

7 We treat the bremsstrahlung induced by initial electron beam in converter, and the production
8 of a desirable radio-isotope due to the photo-nuclear reaction caused by this bremsstrahlung. By
9 way of illustration, the yield of a number of some, the most in practice applicable, radio-isotopes
10 is evaluated. The acquired findings persuade us that usage of modern electron accelerators offers a
11 practicable way to produce the radio-isotopes needful nowadays for various valuable applications in
12 the nuclear medicine.

13 PACS numbers: PACS number(s): 25.20.-x

14 *Keywords:* radio-isotope production, nuclear medicine.

DR.RUPNATHJI(DR.RUPAK NATH)

1. Introduction

Nowadays, it is rather impossible to find any branch of science, industry, medicine, forensic, etc., in which the radio-isotopes are not widely used [1–6]. Although there is a series of unstable natural isotopes arising from the decay of primordial uranium and thorium, the most of about 200 radio-isotopes used for now on a regular basis are produced artificially. Despite all the nuclear reactors produce the manifold radio-isotopes as a result of fission of ^{235}U contained in their fuels, the recovery of these radio-isotopes is extremely problematic issue, and they would not be received for primary applications, especially for medical use. At present radio-isotope marketable production is primarily brought about by exposition of the appropriate element to neutrons in a nuclear reactor, or to charged particles, like protons, deuterons, or alpha particles, in a cyclotron [7]. As a general rule, it is far more difficult to make a radio-isotope in a cyclotron than in a reactor. Cyclotron nuclear reactions are less productive and less predictable than ones performed in a reactor. The variety of cyclotron-produced radio-isotopes is tightly restricted too. Economic factors would also militate against cyclotron production. In fact, it proves to be anyway not competitive with the reactor radio-isotope production.

As to reactor-based manufacturing, there are two processes to produce isotopes: fission of ^{235}U by neutrons within an exposed target, with subsequent recovery of a desirable isotope out of fission fragments, and neutron capture by nucleus of an appropriate sample, which results in elaboration of a required isotope [7]. The ^{235}U fission cross-section σ_{nf} is well known to be at least a factor of about 100 greater than the typical neutron capture $A(Z, N)(n, \gamma)A'(Z, N + 1)$ cross-section to produce some radio-isotope $A'(Z, N + 1)$ that could other-ways be recovered from ^{235}U fission fragments. That is why the radio-isotope consumers community world-through dismissed the neutron capture as a viable process for production of the primary needful radio-isotopes in quantities required to meet global demand, though this process could be used to make minor radio-isotope amounts to provide a stable domestic supply. For instance, in Russia different radio-isotopes, including $^{99}\text{Mo}/^{99m}\text{Tc}$, are produced on the Leningrad power station using the neutron capture reactions in the channel of the RBMK-1000 reactor [8].

Thus, in these days, the most of world's production of primary radio-isotopes is carried

46 provide a thermal neutron flux ($10^{14} - 10^{15}$)n/(sec cm²), and are fueled with low enriched
47 uranium (*LEU*), or in some cases with (*HEU*) as well [7]. These reactors have become
48 indispensable for the industrial production of marketable radio-isotopes, in particular medical
49 isotopes to supply the rapidly increasing demand for diagnostic and therapeutic procedures
50 based on nuclear medicine techniques. The nuclear-medicine community defines the medical
51 isotopes to include first of all the isotope ⁹⁹Mo, that is the precursor to the short-living ^{99m}Tc
52 that's used in $\approx 85\%$ of all the nuclear medicine procedures worldwide, and also ¹³¹I, ¹³³X and
53 other manifold radioactive materials used to produced radiopharmaceuticals [2, 4, 7, 9, 10].
54 The medical radio-isotope recovery is humanly the most vital outcome of nuclear physics and
55 industry.

56 The supply reliability of radio-pharmacies, hospitals, clinics and outpatients centers with
57 the radio-isotopes is currently the primary concern of world nuclear-medicine community
58 [7]. In actual fact, recent experience suggests that unplanned emergent reactor shutdowns
59 would cause severe supply disruption. A number of contingency incidents during last years has
60 been pointing up unreliability in the supply of medical radio-isotopes, particular ⁹⁹Mo/^{99m}Tc.
61 Some 95% of the world's supply of these comes from only five reactors, all of them are over 40
62 years old [7]. So the greatest single threat to supply reliability is the approaching obsolescence
63 of the aging reactors that current large-scale producers utilize to irradiate *HEU* targets to
64 elaborate the needful radio-isotopes. Last years, there took place a number of significant
65 disruptions in medical radio-isotope supply, some of which have been lasting by now [7, 11].
66 For instance, the concern about the long-term supply of medical radio-isotopes has been
67 exacerbated when the shutdown of research reactor *HFR* in the Netherlands since August
68 2008 has caused ⁹⁹Mo shortage world-wide. The most productive and oldest, yet a while ago
69 refurbished, Canada's *NRU* reactor was shutdown in the summer 2009 [12], after the heavy
70 water leak was discovered in May 15, 2009. It is not clear if and when the *NRU* could be
71 restarted, or how to make up for its outage. The worldwide supply of radio-isotopes is likely
72 to be unreliable unless newer production sources come on line.

73 Besides posing a threat to patients treatment, the current method used by the world's
74 main producers increases the menace of nuclear terrorism, as it employs weapons-grade *HEU*.
75 So the burning question is now to eliminate, or at least minimize, the *HEU* use in reactor
76 fuel, irradiated targets, and production facilities. Only very few small-scale producers, *e.g.*

78 the *LEU* targets [7]. The bulk of consumed radio-isotopes are still obtained utilizing *HEU*
79 and, to the best of knowledge, the conversion to the *LEU* targets is not believed before
80 long. Especially the radio-isotope producing community had been counting on the to-be-
81 built reactors *MAPLE1* and *MAPLE2*, and on the related processing facilities at Chalk-
82 River site, Canada, which would not have used the *HEU*. Yet the *MAPLEs*, designed as
83 a replacement for *NRU*, did not perform as contemplated, and in May 2008 Atomic Energy
84 of Canada Ltd. made the decision to end the *MAPLE's* project [13]. This has, in fact, put
85 on hold any plans to convert to *LEU*-based large-scale radio-isotope production. Instead,
86 the world community these days needs both new radio-isotope production inventions and
87 the facilities that will continue work safely in the long term, without using weapon-grade
88 uranium.

89 In this respect, we treat in what follows the photo-production of various radio-isotopes,
90 Sections 3, 4, which is due to the bremsstrahlung induced in converter by initial electron
91 beam of electron accelerator, Section 2. Also we consider, in Section 5, the case when a
92 desirable isotope results in decaying a parent radio-isotope that stems itself in the photo-
93 production. At last, in Section 6, the all-round discussion of findings persuades us that the
94 most preferable way to produce radio-isotopes is the usage of electron beams provided by
95 modern electron accelerators. What encourages our work is the exploration by now carried
96 out in the Fefs. [14–17].

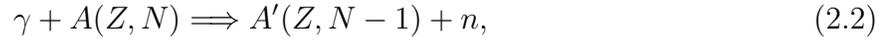
97 2. Bremsstrahlung in converter

98 As was proclaimed above, the purpose is to acquire how to work out the various radio-
99 isotopes, needful to-day for manifold applications in technology, science and medicine, by
100 making use of electron beams delivered by microtrons, linear electron accelerators, etc. That
101 beam, with an electron energy distribution $\rho_e(E_e)$ and a current density $J_e(t)[A/cm^2]$ (gener-
102 ally speaking, time dependent), travels through the converter (see Fig. 1), which is prepared
103 of some proper heavy element, such as *W*, *Pt* etc. The bremsstrahlung is thereby induced with
104 current density

$$I(F) = \frac{\mathcal{N}_\gamma(E_\gamma)}{\dots} \quad (2.1)$$

105 expressed in terms of the photon number $\mathcal{N}_\gamma(E_\gamma)$ with the energy $E_\gamma = |\mathbf{k}| = k$, per
 106 $1\text{cm}^2, 1\text{s}, 1\text{MeV}$.

107 In turn, that γ -ray flux, interacting with respective nuclei of the sample (see Fig. 1),
 108 induces the photo-nuclear reaction



109 so that a desirable isotope $A'(Z, N - 1)$ comes out. Certainly, this process (2.2) can only
 110 be realized, if the energy E_γ of γ rays is, at least, greater than the neutron binding energy
 111 B_n of a considered nucleus $A(Z, N)$, $E_\gamma > B_n \approx 8\text{MeV}$. Actually, the isotope $A(Z, N - 1)$
 112 production process will successfully run provided E_γ is of the order of, and comes over the
 113 energy E_{GR} of giant resonance in the photo-nuclear reactions (2.2) on respective nuclei,
 114 $E_\gamma \gtrsim E_{GR}(Z, N) \sim 13 \div 19\text{MeV}$ [18]. As a matter of course, an electron must have got
 115 the energy $E_e > E_\gamma$ in order to give rise to the bremsstrahlung with the required energy E_γ .
 116 Thus, only the processes involving the electron and photon energies

$$E_\gamma, E_e \gtrsim E_{GR} \quad (2.3)$$

117 are to be taken into consideration and explored, which is the key point of our treatment.
 118 Next, we limit the current study by the condition

$$E_e \leq 100\text{MeV} \quad (2.4)$$

119 as well. The guide relations (2.3), (2.4) govern all the presented calculations, specifying
 120 the energy area where the acquired findings hold true. Also, in the ordinary way, all the
 121 evaluations we make in the work are the first α -order, and we abandon contributions from
 122 all the high α -order processes.

123 In passing across converter, a high energy electron is primarily known to lose its energy
 124 (see e.c. Refs. [19–21]) due to the bremsstrahlung by scattering in the fields of nuclei of heavy
 125 atoms of converter. As the relation (2.3) holds, the angular distribution of scattered electrons
 126 as well as emitted photons has got a sharp maximum in momentum direction of an initial
 127 electron. Both electrons and photons spread within a small, rather negligible solid angle
 128 $\Theta \sim m/E_e$ around direction of the initial electron momentum [19–21]. Then, with proper

130 between the momenta of incident electron and emitted photon, a very handy expression for
 131 the cross-section to describe the photon energy distribution results (see *e.g.* Refs. [20, 22, 23]):

$$\begin{aligned} \frac{d\sigma_b(k)}{dk} &= \frac{2Z_C^2}{137} r_0^2 \frac{1}{k} \times \\ &\times \left\{ \left(\frac{E_e^2 + E_e'^2}{E_e^2} - \frac{2E_e'}{3E_e} \right) \cdot \left(\ln M + 1 - \frac{2}{b} \arctan b \right) + \right. \\ &\left. + \frac{E_e'}{E_e} \left(\frac{2}{b^2} \ln(1 + b^2) + \frac{4(2 - b^2)}{3b^3} \arctan b - \frac{8}{3b^2} + \frac{2}{3} \right) \right\}, \end{aligned} \quad (2.5)$$

132 where $k = E_\gamma$ stands for the energy of radiated γ -quantum, $E_e' = E_e - k$, Z_C is the atomic
 133 number of the converter material, and

$$b = \frac{2E_e E_e' Z_C^{1/3}}{C m k}, \quad \frac{1}{M} = \left(\frac{m k}{2E_e E_e'} \right)^2 + \frac{Z_C^{2/3}}{C^2}, \quad C = 111, \quad r_0 = \frac{e^2}{m} = 2.818 \cdot 10^{-13} \text{ cm}.$$

134 Besides the aforesaid bremsstrahlung in the field of nucleus, there exists the bremsstrahlung
 135 by scattering an incident electron by atomic electrons. For a fast electron, $E_e \gg m$, the
 136 cross section of this process is known to coincide with the bremsstrahlung cross section
 137 on nucleus with $Z = 1$ [19–21]. Then, the atomic electrons contribution into the whole
 138 electron bremsstrahlung is taken into account just by replacing the factor Z_C^2 in Eq. (2.5) by
 139 $Z_C(Z_C + \delta)$ with $\delta \lesssim 1$. As for heavy converter atoms $Z_C \gg 1$, this correction is rather of
 140 very small value.

