# INDUCED RADIOISOTOPES INSIDE THE TREATMENT HALL WITH A LINAC FOR RADIOTHERAPY

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## Abstract

When linacs operate above 8 MV an undesirable neutron field is produced whose spectrum has three main components: the direct spectrum due to those neutrons leaking out from the linac head, the scattered spectrum due to neutrons produced in the head that collides with the nuclei in the head losing energy and the third spectrum due to room-return effect; this last are mainly epithermal and thermal neutrons being constant at any location in the treatment hall. These neutrons induce activation mainly in the concrete walls and the linac components. Here the induced radioisotopes have been identified in concrete samples located in the hall and in one of the wedges. The identification has been carried out using a gamma-ray spectrometer.

***Keywords***: Radioisotopes; LINAC; Neutron physics

# 1.- INTRODUCTION

Up to now more than two hundred types of cancer have been identified and are treated by different methods depending on the lesion type and its progression [Lenox 2001; Vega-Carrillo *et al*., 2010], the treatment procedures include surgery, radiotherapy and chemotherapy. The radiotherapy is used as teletherapy or brachytherapy, with electrons, photons (X or $\gamma$), neutrons, protons, alphas and heavy ions. These particles deliver a lethal radiation dose in a tumor seeking the surrounding healthy tissue receives the lowest dose and therefore the least possible damage [Vega-Carrillo *et al*., 2010; Zabihzadeh *et al*., 2009; Ognaro *et al*., 2000; Roussin, Kirk and Trubey 2004; Price, Nath and Holeman 1978].

The x-ray or electron therapeutic beams are produced in linear accelerators or LINACs that produce neutrons when work with voltages larger than 6 MV, exposing the patient to a non-negligible dose [Barquero *et al*., 2005; Kry *et al*., 2007]; this problem is also present in the Hadrontherapy machines. It has been pointed out that the presence of these neutrons is the probable cause of the recurrence or the induction of secondary tumors [Stathakis, Li and Ma 2007; Kafala and Macmahon 2007].

At any point inside the treatment hall the neutron spectrum, $\Phi_E(E)$ is due to direct neutrons, $\Phi_E(E)_{dir}$, leaking out from the head of the LINAC, the neutrons scattered out from the head of the LINAC, $\Phi_E(E)_s$, and those due to room-return, $\Phi_E(E)_{rr}$. The total neutron fluence, $\phi(r)$, can be calculated using equation 1.

$$\phi(r) = \int_{\forall E} \Phi_E(r, E)\, dE \qquad (1)$$

The, $\phi(r)$, depend upon the neutron source strength, Q, the surface area of the hall-treatment inner walls, S, and the distance from the LINAC's head centre and the point of interest, r, as is shown in equation 2.

$$\varphi(r,S,Q) = Q \left[ \frac{a}{4 \pi r^2} + 5.40 \frac{a}{S} + \frac{c(E)}{S} \right] \quad (2)$$

In this equation a is a neutron transmission factor being 1 if the head is mainly lead and 0.85 if the head is mainly tungsten; the c(E) is a value that depends upon the neutron energy being larger for thermal neutrons and lower for neutrons between 1 and 2 MeV; however an average value of 5.60 has been proposed for the c(E) [Vega-Carrillo *et al*., 2007].

The photoneutrons induce activation in the components of the LINAC head, the walls of the treatment hall, the shielding used to protect some organs of the patient and the patient himself. Due to cross section features the activation is mainly produced by thermal neutrons that are part of the room-return neutrons whose intensity is constant in the treatment hall whose main component is by far the concrete in the walls. The induced activity depends upon the irradiation time, the type of nuclei and its abundance. When the induced radioisotopes decay emitting gamma-rays the photons becomes a radiation protection issue for the LINAC personal, medical staff and the patient.

In the bunker the largest component is the concrete, thus the objective of this work was to identify the radioisotopes that are produced in concrete samples located in one of the primary barriers as the LINAC was used to apply a dose in a phantom.

## 2.- MATERIALS AND METHODS

Mostly of the activation products emit gamma rays during their decay; the photon energy helps to identify the radionuclide, while the amount of photons is proportional to the amount of the induced radioisotope. This work was carried out at the Tepic's Center of Cancerology located in the state of Nayarit in Mexico where there is a Varian 15 MV LINAC.

