C$-contaminated waste at LLW disposal facilities is a concern due to $^{14}C$ high mobility in the environment. $^{14}C$ is a long-lived radionuclide with a half-life of 5,730 years. During radioactive decay, the nucleus emits a single beta particle ($\beta^-$) with an energy of 0.156 MeV (mega electron volts).

The primary method of producing $^{14}C$ in a nuclear reactor is by the neutron activation of stable nitrogen-14 ($^{14}N$). Neutron activation of stable oxygen-17 ($^{17}O$) produces the remainder of $^{14}C$. Neutron activation of nitrogen-14 ($^{14}N$), an impurity found in nonfuel reactor components, produces $^{14}C$. Depending on the $^{14}N$ level, the activated metal waste may contain significant amount of $^{14}C$. Additional $^{14}C$ produced in the coolant may contribute to the contamination of other waste types, including ion-exchange resins, concentrated liquids, filter sludge, cartridge filters, and trash [1].

The TRIGA reactor is an open pool reactor with dual operation, featuring two reactors: a 14 MW Steady State Reactor, SSR, and an Annular Core Pulsing Reactor, ACPR - with a maximum of 20000 MW/pulse). This research reactor is operated by the Institute for Nuclear Research Pitesti (RATEN ICN) since 1980, being used for material testing (nuclear fuel and structural materials), fundamental research, and production of radioisotopes for sealed radiation sources for medical, agricultural, and industrial applications [2].

Most of the radioactive waste generated by TRIGA reactor operation falls in the category of low and intermediate level waste (LILW) which may be treated and conditioned to meet the waste acceptance criteria for their disposal in National Repository Băița Bihor.

The liquid wastes are collected and stored in eight tanks, according to the generation sources, and following proper control they are transferred to the Radioactive Waste Treatment Department (STDR) for treatment and conditioning before disposal. Solid LLW are generated by various everyday operations performed in the reactor, which are then sorted and collected as compactable (paper, textile, plastic, rubbers) or non-compactable radioactive waste (tools, metallic parts, glass) and transferred to STDR for processing before disposal. Another category of solid radioactive waste is the spent ion exchange resins generated from TRIGA purification system.

This paper provides information about the activity concentration of $^{14}C$ in the waste produced by the TRIGA reactor and has two major goals: (1) to apply a destructive method in order to convert the waste from solid to liquid form; and (2) to measure $^{14}C$ activity concentration using Liquid Scintillation Counting (LSC).

LSC is a highly sensitive and widely used technique for detecting and quantifying radioactivity. The sample must be prepared so that liquid scintillation analyzer can measure a homogeneous mixture of sample and scintillation solution [3].

The scintillation solution (the cocktail) is made up of a solvent and a solute (scintillator). The counting efficiency is critical in this technique for radioactivity detection and quantification since it can be affected by a variety of factors, including chemical quench that occurs during the transfer of energy from solvent to scintillator. Another very important factor is color quench, which is the reduction of liquid in a solution [4].

To determine the counting efficiency and calculate DPM (Disintegration Per Minute), quench curves must be developed for each radionuclide, in our case $^{14}C$. A quench standard curve is a series of standards, each containing the same amount of nuclide with varying amount of quenching agent. A quench curve uses the relationship between counting efficiency and QIP (Quench Indicating Parameters) to correct the measured CPM (Counts Per Minute) to DPM, [5].

The method used in this work is the tSIE/AEC (transformed Spectral Index of External Standard coupled to Automatic Efficiency Correction). tSIE assigns a numerical value to each quench associated with a sample. As the quench varies, the AEC automatically monitors and adjusts the counting region to avoid unwanted background (Figure 1). The counting efficiency is obtained using the following Eq. (1), [6]:

$$Efficiency\% = \frac{Counts\ per\ minute}{Disintegration\ per\ minute} \qquad (1)$$

