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GAMMA-EMITTING Tc RADIOTRACERS PRODUCTION FOR WASTE DISPOSAL STUDIES
AT MILAN AVF CYCLOTRON

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ABSTRACT

In order to start cyclotron production in Italy of medium-lived gamma-emitting Tc radiotracers for metallobiochemical and waste disposal studies on nuclear fuel, the knowledge of the optimal irradiation parameters is needed.

So, thin-target excitation functions for the principal (p, xn) and (p, xpyn) nuclear reactions on Mo targets of natural isotopic composition, have been measured with the single target activation technique, using the external beam of the variable energy AVF Cyclotron of Milan University, in the proton energy range from 5 to 44 MeV. Thin-target yields at the End Of an Instantaneous Bombardment (EOIB), have been determined (in MBq/C MeV) at 2.5 MeV intervals, on the basis of the decay data from Lederer and Shirley, Table of Isotopes, for the following Tc radionuclides: 94-Tc, 95-Tc, 95m-Tc and 96-Tc, as well as for several Mo, Nb, Zr and Y radionuclides.

Among the Tc radionuclides produced, the 95m-Tc shows an half-life suitable for medium-term experiments, while the shorter-lived 96-Tc shows an half-life suitable for short-term metallobiochemical experiments on laboratory animals.

Furthermore, preliminary production tests have been carried out by irradiation of Mo sheets, 1 mm thick, using the water cooled internal irradiation probe of Milan Cyclotron, with a beam current of 5 μ A for 5 hours.

A reverse phase extraction chromatography method has been set up in order to get a selective separation of Tc radionuclides from both the irradiated Mo target and the Nb, Zr and Y radionuclides.

Metallobiochemical studies on rats have been carried out with trace amounts of ^{95m}Tc , at the Radiochemistry Division of Joint Research Centre, Euratom, Ispra, Varese, in order to get metabolic patterns determination of Tc in animals.

A high-beam current irradiation target for high-activity ^{95m}Tc production with the new Scanditronix MC 40 Cyclotron of JRC Euratom, Ispra, has been designed.

1.- INTRODUCTION

1.1.- Among the radionuclides of technetium, ^{99}Tc is of much interest from the radiological point of view for the following reasons:

- its long half-life ($t_{1/2} = 2.13 \times 10^5$ Y);
- its very high fission yield (6.2%, 27 mg of technetium per gram of ^{235}U burned up in fission)(1);
- the high biogeochemical mobility of TcO_4^- specie.

The amounts of ^{99}Tc formed via the decay of ^{99m}Tc radioisotope used in nuclear medicine (about 50 kCi/Y in Europe) are low being of the order of 10 mg/Y.

A much better knowledge of the behaviour of technetium in the different parts of the ecosystems including man, is necessary to assess the potential environmental and human impact of ^{99}Tc (2,3).

1.2.- The aim of this work is to optimize the irradiation conditions to start in Italy the production of gamma-emitting radiotracers of technetium for research purposes.

Three Tc radionuclides could be conveniently used for experimental studies (4):

- (i,ii) ^{95m}Tc , $t_{1/2} = 61$ d and ^{97m}Tc ; $t_{1/2} = 90$ d,
suitable for long or medium term experiments.
- (iii) ^{96}Tc , $t_{1/2} = 4.3$ d,
suitable for short term experiments.

However, the practical use of ^{97m}Tc poses analytical difficulties due to its detection and measurement (too low energy and abundance of its gamma-emission)⁽⁴⁾.

1.3.- Few data are available from literature about the excitation functions for production of neutron deficient technetium radionuclides^(es:5,6).

The production of Tc radionuclides by (p, xn) reactions on molybdenum seems to be suitable because of:

- low cost of metallic molybdenum;
- its good thermal and electrical conductivities;
- its very high melting point (2620°C);
- the generally higher cross sections of protons in respect to other particles;
- the low stopping power of protons in materials.

2.- MATERIALS AND METHODS

2.1.- Irradiations for thin-target excitation functions determination have been carried out using the external proton beam of the AVF Cyclotron of Milan University. The single target activation technique has been adopted, followed by traditional gamma-spectrometry off-line.

50 cm³ coaxial Ge(Li) and HPGe detectors (Ortec) connected to a 2x4096 multichannel analyzer (Camberra, Series 80) have been used.