In order to identify the induced radioisotopes a gamma-ray spectrometer with a 7.62 Ø x 7.62 cm$^2$ NaI(Tl) scintillator was used. The spectrometer was calibrated, in energy and efficiency, using three standard gamma sources: $^{60}$Co, $^{137}$Cs and $^{22}$Na. For each calibration the experimental data were used to obtain fitted functions.

The spectrometer was installed on a Styrofoam base and put in operational mode outside of the treatment room in room far from the LINAC to avoid radiation damage during beam-on, as is shown in figure 1.


Figure 1.- Gamma-ray spectrometer with a 7.62 Ø ×7.62 cm$^2$ NaI(Tl) detector.

The gamma-ray background was measured for 24 hours before the experiments; this spectrum was used to make corrections in the measured pulse height spectra.

In the experiments the accelerator was programmed to deliver 1200 monitor units (MU) at a rate of 300 MU/min using 15 MeV-photon beam in a 20 x 20 cm$^2$ irradiation field size in the isocenter located 5 cm depth of a 30 x 30 x 15 cm$^3$ solid water phantom. The isocenter irradiation time was 4 minutes. After the irradiation the cooling time was measured to make the proper corrections. In order to determine the radioisotopes induced in the concrete, three 2.54 Ø x 1.0 cm$^2$ concrete samples, with 2.34 ± 0.08 g/cm$^3$ density, were prepared using the

National Bureau of Standards composition (NBS concrete) [Harima 1993] shown in the table 1.

Table 1.- Composition of the NBS concrete.

| Element (Atomic number) | Weight fraction [o/w] |
|---|---|
| H (1.008665) | 0.006 |
| O (15.9994) | 0.500 |
| Si (28.086) | 0.315 |
| Al (26.9815) | 0.048 |
| Na (22.9898) | 0.017 |
| Ca (40.0800) | 0.083 |
| K (55.8470) | 0.012 |
| Mg (39.1020) | 0.019 |

Each concrete sample was irradiated independently using the same LINAC´s irradiation features. The samples were localized on a primary concrete barrier in the aim to be part of the concrete wall as is shown in figure 2.


Figure 2.- Site where the concrete samples were located in the treatment room.

After the irradiation the concrete samples were measured with the spectrometer and a pulse height spectrum was obtained, here the channel number where the photopeak´s maximum show up was used with the calibration fitted function to estimate the photon energy, and with this the identity of the radioisotope was found.

The net area under the photopeaks were obtained, and corrections were carried out due to background, cooling and measuring time; the corrected net counts were used with the efficiency fitted function to estimate the induced activity.

In order to shield some organs during the treatment a wedge is eventually used, thus in order to determine the induced activity in the wedge in the last experiment a wedge was located in the LINAC that was set using the same conditions used to irradiate the concrete samples. After the irradiation the detector was located on the top of the wedge and the pulse height gamma-ray spectrum was measured as is shown in figure 3.

Figure 3.- Spectroscopy system to measure a wedge.

# 3.- RESULTS

In order to determine the energy of the photons, and to identify the induced radioisotopes, the spectrometer was calibrated in energy and in efficiency using the calibration sources. In the table 2 are the channel number where the photopeak shows up and the photon detection efficiency in function of the photon energy of the sources using during the calibration.

Table 2.- Source, energy, photopeak channel and detection efficiency.

| **Calibration source** | **Photon energy [keV]** | **Photopeak channel** | **Efficiency [%]** |
|---|---|---|---|
| $^{22}$Na | 511 | 115 ± 2 | 11.25 ± 0.01 |
| $^{137}$Cs | 661 | 148 ± 2 | 12.62 ± 0.01 |
| $^{60}$Co | 1173 | 257 ± 2 | 4.14± 0.01 |
| $^{22}$Na | 1274 | 278 ± 2 | 3.23± 0.01 |
| $^{60}$Co | 1332 | 291 ± 2 | 2.82 ± 0.01 |

Using the values in the second and third columns a linear fit was carried out. The resulting linear function is shown in equation 3. The correlation coefficient was 1.

$$E(Ch) = (29.2971 \pm 3.2186) + (4.6809 \pm 0.0140)\,Ch \qquad (3)$$

Here, the photon energy, E, is in keV while, Ch is the channel number of the photopeak maximum. En figure 4 is shown the experimental data and the fitted function.