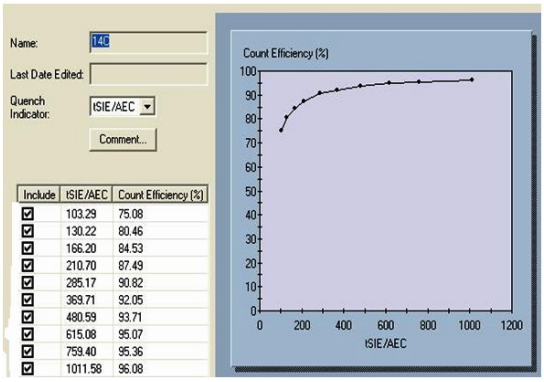



Fig. 1. Quench curve $^{14}C$

## Materials and methods

### *Materials*

The radioactive waste generated by the TRIGA reactor contains a wide range of radionuclides, therefore to measure the concentration activity of $^{14}C$ in each category of waste, it has to be transferred in liquid phase and separated from other interfering radionuclides (i.e. mainly gamma radionuclides that emit both gamma rays and beta particles by their disintegration).

After the application of the first method, representative samples of solid waste type paper (labeled C1-H&C10-H) resulting from radiochemical laboratories, and spent ion exchange resin resulting from purification system (labeled C1-R&C10-R) were sampled and analyzed by liquid scintillation cocktail PERMAFLUOR $E^+$, whose chemical composition is shown in the table below.

Table 1. Chemical composition of PERMAFLUOR E+

| *Component* | *Name* | *Composition (weight %)* |
|---|---|---|
| ***Solvents*** | 1,2,4-trimethylbenzene<br>1-methoxy-2-propanol | 80-100<br>10-20 |
| ***Scintillators*** | 2,5-Diphenyloxazole (PPO)<br>1,4-Bis-(2-methylstyryl)-benzene (bis-MSB) | ≤ 2.5<br>≤ 2.5 |

After the application of the second method, representative samples of solid waste type paper (labeled B2-P, B3-P, B5-P, B6-P) resulting from radiochemical laboratories, and spent ion exchange resin resulting from purification system (labeled B2-R, B3-R, B5-R, B6-R) were sampled and analyzed by liquid scintillation cocktail Hionic-Fluor, whose chemical composition is shown in the table below.

Table 2. Chemical composition of Hionic-Fluor

| *Component* | *Name* | *Composition (weight %)* |
|---|---|---|
| ***Solvents*** | 1,2,4-trimethylbenzene<br>Phosphoric acid, butyl ester, with 2.2'-iminobis(ethanol)<br>Ethyyhexyl phosphate diethanolamine salt<br>Alkylphenol polyglycolether<br>Triethyl phosphate<br>Alkylphenol ploxyglycolether<br>Sodium dioctyl sulphosuccinate | 40-60<br>10-20<br>2.5-10<br>2.5-10<br>2.5-10<br>2.5-10<br>2.5-10 |
| ***Scintillators*** | 2,5-Diphenyloxazole (PPO)<br>1,4-Bis-(2-methylstyryl)-benzene (bis-MSB) | 2.5<br>2.5 |

### *Methods and experimental setup*

*Gamma ray spectrometry*

The gamma ray spectrometry is a non-destructive technique that does not require a laborious sample preparation. Gamma-ray spectrometry allows identifying and quantifying a wide range of radioisotopes [7] due to well-defined gamma ray energies and high-resolution γ-ray spectrometers available. The main components of the gamma-ray spectrometry are a detector interface module (DIM-ORTEC), a DigiDART portable multichannel analyzer, Gamma Vision 32 software for energetic spectra acquisition, and Genie2000 software for spectra analysis. The first step in gamma spectrometry analysis is the energy and efficiency calibration to obtain accurate and reliable results. For gamma measurements of paper and resin samples in contact with the HPGe detector, the configuration was established for plastic vials type TRICARB, with a volume of 10 ml.

Gamma ray spectrometry was used to analyze the radioactive solid waste, including paper and spent ion exchange resins.

$^{137}Cs$ has a 30.2-year half-life ($T_{1/2}$). When it undergoes radioactive decay, about 94% of the time the $^{137}Cs$ nucleus decays to Barium -137m ($^{137m}Ba$, a metastable state of $^{137}Ba$), and emits a 514 keV beta particle ($\beta^-$, a negative electron emitted from the nucleus). Approximately 6% of the initial $^{137}Cs$ atoms decay directly to $^{137}Ba$, emitting a 1,176 keV beta particle. Some of $^{137}Cs$ atoms decay to $^{137m}Ba$, and therefore produce a 514 keV beta particle, while 90% of subsequent $^{137m}Ba$ atoms produce a 662 keV (0.662 MeV) gamma ray. The 662 keV gamma ray is often associated with $^{137}Cs$, due to the short half-life of $^{137m}Ba$ (≈153 seconds) [3]. $^{137}Cs$ has a relatively low melting point of 28.5 °C and it becomes easily volatile at high temperature.