141 The bremsstrahlung, with all the feasible energies $k = E_\gamma$, causes the mean energy loss
 142 of electron on a unit of path [19, 20]

$$- \frac{dE_e(x)}{dx} = \mathcal{N}_C \cdot E_e(x) \cdot \varphi_{rad}(E_e), \quad (2.6)$$

143 The number \mathcal{N}_C of scattering atoms of converter in 1 cm^3 is

$$\mathcal{N}_C = \frac{\rho_C \cdot 6.022 \cdot 10^{23}}{A_C}, \quad (2.7)$$

144 where ρ_C is the density of converter material, and A_C is its atomic weight. The quantity φ_{rad}
 145 is written in the form

146 The coefficient K_C , very slightly varying with the energy E_e , provided $E_e \gtrsim 10$ MeV, can
 147 be found in Refs. [19, 20, 24] for various heavy atoms. So, upon passing a path x , an electron
 148 with initial energy $E_e(0)$ will have got, in consequence of the radiative losses, the energy

$$E_{e\ rad}(x) \approx E_e(0) \exp[-x\mathcal{N}_C\varphi_{rad}]. \quad (2.9)$$

149 In fast electrons, $E_e \gg m$, elastic scattering on heavy nuclei of converter, the angular dis-
 150 tribution has got a very sharp maximum, within the solid angle $\Theta < (m/E_e)^2$, and therefore
 151 can be leaved out of our consideration [19–21].

152 In treating the fast electron collision with atomic electrons, without photon emitting, we
 153 are to consider two cases. Firstly, let the momentum Δ_I transferred to an atomic electron be

$$\Delta_I \lesssim I_Z \approx 13.5 Z_C \text{ eV}, \quad (2.10)$$

154 the ionization potential of atom. Apparently, as $\Delta_I \ll E_e$, a scattering angle is negligible.
 155 The mean electron energy loss on a unit of path, caused by its inelastic collisions with atoms,
 156 is described by the expression (see Refs. [19, 20, 23])

$$-\frac{dE_e(x)}{dx} = 2\pi r_0^2 m \mathcal{N}_C Z_C \ln \frac{E_e^3(x)}{2mI_Z^2}, \quad (2.11)$$

157 which can be rewritten in the form

$$x = -\frac{1}{6\pi r_0^2 m \mathcal{N}_C Z_C} \int_{E_e(0)}^{E_{eI}(x)} \frac{dE}{\ln[E(2mI_Z^2)^{-1/3}]}, \quad (2.12)$$

158 where $E_e(0)$ is the electron energy at the starting edge of converter, and $E_{eI}(x)$ stands for
 159 the electron energy upon passing the distance x , which is caused by the ionization losses.

160 With the conditions (2.3), (2.4), we can actually presume

$$\ln E \approx \ln E_e^{av}, \quad E_e^{av} = \frac{E_e(0) + E_{GR}}{2} \quad (2.13)$$

161 in the Eq. (2.12). Then we arrive at the estimation of the energy loss on the distance x due
 162 to the inelastic electron collisions with atoms

163 Secondly, when, unlike (2.10), the momentum transferred $\Delta_I \gg I_Z$, yet still $\Delta_I \ll E_e$ any-
 164 way, atomic electrons can be considered as free ones, and the fast electron interaction with
 165 they reduces to the elastic forward scattering on free resting electrons [19, 21], which causes
 166 no energy loss, as a matter of fact.

167 Amenably to Eqs. (2.9), (2.12)-(2.14), the electron with the incident energy $E_e(0)$ at the
 168 starting edge of converter has got the energy

$$E_e(x) \approx E_{e\text{rad}}(x) - \frac{6\pi r_0^2 m Z_C \ln[E_e^{av}(2mI_Z^2)^{-1/3}]}{\varphi_{\text{rad}}} \left(1 - \frac{E_{e\text{rad}}(x)}{E_e(0)}\right) \approx$$

$$\approx E_{e\text{rad}}(x) + \Delta E_{eI}(x), \quad (2.15)$$

169 upon passing the path x through converter (see Fig. 1). Just this, x -dependent, energy
 170 $E_e(x)$ is to be substituted into Eq. (2.5) to describe the bremsstrahlung of an electron at
 171 the distance x from the starting edge of converter. Thus, the bremsstrahlung production
 172 cross-section (2.5) turns out to be function of the distance x , via the electron energy $E_e(x)$
 173 (2.15).

174 In the actual evaluation explicated further in Sections 3, 4, the converter thickness R_C
 175 proves to be chosen so that there are no electrons with the energies $E_e(R_C) \gtrsim 10 \text{ MeV} \gg m$
 176 at the final edge of converter.

177 As expounded above, only the bremsstrahlung with $k \gtrsim 10 \text{ MeV} \gg m$, described by Eq.
 178 (2.5), is of value to induce the desirable photo-nuclear reaction (2.2). This bremsstrahlung,
 179 caused by the initial electron beam with the energy distribution $\rho_e(E_e)$ and the current
 180 density $J_e(t)$, when stems at a distance x from the starting edge of converter, is described by
 181 the photon current density (2.1)

$$J_\gamma(x, k, E_e, Z_C, \rho_C, t) = \rho_e(E_e) J_e(t) \mathcal{N}_C \frac{d\sigma_b(k, E_e(x), Z_C)}{dk}, \quad (2.16)$$

182 where the cross section $d\sigma_b/dk$ is given by Eq. (2.5) with the electron energy $E_e(x)$ (2.15).
 183 This γ -flux spreads then forward, as was explicated above.

184 In this bremsstrahlung passing the path $(R_C - x)$ from a point x up to the final edge
 185 of converter R_C (see Fig. 1), there are three processes which cause the continuing γ -ray
 186 absorption [19-21] : 1) the e^+e^- -pairs production; 2) the photo-effect; 3) the Compton

188 $k \gtrsim 10$ MeV [19–21]. Consequently, the bremsstrahlung current density $J_\gamma(x, k)$ (2.16)
 189 decreases, becoming at the final edge of converter

$$J_\gamma(x, k, R_C) = J_\gamma(x, k) \cdot \exp\left(-\frac{R_C - x}{l_C(Z_C, \mathcal{N}_C, k, \rho_C)}\right), \quad (2.17)$$

190 where the length of absorption l consists from three aforesaid parts

$$\frac{1}{l_C} = \frac{1}{l_{pair}} + \frac{1}{l_{photo}} + \frac{1}{l_{Com}}. \quad (2.18)$$

191 Generally speaking, a tiny small quantity $1/l_{\gamma n}$, caused by the reactions like (2.2), should
 192 have been added to right-hand side of Eq. (2.18), for conscience's sake. The values of l for
 193 various materials are found, for instance, in Refs. [20, 24]. Let us mention that we deal with
 194 the γ -ray energies just above the so-called “area of maximum transparency” [19, 20, 24].

195 As understood, precision of all the carried out calculations is proved to be at least of the
 196 order $\sim \frac{m}{E_{GR}}$, $\sim \frac{I_Z}{E_{GR}}$, that is anyway none the worse than $\sim 10\%$.

197 With taken into consideration the restrictions imposed by the guide conditions (2.3),
 198 (2.4), we shall now discuss how the cascade of electrons and photons, practicable to the
 199 isotope production (2.2), would emerge. The processes in those an electron with the energy
 200 $E_e < E_{GR}$ participates can't anyway lead to any discernible contribution into the photo-
 201 neutron production (2.2) of the desired isotope $A'(Z, N - 1)$. In slowing-down from the
 202 initial energy $E_e(0)$ to the energy E_{GR} , an electron loses the energy

$$\tilde{\Delta} \approx E_e(0) - E_{GR}. \quad (2.19)$$

203 This energy loss $\tilde{\Delta}$ itself isn't considered to be small. So, at the maxima currently treated
 204 electron energy $E_e(0) = 100$ MeV, we would have got $\tilde{\Delta} \approx 85$ MeV, and for the timely most
 205 vital $E_e(0) = 50$ MeV we would arrive at $\tilde{\Delta} \approx 35$ MeV. As generally received [20, 25], the
 206 primary share of this energy lost $\tilde{\Delta}$ is radiated most probably as the γ -rays with energies

$$\tilde{k} = \tilde{E}\gamma \approx \frac{\tilde{\Delta}}{2}. \quad (2.20)$$

207 Only a small part of this energy loss $\tilde{\Delta}$ is emitted as a flux of comparatively soft photons,
 208 and γ -radiating with the energies $k = E_\gamma > \tilde{k}$ proves to be all the more negligible [20, 25].
 209 As was already discussed above, in absorbing a photon with the considerable energy \tilde{k} (2.20),

$$E^+ \approx E^- \approx \frac{\tilde{k}}{2} \approx \frac{\tilde{\Delta}}{4}. \quad (2.21)$$

211 Surely, there is no reason to suggest these energies to be as small as negligible, yet anyway
 212 they are nevertheless substantially smaller than the initial electron energy $E_e(0)$. Thus for
 213 the timely most vital case $E_e(0) = 50 \text{ MeV}$, we have got $E^\pm \approx 8 \text{ MeV} < E_{GR}$, so that
 214 the thereby produced e^+ , e^- can never contribute to the isotope production (2.2) at all,
 215 which is understood in observing Fig. 2. Put another way, there would be a cascade, but
 216 the particles participating therein would have got energies beyond the key condition (2.3).
 217 At the largest initial electron energy we currently consider (2.4), $E_e(0) = 100 \text{ MeV}$, there
 218 would be $E^\pm \approx 20 \text{ MeV}$, so as, generally speaking, these e^+ , e^- themselves would give rise
 219 to the bremsstrahlung which could in turn serve to the isotope $A'(Z, N - 1)$ photo-neutron
 220 production (2.2). Yet this isotope production, caused by those secondary electrons with
 221 energies $E^\pm \approx 20 \text{ MeV}$, is anyway 10 times as small as the production due to the initial
 222 electrons with $E_e(0) = 100 \text{ MeV}$ themselves, which comes to light in observing the findings
 223 presented in tables 5,6,7, Section 4. Thus, when we abandon, even at $E_e(0) = 100 \text{ MeV}$, the
 224 above explicated cascade, the thereby inherent ambiguities will never come over $\approx 10\%$.
 225 That is why we do not draw into consideration the bremsstrahlung which would be induced,
 226 in converter or in sample, by the electrons those themselves would be originated by absorption
 227 of the bremsstrahlung, which in its turn is due to scattering an initial electron on nuclei in
 228 converter.

229 Upon integrating Eq. (2.17) over the initial electron energy distribution and over the
 230 converter length, we obtain the bremsstrahlung flux at the final edge of converter

$$J_{\gamma C}(k, R_C, Z_C, \rho_C, E_e^b, E_e^u, \Delta_e, t) = \int_{E_e^b}^{E_e^u} dE \int_0^{R_C} dx J_\gamma(x, k, R_C, E, Z_C, \rho_C, t), \quad (2.22)$$

231 where E_e^b , E_e^u are, respectively, the bottom and upper energies of the electron distribution in
 232 beam, and Δ_e is to describe its width. In our further actual evaluations, the electron energy
 233 varies between the limits E_e^b , E_e^u , and we choose

$$\rho_e(E) = \frac{1}{\Lambda} \exp[-((E - \bar{E})/\Lambda)^2] \quad \bar{E} = \frac{E_e^b + E_e^u}{2} \quad (2.23)$$

$$1 = \int_{E_e^b}^{E_e^u} dE \rho_e(E).$$

234 Surely, when $\Delta_e \rightarrow 0$, Eq. (2.23) reduces to the δ -function electron energy distribution. Also,
 235 let us recall the initial electron current density J_e in Eqs. (2.16), (2.17), (2.22) is given in
 236 $\text{A}/\text{cm}^2 = 10^{19} e^- / (1.602 \cdot \text{sec} \cdot \text{cm}^2)$ where e^- is the electron electric charge.

237 3. Radio-isotope photo-production in sample

238 Traveling forward, the bremsstrahlung flux (2.22) intrudes into the sample (see Fig. 1)
 239 that incorporates the isotope $A(Z, N)$ which serves to produce the desirable radio-isotope
 240 $A'(Z, N - 1)$ due to the photo-nuclear reaction (2.2). As well known, this process is caused
 241 by the giant resonance in the nuclear photo-absorption [18]. By now, there exist numerous
 242 reliable measurements of the cross-sections $\sigma_{\gamma n}(k, Z, N)$ of the neutron γ -production (2.2)
 243 for manifold nuclei. The respective data are put to use in our evaluations. The errors
 244 in these $\sigma_{\gamma n}$ measurements may rather amount $\sim 10\%$, which puts a bound to the accuracy
 245 attainable in our evaluations. If anything, it is to point out that at the large converted γ -ray
 246 energies, $E_\gamma \gtrsim 30 \text{ MeV}$, the contribution to (2.2) from area beyond the giant-resonans nuclear
 247 photo-absorption would be discernible because at these energies there exists the nuclear
 248 photo-absorption due to the surface absorption, the virtual quasi-deuteron absorption, and
 249 the absorption caused by the nucleon polarizability in nucleus [26]. Though this contribution
 250 ought to have been taken into account, its impact onto the quantities we have been considering
 251 were hardly more than a few per cent, even at $E_e(0) = 100 \text{ MeV}$.