Using the values in the second and the fourth columns in table 2, a function was fitted to determine the detection efficiency in terms of the photon energy; the fitted efficiency function is shown in equation 4.

$$\eta(E) = \frac{0.1266 \pm 0.0017}{1 + \left( \frac{E \quad (641.7565 \pm 6.3696)}{(370.0561 \pm 8.4737)} \right)^2} \tag{4}$$

Here, E is the photon energy in keV and η(E) is the efficiency in %. The máximum efficiency is 12.66% for 641.7 keV photons.

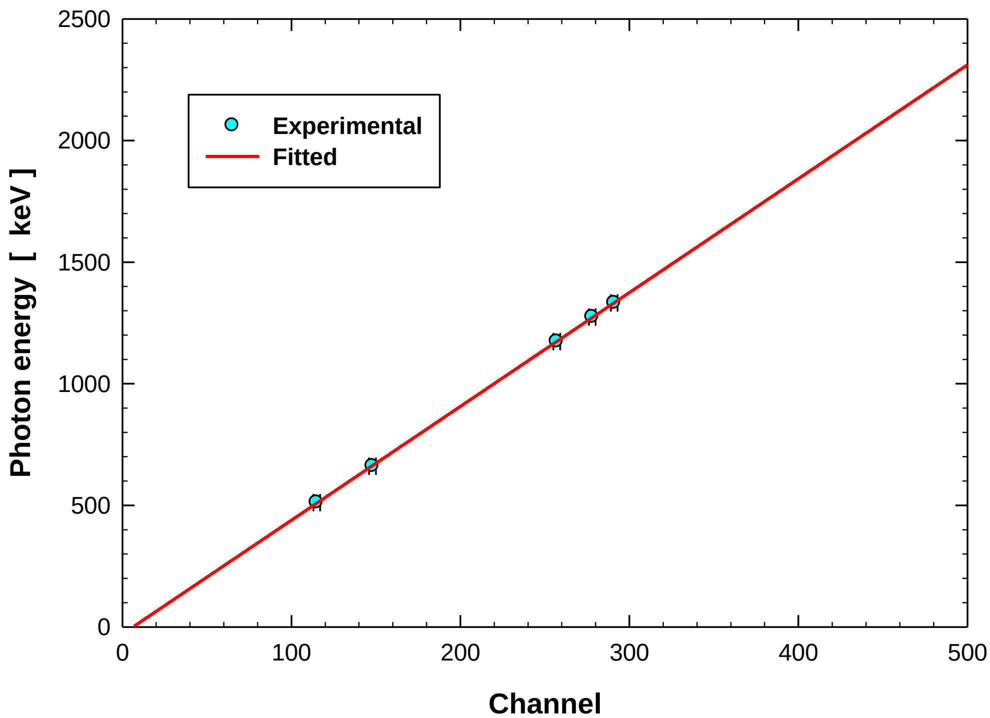


Figure 4.- Calibration of the detector.

In figures 5, 6 and 7 are shown the pulse height spectra of the three concrete samples; in the figures the identity of the photopeaks are included being: 846 keV, 1368 keV and 1778 keV which are emitted by $^{56}$Mn, $^{24}$Na and $^{28}$Al respectively.

The features of the induced radioisotopes in the concrete are shown in the table 3.

Table 3.- Features of the radioisotopes induced in the concrete samples.

| Element | Nuclide | Gamma lines measured [keV] | Half life |
|---|---|---|---|
| Al | $^{28}$Al | 1778.8 | 2.24m |
| Na | $^{24}$Na | 1368.6 | 14.96 h |
| Mn | $^{56}$Mn | 846.8 | 2.58 h |