$^{60}Co$ has a half-life of 5.2 years [3]. However, there is an isometric excited state of $^{60}Co$ with a measurable half-life of 10.5 minutes.

This isometric state has a half-life long enough to allow for direct decay to nickel-60 ($^{60}$Ni) with the emission of a negative beta particle ($\beta^-$) in less than 1% of the time period. Otherwise, this isometric form decays to the ground state of $^{60}$Co by the emission of a gamma ray [3]. $^{60}$Co has a melting point of 1495 °C.

Gamma spectrometry revealed only $^{60}$Co in the analyzed spent ion exchange resins samples, with an activity concentration of $4.25 \times 10^3 \pm 5.25 \times 10^1$ kBq/kg, while $^{137}$Cs was detected in the solid waste paper samples, with an activity concentration of 2.75 ± 0.26 kBq/kg.

*Combustion of solid radioactive waste*

To measure the $^{14}$C content in the solid radioactive waste, this radionuclide has to be extracted from the waste matrix in a solution and, because it is a low beta emitter, the absence of other beta-gamma emitters in the samples to be analyzed by LSC is a prerequisite.

The PerkinElmer Sample Oxidizer, Model 307, provides an automatic method for preparing a sample for measuring $^{14}$C by LSC. According to the Operation Manual of the equipment [8], the performance during the combustion process requires that all carbon isotopes, including $^{14}$C, be oxidized to carbon dioxide gas. Dioxide gas is trapped by vapour-phase reaction with an amine (CARBO-SORB E), and the resulting product (CARBONATE) is mixed with the LSC cocktail (PERMAFLUOR E+) directly in the counting vial (Figure 2), [9].



Fig.2. Model 307 PerkinElmer Sample Oxidizer

Before the combustion of the sample waste, preliminary tests are performed to evaluate the $^{14}$C recovery according to the Operational Manual, using a verification procedure. One of the prepared combusto-cones received 0.2mL of $^{14}$C inactive organic SPEC-CHEC from Packard solution via pipette. The cone was then inserted into the ignition basket and the sample was burned.

When the program was completed, the $^{14}$C collection vial was removed and labeled with 1BKG. The same procedure as in step two was applied for the next three vials: 2-STD, 3-STD and 4-STD. Then, 0.2 mL standard solution from Packard ($^{14}$C organic SPEC-CHEC standard with certified concentration of $9.29 \times 10^5$ DPM/mL ± 3% at May 2017) was pipetted into each of the three vials. Then, 0.2 mL of $^{14}$C SPEC-CHEC solution radioactive was pipetted into a combusto-cone and, the sample was immediately combusted. The $^{14}$C collection vial was labeled with 5REC. Steps 5 and 6 were completed by repeating the previous step. The $^{14}$C collection vials were labeled with 6REC and 7REC. Following stabilization, the seven vials were counted by liquid scintillation using TriCarb3110TR. The recovery is defined by Eq. (2):

$$\%Recovery = \left[\frac{REC\ sample\ dpm}{Avg\ STD\ dpm}\right] \times 100 \qquad (2)$$

The $^{14}$C recovery yield was in the range of 95-100% (see Table 3) with an average of 97.8%, this value being used to correct the experimental results obtained on the radioactive waste paper-type and spent ion exchange resin.

Table 3. $^{14}$C recovery

| Sample code | DPM [dpm] | Recovery (%) |
|---|---|---|
| 1BKG | 43 | |
| 2-STD | 175618 | |
| 3-STD | 172306 | |
| 4-STD | 172245 | |
| 5REC | 164911 | 95 |
| 6REC | 171032 | 98.6 |
| 7REC | 174872 | 100 |
| Average Rec = 97.8% | | |

The dry samples (paper or resin) were weighed (0.2 g) and loaded into combusto-cones. The combusto-cones are made of natural cellulose fiber, which produces no residue in the combustion process and has no effect on the resulting samples that can be examined by LSC. The whole procedure of combustion takes 0.6-0.9 minutes, at 1100 °C with oxygen flow.

