reduction in the *bremsstrahlung* intensity, even when multiple segments are used, but provides excellent protection against target rupture during irradiation and handling. Aluminum is a good choice for target cladding because it has been used in high-powered electron beams with little degradation from such processes as oxidation by the radiolysis products of water.

Other materials with similar properties include silicon carbide (SiC), titanium, and Inconel® 718, as well as aluminum alloys, titanium alloys, and stainless steel alloys. There is also less volumetric heating with the low-Z materials.

Regardless of the shape or material of construction, the target capsule lid 232 is optionally coated on its inner surface with a high-Z material, illustratively such as tantalum (Ta) 234. The thickness of an illustrative Ta coating 234 is about 120 to about 220 microns (μ). Preferably, the thickness of high-Z material coating 234 is about 150 to about 190 μ, and more preferably, it is about 160 to about 180 μ. The high-Z material coating is preferably sprayed onto the metallic surface of the capsule lid, which becomes the inner surface of the capsule lid after closure.

Tantalum has been used as a converter for the production of *Bremsstrahlung* photons in electron beam bombardment of radium at thicknesses of about 1 to about 3 mm [Diamond et al., *J Appl Phys* **129**:104901 (March 09, 2021)]. Such tantalum thicknesses are up to about 20-fold greater than those utilized herein.

The one or more target capsules 220 can include an air gap 238. The air gap 238 surrounds and/or contacts the high-Z material coating 234 and

the ^{226}Ra target 230. The air gap 238 can act as a heat sink to dissipate heat during activation of the ^{226}Ra target 230.

The target capsule enclosure system 200 further includes a beam stop 240 positioned behind the one or more target capsules 220. The beam stop 240 is preferably comprised of a gamma-radiation shielding material as are well-known. Illustrative beam stop materials include high density (HD) concrete blocks, supplied by Veritas Medical Solutions, Harleysville, PA, USA, and stainless steel. The beam stop 240 is positioned along the incident path (e.g., the same axis) as the electron beam 216.

Further, because the bombardment process can cause the target capsule enclosure system 200 to heat up, the target capsule enclosure system 200 preferably includes a volume 250 for a cooling medium or heat sink. In some embodiments, the cooling volume 250 is comprised of gas. In a preferred embodiment, the cooling volume 250 is filled with air. In other embodiments, the cooling volume 250 is filled with a liquid coolant such as water.

After electron bombardment of the target ^{226}Ra-containing capsule has ceased, the hermetically sealed target capsule is opened, the produced ^{225}Ac is separated from the remainder of the starting ^{226}Ra and various reaction products and daughter radionuclides. These separation methods are well known in the art and include elution processing, including the use of diglycolamide (DGA) materials dispersed onto a porous inert resin or silica support as discussed in U.S. Patents No. 7,087,206, No. 7,157,022 and No. 7,553,461. So-called UTEVA® (Uranium and TEtraValent

Actinides) (dipentyl pentylphosphonate) resins, both of which are available from Eichrom Technologies, Inc.

Illustratively, radium is provided by EZAG/Georgia (Atlanta, GA, USA) with 10 µCi of ^{226}Ra activity in a solution of 0.1 M HCL. The activation (i.e., formation of a radioisotope product) can be for 30 hours at LEAF at ANL, or IBA in Belgium. LEAF is a good source for this activation because of the redundancy of their beamlines and the existence of a universal target station and hot cell.

The produced ^{225}Ac is thereafter usually recovered. The recovery is typically as an aqueous salt solution of a pharmaceutically acceptable anion such as nitrate or a halide such as chloride or bromide. DGA resins available from Eichrom Industries, Inc. (Lisle, IL, USA) are useful for separation of aqueous solutions of actinium salts from radium salts.

Illustratively of a commercial product containing ^{225}Ac, an FDA-approved ^{225}Ac nitrate aqueous solution is available from Oak Ridge National Laboratory. The ^{225}Ac so produced is typically diluted in a pharmaceutically acceptable aqueous diluent for use.

Fig. 7 illustrates a combined control system 300 that can be provided to integrate individual control systems of the accelerator 110, and beamline 130 discussed in reference to FIG. 5 to produce an electron beam, such as the electron beam 216 discussed in reference to FIG. 6.

The combined control system 300 includes a beamline subsystem 305. The beamline subsystem can

include a first beam optics 310 that accepts an electron beam from the accelerator 110.

The beam optics 310 can be used to correct and steer the electron beam received from the accelerator 110. The beam optics 310 can be coupled to a diagnostic component 320 that can be used to analyze a current or a position of the electron beam. The diagnostic component 320 can further be coupled with a second beam optics 330 used for focusing the electron beam.

The second beam optics 330 can be coupled with a third beam optics 340 for further correcting and steering the electron beam. Therefrom, the third beam optics 340 can be coupled with a fourth beam optics 350 comprising an achromatic bend system.