The gamma-spectrometer was calibrated both for energy and efficiency by a 4 μCi source of ^{226}Ra (Amersham), with a certified overall uncertainty of 1.5%.

The gamma measurements of the various radionuclides have been carried out for not less than 3 half-lives in order to obtain statistical errors lower than 1%.

The total statistical error due to: photopeak area, efficiency and target thickness, is of the order of a few percent in any case.

2.2.- Yield calculation

Yield calculations have been carried out with the conventional formula, and the decay data from "Lederer and Shirley: Table of Isotopes"⁽⁴⁾:

$$Y = \frac{C \lambda^2 \exp(\lambda t_w) t_{irr}}{S(dE/dx)_{\bar{E}} Q \epsilon \alpha (1 - \exp(-\lambda t_m)) (1 - \exp(-\lambda t_{irr}))}$$

where:

- C, ϵ , α = photopeak counts, efficiency and abundance;
- $S(dE/dx)_{\bar{E}}$ = ΔE = thin target energy loss (MeV);
- Q = integrated proton charge (μ coulomb);
- t_w, t_m, t_{irr} = waiting, measuring and irradiated times (s);
- λ = decay constant (s^{-1}).

Finally, the range and stopping power $(dE/dx)_{\bar{E}}$ calculations have been based on the Bethe-Bloch equation⁽⁷⁾.

The thin target excitation functions have been measured at about 2.5 MeV intervals in the proton energy range from 5 to 45 MeV. At proton energies lower than 18 MeV aluminium absorbers were used⁽⁷⁾.

The results are reported in MBq/C MeV, where:

by definition: $1 \mu Ci / \mu Ah \text{ MeV} = 10.28 \text{ MBq/C MeV}$.

2.3.- In Tables I and II are reported the main radionuclides of technetium, molybdenum, niobium, zirconium and yttrium in the gamma spectra.

TABLE I - Main neutron deficient technetium radionuclides with their optimal gamma emissions and waiting times.

MAIN RADIONUCLIDES OF TECHNETIUM
 $t_{1/2} > 5 \text{ hours}$

A Tc	t 1/2	E_{γ} [keV], α (%)	waiting time	employed γ
97m	90 d	96 (0.31)		
96	4.3 d	778 (99.1) 812 (81.5) 850 (96.9)	3 d	850
95m	61 d	204 (66) 582 (32.5) 835 (28.1)	40-60 d	582
95	20 h	765 (93) 1074 (4)	1 d	1074
94	4.9 h	702 (99.8) 850 (97.7) 871 (100)		702

TABLE II - Main radionuclides produced by secondary reactions on molybdenum.

OTHER RADIONUCLIDES PRODUCED

- I) Mo (p, pxn)^A Mo A ÷ 89-99
- II) Mo (p, αxn)^A Nb A ÷ 88-98
- III) Mo (p, αdxn)^A Zr A ÷ 86-89

RADIO-NUCLIDE	t 1/2	E _γ [keV], α (%)	waiting time
⁹⁹ Mo	66 h	739.4 (12.6)	6 d
⁹⁵ Nb	35 d	765 (99.8)	60 d
^{92m} Nb	10.15 d	934 (99.2)	2 d
⁸⁸ Zr	83.4 d	394 (97.3)	60 d
⁸⁸ Y _D	106.6 d	898 (91.3) 1836 (99.3)	60 d
⁸⁷ Y _D	80.3 h	484 (92)	2 d
^{87m} Y _D	13. h	381 (78)	

Among the Tc radionuclides were considered only those having half-lives higher than 5 hours. ^{97m}Tc was not considered due to its low gamma energy and branching ratio.

The other radionuclides of Mo, Nb, Zr and Y have been identified only as tracers to test a suitable radiochemical purification of technetium.

Finally there is no evidence of Y radionuclides production by direct reactions, but only via the decay of Zr radionuclides.

In Tables I and II are also reported the "optimal" gamma emissions and waiting times chosen to start the measurements of the various radionuclides.

2.4.- Radiochemical separation of ^{95m,96}Tc

- Dissolution of irradiated metallic Mo target in 7 N HNO₃;
- filtration of molybdic acid;
- extraction of residual Mo with 0.25 M HDEHP (Di-Ethyl-Hexyl-Phosphoric-

- Acid) in mesitylene; Nb, Zr (and Y) are coextracted;
- washing of the solution by isopropyl ether to remove trace of HDEHP;
- evaporation near to dryness;
- dissolution in physiological (or other) medium.