When using PERMAFLUOR E+, the counting efficiency will be partially dependent on the ratio of the volume of PERMAFLUOR E+ to CARBO-SORB E dispensed. Taking into account this finding, we decided to use a mixture of 10ml CARBO-SORB E and 10ml PERMAFLUOR E+ in a routine sample preparation [8], with the process gases passing through one bubble flask containing 50 mL of concentrated HCl to retain any potential $^{137}$Cs released in gaseous forms from the solid waste sample. The ashes from the combustion process may contain other radionuclides, such as $^{60}$Co, due to the lower combustion temperature (1100 °C) compared to its melting temperature.

$^{14}$C concentration in the samples obtained by combustion was measured by LSC, using Low Activity Count Mode (typical count rate between 50 and 500 CPM, and count time of 600-1000 minutes). The uncertainties (2σ%) are minor due the low values of activities from the liquid scintillation counting.

*Acid dissolution and wet oxidation*

The analytical method used for inorganic and organic $^{14}$C measurement in solid and spent ion exchange resin waste generated by the TRIGA reactor operation is based on the acid dissolution and wet oxidation, adapted after the method developed by Magnusson et al. for $^{14}$C measurement in spent ion exchange resins and process water [10].

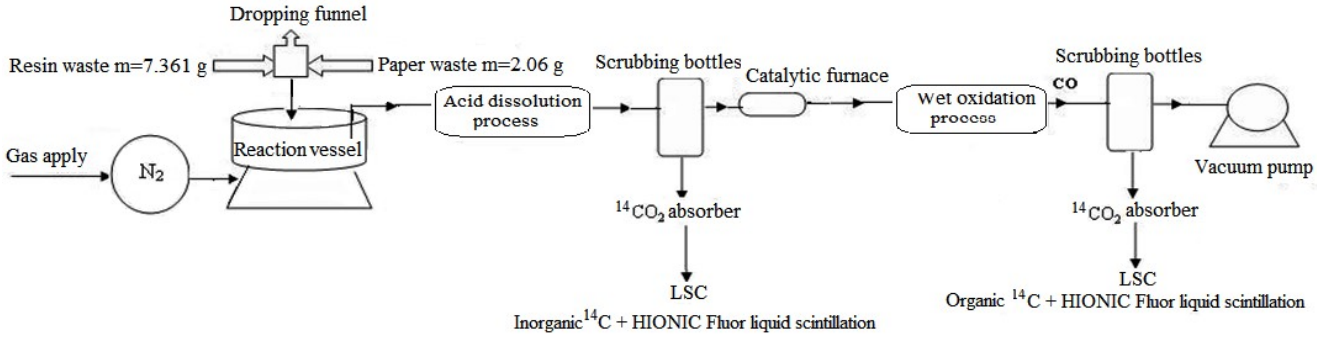



Fig. 3. Flow diagram of sample preparation for acid stripping and wet oxidation

## Results and discussion

### *Combustion of solid radioactive waste*

To determine the concentration of $^{14}C$ in solid waste paper type, ten samples (labeled C1-H to C10-H) were analyzed. Figure 4 shows that there are no significant differences between the average $^{14}C$ activity concentration of 3.19± 0.76 kBq/kg (Table 4) and the background activity concentration of 3.08±0.72 kBq/kg. At the end of the combustion process, to follow the $^{137}Cs$, 10mL of solution were taken from bubble flask and measured by gamma spectrometry. Following the measurements carried out by gamma spectrometry of the solution sampled from the reaction vessel $^{137}Cs$ with an activity of 2.35±0.19 kBq/kg was found, very close to the initial activity measured by gamma spectrometry (2.75±0.26 kBq/kg).