In an exemplary embodiment, the achromatic bend system facilitates the bending of the electron beam. For instance, three magnets are used for the achromatic bend system to bend the electron beam path 270°. The first and third magnets each provide a 70° bend and the second magnet provides a bend of 130° to provide the complete bend of 270°.

From the fourth beam optics 350, the electron beam can travel down one of three paths. If the electron beam matches one or more predetermined criteria for production, the electron beam can be bent by the fourth beam optics 350 toward a second diagnostic component 360 for further analysis of the current or the position of the electron beam.

The second diagnostic component 360 can be coupled with a fifth beam optics 370 for correction and steering, which can further be coupled with a sixth beam optics 380 for focusing. The sixth beam optics 380 can be coupled to a third diagnostic

component 390 for another current and position analysis of the electron beam before transporting the electron beam to a target (such as ^{226}Ra housed in the target holder 150 described above with reference to FIG. 5).

Alternatively, if the electron beam does not match the predetermined criteria for production, the fourth beam optics 350 can pass the electron beam to a fourth diagnostic component 392. In some embodiments, the fourth diagnostic component 392 includes a beam dump or beam stop. However, if the electron beam is not used for production, the fourth beam optics 350 can pass the electron beam to a fifth diagnostic component 394 such as a spectrometer for further analyzing.

In an exemplary embodiment, the electron beam can enter and exit the fourth beam optics 350 in substantially the same plane. That is to say, the achromatic bend system of the fourth beam optics 350 does not affect a vertical elevation of the electron beam.

However, in other embodiments, the electron beam can exit the fourth beam optics 350 in a different plane than the plane at which the electron beam enters the fourth beam optics 350. In other words, in some cases, the achromatic bend system of the fourth beam optics 350 can affect the vertical elevation of the electron beam.

It can be appreciated that the beamline subsystem 305 can include other variations, such as the addition or omission of certain components. Such variations are within the spirit of this disclosure.

The electron activation and delayed counting method is very suitable for investigating

the total production cross-section of ^{225}Ac. Several electron accelerator facilities (national and international) can provide electron beams at about 40 MeV energy. For example, the Low-Energy Accelerator Facility (LEAF) at Argonne National Laboratory (ANL) is very convenient. Additionally, IBA in Belgium can facilitate this mission. Other accelerator facilities can be contacted and utilized, such as ELBE in Dresden, Germany, or the IBA TT300-HE Rhodotron® facility at NorthStar Medical Radioisotope, LLC in Beloit, WI, USA.

Illustratively, the ^{225}Ac yield measurement is obtained by bombarding a target of a homogenized mixture of 100 µg of $RaBr_2$ and 1 mg of Al_2O_3 (acting as a filler) placed inside a hollow cylinder with generally rounded ends (e.g., a capsular structure) 8 mm in diameter and 5 mm in height and to be covered with a 0.1 mm thick aluminum lid 232 and placed inside the activation vacuum chamber. The activation process (e.g., the bombardment of the target 230 in the target holder 150)is for about 30 hours. Then, an offline measurement can be carried out to determine the activities of the activation products using a gamma-ray detector.

The electron-beam current is monitored for the total charge using a methods and apparatus well-known to those skilled in the art. One illustrative apparatus is a Faraday cup. Another illustrative apparatus is a current transformer, also sometimes referred to as a current transducer, such as the ACCT device sold by Bergoz Instrumention headquartered in Saint-Genis-Pouilly, France.

The total production cross-section of ^{225}Ac (from both neutron and proton removal channels) can

be directly obtained by measuring the activity of the 218.0 keV (I_γ= 11.44%) gamma line resulting from the decay of ^{221}Fr ($T_{1/2}$= 4.801 m) and measuring the activity of the 440.45 keV (I_γ= 25.9%) gamma line from the decay of ^{213}Bi($T_{1/2}$= 45.59 minutes, β^- BR: 97.86%), which both are in secular equilibrium with ^{225}Ac during the counting period.

The period for counting is typically less than an hour on day 18 after the end of the bombardment process. Referring back to Fig. 4, it is shown that the expected maximum relative activity of ^{225}Ac occurs on day 18 [Maslov et al., *Radiochemistry,* **48(2):**195-197 (2006)]. The detection utilizes an HPGe detector with a standard lead shielding.

Although there are no reported measurements of the $^{226}Ra(e^-,n)^{225}Ra$ and $^{226}Ra(e^-,p)^{225}Fr$ $-\beta$ decay$\rightarrow$ ^{225}Ra cross-sections, the measured data by Gerab et al., above, on a similar beam-target system, i.e., $^{238}U(e^-,n)^{237}U$, at the same proposed energy range of the electrons indicate that the yields of ^{225}Ac are reasonable. The yield of ^{225}Ra is calculated using a 100 mg of ^{226}Ra, which is equivalent to about 2.7E+20 atoms of radium.