252 Absorption of the γ -flux goes on inside sample in much the same way as in converter, yet
 253 l_C (2.18) gives place to $l_S(Z_S, \mathcal{N}_S, \rho_S, k)$ of the sample. Upon passing a distance y from the
 254 starting edge of sample (see Fig. 1), the γ -flux (2.22) modifies as follows

$$\begin{aligned} J_{\gamma S}(y, k, R_C, Z_C, \rho_C, E_e^b, E_e^u, \Delta_e, t) = \\ = J_{\gamma C}(k, R_C, Z_C, \rho_C, E_e^b, E_e^u, \Delta_e, t) \exp\left[-\frac{y}{l_S(Z_S, \mathcal{N}_S, \rho_S, k)}\right]. \end{aligned} \quad (3.1)$$

255 Then the density of atoms $\mathcal{N}_{ris}(y, k, Z, N - 1, t)$ of the desirable radio-isotope $A'(Z, N - 1)$,
 256 produced per 1s by the current density (3.1), with a given k , at the distance y (see Fig.1) is

$$\begin{aligned} & \frac{d\mathcal{N}_{ris}(y, k, Z, N - 1, t)}{dt} = \\ & = \mathcal{N}_S(Z, N) \cdot \sigma_{\gamma n}(k, Z, N) \cdot J_{\gamma S}(y, k, R_C, Z_C, \rho_C, E_e^b, E_e^u, \Delta_e, t), \end{aligned} \quad (3.2)$$

258 where the density of sample atoms

$$\mathcal{N}_S(Z, N) = \frac{\rho_S \cdot 6.022 \cdot 10^{23}}{A_S} \quad (3.3)$$

259 is given in terms of the sample density ρ_S and the atomic weight A_S . When the isotope
260 $A(Z, N)$, needful to produce $A'(Z, N - 1)$, constitutes only some part \mathcal{A}_{bn} of the sample
261 material, the density ρ_S in (3.3) is

$$\rho_S(Z, N) = \mathcal{A}_{bn} \bar{\rho}_S, \quad (3.4)$$

262 where $\bar{\rho}_S$ is the whole sample density, in particular the density of the natural element A_S .
263 Unlike, the quantity l_S in Eq. (3.1) is determined by the total density $\bar{\rho}_S$ anyway.

264 Upon integrating the quantity (3.2) over the length of sample and over the photon energy
265 k , we come to describe the total amount of radio-isotope produced inside the sample, per 1
266 s, per 1cm^2 of a sample area,

$$\begin{aligned} & \frac{d\mathcal{N}_{ris}(Z, N - 1, t)}{dt} = J_e(t) \cdot \mathcal{N}_{ris}^0(Z, N - 1), \quad (3.5) \\ & \mathcal{N}_{ris}^0(Z, N - 1) = \mathcal{N}_S(Z, N) \cdot \mathcal{N}_C(Z_C, N_C) \times \\ & \times \int_{E_e^b}^{E_e^u} dE \rho_e(E) \int_0^{R_C} dx \int_0^\infty dk \left(\frac{d\sigma_b(k, E_e(x), Z_C)}{dk} \right) \sigma_{\gamma n}(k, Z, N) \times \\ & \times \left(1 - \exp\left(-\frac{R_S}{l_S(k, Z_S, N_S)}\right) \right) \cdot l_S(k, Z_S, N_S) \times \\ & \times \exp\left(-\frac{R_C - x}{l_C(k, Z_C, N_C)}\right). \end{aligned} \quad (3.6)$$

267 The integration over the photon energy k is actually restricted by the area where the product

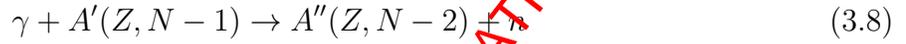
$$\left(\frac{d\sigma_b(k)}{dk} \right) \cdot \sigma_{\gamma n}(k) \quad (3.7)$$

268 has got a discernible value. Beyond any questions, the values $k \lesssim B_n$ and $k \gtrsim E_e$ contribute

The expression (3.5) represents a source to produce this isotope $A'(Z, N - 1)$. To proceed further, we are to recall that the produced radio-isotope $A'(Z, N - 1)$ is not stable, and its decay is governed by the life-time τ_s , so that a number of decays per 1s reads ordinarily

$$\frac{\mathcal{N}_{ris}(t, \tau_s)}{\tau_s}.$$

270 Yet the isotope $A'(Z, N - 1)$ itself undergoes irradiation by the same γ -flux (3.1) as the
271 original isotope $A(Z, N)$ does. Then the photo-nuclear reaction



272 results in depletion of the elaborated desired isotope $A'(Z, N - 1)$,

$$- \mathcal{N}_{ris}(t, \tau_s) \frac{J_e(t) \mathcal{N}_{ris}^0(Z, N - 1)}{\mathcal{N}_S(Z, N)}. \quad (3.9)$$

273 Then, amenably to the common equation

$$\frac{d\mathcal{N}_{ris}(t, \tau_s)}{dt} = J_e(t) \mathcal{N}_{ris}^0(Z, N - 1) - \frac{\mathcal{N}_{ris}(t, \tau_s)}{\tau_s} - \mathcal{N}_{ris}(t, \tau_s) \frac{J_e(t) \mathcal{N}_{ris}^0(Z, N - 1)}{\mathcal{N}_S(Z, N)}, \quad (3.10)$$

274 we obtain the radio-isotope amount, per 1cm^2 area of the sample, elaborated during an
275 exposition time T_e

$$\mathcal{N}_{ris}(T_e, \tau_s) = \mathcal{N}_{ris}^0 \int_0^{T_e} dt J_e(t) \exp[t/\tilde{\tau}_s] \cdot \exp[-T_e/\tilde{\tau}_s], \quad (3.11)$$

$$\frac{1}{\tilde{\tau}_s(J_e(t))} = \frac{1}{\tau_s} + \frac{J_e(t) \mathcal{N}_{ris}^0(Z, N - 1)}{\mathcal{N}_S(Z, N)}. \quad (3.12)$$

276 Although, strictly speaking, the cross-section $\sigma_{\gamma n}(k, Z, N)$ in the expression \mathcal{N}_{ris}^0 in Eq. (3.9),
277 and in the last terms in Eqs. (3.10), (3.12) would give place to $\sigma_{\gamma n}(k, Z, N - 1)$, we utilize
278 here $\sigma_{\gamma n}(k, Z, N - 1) \approx \sigma_{\gamma n}(k, Z, N)$ in the evaluations of these correction terms. For a
279 time-independent initial electron current J_e , Eq. (3.11) reduces to

280 When $T_e \ll \tau_s$, this gets simplify, giving just

$$\mathcal{N}_{ris}(T_e, \tau_s) = \mathcal{N}_{ris}^0 J_e T_e. \quad (3.14)$$

281 Let us mention that though the correction (3.9) is to be allowed for, its impact on the isotope
282 production is very small, rather negligible, at the values of T_e , J_e currently treated.

283 It is to designate that we have been using, all over the carried out calculations, just the
284 life-time τ , yet not the so-called half-decay period $T_{1/2} = \tau \ln 2$.

285 It is generally accepted (see, for instance, Refs. [14–17, 27]) to describe the radio-isotope
286 production in terms of the yield Y [Bq/(h · μ A · mg $A(Z, N)$)] of the produced activity in
287 Bq per 1h of exposition time, per 1 μ A of the initial electron current, and per 1mg of the
288 isotope $A(Z, N)$ in the sample, which serves to produce the desirable isotope $A'(Z, N - 1)$.
289 Accordingly its definition, this characteristic Y is expressed through the quantity (3.11)

$$Y = \frac{\mathcal{N}_{ris}(Z, N - 1, J_e, E_e^b, E_e^u, R_C, R_S, \mathcal{A}_{bn}, T_e, \tau_s)}{R_S(\text{cm}) \cdot \rho_S(\text{mg/cm}^3) A(Z, N) \cdot \tau_s(\text{s}) \cdot T_e(\text{h}) \cdot J_e(\mu\text{A})}. \quad (3.15)$$

290 It is also of use to discuss the total yield of activity produced by the initial electron current
291 J_e inside the whole actual sample with 1cm² area and thickness R_S , during exposition time
292 T_e

$$\mathcal{Y}(\text{Bq}) = Y \cdot R_S(\text{cm}) \cdot \bar{\rho}_S(\text{mg/cm}^3) \cdot \mathcal{A}_{bn} \cdot J_e(\mu\text{A}) \cdot T_e(\text{h}). \quad (3.16)$$

293 Beside Y , \mathcal{Y} (3.15), (3.16), it is of value to consider the total amount of radio-isotope
294 $A'(Z, N - 1)$ elaborated in the whole sample

$$\mathcal{M}_{Z, N-1}(\text{g}) = \frac{\mathcal{N}_{ris}(Z, N - 1, J_e, E_e^b, E_e^u, R_C, R_S, \mathcal{A}_{bn}, T_e, \tau_s) \cdot \mathcal{A}_{bn} \cdot (Z + N - 1)}{6.022 \cdot 10^{23}}, \quad (3.17)$$

295 where $(Z + N - 1) = A - 1$ is the corresponding atomic weight. In Sections 4 and 5, we
296 display the results of Y and \mathcal{M} evaluations. Apparently, a \mathcal{Y} value is directly expressed
297 through a Y value accordingly (3.16).

$$A(Z, N) + \gamma = A'(Z, N - 2) + 2n, \quad (3.18)$$

$$A(Z, N) + \gamma = A'(Z - 1, N) + p, \quad (3.19)$$

$$A(Z, N) + \gamma = A'(Z - 1, N - 1) + p + n \quad (3.20)$$

299 are generally known to take place as well. Yet their thresholds are nearly twice as much as
 300 the threshold of the reaction (2.2), and their cross-sections are about ten times as small as
 301 the cross-section of the reaction (2.2) [18]. So, with accuracy quite sufficient, the processes
 302 (3.18), (3.19), (3.20) are not competitive with the considered main photo-production (2.2) of
 303 the isotope $A'(Z, N - 1)$. Surely, when desired, the yield of isotopes $A'(Z, N - 2)$, $A'(Z -$
 304 $1, N - 1)$, $A'(Z - 1, n)$ from irradiated sample would be calculated as well.

305 Let us recall that the eventual results (3.11)-(3.17) are governed by the manifold pa-
 306 rameters, which characterize 1) the initial electron beam, $J_e, T_e, \bar{E}_e, E_e^b, E_e^u, \Delta_e$; 2) the con-
 307 verter, $\sigma_b, \mathcal{N}_C, \rho_C, R_C, l_C, K_C$; 3) the sample and the produced radio-isotope, $\sigma_{\gamma n}, \mathcal{N}_S, \rho_S,$
 308 $Z_S, N_S, \mathcal{A}_{bn}, l_S, R_S, N, Z, \tau_s$. In involving these quantities into consideration, the proper dis-
 309 cussions were explicated above. The dependence of $Y, \mathcal{M}, \mathcal{Y}$ on these parameters will be
 310 considered in next Section 4 for some radio-isotopes, produced immediately in the reaction
 311 (2.2). Thereafter, in Section 5, we inquire into the event that the decay

$$A'(Z, N - 1) \implies A^m(Z', N') \quad (3.21)$$

312 of this, at the first step obtained radio-isotope $A'(Z, N - 1)$, serves, in turn, as a source to
 313 produce the second-step radio-isotope A^m , which is eventually put to use in manufacturing
 314 the needful practicable preparation.

315 4. Evaluation of the radio-isotope production characteristics

316 Now we evaluate the quantities $Y, \mathcal{M}, \mathcal{Y}$, acquired above, for some examples, which typify
 317 the radio-isotope production using the electron beam. All over further consideration, the
 318 converter is presumed to be prepared of ^{nat}W (the natural tungsten) with a varying thickness
 319 $R_W(\text{cm})$, and three cases will be considered: the production of ^{99}Mo , ^{237}U , ^{117m}Sn , with
 320 varying the sample thickness $R_{\text{Mo}}, R_{\text{U}}, R_{\text{Sn}}$, the initial electron energy E_e and the current

322 electron current provided by the electron linear accelerator or microtron. The purpose is
 323 to visualize the dependence of the production characteristics $Y, \mathcal{M}, \mathcal{Y}$ (3.15)-(3.17) on the
 324 aforesaid parameters.