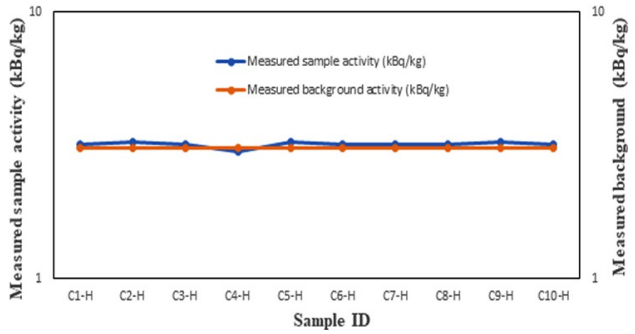



Fig. 4. Measured activity of $^{14}C$ in solid waste paper type

Table 4 Experimental data on $^{14}C$ measurement in solid waste paper type

| Sample ID | Activity ± uncertainty counting [kBq/kg] | Activity ± uncertainty counting * [kBq/kg] |
|---|---|---|
| C1-H | 3.25±0.75 | 3.17±0.74 |
| C2-H | 3.33±0.79 | 3.25±0.78 |
| C3-H | 3.25±0.75 | 3.17±0.74 |
| C4-H | 3.00±0.73 | 2.93±0.72 |
| C5-H | 3.33±0.79 | 3.25±0.78 |
| C6-H | 3.25±0.77 | 3.17±0.76 |
| C7-H | 3.25±0.79 | 3.17±0.78 |
| C8-H | 3.25±0.79 | 3.17±0.78 |
| C9-H | 3.33±0.77 | 3.25±0.76 |
| C10-H | 3.25±0.79 | 3.17±0.78 |
| Average activity =3.19±0.76 kBq/kg | | |

* Measured Activity Corrected for Combustion Recovery (97.8%)

### *Combustion of spent ion exchange resin*

For a more accurate assessment of the $^{14}C$ activity concentration in spent ion exchange resin waste, ten samples (labeled C1-R to C10-R) were analyzed. Figure 5 shows that there are no significant differences between the $^{14}C$ activity concentration of (3.16±0.76 kBq/kg) and the background activity concentration of (3.08±0.74 kBq/kg). At the end of the combustion process, $^{14}C$ is retained together with liquid scintillation, while $^{60}Co$ will remain in the ashes resulting from the combustion process.

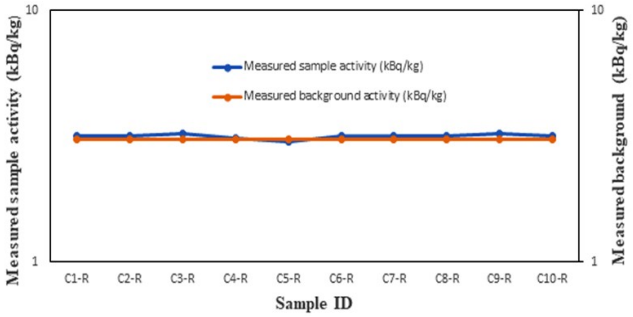



Fig.5. Measured activity of $^{14}C$ in spent ion exchange resin waste

Table 5 Experimental data on $^{14}C$ measurement in spent ion exchange resin waste

| Sample ID | Activity ± uncertainty counting [kBq/kg] | Activity ± uncertainty counting * [kBq/kg] |
|---|---|---|
| C1-R | 3.25±0.79 | 3.17±0.78 |
| C2-R | 3.25±0.78 | 3.17±0.77 |
| C3-R | 3.33±0.78 | 3.25±0.77 |
| C4-R | 3.16±0.76 | 3.09±0.75 |
| C5-R | 3.08±0.70 | 3.01±0.69 |
| C6-R | 3.08±0.77 | 3.17±0.76 |
| C7-R | 3.25±0.74 | 3.17±0.73 |
| C8-R | 3.25±0.79 | 3.17±0.79 |
| C9-R | 3.33±0.83 | 3.25±0.82 |
| C10-R | 3.25±0.83 | 3.17±0.82 |
| Average activity =3.16±0.76 kBq/kg | | |

* Measured Activity Corrected for Combustion Recovery (97.8%)

### *Acid stripping and wet oxidation of solid radioactive waste*

The first category of waste of interest for $^{14}C$ measurement is the solid waste paper type generated from the TRIGA reactor operation and radiochemical laboratories. A stage of acid stripping and a stage of wet oxidation were applied. Samples of paper waste (2.06 g each) were placed in a reaction vessel connected to a gas collection line consisting of two 7mL traps of 2M NaOH (B2, B3-anorganic $^{14}C$) and two 7mL traps of 2M NaOH (B5, B6-organic $^{14}C$).