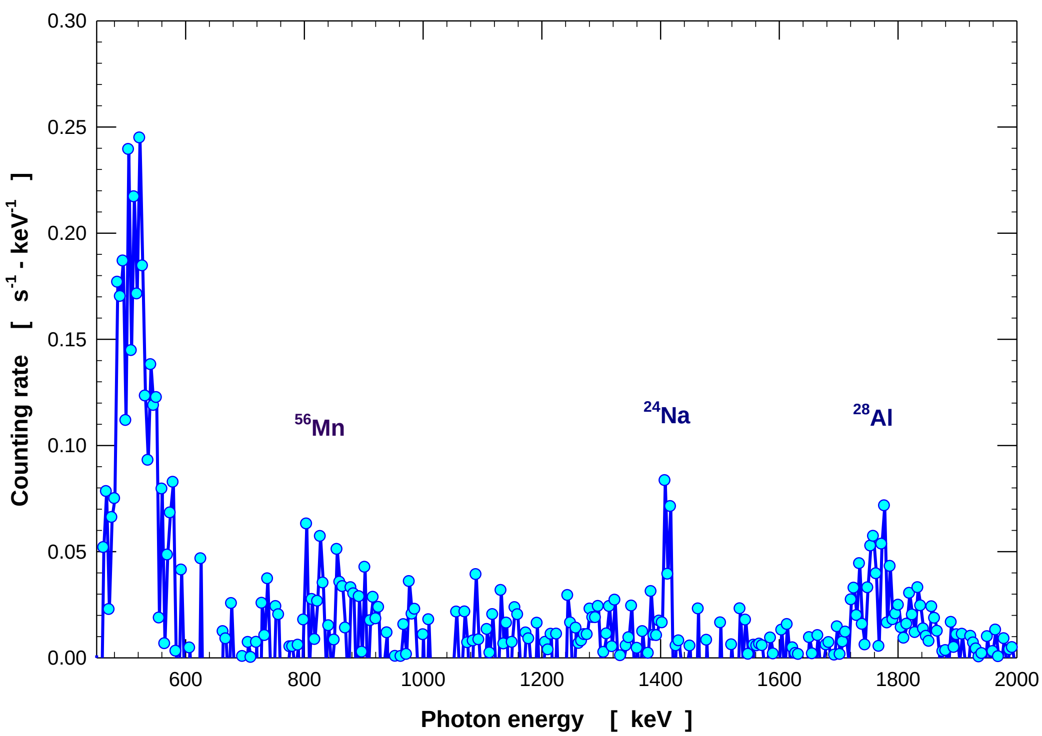


Figure 5.- Induced activity in concrete sample N° 1.

Using the corrected net counts under the photopeaks measured in the concrete samples and the efficiency function the specific activity in concrete was calculated whose values are shown in table 4.

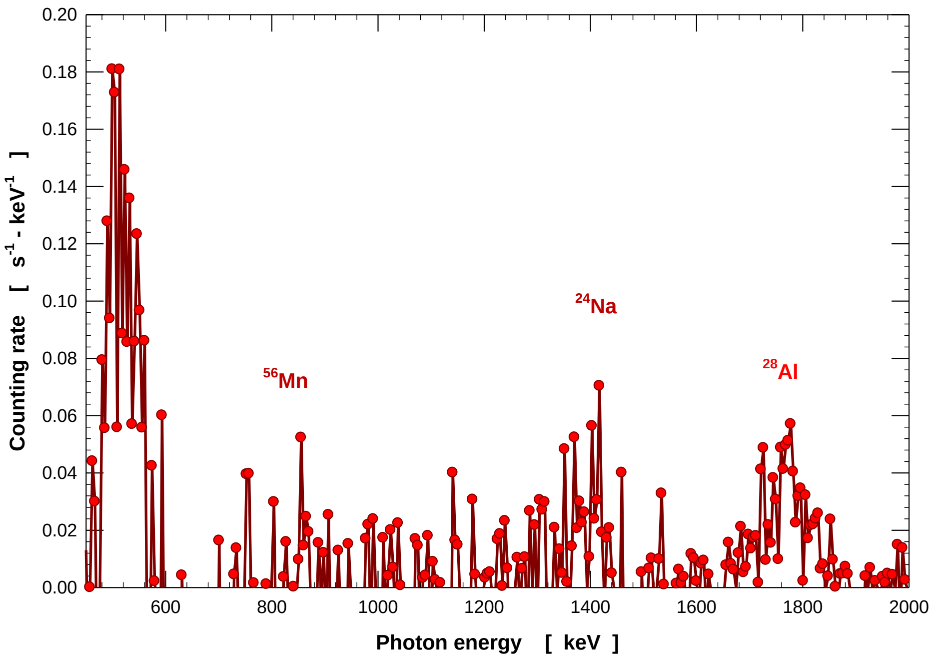


Figure 6.- Induced activity in concrete sample N° 2.