325 First of all we treat the reaction



326 providing the production of the isotope ${}^{99}\text{Mo}$, which is known to be the most applicable [4, 7],
 327 as discussed in Introduction. Let us recall the ${}^{99}\text{Mo}$ life-time $\tau_{99\text{Mo}} \approx 96\text{h}$.

328 As indicated by Eqs. (3.18), (3.19), (3.20), the isotopes ${}^{98}\text{Mo}$, ${}^{98}\text{Nb}$, ${}^{99}\text{Nb}$ could be re-
 329 covered as well, if required.

330 In order to elucidate the key point of treatment, we display in Fig. 2. the γ -flux $J_{\gamma C}(k)$
 331 (2.22) at the various thickness R_W of W-converter and at the various initial electron energy
 332 (2.23). The behavior of $J_{\gamma C}(k)$ is to be correlated with the energy dependence of the cross-
 333 section of the reaction (4.1) [28]. As understood, only the area of k -values where $J_{\gamma C}$ and
 334 $\sigma_{\gamma n}$ overlap determines the evaluated quantities (3.5)-(3.17) to describe the radio-isotope
 335 ${}^{99}\text{Mo}$ production, which we are treating now. The γ -rays with energies k beyond this area
 336 are out of value. As the function $\sigma_{\gamma n}$ is well known to be, more or less, of the same form
 337 and magnitude for all the heavy and middle weight nuclei, Fig. 2 typifies the calculation of
 338 radio-isotope production by means of electron beam.

339 As explicated in Section 2, the simultaneous treatment of botch bremsstrahlung produc-
 340 tion and absorption and electron energy losses serves to realize how the isotope yield does
 341 depend on the converter thickness R_W . This dependence is typified by table 1. As under-
 342 stood there exists the most preferable R_W -value for given material of the converter and the
 343 incident electron energy. In actual radio-isotope manufacturing, just this R_C is to be utilized.
 344 Let us mention that the quantity $Y \approx 3.2 \text{ kBq}/(\text{h } \mu\text{A mg}^{100}\text{Mo})$ was obtained in Ref. [14] at
 345 $R_W = 0.3\text{cm}$, which is some greater than the most preferable value $R_W \approx 0.17\text{cm}$. As seen,
 346 the result of Y measurement in Ref. [14] does actually coincide with ours in table 1, with a
 347 reasonable accuracy.

348 The dependence of Y, \mathcal{M} on the R_S value at the various electron energies E_e gets under-
 349 stood from the data given in the tables 2, 3, 4. This Y, \mathcal{M} behaviour is due to simultaneous
 350 run of the isotope ${}^{99}\text{Mo}$ photo-production and the γ -rays absorption in the Mo sample, as

stantially slower than linearly. That is why the quantity Y decreases, and \mathcal{M} tends to some limit by increasing R_{Mo} .

The quantity \mathcal{Y} (3.16) behaves rather alike \mathcal{M} . With the same parameters, as in table 3, for the natural ^{nat}Mo sample, $\rho_{\text{Mo}} = 9,8\text{g/cm}^3$, $\mathcal{A}_{bn} = 0.1$, with the thickness $R_{\text{Mo}} = 2\text{cm}$ and 1cm^2 area, during 1h exposition time, we have got

$$\mathcal{Y}_{99\text{Mo}} \approx 1.7 \cdot 10^{10}\text{kBq}, \quad (4.2)$$

which is rather noteworthy. If anything, by dividing the yield (3.16) on total sample mass, one might treat the so-called specific activity $\mathcal{Y}_{99\text{Mo}}^{sp}$, which measures the activity of ^{99}Mo per unit mass of reaction products,

$$\mathcal{Y}_{99\text{Mo}}^{sp} = \frac{\mathcal{Y}_{99\text{Mo}}}{\rho_{99\text{Mo}} \cdot R_{99\text{Mo}} \cdot 1\text{cm}^2} \approx 10^9 \frac{\text{kBq}}{\text{g}}. \quad (4.3)$$

Yet this quantity would be rather of small use, as it does actually depend on the sample and converter parameters, $R_C, R_S, Z_C, Z_S, \rho_C, \rho_S$, the exposition time T_e , the percentage \mathcal{A}_{bn} of ^{100}Mo in the sample, and so on. That is why we have been making use of $\mathcal{Y}_{99\text{Mo}}$ itself without having recourse to $\mathcal{Y}_{99\text{Mo}}^{sp}$ (4.3).

Fig. 3 offers the time dependence of the quantities Y (3.15) and \mathcal{M} (3.17). They represent the produced activity and mass as a function of exposition time T_e in hours. With T_e increasing, the quantity \mathcal{M}_{res} grows tangibly slower than linearly. Consequently, $Y(T_e)$ decreases and $\mathcal{M}(T_e)$ tends to a finite limit when T_e increases. As seen, there is no reason for too long exposition time.

Table 5 demonstrates how the quantities R_{W} , Y and \mathcal{M} depend on the initial electron energy. As seen, the most preferable R_{W} value increases smoothly with electron energy growth. The feature to emphasize is the sharp augmentation of Y , \mathcal{M} in coming from $\bar{E}_e = 20\text{ MeV}$ to $\bar{E}_e = 25\text{ MeV}$ and then to $\bar{E}_e = 50\text{ MeV}$, yet the relatively slower enhancement shows up by increasing \bar{E}_e from $\bar{E}_e = 50\text{ MeV}$ to $\bar{E}_e = 100\text{ MeV}$.

The next example of considerable practical interest [29] is the photo-production of the tin isomer radio-isotope ^{117m}Sn



We put to use the cross-section of this reaction acquired from Ref. [30]. The results of Y

378 for various thicknesses R_W and R_{Sn} of the W converter and of the natural tin ^{nat}Sn sample,
 379 with 1cm^2 area. Let us recall that the isotope ^{118}Sn constitutes about 24% of the natural tin,
 380 that is $\mathcal{A}_{bn} \approx 0.24$ in (3.4), $\bar{\rho}_{Sn} = 7\text{g/cm}^3$, and the isomer ^{117m}Sn life time $\tau_{117m}Sn \approx 20.2\text{d}$
 381 [24]. As seen, this table 6 offers the same dependence of Y (3.15) and \mathcal{M} (3.17) on the
 382 electron energy for the ^{117m}Sn production, as the table 5 for the production of ^{99}Mo does.
 383 Accordingly to the data in this table 6, the quantity \mathcal{Y} (3.16) at $\bar{E}_e = 50\text{ MeV}$, $R_{Sn} = 2\text{cm}$
 384 proves to be

$$\mathcal{Y}_{117m}Sn \approx 0.8 \cdot 10^{10}\text{kBq}, \quad (4.5)$$

385 which is of the same order, as the \mathcal{Y} (4.2) for ^{99}Mo production.

386 At last, we discuss the production of the widely applied [31], specifically in the nuclear
 387 fuel research, radio-isotope ^{237}U ,



388 The cross section of this reaction is acquired from Ref. [32]. All the consideration runs in
 389 much the same way as in the cases of treating the ^{99}Mo and ^{117m}Sn production. Yet now we
 390 evaluate the quantities Y (3.15), \mathcal{M} (3.17) not just at the time T_e , the finish of the exposition,
 391 but in one day after the 5h-long irradiation. The reason to do so is that the experimental
 392 measurements of the ^{237}U production were carried out in Ref. [15] just under such conditions.
 393 Apparently, as the time of observation T , counting from the start of irradiation, is longer
 394 than the exposition time T_e , the quantities (3.15), (3.17) are to be replaced by

$$Y(T) = Y(T_e) \exp[-(T - T_e)/\tau_{237}U], \quad (4.7)$$

$$\mathcal{M}(T) = \mathcal{M}(T_e) \exp[-(T - T_e)/\tau_{237}U], \quad (4.8)$$

395 with the ^{237}U life time $\tau_{237}U = 6.75\text{d}$, $T - T_e = 1\text{d}$, which are presented in table 7. For
 396 the parameters utilized in Ref. [15], $R_W = 0.3\text{cm}$, $\bar{E}_e = 24\text{ MeV}$, $\Delta_e \rightarrow 0$, we have
 397 got $Y_U \approx 1.35\text{ kBq}/(\text{h } \mu\text{A mg}^{238}U)$, which is in accordance with the result obtained in [15],
 398 $Y_U \approx 1.1\text{ kBq}/(\text{h } \mu\text{A mg}^{238}U)$. Let us recall the isotope ^{238}U constitutes 99.276% of the natural
 399 U, that is $\mathcal{A}_{bn} \approx 1$ in (3.4), (3.16), (3.17), and $\rho_U = 18.7\text{g/cm}^3$. Then, utilizing the data
 400 from table 7, and choosing $\bar{E}_e = 50\text{ MeV}$, $R_U = 2\text{cm}$, $T_e = 5\text{h}$ (unlike the cases of

$$\mathcal{Y}_{237\text{U}} \approx 35 \cdot 10^{10} \text{ kBq}, \quad (4.9)$$

402 that is still more significant than the \mathcal{Y} values for ^{99}Mo and ^{117}Sn , (4.2), (4.5).

403 5. Production of a practicable radio-isotope via an isotope-precursor

404 In a number of important cases, a radio-isotope of practical use $A^m(Z', N')$ is generated
405 by decaying

$$A'(Z, N - 1) \implies A^m(Z', N') + \gamma \quad (5.1)$$

406 an isotope $A'(Z, N - 1)$ obtained in the photo-nuclear reaction (2.2), which was described
407 in previous Section 4. Thus, the parent isotope decay (5.1) is now a source to produce a
408 needful eventual radio-isotope $A^m(Z', N')$ with a life-time τ_m . The density of atoms \mathcal{N}_{ris}^m of
409 this isotope A^m produced by the γ -flux (3.1) inside a given sample is then described by the
410 common equation

$$\frac{d\mathcal{N}_{ris}^m(t, \tau_s, \tau_m)}{dt} = p_m \frac{\mathcal{N}_{ris}(t, \tau_s)}{\tau_s} - \frac{\mathcal{N}_{ris}^m(t, \tau_s, \tau_m)}{\tau_m}. \quad (5.2)$$

411 Here p_m stands to allow for the fact that the isotope decay (5.1) constitutes a share p_m of all
412 the possible decays of $A(Z, N - 1)$. Amenably Eq. (5.2) we generally obtain the amount of
413 radio-isotope $A^m(Z', N')$ for the sample with 1cm^2 area, at the total time T , counting from
414 the exposition start,

$$\mathcal{N}_{ris}^m(T, \tau_s, \tau_m) = p_m \frac{\exp[-T/\tau_m]}{\tau_s} \int_0^T dt \exp[t/\tau_m] \mathcal{N}_{ris}(t, \tau_s), \quad (5.3)$$

415 with the quantity $\mathcal{N}_{ris}(t, \tau_s)$ given by Eqs. (3.10)-(3.14). Ordinarily, we are dealing with the
416 practicable case $T \geq T_e$. In calculating \mathcal{N}_{ris}^m (5.3), we have abandoned leaking the isotope
417 $A^m(Z', N')$ due to the feasible photo-nuclear reaction $A^m(Z', N')(\gamma, n)A''(Z', N' - 1)$ during
418 exposition time T_e . In the case a constant initial electron current J_e irradiates converter
419 during the exposition time T_e , and afterwards disappears, the general Eq. (5.3) reduces to

$$\mathcal{N}_{ris}^m(T, T_e, \tau_s, \tau_m) = \mathcal{N}_{ris}^0 J_e p_m \frac{\tilde{\tau}_s}{\tau_s} \left(\exp[-T/\tau_m] \left(\tau_m \left(\exp[T_e/\tau_m] - 1 \right) - \right.$$

$$-\tau_- \left(\exp[T_e/\tau_-] - 1 \right) + \tau_- \left(1 - \exp[-T_e/\tilde{\tau}_s] \right) \left(\exp[T/\tau_-] - \exp[T_e/\tau_-] \right) \Bigg), \quad (5.4)$$

$$\frac{1}{\tau_-} = \frac{1}{\tau_m} - \frac{1}{\tilde{\tau}_s}.$$

420 With replacing the quantity $\mathcal{N}_{ris}(T_e, \tau_s)$ in Eqs. (3.15)-(3.17) by $\mathcal{N}_{ris}^m(T, T_e, \tau_s, \tau_m)$ (5.3),
 421 (5.4), and τ_s by τ_m as well, the quantities Y^m and \mathcal{M}^m are defined to describe the eventual
 422 isotope $A^m(Z', N')$ production.