For acid stripping stage, 100mL $H_2SO_4$ were used (Figure 6), while for wet oxidation stage, 30mL $K_2S_2O_8$, 12mL $AgNO_3$ and 5mL distillation water were used (Figure7).

To measure the $^{14}C$ released in the gas phase during acid stripping/wet oxidation, two samples from the B2 and B3 inorganic $^{14}C$ traps, and two samples from the B5 and B6 organic $^{14}C$ traps, were prepared using 1ml solution resulted from the acid stripping/wet oxidation with 10ml of HionicFluor liquid scintillation cocktail. The results obtained by LSC measurements are presented in Table 6.

A sample from the reaction vessel was also analyzed using γ-spectrometry to determine if any other radionuclides, in our case $^{137}Cs$, were removed from the solid waste during acid stripping/wet oxidation. After measuring the solution from the reaction vessel, $^{137}Cs$ was found to have an activity 2.25±0.12 kBq/kg, which was similar to the initially measurement on the paper sample by gamma spectrometry (2.75±0.26 kBq/kg). This result indicates that the $^{137}Cs$ was completely retained in the reaction vessel, and it is not possible to alter the $^{14}C$ activity measurements obtained by liquid scintillation counting.

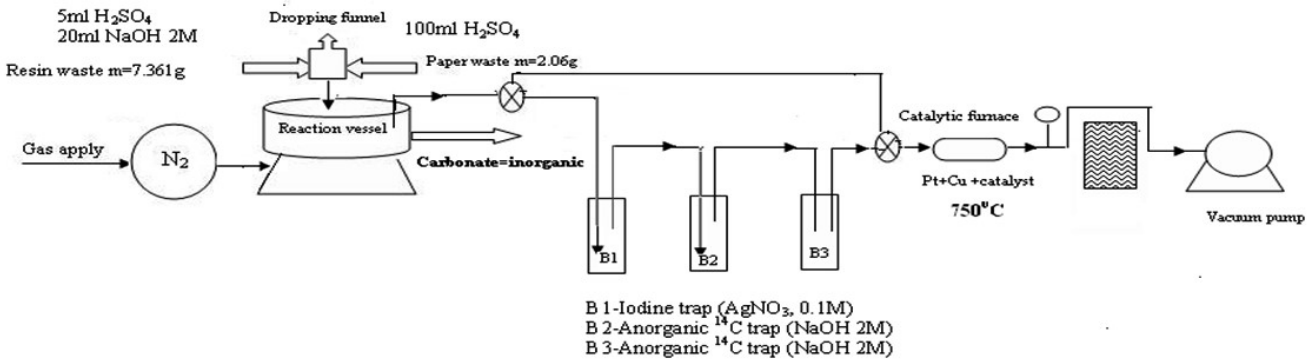



Fig. 6. Acid stripping experimental setup for separation of inorganic $^{14}C$

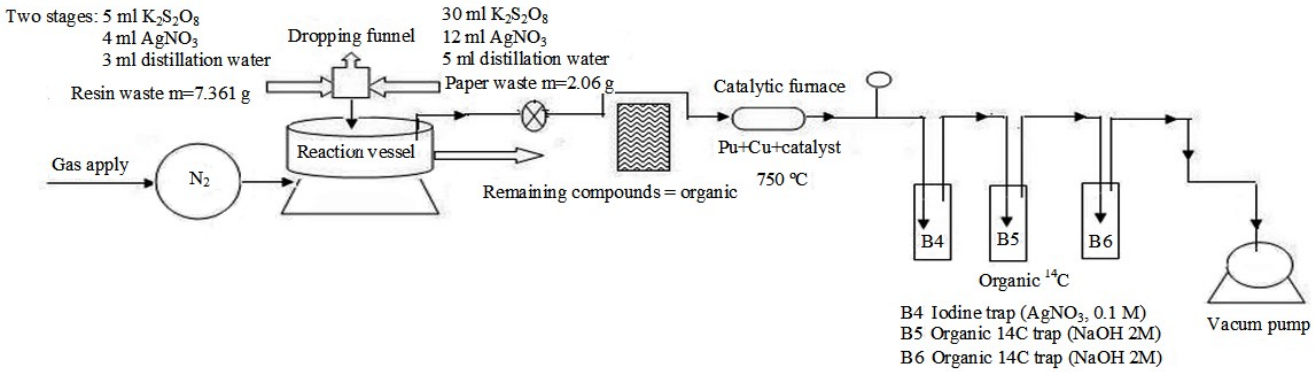



Fig. 7. Wet oxidation experimental setup for separation of organic $^{14}C$

Table 6 Experimental data on $^{14}C$ measurement in solid waste type paper

| Sample ID | Inorganic $^{14}C$ activity [DPM] | Inorganic $^{14}C$ activity [DPM] | Inorganic $^{14}C^*$ Activity ± uncertainty counting [kBq/kg] | Organic $^{14}C^*$ Activity ± uncertainty counting [kBq/kg] |
|---|---|---|---|---|
| #1-B2-P | 37 | | - | |
| #1-B3-P | 37 | | - | |
| #1-B5-P | | 39 | | 1.13 ± 0.25 |
| #1-B6-P | | 39 | | 1.13 ± 0.25 |
| Background | 37 | | Total $^{14}C$ organic activity =1.13 ± 0.25 kBq/kg | |

*$^{14}C^*$ activity = $^{14}C$activity-background*

***Acid stripping and wet oxidation of spent ion exchange resin***

The second waste category of interest for $^{14}C$ measurement is the resin waste type paper generated by the TRIGA purification system, for which we performed one stage of acid stripping and two stages of wet oxidation. The experimental tests were done on 7.361g sample of resin waste using 5mL $H_2SO_4$ and 20mL NaOH 2M as stripping acids (Figure 5) and 5mL $K_2S_2O_8$, 4mL $AgNO_3$ and 3mL distillation water as reagent oxidation (Figure 6), with two wet oxidation stages. The reaction vessel was connected to a gas collecting line consisting of two 10mL traps of 2M NaOH (B2, B3-inorganic $^{14}C$) and two 10mL traps of 2M NaOH (B5, B6-organic $^{14}C$).