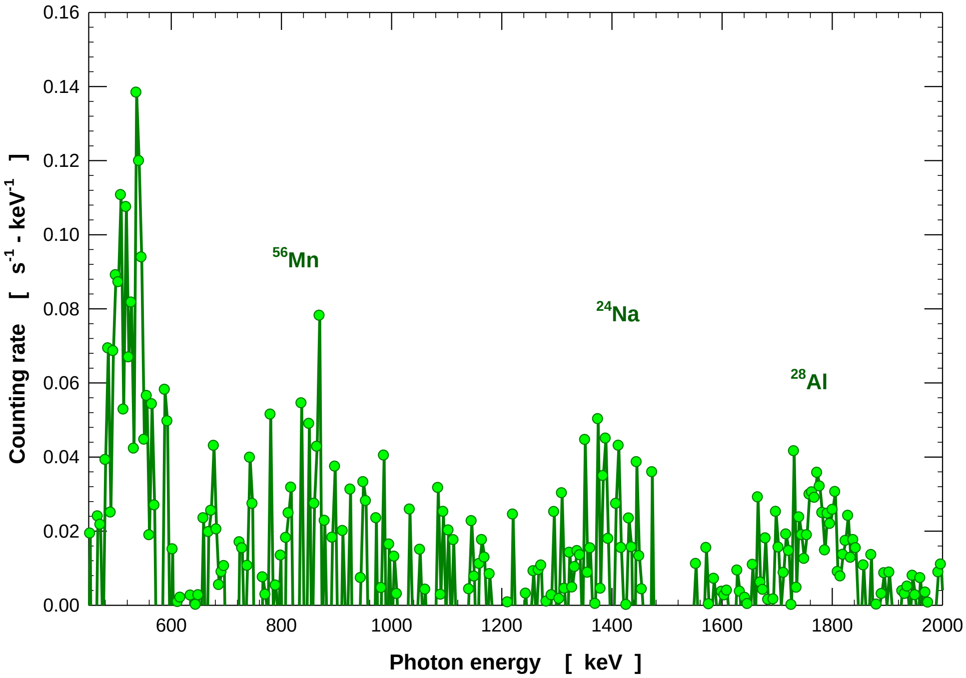


Figure 7.- Induced activity in concrete sample N° 3.

Table 4.- Specific activities of the induced radioisotopes in the concrete samples.

| Concrete sample | Radioisotope | Specific activity [Bq/gr] |
|---|---|---|
| 1 | $^{56}$Mn | 0.1684 ± 0.0151 |
| | $^{24}$Na | 0.2981 ± 0.0270 |
| | $^{28}$Al | 1.8674 ± 0.1680 |
| 2 | $^{56}$Mn | 0.1314 ± 0.0118 |
| | $^{24}$Na | 0.6720 ± 0.0604 |
| | $^{28}$Al | 2.2951 ± 0.2064 |
| 3 | $^{56}$Mn | 0.1630 ± 0.0201 |
| | $^{24}$Na | 0.5361 ± 0.0484 |
| | $^{28}$Al | 1.7671 ± 0.1591 |

The mean values of the induced activity in the three concrete samples were: 0.1543 ± 0.0199 Bq due to $^{56}$Mn, 0.5021 ± 0.1893 Bq due to $^{24}$Na and 1.977 ± 0.2804 Bq due to $^{28}$Al.

The primary and secondary barriers in the treatment hall are several tons of concrete that are activated during a patient treatment, behaving as a 4 $\pi$ source that deliver a dose in the hall lasting up to few hours after the treatment.

In figure 8 is shown the pulse height spectrum of the radioisotopes induced in the wedge, where the main peaks were 846, 1811 and 2112 keV that are emitted by $^{56}$Mn. This radioisotope has a half-life of 2.58 h, which often is removed after the treatment, due to its geometry and weight the wedge is carried near the chest of the auxiliary or medical staff exposing them to photons.

The geometry used in the induced activity in the wedge was different to the geometry used to determine the spectrometer efficiency; therefore in this case the specific activity was not determined.