The total production cross-section at an electron beam energy of 39 MeV (mid-target energy) is equal to (2 x 2.5) milli-barn (mb; 1E-27 square centimeter (cm^2) as indicated in Fig. 3, where the sum of $^{226}Ra(e^-,n)^{225}Ra$ and $^{226}Ra(e^-,p)^{225}Fr$ is about double the value of $^{238}U(e^-,n)^{237}U$ cross-section. The beam current of 3.125 mA, with a full width at half-maximum (FWHM), also called half-power beam width, beam spot of 7 mm results in an electron flux of 4.9E+16 $e^-/(cm^2.s)$. [$e^-/(cm^2.s)$ is the unit of flux

for the number of incident electrons per unit area per unit time.]

The reaction rate is then equal to 4E+10 of ^{225}Ra/s, some of which will decay during the production with a decay constant of 5.38E-7 (1/s). [^{225}Ra/s is the number of ^{225}Ra atoms produced per unit time, used here to provide the production rate of the important ^{225}Ra- isotope that decays to ^{225}Ac; 1/s is the decay constant unit or the probability for a single disintegration to take place per unit time.] After 6.5 days of bombardment, the total number of ^{225}Ra atoms produced is 2E+16 atoms, to be compared with the 3E+15 atoms of ^{225}Ra estimated using the simulated photon flux shown in Fig. 1 for a tantalum converter (two discs).

The high-intensity electron beam bombardment (e.g., irradiation) is carried out for a time sufficient to produce a desired amount of ^{225}Ac, taking into account the decay of ^{225}Ac. Typical bombardment (e.g., irradiation) times are 4 to about 30 days, and preferably about 10 to about 25 days.

Each of the patents, patent applications and articles cited herein is incorporated by reference. The use of the article “a” or “an” is intended to include one or more.

The foregoing description and the examples are intended as illustrative and are not to be taken as limiting. Still, other variations within the spirit and scope of this invention are possible and will readily present themselves to those skilled in the art.

CLAIMS

1. A method for converting ^{226}Ra to ^{225}Ac by electron beam bombardment with high energy electrons without the use of a converter that comprises the steps of:

a) bombarding a target comprised of ^{226}Ra present within a hermetically sealed capsule with an electron beam having an average effective beam power of about 20 to about 250 kW at a beam energy of about 25 to about 100 MeV, said capsule having a capsule lid through which said beam of electrons passes prior to impacting said ^{226}Ra, the capsule lid optionally having a high-Z material coating having a thickness of about 120 to about 220 microns (μ) on its internal capsular surface through which said beam of electrons also passes prior to impacting said ^{226}Ra target; and

b) maintaining said bombardment for a time period sufficient to remove a neutron and or a proton from said ^{226}Ra target and form ^{225}Ac in a commercial scale.

2. The method according to claim 1, wherein the formed ^{225}Ac is recovered.

3. The method according to claim 1, wherein said high-Z material coating is present.

4. The method according to claim 1, wherein said capsule is comprised of aluminum or titanium.

5. The method according to claim 4, wherein said capsule is provided in the form of a

hollow cylinder with generally rounded ends, a hollow cone, or a hollow truncated cone.

6. The method according to claim 5, wherein said capsule lid is positioned at an end along an axis of the capsule that is different from a long axis of the capsule.

7. The method according to claim 5, wherein said capsule lid is positioned at the end of the capsule that is along a long axis of the capsule.

8. The method according to claim 1, wherein said time period for bombardment is maintained for about 4 days to about 30 days.

9. The method according to claim 1, wherein said average electron beam power is at about 60 to about 200 kW.

10. The method according to claim 1, wherein said beam energy is at about 25 to about 65 MeV electrons.

11. A method for converting a ^{226}Ra target to ^{225}Ac by electron beam bombardment of said ^{226}Ra target with high energy electrons without the use of a converter that comprises the steps of:

a) bombarding a target comprised of ^{226}Ra present within a hermetically sealed capsule with an electron beam having an average effective beam power of about 60 to about 200 kW at a beam energy of about 25 to about 65 MeV, said capsule having a capsule lid through which said beam of electrons passes prior to

impacting said ^{226}Ra, the capsule lid optionally having a high-Z material coating having a thickness of about 120 to about 220 microns (μ) on its internal capsular surface through which said beam of electrons also passes prior to impacting said ^{226}Ra target; and

b) maintaining said ^{226}Ra target bombardment for a time period of about 4 days to about 30 days to form ^{225}Ac in a commercial scale.

12. The method according to claim 11, wherein said ^{226}Ra target is present as a halide or nitrate salt.

13. The method according to claim 11, wherein the formed ^{225}Ac is recovered.

14. The method according to claim 11, wherein said capsule is comprised of aluminum.