423 Hereafter, using the Eq. (5.4), we treat the production of the most extensively employed
 424 radio-isotope ^{99m}Tc [4, 7], which stems in the ^{99}Mo β -decay



425 The branching of the β -decay of ^{99}Mo into the isomer ^{99m}Tc , with the life-time $\tau_m \approx 10\text{h}$
 426 , amounts $\approx 85\%$, that is $p_m \approx 0.85$ in Eq. (5.4) [33]. In other cases ^{99}Mo decays giving
 427 the practically stable ^{99}Tc isotope with $\tau_{\text{Tc}} \approx 4.4 \cdot 10^5 \text{y}$ [14, 24, 33]. All the results presented
 428 hereafter are obtained for the Mo sample of 1cm^2 area, as had been doing in previous Sections
 429 2, 3, 4.

430 Tables 8, 9 show that for a given T_e there exists the most preferable time T_{max} , counting
 431 from the exposition start, when the yield of ^{99m}Tc activity Y_{Tc^m} and the mass $\mathcal{M}_{\text{Tc}^m}$ have
 432 got their maxima. Therefore the radio-isotope ^{99m}Tc is to be extracted out of the Mo sample
 433 upon the time T_{max} best of all. This fact is thought to be of a practical value, though the
 434 dependence of Y_{Tc^m} and $\mathcal{M}_{\text{Tc}^m}$ yield on T sees to be rather smooth.

435 Table 10 shows the activity yield Y_{Tc^m} decreases and the mass $\mathcal{M}_{\text{Tc}^m}$ tends to a certain
 436 limit as the thickness R_{Mo} of Mo sample increases. That is so because the quantity \mathcal{N}_{ris}^m
 437 (5.3) increases substantially slower than linearly, just alike the quantity \mathcal{N}_{ris} (3.11) does.

438 Tables 11, 12 figure the quantities $Y_{\text{Tc}^m}(T)$, $\mathcal{M}_{\text{Tc}^m}(T)$ calculated at $T = T_e$ and $T =$
 439 T_{max} , for the various initial electron energies \bar{E}_e (attached by the associated parameters
 440 E_e^b , E_e^u , Δ_e as in table 5), with choosing the most preferable values of the converter thickness
 441 R_W and the time T_{max} for each \bar{E}_e . It is of interest to correlate the results obtained for the
 442 Mo foil, $R_{\text{Mo}} = 0.01\text{cm}$, with those for the thick enough Mo sample, $R_{\text{Mo}} = 2\text{cm}$. Just
 443 for that matter, the evaluation firstly carried out at $R_{\text{Mo}} = 0.01\text{cm}$ is then replicated at
 444 $R_{\text{Mo}} = 2\text{cm}$, with the results offered in tables 11 and 12, respectively.

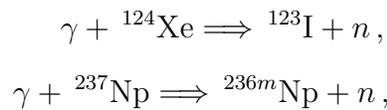
445 Accordingly the data in table 12, the radio-isotope production characteristic \mathcal{Y} (3.16),

$$\mathcal{Y}_{\text{Tc}^m}(T_{max}) \approx 1.2 \cdot 10^{10} \text{ kBq}, \quad (5.6)$$

447 that is of the same order as the corresponding value (4.2) for ^{99}Mo . In other words, let one
 448 irradiate the natural ^{nat}Mo sample, with the 1cm^2 area and the thickness $R_{\text{Mo}} = 2\text{cm}$, during
 449 $T_e = 1\text{h}$ by the γ -flux originated by the electron beam, with $\bar{E}_e = 50\text{ MeV}$ and $J_e = 1\text{A/cm}^2$,
 450 in the ^{nat}W converter with the thickness $R_{\text{W}} = 0.3\text{cm}$. Then, the ^{99}Mo activity (4.2) would
 451 be elaborated by the end of exposition, and, in turn, the ^{99m}Tc activity (5.6), comparable
 452 with (4.2), would be generated at the time $T_{max} = 23.5\text{h}$

453 It is to mention that upon extracting the isotope ^{99m}Tc out of the Mo sample at $T = T_{max}$,
 454 the next amount of ^{99m}Tc isotope, comparable with that at $T = T_{max}$, would be accumulated
 455 in the Mo sample in $T_1 \approx \tau_{99\text{Tc}} \ln(\tau_{99\text{Mo}}/\tau_{99\text{Tc}}) \approx 23\text{h}$, as can be realized from Eq. (5.4).
 456 Yet further repeatedly, over and over again, withdrawing ^{99m}Tc out of the sample is usually
 457 thought to be rather of less efficiency because of diminishing the ^{99}Mo amount.

458 Of course, the examples treated in the presented work do not cover all the area of the
 459 radio-isotope application in these days. In particular, there exists a number of practicable
 460 isotopes eligible to be wrought up by the method described hereupon, in the photo-nuclear
 461 reactions such as



462 and so on [6, 16]. Further investigations in this way are believed to be carried out before
 463 long.

464 Aforesaid obtaining ^{99m}Tc out of ^{99}Mo typifies manufacturing the practicable radio-
 465 isotope due to decay of some preceding isotope, procured at the first step, in the photo-nuclear
 466 reaction (2.2).

467 The values of Y , \mathcal{Y} , \mathcal{M} acquired in Secs. 4, 5 are believed to be of practical interest,
 468 which is discussed next. Let us here recollect that accuracy of our findings is at all the points

6. Findings consideration

471 Once, for all we have by now acquired, there emerge alluring prospects of the radio-
472 isotopes photo-production around electron linear accelerators.

473 Hereafter we correlate and contrast salient features of the routine reactor-based radio-
474 isotope production, even though with the conversion from the *HEU*- to *LEU*-targets, and
475 the electron accelerator-based radio-isotope production, addressing advantages of the last,
476 specifically with respect to the case of recovery of ^{99}Mo and ^{99m}Tc , which are by far the
477 major medical isotopes salable and consumed to-day [4, 7, 9, 10]. We follow the timely
478 industry convention, and quantify the radio-isotope production and supply in terms of *6-day*
479 *curies per week* [7, 9, 10], which is nominally the quantity of ^{99}Mo activity remaining 6 days
480 after the recovered ^{99}Mo leaves the producer's facility, provided the ^{99}Mo has been elaborated
481 during one week, and then was refined and processed before shipment to the market.

482 Let the electron beam with $J[\text{A}/\text{cm}^2]$ and $E_e = 50 \text{ MeV}$ (see Fig. 1) irradiate the
483 tungsten converter with $R_W = 0.3\text{cm}$, and the γ -flux, converted from this electron beam,
484 produce the isotope Mo^{99} in the Mo sample, with $R_{\text{Mo}} = 2\text{cm}$ and 1cm^2 area, amenably to
485 the photo-nuclear reaction (4.1). Then, with allowance for the time-dependence of Y (3.15),
486 \mathcal{Y} (3.16), \mathcal{M} (3.17) (see Fig. 3), and the data given by tables 2, 3, we infer that the total
487 yield of activity by the end of exposition would be

$$\mathcal{Y}(T_e, J_e, \mathcal{A}_{bn}) = J_e \cdot T_e \cdot \mathcal{A}_{bn} \cdot 1.7 \cdot 10^{11} \text{ kBq} \approx 5 \cdot 10^3 \cdot J_e \cdot T_e \cdot \mathcal{A}_{bn} \text{ Ci}, \quad (6.1)$$

488 provided the exposition time $T_e \lesssim 15\text{h}$. At $T_e = 1\text{h}$ and $J_e = 1\text{A}/\text{cm}^2$, we have got the
489 value (4.2) given above. The accelerator can be turned on and off at will and without
490 any consequences, and exchanging the irradiated targets is rather a simple thing, which
491 are apparent advantages of the accelerator-based radio-isotope production over the routine
492 reactor-based one. So we are in position of irradiating a set of Mo targets successively, one
493 after the other with the exposition time of each one equal to the most efficient value $T_e \approx 15\text{h}$.
494 Then, the yield of activity produced in every one of those samples is

$$\mathcal{Y}(15\text{h}, J_e, \mathcal{A}_{bn}) \approx 5 \cdot 10^3 \cdot J_e \cdot 15 \cdot \mathcal{A}_{bn} \text{ Ci}, \quad (6.2)$$

495 As understood, this way leads to the greatest yield of activity generally attainable during a

497 total exposition time consumed in one week constitutes $\approx 150\text{h}$. That series of ten targets
 498 expositions results in the total yield of activity per one week

$$\mathcal{Y}(10 \times 15\text{h}, J_e, \mathcal{A}_{bn}) \approx 5 \cdot 10^3 \cdot J_e \cdot 15 \times 10 \cdot \mathcal{A}_{nb} \text{ Ci}, \quad (6.3)$$

499 As observed, this total activity is accumulated in the separated samples, taken together. On
 500 the other hand, we can continually irradiate one single sample one week long, *i.e.* again for
 501 $\approx 150\text{h}$. In this case the evaluation accordingly Sections 3, 4 (Fig. 3, table 3) results in the
 502 total yield of activity accumulated per one week in that single target

$$\mathcal{Y}(150\text{h}, J_e, \mathcal{A}_{bn}) \approx 3.2 \cdot 10^3 \cdot J_e \cdot 150 \cdot \mathcal{A}_{nb} \text{ Ci}, \quad (6.4)$$

503 which shows up to be noticeably smaller than the quantity (6.3). Let us opt a realizeable
 504 value $J_e = 10\text{mA}/\text{cm}^2$, and presume that we operate targets composed of the pure isotope
 505 ^{100}Mo , *i.e.* $\mathcal{A}_{bn} = 1$ in the expressions (6.1)-(6.4). Then we arrive at

$$\mathcal{Y}(10 \times 15\text{h}, 10\text{mA}, 1) \approx 7.5 \cdot 10^3 \text{ Ci}, \quad (6.5)$$

$$\mathcal{Y}(150\text{h}, 10\text{mA}, 1) \approx 4.8 \cdot 10^3 \text{ Ci}. \quad (6.6)$$

506 Recalling $\tau_{99}\text{Mo} = 96\text{h}$, the aforesaid *6-day curies* activities corresponding to the quantities
 507 (6.5), (6.6) are directly evaluated

$$\mathcal{Y}_{6\text{-day}}(10 \times 15\text{h}, 10\text{mA}, 1) \approx 1.67 \cdot 10^3 \text{ Ci}, \quad (6.7)$$

$$\mathcal{Y}_{6\text{-day}}(150\text{h}, 10\text{mA}, 1) \approx 1.07 \cdot 10^3 \text{ Ci}. \quad (6.8)$$

508 These quantities (6.5)-(6.8), evaluated with practicable ^{100}Mo targets and a realizable electron
 509 beam, prove to be competitive with the marketable *large-scale* productivity of the *large-scale*
 510 *producers*, who furnished on the market more than 1000 *6-day curies* of ^{99}Mo *per week*,
 511 recovered on the routine reactor basis with operating *HEU* targets [7].

512 Nowadays, the pure laboratory study [14–17] of the processes (4.1), (4.4), (4.6), with using
 513 foils of natural Mo, Sn, U as irradiated targets, have blazed the trail towards *the large-scale*
 514 radio-isotope manufacturing based on the electron-accelerator driving photo-neutron nuclear

516 In reactor-based radio-isotope producing, no matter whether the *HEU*- or *LEU*-target
517 is used, the quantity of ^{99}Mo available for sale and harnessing is much less than the total
518 quantity of ^{99}Mo produced in an irradiated target because of this 6 day delay and, primarily,
519 because of losses caused by the very sophisticated and time-consuming target processing, still
520 before shipment to the market. Upon irradiating and then cooling, the targets are processed
521 into *hot cells facilities*, which can cost as much as tens of millions of dollars to construct, and
522 which are very sophisticated to operate [7, 11]. The point is to recover a thoroughly purified
523 desired radio-isotope (for instance ^{99}Mo) out of a target where this constitutes, at best, a
524 few per cent among ^{235}U fission fragments [34]. In particular, the isotope ^{99}Mo , several hours
525 after a moment of fission, constitutes $\sim 6\%$ of fission fragments. The other way round, in
526 the accelerator-based photo-neutron production, there requires no *hot-sells* and subsidiary
527 equipment for targets processing after the end of exposition, as a matter of fact. As well,
528 the desired isotope, *e.g.* ^{99}Mo , is immediately elaborated within a pure molybdenum target,
529 so that there is no need to purify anything and manage any wastes. Therefore the aforesaid
530 6-day term for calibrating activity of the shipment (*6-day curies*) is to be recounted just from
531 the end of target exposition.