2.5.- Quality control

- Tc radiochemical yield : 90%;
- decontamination factor from Mo, Zr, Nb (and Y) : 10^6 ;
- radiochemical purity : 99%;
- radionuclidic purity : 99%.

3.- RESULTS

3.1.- Excitation functions

The thin-target excitation functions for the production of ^{94}Tc , $^{95\text{m}}\text{Tc}$, ^{95}Tc and ^{96}Tc are shown in Fig. 1.

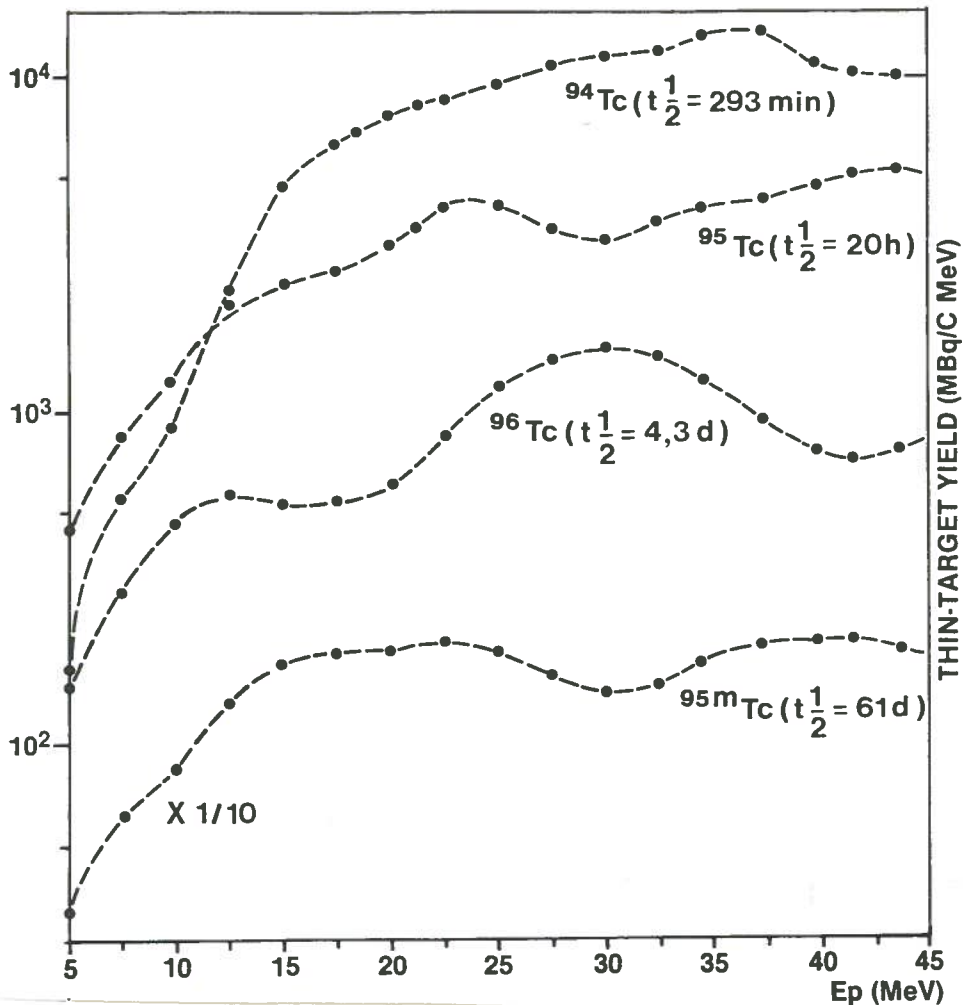


FIG. 1 - Thin-target excitation functions for ^{NAT}Mo (p,xn) reactions.

The data refer to the (p,xn) reactions on molybdenum of natural isotopic composition (^{92}Mo , ^{94}Mo , ^{95}Mo , ^{96}Mo , ^{97}Mo , ^{98}Mo and ^{100}Mo).

In the case of ^{95}Tc , the yield does not include the contribution of the metastable level $^{95\text{m}}\text{Tc}$, which charges the ground level with abundance of 3.9% (I.T.) (see Fig. 2).