To measure the $^{14}C$ released in the gas phase during acid stripping/wet oxidation, two samples from the B2 and B3 inorganic $^{14}C$ traps, as well as two samples from the B5 and B6 organic $^{14}C$ traps, were prepared using 1ml solution resulted from the acid stripping/wet oxidation with 10mL of HionicFluor liquid scintillation cocktail. The results obtained by LSC measurements are shown in Table 7.

Table 7 Experimental data on $^{14}C$ measurement in solid spent resin waste

| Sample ID | Inorganic $^{14}C$ activity [DPM] | Inorganic $^{14}C$ activity [DPM] | Inorganic $^{14}C^{*}$ Activity ± uncertainty counting [kBq/kg] | Organic $^{14}C^{*}$ Activity ± uncertainty counting [kBq/kg] |
|---|---|---|---|---|
| #1-B2-R | 40 | | 0.80 ± 0.04 | |
| #1-B3-R | 36 | | - | |
| #1-B5-R | | 38 | | 0.22 ± 0.012 |
| #1-B6-R | | 36 | | - |
| Background | 37 | | $^{14}C$ inorganic = 0.80 ± 0.04 | $^{14}C$ organic = 0.22 ± 0.012 |

*$^{14}C^{*}$ activity = $^{14}C$activity-background*

## Conclusions

The determination of $^{14}C$ is essential in the treatment and conditioning of the radioactive waste generated by TRIGA reactor operation in accordance with the waste acceptance criteria for disposal at the National Repository Băița-Bihor. The main gamma emitters present in the paper-type solid radioactive waste and spent ion exchange resin are $^{137}Cs$ and $^{60}Co$, respectively. To measure the activity concentration of $^{14}C$ from this radioactive waste, an important step is to select methods that have as main objective separating this radionuclide from interference, such as $^{137}Cs$ and $^{60}Co$.

$^{14}C$ was extracted from the waste of interest using combustion and acid dissolution/wet oxidation, while the carbon content of the waste from the TRIGA reactor was determined using liquid scintillation spectrometry. Samples that are not directly soluble in liquid scintillation cocktails, such as solid waste type paper and spent ion exchange resin from TRIGA reactor operation, are processed using the sample oxidation technique. The combustion method offers many benefits when analyzing this type of sample, including the following: 1) a very small amount of sample is used; 2) the sample is rapidly processed; 3) their color quenching is removed; and 4) background counts and chemical quenching variation are reduced. For paper-type solid waste and spent ion exchange resin, the carbon activity value given by the combustion method is around 3.19 ± 0.76 kBq/kg and 3.16 ± 0.76 kBq/kg, respectively.