532 Used either *HEU*- or *LEU*-target, one of the most important issue to take care of is
533 anyway to eliminate, or at least to minimize, the weapon-usable waste streams resulting
534 from radio-isotope production. In particular concern is that little or no progress is being
535 made for now in this way. Only a very small fraction, typically about 3%, of the ^{235}U in a
536 target undergoes fission in reactor-based radio-isotope, *e.g.* ^{99}Mo , producing [7, 11]. The vast
537 majority of the uranium in the target, along with other fission products and target materials,
538 are eventually treated as wastes, no matter whether the *HEU*- or *LEU*-target is used. Tens
539 of kilograms of *HEU* wastes are annually accumulated worldwide. By contrast, the electron-
540 accelerator-based radio-isotope production has nothing to do with any radioactive wastes,
541 there is no waste stream at all, in actual fact.

542 The decay product of ^{99}Mo , the isotope ^{99m}Tc (see Section 5), we are primarily focused on,
543 is used in about two-thirds of all the diagnostic and therapeutic nuclear-medical procedures
544 all over the world [5, 9, 11, 12]. The metastable radio-isotope ^{99m}Tc having got the short
545 life-time, the ^{99}Mo recovered out of an irradiated target is shipped to radio-pharmacies and
546 hospitals within the *technetium generators* that are *eluted* to obtain the desired ^{99m}Tc at

548 that are contained in a *generator* on the day of, or the day after its delivery to an user [4, 7, 11].
549 In the considered photo-neutron radio-isotope production, an irradiated Mo target could be
550 processed in the *Tc-generator* just after the end of exposition, which is again an evident
551 advantage over the routine reactor-based production, as the last requires a considerable time
552 and work to prepare that irradiated *HEU*- or *LEU*-target for usage in the *Tc-generator*. Of
553 course, the appropriate required *Tc-generator* is anew to be designed and built for recovering
554 ^{99m}Tc from an irradiated Mo sample, upon photo-producing the ^{99}Mo radio-isotope therein,
555 instead of the routine *Tc-generator* to process the blend of different Mo isotopes extracted
556 out of ^{235}U fission fragments. The findings explicated in Section 5 will serve for all these
557 actual purposes. The method how to recover the Tc from Mo irradiated targets are by now
558 elaborated as well [8, 36].

559 As readily understood [7], refurbishing the obsolete reactors and converting from *HEU*-
560 based to *LEU*-based radio-isotope production would be anyway time consuming, at least 5-6
561 years long, and technically sophisticated, at least not less than to bring online the accelerator-
562 based radio-isotope production. Along with other complexities, the conversion would anew
563 require the very expensive construction of the special *hot-cells* for processing now the *LEU*-
564 targets, which are not involved at all into the accelerator-based photo-neutron radio-isotope
565 production.

566 In the routine radio-isotope reactor-based elaboration, there is a very long implicated
567 and vulnerable supply chain of manifold operations, beginning with the *HEU* provision of
568 targets producers and terminating in treating end-users. Any contingency in a single link
569 results in a fatal malfunction of all the chain, all the more that diverse operations are per-
570 formed at different sites, in different countries, and even at different continents. In contrast,
571 radio-isotope photo-neutron production would be accomplished at one single site: from an
572 unsophisticated target preparation straightforwardly to radio-pharmaceutical manufactures,
573 or, as *e.g.* in the ^{99}Mo production case, to charging the *Tc-generator*. There is no issue of
574 shipment of the ^{99}Mo product to the ^{99m}Tc *generator* manufacturing facilities. The losses
575 of radio-isotope yield caused by decay rate would be then minimized, and even almost elim-
576 inated, by co-locating all the engaged facilities. Under such circumstances, any irradiated
577 ^{100}Mo target, upon utilizing by *Tc-generator*, would be restored, and then exposed anew.
578 A circle of this kind could many times be repeated which would allow saving the stick of

580 agenda would offer the possibility of self-contained generator systems being feasible for cen-
581 tral radio-pharmaceutical labs for a grope of hospitals. So, for all we have acquired, there
582 offers a new stream from ^{99}Mo production to an end-user consumption of *kits* prepared with
583 ^{99m}Tc .

584 As understood, see Section 4, the nuclear photo-neutron process $A(Z, N)(\gamma, n)A'(z, N-1)$
585 can serve to produce the great variety of desired radio-isotopes, not only with $A \sim 100$,
586 $A \sim 140$, *i.e.* not only with A placed within the humps of mass distribution of uranium
587 fission fragments. Especially, it is to indicate the isotope ^{201}Tl , that is thought to replace
588 $^{99}\text{Mo}/^{99m}\text{Tc}$ usage, and a number of specific radio-isotopes used in the positron emission
589 tomography (*PET*), ^{13}N , ^{18}F , $^{82}\text{Sr}/^{82}\text{Rb}$, ^{45}Ti , ^{60}Cu , and so on [35], which are not available
590 in the uranium fission process.

591 The above discussions are leading to consideration of building new and operating to-day
592 existing electron linear accelerators (e-linacs) for the radio-isotope production. As under-
593 stood, see Eqs. (6.1)-(6.8), the for now deployed 1/2MW e-linac *TRIUMF* [11, 37], with
594 electron energy $E_e = 50\text{ MeV}$ and current density $J_e = 10\text{ mA/cm}^2$ can be considered to be
595 eligible for manufacturing 1000 *6-day curies* ^{99}Mo activity per week, *i.e.* for the *large scale*
596 ^{99}Mo production. So, a single machine of this kind could manufacture and supply the ^{99}Mo
597 marketable quantity comparable to productivity of a single *large scale* producer, provided the
598 required ^{100}Mo pure targets are available. The manifold efficient methods and technologies
599 to separate various isotopes are by now developed and deployed, see *e.g.* Refs. [6, 8]. So,
600 recovery of a pure singe-isotope target, *e.g.* the pure ^{100}Mo isotope target, is believed to be
601 not over-expensive, when the *large scale* radio-isotope photo-neutron manufacture would be
602 validated.

603 Laboratories around the world, such as *TRIUMPF* (Canada), *BNL*, *ORNL* (U.S.),
604 *IRN-Orseay*, *GANIL* (France), *ELBE* (Deutshland) [37-39], have expertise and facilities
605 that can be used immediately. The construction of far more powerful e-linacs, with $E_e =$
606 50 MeV , $J_e = 100\text{ mA/cm}^2$, are by now under way, and they are believed to be commissioned
607 before long, in 3-4 years, which would underpin a long-term enhancement of desired radio-
608 isotopes production [11]. The estimated cost of such new accelerator is about \$50 millions,
609 whereas the cost of an research and test reactor, with the thermal neutron flux $\approx (10^{14} -$
610 $10^{15})\text{ n}/(\text{s cm}^2)$, is assessed to be at least \$300-\$400 millions. For instance, construction cost

612 of euros [7]. Just fixing the *MAPLE* reactors would have cost tens of millions of dollars,
613 whereas building such new reactor or refurbishing *NRU* would have cost hundreds of millions
614 of dollars. Even 5-years license extension for *NRU* would have required expenditure of
615 about hundred of millions of dollars [7, 11]. Similarly, the reactor operations are far more
616 costly than the e-linac operations. Power consumption, dominating the operating costs, is
617 roughly estimated to be a few *MW*s for an aforesaid e-linac, and the total operating costs
618 are assessed to constitute about 10% of the capital investment. Such an accelerator facility,
619 as treated above, would be viewed as a single-purposed facility operating strictly for radio-
620 isotope production business.

621 The γ -flux, converted from electron beam of an electron accelerator, can also be used
622 for the photo-fission of ^{238}U , utilizing the natural or depleted uranium targets, with subse-
623 quent recovering the desired radio-isotope, *e.g.* ^{99}Mo , from the fission fragments blend [11].
624 The heretofore treated photo-neutron production of radio-isotopes is certain to be far more
625 efficient and viable than the radio-isotope recovery out of the fission fragments of the ^{238}U
626 photo-fission. In order to grasp the reason one is first to recollect that cross-sections $\sigma_{\gamma n}$ of
627 the reaction (2.2) are akin the cross-section $\sigma_{\gamma f}$ of the ^{238}U photo-fission, both being of the
628 same order [40]. Target nuclear densities are of the same order as well. Yet the desired radio-
629 isotope, *e.g.* ^{99}Mo , constitutes at best only a few per cent, never more than $\sim (5 - 6)\%$,
630 among ^{238}U photo-fission fragments. Thus, given the γ -flux causing both reactions is the
631 same, the yield of photo-neutron reaction proves to be far more abundant than one from
632 processing the irradiated ^{238}U sample upon the ^{238}U photo-fission. Anyway, the anew target
633 processing and generator-manufacturing facilities are to be deployed, in using both photo-
634 production, $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$, and photo-fission ^{238}U process, $^{238}\text{U}(\gamma, F)$. Yet although by
635 this ^{99}Mo photo-fission production, just alike in the photo-neutron process, the accelerator
636 does not produce radioactive waste from its operation, the waste from the irradiated targets
637 chemical processing to recover, extract and purify ^{99}Mo would be similar to the waste of the
638 reactor-based production. The ^{99}Mo recovery from ^{238}U photo-fission fragments and from
639 ^{235}U thermal-neutron fission fragments are actually analogous. In either methods, the cap-
640 ital investments emerge to be very high, as the special facilities, in particular the *hot-sells*,
641 are required to deal with the emission and disposal of highly radioactive fission products.
642 In contrast, in the radio-isotope photo-neutron production, there are neither uranium fission

644 producing, there occur no secondary trans-uranic nuclei, in particular ^{239}Pu , associated with
645 radio-isotope producing based on the ^{238}U photo-fission. As understood, see Eqs. (6.1)-(6.8),
646 the mass of about 20g of 100% enriched ^{100}Mo is quite sufficient to design a practicable tar-
647 get for the large-scale ^{99}Mo photo-neutron production, whereas an depleted ^{238}U target for
648 the photo-fission radio-isotope production would require the mass of at least $\sim 200\text{g}$ [11].
649 This large target mass is a substantial challenge in procuring required purity of the obtained
650 medical radio-isotopes. Contamination possibility of a produced radio-isotope, *e.g.* ^{99}Mo ,
651 even increases due to the much larger mass of the photo-fission ^{238}U target as compared to
652 the mass of the ^{235}U target in the case of the thermal neutron fission. So, as it has been
653 coming to light, the photo-neutron production techniques has got a lot of advantages over
654 the photo-fission one. Surely, it is least of all to say that these two approaches rule each other
655 out. They are naturally to complement each other to procure the most reliable radio-isotope
656 supply.

657 Further calculations and laboratory measurements are required to verify and validate the
658 proof-of-principles that have been treated in the work presented.

659 Acknowledgments

660 Authors are thankful to G.D. Maslov, Z. Pantelev, Yu. P. Gangrsky for the valuable
661 discussions.

662 [1] Isotope Production and Application in the 21st Century. Proceedings of the Third Internal
663 Conference on Isotopes, Vancouver, Canada, 6-10 September, 1999. World Scientific Pub. Co.
664 In. Vancouver, B.C. Stevenson, 2000.

665 [2] F.F.R. Knapp, S. Mirzadeck, et al., Journal of Radioanalytical and Nuclear Chemistry 263
666 (2005) 503.

667 [3] Isotope Production and Applications. Workshop on the Nation's Needs for Isotopes: Present
668 and Future. Rockville, MD, August 5-7 2008. U.S. Department of Energy, 2008.

669 [4] Isotopes for Medicine and Life Science. Committee on Biomedical Isotopes. Ed. S.J. Adelstein,
670 F.J. Manning. National Academies Press, Washington D.C., 1999.