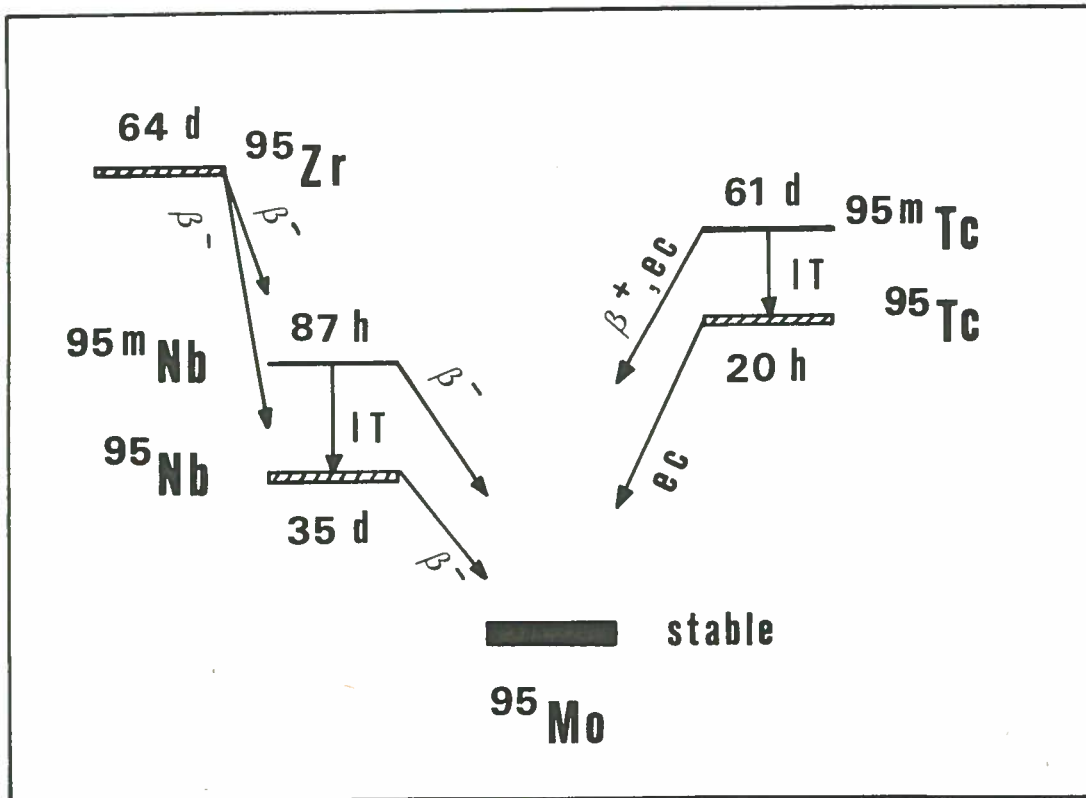


FIG. 2 - Simplified decay scheme of 95-isobar.

On the contrary, in the case of ^{96}Tc , the yield includes the contributions of the short-lived metastable level $^{96\text{m}}\text{Tc}$ ($T_{1/2} = 52$ min, I.T. = 98%).

^{94}Tc and $^{95\text{m}}\text{Tc}$ are produced by direct (p,xn) reactions only.

3.2.- In Fig. 3 is shown a typical Ge(Li) spectrum of an irradiated molybdenum target 4 months after the end of bombardment (EOB).

Typical gamma-emissions of long-lived Nb, Zr, and Y radionuclides are evident.

A suitable radiochemical separation has been set up in order to deliver a high-radionuclidic purity solution of technetium radiotracers for metallobiochemical studies on laboratory animals.