Most of the information available on the measurement and characterization of $^{14}C$ in solid waste and spent ion exchange resin comes from studies conducted using methods that were generally intended to assess the total $^{14}C$ content. However, the chemical forms of $^{14}C$ (organic and inorganic), which behaves differently in environmental components, are an important factor when estimating doses arising from the releases to the environment. This represents an essential advantage in using the acid stripping/wet oxidation. The acid stripping/wet oxidation method yields carbon activity values of approximately 1.13 ± 0.25 kBq/kg for paper-type solid waste, and 0.80 ± 0.04 kBq/kg (inorganic $^{14}C$) and 0.22 ± 0.012 kBq/kg (organic $^{14}C$) for spent ion exchange resin.

From the perspective of the $^{14}C$ activity concentration, the values of the $^{14}C$ activity concentration in the samples obtained after the application of the destructive methods on solid waste type paper and spent ion exchange resin as well as the measurement by liquid scintillation counting are very close, concluding that both methods are indicated/suitable to be applied in the characterization of radioactive waste from the operation of the TRIGA reactor.

## References


[1] Idaho National Engineering Laboratory (1996) *"Selected Radionuclides Important to Low-Level Radioactive waste Management"*, DOE/LLW-238 rep., Idaho Oper. Off., USA

[2] Barbos, D., Ciocanescu, M., Paunoiu, C. (2016) "TRIGA 14 MW Research Reactor Status and Utilization", incl. in "*History, Development and Future of TRIGA Research Reactors*", International Atomic Energy Agency, Technical Reports Series No 482, ISSN 0074-1914, pp. 1-10.

[3] Passo, C.J., Cook, G.T. (1994) *"Handbook of Environmental Liquid Scintillation Spectrometry. A Compilation of theory and methods"*, Packard Instrument Company.

[4] L'Annunziata, M.F. (2003) *"Handbook of Radioactivity Analysis*", Elsevier Science, USA.

[5] Kessler, M.J. (Ed.) (1989) *"Liquid Scintillation Analysis. Science and Technology"*, Packard Instrument Company.

[6] PerkinElmer Inc. *"QuantaSmartTM for the Tri-Carb® Liquid Scintillation Analyzer (Models B2810TR, B2910TR, B3110TR, and B3180TR/SL). Reference Manual"*, USA

[7] ORTEC AMETEK *"ORTEC Solid-State photon Detector GEMI15P4 - Reference Manual"*, HPGe Radiation Detector Types, GEM P-type Coaxial High Purity Germanium (HPGe) Radiation Detectors, USA.

[8] Bujoreanu, L., Bujoreanu, D. (2014) "LSC Method for C-14 Measurement in Solid Radioactive Waste", Proc. of 7th Ann. Int. Conf. on Sust. Develop. through Nucl. Res. and Education, Nuclear 2014, ICN Pitesti, Romania.

[9] PerkinElmer Inc. *"Model 307 PerkinElmer Sample Oxidizer. Reference Manual"*, USA.

[10] Magnusson, Å., Stenström, K., Aronsson, P.-O. (2007) "$^{14}C$ in spent ion-exchange resins and process water from nuclear reactors:A method for quantitative determination of organic and inorganic fractions", *J. of Radioanalytical and Nucl. Chemistry*, Vol. 275(2), pp. 261-273.

[11] Bucur, C., Fulger, M., Florea, I., Tudose, A. (2018) "$^{14}C$ Content in CANDU Spent Fuel Claddings and Its Release Under Alkaline Conditions", *Radiocarbon Journal*, Vol. 6(6), pp. 1773-1786, https://doi.org/10.1017/RDC.2018.132, Selected Papers from the European Commission CAST (Carbon-14 Source Term) Project.

[12] Bujoreanu, L. (2025) "Methods for Determining 3H from Radioactive Waste Generated by TRIGA Reactor", *J. of Nuclear Research and Development*, Nr. 29, pp. 53-58.