- 672 [6] M.J. Rivard, L.M. Bodeck, R.A. Butler, et al., Applied Radiation and Isotopes 63 (2005) 157.
- 673 [7] Medical Isotope Production without Highly Enriched Uranium. National Research Council of
674 the National Academies. C.G. Whipl (chair). The National Academies Press, Washington,
675 D.C. 2009.
- 676 [8] I.N. Bekman, Radioactivity and Radiation (Lecture 7). Moscow State University, Moscow,
677 2006;
- 678 T. S. Bigelow, et al., Production of stable isotopes utilizing the plasma separation process,
679 WILEY, Inter Science, 2005;
- 680 M. D. Matthews, Systems and Methods for Isotope Separation. Pub. No.: U.S. 2007/0272557
681 A1, Nov. 29, 2007.
- 682 [9] R.W. Atcher, Journal of Nuclear Medicine, 50 (2009) 1111.
- 683 [10] C.R. Goldfarb, S.R. Rarmett, L. Zuckier, Nuclear Medicine Board Review, Thieme, National
684 Academies Press, Washington, D.C. 2007.
- 685 [11] Making Medical Isotopes. Report of the Task Force on Alternatives for Medical-Isotope Pro-
686 duction. Ed. A. Fong, T.I. Meyer, K. Zala. AAPS, Canada, TRIUMF, 2008.
- 687 [12] D. Akin, Edmonton Journal, May 21 (2009).
- 688 [13] S. West, CBC News, January 16, 2008.
- 689 [14] A.B. Sabel'nikov, O.D. Maslov, et al., Radiochemistry 48 (2006) 191.
- 690 [15] A.B. Sabel'nikov, O.D. Maslov, et al., Radiochemistry 48 (2006) 187.
- 691 [16] S.N. Dmitriev, O.D. Maslov, A.B. Sabel'nikov, et al., Radiochemistry 40 (1998) 552.
- 692 [17] S. N. Dmitriev, N.G. Zaitzeva, Radiochemica Acta, 93 (2005) 571.
- 693 [18] Landolt-Börnstein, Elementary Particles, Nuclei and Atoms, 16 A, Ed. by H. Shopper,
694 Springer, 2000;
- 695 A. B. Migdal, The Theory of Finite Fermi Systems and the Nuclei Properties, "Nauka",
696 Moscow, 1965.
- 697 [19] A. I. Akhiezer, V.B. Berestetskii, Quantum Electrodynamics, "FM", Moscow, 1959.
- 698 [20] W. Heitler, The Quantum Theory of Radiation, Clarendon press, Oxford, London, 1954.
- 699 [21] V.B. Berestetskii, E.M. Lifshits L. P., Pitaevskii, Relativistic Quantum Theory, Pergamon,
700 Oxford, 1971.
- 701 [22] L.I. Shiff, Phis.Rev. 83 (1951) 252.
- 702 [23] H. Bethe and W. Heitler, Proc. Roy. Soc. A 146 (1934) 83.

- 703 [24] The Nuclear Handbook, Ed. O.R. Frisch, George Newnes Limited, London, 1958;
704 The Table s of Physical Quantities, Ed. I.K. Kikoin, “Atomizdat”, Moscow, 1976.
- 705 [25] J.F. Carlson, J.R. Oppenheimer, Phys.Rev. 51 (1936) 220;
706 H.J. Bhabha, W. Heitler, Proc. Roy. Soc., A 159 (1936) 432;
707 L. Jànossy Cosmic Rays. Oxford, 1948.
- 708 [26] M. Ericson, M. Rosa-Clot, Z. Phys. A 324 (1991) 373;
709 B. Baumann, et al., Phys. Rev. C 38 (1988) 1940;
710 E.Hayward, Phys. Rev. C 40 (1989) 467.
- 711 [27] S. C. Srivastava, et al., Nuclear Medicine and Biology Advances, Ed. C. Raynaud, Pergamon
712 Press, London, 1983.
- 713 [28] H. Beil, et al., Nucl. Phys. A 227 (1974) 427.
- 714 [29] S. C. Srivastava, et al., Clinical Cancer Research 4 (1998) 61.
- 715 [30] A. Lepretre, et al., Nucl. Phys. A 219 (1974) 69.
- 716 [31] Ch. Berthelot, et al., Proc. Modern Trends in Activation Analysis, Copenhagen V. 1, (1986)
717 663.
- 718 [32] A. Veyssiere, H. Beil, R. Berger, et al., Nucl.Phys. A 199 (1973) 45;
719 J.T. Caldwell, E.J. Dowdy, B.L. Berman, Phys. Rev. C 21 (1980) 1215.
- 720 [33] C. M. Lederer, et al., Table of Isotopes, J. Wiley and sons, INC, New York, London, Sydney,
721 1968;
722 F.D.Sowby, Radionuclide Transformations: Energy and Intensity of Emission. ICRP Publica-
723 tion 38, Pergamon, 1983;
724 Nuclear Data Services.//www-nds.iaea.org/ENSDF
- 725 [34] S. Katcoff, Nucleonics, 18 (1960) 201;
726 Yu. A. Ziskin, A. A. Lbov, L. I. Sel’genkov Fission Products and their mass distributions.
727 GOSATOMIZDAT, Moscow, 1963;
728 Yu. P. Gangrsky, B. N. Markov, V. P. Pereligin, Fission Fragments Registration and Spec-
729 trometry. Energoatomizdat, Moscow, 1992.
- 730 [35] J.Lewis, et all., Q. J. Nucl. Med. Mol. Imaging, 52(2) (2008) 101;
731 S. Jurisson, et all., O. J. Nucl. Med. Mol. Imaginig, 52 (2008) 222.
- 732 [36] V. S. Skuridin, E. V. Chibisov, Patent RF \mathcal{N} 2161132, 27.12.2000. // ru-patent. info/21/60-
733 64/2161132htm .

- 734 [37] S. Koscielniak, F. Ames, Y. Bylinsky, et al., in: Proceedings of EPAC08, 11h European
735 Particle Accelerator Conference, Genoa, Italy, June 23-27, 2008., TRI-PP-08-06, August 2008.
- 736 [38] K.H. Guber, T.S. Bigelow, C. Ausmus, et al., Int. Conf. on Nucl. Data for Science and
737 Technology 2007, EDP Sciences, 2008. (<http://nd2007.edpsciences.org>).
- 738 [39] E. Altstadt, C. Beckert, H. Freiesleben, et al., Annals of Nuclear Energy 34 (2007) 36;
739 C. Kaya, U. Lehnart, Proceedings of DIPAC09, Basel, Sw. June 2009.
- 740 [40] A.Veyssiere, et al., Nucl. Phys. A 199 (1973) 45;
741 J.D.T. Arrudantro, et al., Phys. Rev. C 14 (1976) 1499;
742 J.T. Caldwell, et al., Phys. Rev. C 21 (1984) 1215.

DR.RUPNATHJIK(DR.RUPAK NATH)

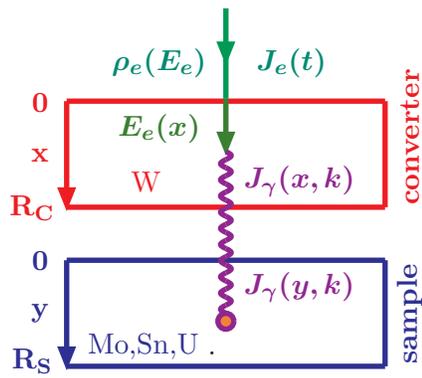


Fig. 1. The setup scheme.

DR.RUPNATHJIK (DR.RUPAK NATH)

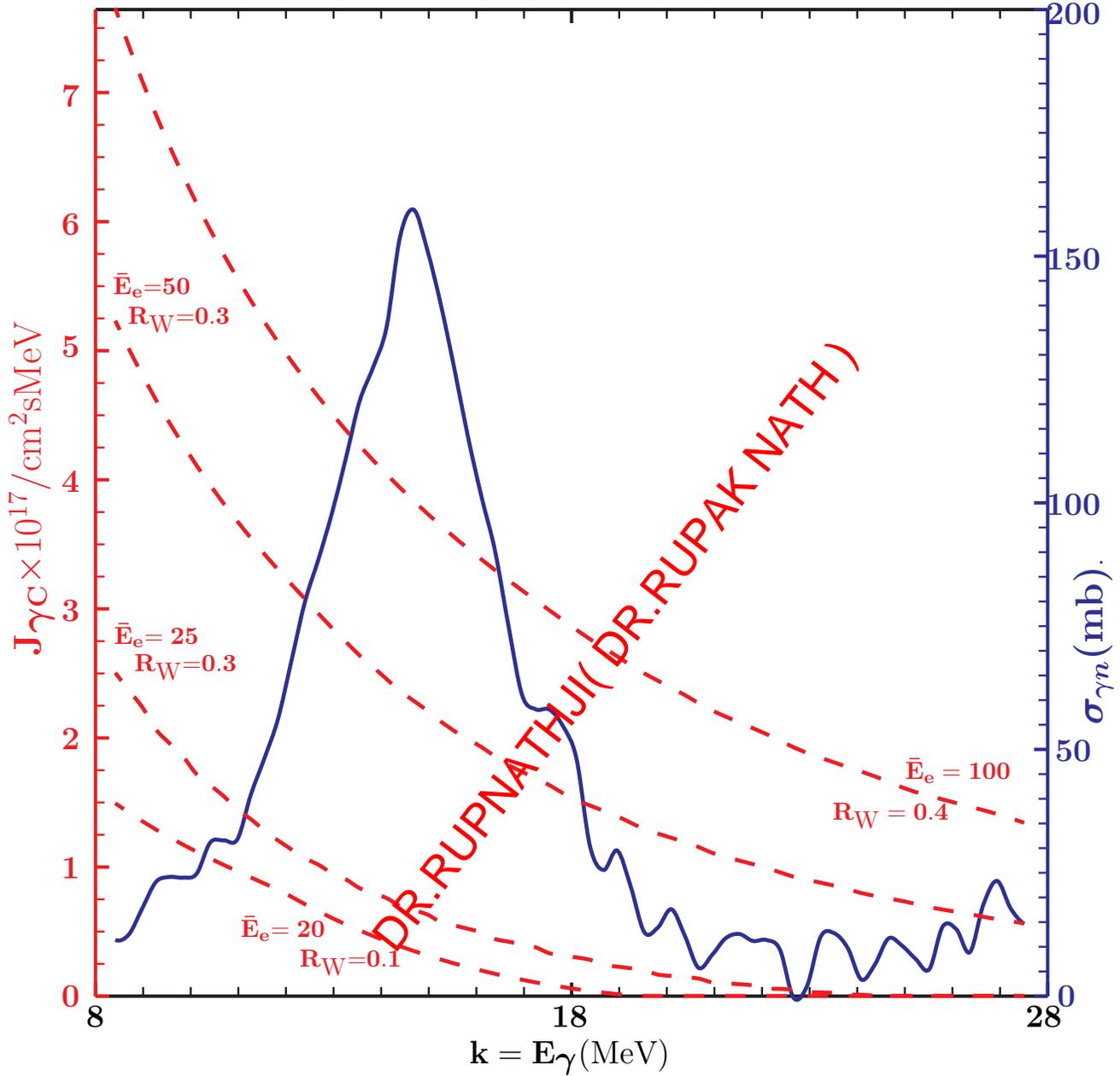


Fig. 2. The dashed curves represent the k -dependence of the γ -flux (2.22) at the final edge of converter for various \bar{E}_e (MeV) and the most preferable thicknesses R_W (cm), which are plotted alongside the respective curves. The electron energies are distributed around the given \bar{E}_e (MeV) accordingly Eq. (2.23) with the E_e^b , E_e^u , Δ_e values chosen as in table 5. The initial electron current density $J_e = 1\text{A}/\text{cm}^2$. The solid curve represents k -dependence of the cross-section of reaction in Eq. (4.1).