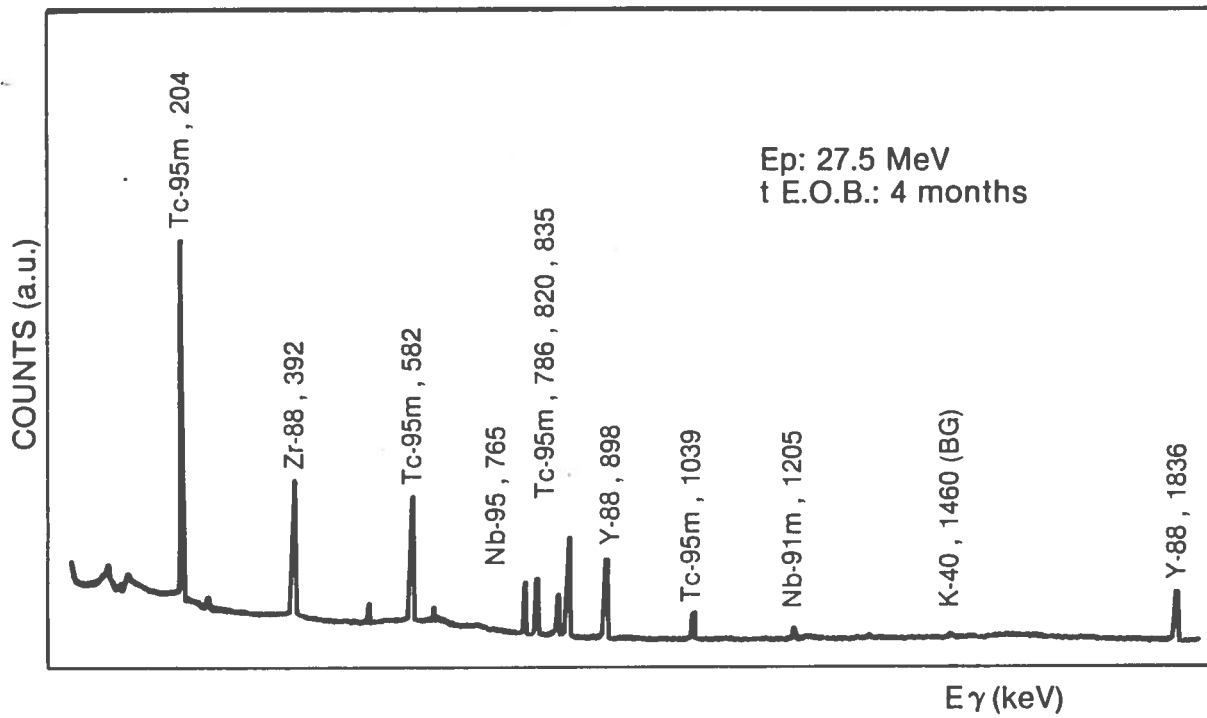


FIG. 3 - Ge(Li) spectrum of a typical irradiated Mo target 4 months after EOB.

3.3.- In Table III and Fig. 4 are summarized the results of the P.OS administration of $^{95m,96}\text{Tc}$ (pertechnetate) in physiological solution (saline 0.9%) to 9 male Sprague-Dawley rats.

4.- CONCLUSIONS

4.1.- Production of ^{95m}Tc

The experimental data show a slight dependence on proton energy of the excitation function for the reactions $^{\text{nat}}\text{Mo} (p, xn) ^{95m}\text{Tc}$ in the range from 10 to 45 MeV (see Fig. 2).

A typical irradiation of a 20 MeV thick molybdenum target (es.: 40→20 MeV or 35→15 MeV) shows a thick target yield of about 2mCi of ^{95m}Tc at the end of a 5 μA x 10 hours irradiation run.

The development of an "irradiation chamber" for higher intensity beam (up to 65 μA) are in progress at the JRC (Ispra), where a new 40 MeV Cyclotron (Scanditronix MC 40) has been installed in recent years.

4.2.- Production of ^{96}Tc

The excitation function presents in this case a well shaped maximum of 1.5 GBq/C MeV at 30 MeV (see Fig. 3).