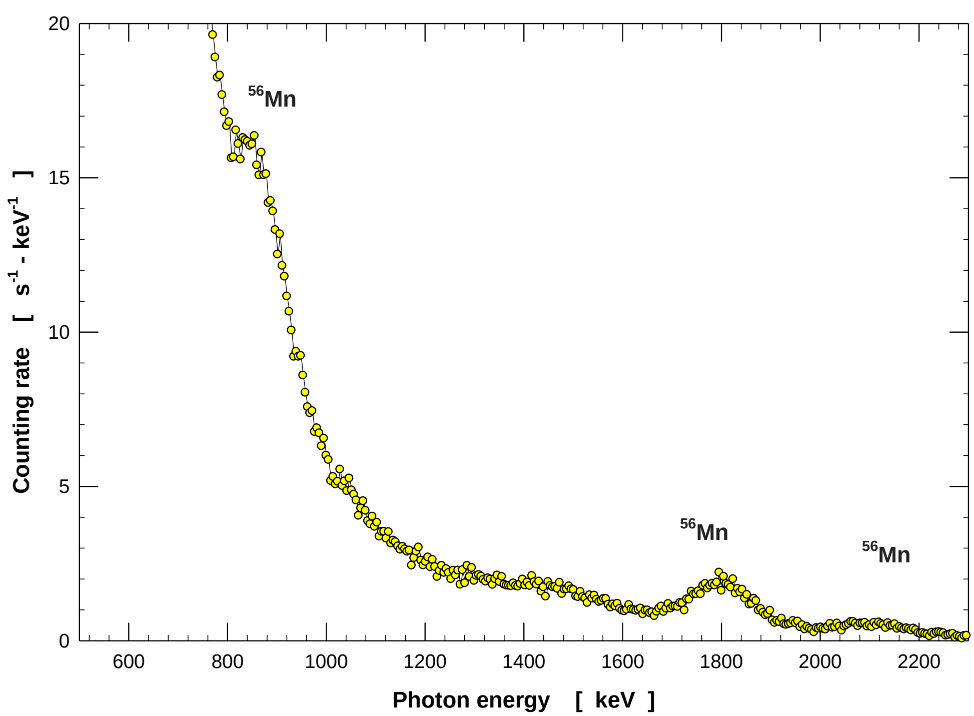

Figure 8.- Pulse height spectrum of the wedge.

# 4.- DISCUSSION

During the use of a 15 MV LINAC photoneutrons are produced that induce the activation of the concrete and a wedge. The induced activity it is not considered in radiological protection program in the facility because the emitted photons delivers an undesirable dose to the radiation workers and to the patient.

The induced radioisotopes were $^{28}Al$, $^{24}Na$ and $^{56}Mn$ whose half-life varies from few minutes up to several hours, in order to improve the ALARA criteria is important that the staff of a LINAC be aware of what elements are inside of the room which are easy to be activated.
Assuming that neutrons can induce activation 5 cm-depth in the concrete walls, the radiotherapy room can be estimated as a gamma-ray shell, where at least 50% of the photons will be returned to the room reaching the patient body. Due to the half life features of the induced radioisotopes the photons also deliver a dose to the personal that go into the room to assist the patient.

The most important radioisotopes induced in the concrete have been identified however, due to limitations of the measuring spectrometer, possible exception of very short-lived or pure beta-emitting nuclides were not identified.

# 5.- CONCLUSIONS

Induced radioisotopes, in the concrete and a wedge, have been identified during the operation of a 15 MV LINAC. The radioisotopes are produced by the photoneutrons produced during the LINAC operation.

In the concrete the induced radioisotopes were $^{56}$Mn, $^{24}$Na and $^{28}$Al that during their decay produce 846.8, 1368.6 and 1178.8 keV photons respectively with a half life that goes from few minutes up to several hours.

The average specific activity of the three concrete samples used is 0.1543, 0.5021 and 1.977 Bq per gram of concrete due to $^{56}$Mn, $^{24}$Na and $^{28}$Al respectively.

In the wedge the induction of $^{56}$Mn was identified, because the measuring geometry used in the calibration of the spectrometer was different to the geometry used to measure the wedge activity, in this case the specific activity was not determined.

## Acknowledgments

The first two authors, HALM and ERP, thank to CONACyT (Mexico) for the scholarship to study the PhD and the MSc program. This work is part of the project MONITOR 2, partially supported by the COZCyT.

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