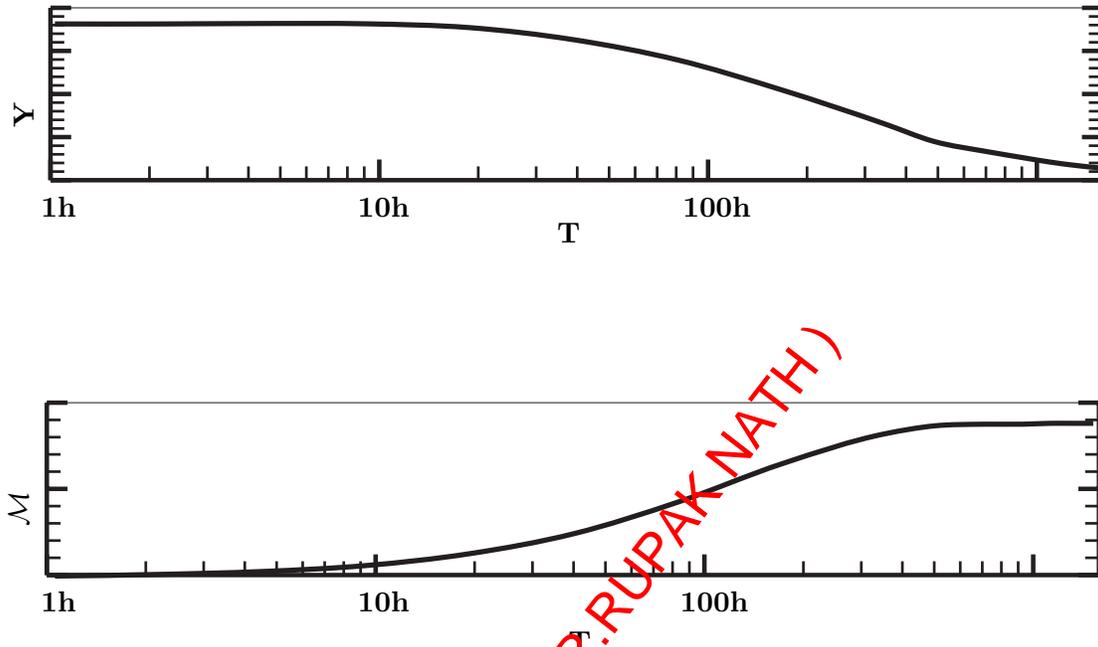


Fig. 3. Time dependence of the yield of activity Y [$\text{Bq}/(\text{h} \cdot \mu\text{A} \cdot \text{mg}^{100}\text{Mo})$] and amount \mathcal{M} ($\text{mg}10^{-1}$) obtained with the converter thickness $R_W = 0.3\text{cm}$ by irradiation of the natural ^{nat}Mo sample, with 1cm^2 area and thickness $R_{\text{Mo}} = 0.01\text{cm}$ (foil), by electrons with $\bar{E}_e = 25\text{MeV}$, $J_e = 1\text{A}/\text{cm}^2$.

DR.RUPNATHUJ DR.RUPAK NATH)

Table 1

The yield of activity Y [kBq/(h · μ A · mg¹⁰⁰Mo)] and amount \mathcal{M} (mg10⁻²) of ⁹⁹Mo at various converter thickness R_W (cm), upon irradiating the natural ^{nat}Mo sample, with 1 cm² area and $R_{Mo} = 0.01$ cm (foil), by electrons with $E_e = 25$ MeV, $J_e = 1$ A/cm², during 1h.

R_W	0.1	0.15	0.175	0.2	0.25	0.30
Y	3.63	4.09	4.07	3.99	3.80	3.62
\mathcal{M}	0.18	0.2	0.2	0.196	0.187	0.177

Table 2

The yield of activity Y [kBq/(h · μ A · mg¹⁰⁰Mo)] and amount \mathcal{M} (mg10⁻²) of the ⁹⁹Mo at various sample thickness R_{Mo} (cm), upon irradiating the natural ^{nat}Mo sample during 1h by electrons with $E_e = 25$ MeV, $J_e = 1$ A/cm², with the converter thickness $R_W = 0.15$ cm.

R_{Mo}	0.01	0.5	1.0	1.5	2.0	4.0
Y	4.09	3.75	3.44	3.17	2.93	2.186
\mathcal{M}	0.2	9.2	16.8	23.4	28.65	42.9

continuing	R_{Mo}	6.0	8.0	10.0	12.0	14.0
	Y	1.69	1.37	1.12	0.948	0.818
	\mathcal{M}	49.73	53.3	55.0	56.2	56.8

Table 3

The same as in table 2, yet for $R_W = 0.3$ cm, and for the initial electron energy distributed around $\bar{E}_e = 50$ MeV accordingly Eq. (2.23) with $E_e^b = 48.5$ MeV, $E_e^u = 52.5$ MeV, $\Delta_e = 0.5$ MeV.

R_{Mo}	0.01	0.5	1.0	1.5	2.0	2.5
Y	11.73	10.73	9.86	9.07	8.37	7.78
\mathcal{M}	0.58	26.3	48.4	66.8	82.2	94.4

Table 4

The same as in table 3, yet for $R_W = 0.4$ cm, and for the initial electron energy distributed around $\bar{E}_e = 100$ MeV accordingly Eq. (2.23) with $E_e^b = 95$ MeV, $E_e^u = 105$ MeV, $\Delta_e = 1$ MeV.

R_{Mo}	0.01	0.5	1.0	1.5	2.0	2.5
Y	19.45	17.80	16.33	15.03	13.84	12.82
\mathcal{M}	0.95	43.7	80.1	110.6	136.1	157.2

Table 5

The yield of activity Y [kBq/(h · μ A · mg¹⁰⁰Mo)] and amount \mathcal{M} (mg10⁻²) of ⁹⁹Mo at various initial electron energy distributions described by \bar{E}_e , E_e^b , E_e^u , Δ_e , all in MeV, as given in Eq. (2.23), and at the most preferable respective thicknesses R_W (cm). The natural ^{nat}Mo sample, with the thickness $R_{Mo} = 0.01$ cm and 1cm² area, is irradiated by the electron current $J_e = 1$ A/cm², during 1h.

\bar{E}_e	20	25	50	100
E_e^b	19.5	24.5	48.5	95
E_e^u	20.5	25.5	52.5	105
Δ_e	0.2	0.2	0.5	1.0
R_W	0.1	0.180	0.3	0.4
Y	2.0	4.00	11.73	19.45
\mathcal{M}	0.1	0.2	0.58	0.95

DR.RUPNATHJI (DR.RUPAKNATH)

Table 6

The same as in table 5, yet here the quantities $Y[\text{kBq}/(\text{h} \cdot \mu\text{A} \cdot \text{mg}^{118}\text{Sn})]$ and $\mathcal{M}(\text{mg}10^{-2})$ are obtained for $^{117}\text{Sn}^m$ production from the natural tin ^{nat}Sn sample, with the thicknesses

$$R_{\text{Sn}} = 0.01\text{cm (foil)}, R_{\text{Sn}} = 2\text{cm, and } 1\text{cm}^2 \text{ area.}$$

\bar{E}_e	20	25	50	100
E_e^b	19.5	24.5	48.5	95
E_e^u	20.5	25.5	52.5	105
Δ_e	0.2	0.2	0.5	1.0
R_W	0.1	0.15	0.3	0.4
$Y, R_{\text{Sn}} = 0.01$	0.456	1.04	5.48	5.48
$Y, R_{\text{Sn}} = 2.0$	0.34	0.78	2.37	4.08
$\mathcal{M}, R_{\text{Sn}} = 0.01$	0.27	0.62	1.89	3.26
$\mathcal{M}, R_{\text{Sn}} = 2.0$	40.84	93.00	283.6	487.5

DR. RUPNATHIJI (DR. RUPAK NATHI)

Table 7

The same as in table 6, yet the quantities $Y[\text{kBq}/(\text{h} \cdot \mu\text{A} \cdot \text{mg}^{238}\text{U})]$ and $\mathcal{M}(\text{mg}10^{-2})$ are obtained for ^{237}U produced from the natural ^{nat}U .

\bar{E}_e	20	25	50	100
E_e^b	19.5	24.5	48.5	95
E_e^u	20.5	25.5	52.5	105
Δ_e	0.1	0.1	0.5	1.0
R_W	0.15	0.20	0.35	0.45
$Y, R_U = 0.01$	1.01	1.77	4.08	6.64
$Y, R_U = 2.0$	0.45	0.78	1.78	2.89
$\mathcal{M}, R_U = 0.01$	6.3	11.07	25.44	41.41
$\mathcal{M}, R_U = 2.0$	558.4	978.9	2234	3626

Table 8

The time T_{max} (h) of maximum accumulation of the isotope ^{99m}Tc and the respective yield of activity $Y[\text{kBq}/(\text{h} \cdot \mu\text{A} \cdot \text{mg}^{100}\text{Mo})]$ and amount $\mathcal{M}_{\text{Tc}^m}(\text{mg}10^{-5})$, as functions on the time T_e (h) of irradiation of the natural ^{nat}Mo sample, with 1cm^2 area and $R_{\text{Mo}} = 0.01\text{cm}$ (foil), by electrons with $J_e = 1\text{A}/\text{cm}^2$, $\bar{E}_e = 25\text{MeV}$, at the converter thickness $R_W = 0.3\text{cm}$.

T_e	0.5	1	5	10	15	20
T_{max}	20	23	25	28	30	32
Y_{Tc^m}	2.54	2.52	2.44	2.32	2.21	2.15
$\mathcal{M}_{\text{Tc}^m}$	5.65	11.3	54.3	103	147	188

Table 9

The $T(h)$ -dependence of the yield of activity Y_{Tc^m} [kBq/(h · μ A · mg¹⁰⁰Mo)] and amount \mathcal{M}_{Tc^m} (mg10⁻⁵) of ^{99m}Tc which results inside the natural ^{nat}Mo sample, with 1cm² area and the thickness $R_{Mo} = 0.01$ cm (foil), irradiated during $T_e = 0.5$ h by electrons with $\bar{E}_e = 25$ MeV, $J_e = 1$ A/cm²; the converter thickness $R_W = 0.3$ cm.

T	0.5	1.5	5.0	10	20	30
Y_{Tc^m}	0.092	0.434	1.43	2.07	2.54	2.50
\mathcal{M}_{Tc^m}	0.2	0.96	3.19	4.60	5.62	5.56

continuing	T	40	50	60	80	100
	Y_{Tc^m}	2.32	2.11	1.9	1.55	1.26
	\mathcal{M}_{Tc^m}	5.16	4.70	4.24	3.44	2.79

DR.RUPNATHUJ (DR.RUPAKNATHUJ)

Table 10

The dependence of the yield of ^{99m}Tc activity $Y_{\text{Tc}^m} [\text{kBq}/(\text{h} \cdot \mu\text{A} \cdot \text{mg}^{100}\text{Mo})]$ and amount $\mathcal{M}_{\text{Tc}^m} (\text{mg}10^{-5})$ on the thickness $R_{\text{Mo}} [\text{cm}]$ of the natural ^{nat}Mo sample, with 1cm^2 area, irradiated during $T_e = 0.5\text{h}$ by electrons with $J_e = 1\text{A}/\text{cm}^2$, $\bar{E}_e = 25\text{Mev}$. The converter thickness $R_W = 0.3\text{cm}$. All the results are obtained at the time $T = 20\text{h}$, counting from exposition start.

R_{Mo}	0.01	0.5	1	2	4	6
Y_{Tc^m}	2.54	2.30	2.13	1.80	1.36	1.05
$\mathcal{M}_{\text{Tc}^m}$	5.65	264	478	810	209	1405

continuing	R_{Mo}	8	10	12	16	20
	Y_{Tc^m}	0.84	0.7	0.59	0.45	0.36
	$\mathcal{M}_{\text{Tc}^m}$	1502	1549	1573	1590	1595

DR. RUPNATHIJK DR. RUPAK NATHI

Table 11

The yield of activity Y_{Tc^m} [kBq/(h · μ A · mg¹⁰⁰Mo)] and amount \mathcal{M}_{Tc^m} (mg10⁻⁵) of ^{99m}Tc, evaluated at $T = T_e$ (h) and $T = T_{max}$ (h), the most preferable time of ^{99m}Tc extraction, for various initial electron energies \bar{E}_e (MeV). The natural ^{nat}Mo sample, with 1cm² area and thickness $R_{Mo} = 0.01$ cm (foil), is irradiated during $T_e = 1$ h by the current $J_e = 1$ A/cm².

R_W is the converter thickness, preferable at the given \bar{E}_e .

\bar{E}_e	20	25	50	100
R_W	0.1	0.15	0.3	0.4
T_{max}	23	23	23.5	24
$Y_{Tc^m}(T_e)$	0.1	0.2	0.59	0.99
$Y_{Tc^m}(T_{max})$	1.42	2.88	8.28	13.92
$\mathcal{M}_{Tc^m}(T_e)$	0.45	0.91	2.62	4.4
$\mathcal{M}_{Tc^m}(T_{max})$	6.29	12.79	36.8	61.82

Table 12

The same as in table 11, yet with $R_{Mo} = 2$ cm.

\bar{E}_e	20	25	50	100
R_W	0.1	0.15	0.3	0.4
T_{max}	23	23	23.5	24
$Y_{Tc^m}(T_e)$	0.07	0.15	0.42	0.71
$Y_{Tc^m}(T_{max})$	1.02	2.06	5.90	9.91
$\mathcal{M}_{Tc^m}(T_e)$	66.4	134	383	643
$\mathcal{M}_{Tc^m}(T_{max})$	922	1858	5328	8941