TABLE III

***95m*TECHNETIUM 0,3 ml p.os/400g/RAT; X ± S.D.
% DOSE/g (3 ANIMALS EACH GROUP)**

ORGAN DISTRIBUTION

Tissue	after 4 hours without food	after 4 hours with food	after 15 days with food
Brain	0.031 ± 0.017	0.017 ± 0.012	0.0008 ± 0.0005
Lung	0.235 ± 0.012	0.099 ± 0.016	0.0017 ± 0.0009
Thymus	0.094 ± 0.010	0.046 ± 0.009	0.0003 ± 0.0001
Heart	0.102 ± 0.033	0.069 ± 0.018	0.0007 ± 0.0004
Liver	0.446 ± 0.020	0.264 ± 0.112	0.0046 ± 0.0020
Spleen	0.144 ± 0.007	0.077 ± 0.025	0.0027 ± 0.0011
Kidney	1.322 ± 0.085	0.720 ± 0.149	0.1183 ± 0.0326
Pancreas	0.114 ± 0.016	0.053 ± 0.008	0.0003 ± 0.0002
Stomach	3.419 ± 0.356	2.016 ± 0.882	0.0037 ± 0.0017
Small Intestine	0.367 ± 0.119	0.408 ± 0.159	0.0014 ± 0.0005
Large Intestine	0.167 ± 0.076	0.101 ± 0.025	0.0014 ± 0.0008
Testes	0.124 ± 0.009	0.068 ± 0.015	0.0037 ± 0.0017
Epididymis	0.115 ± 0.021	0.064 ± 0.020	0.0033 ± 0.0011
Skin	0.679 ± 0.326	0.049 ± 0.245	0.1985 ± 0.1443
Fat	0.535 ± 0.460 (2 rats)	0.057 ± 0.030	0.0038 ± 0.0019
Muscle	0.050 ± 0.007	0.025 ± 0.011	0.0010 ± 0.0004
Femur	0.142 ± 0.046	0.087 ± 0.026	0.0015 ± 0.0004
Carcass	0.199 ± 0.005	0.081 ± 0.012	0.0073 ± 0.0011
Blood	0.485 ± 0.029	0.266 ± 0.051	0.0012 ± 0.0008
Plasma*	66.49 ± 6.90	57.95 ± 3.67	19.16 ± 6.47
RBC*	33.51 ± 6.90	42.04 ± 3.67	80.84 ± 6.47

* = % total blood

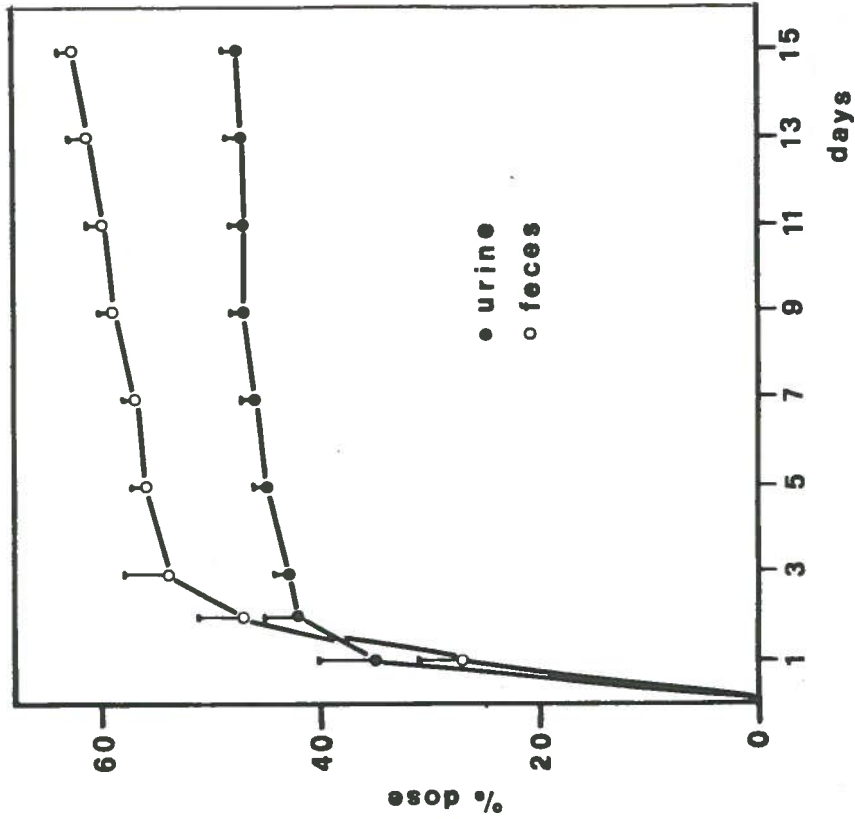


FIG. 4 - Cumulative excretion pattern of ^{95m}Tc in rats after p.os administration of 0.3 ml/rat.

Large activities of this radionuclide can be produced even using a low beam intensity by irradiation in the 35→25 MeV proton energy range. A typical 5 μ A x 10 hours irradiation can deliver about 75 mCi of this radionuclide at the EOB.

4.3.- Biological aspects

^{95m}Tc in rat organs 4 hours after p.os administration was mainly present in : lung, liver, kidney, stomach, intestine and femur. The organ content was higher when the animals were not fed (see Table III).

Rapid elimination during the first 2 days, reaching at day 15 after application about 60% of the dose in the feces and about 30% in urine (see Fig. 4).

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