Radionuclide Production

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Introduction

For the 20 or 25 years which followed the 1939–1945 war, radionuclide production for biomedical applications was mostly centred on major nuclear reactor installations <1,2,3>. The last decade has, however, witnessed a rapid growth in the use of particle accelerators for this purpose, as extensively reviewed by Silvester and Waters in 1979 <4>, following from certain favourable characteristics of accelerator–produced, neutron–defficient radionuclides.

Both commercial radionuclide producers and research workers have added accelerators to their armamentarium. The machines have mostly been cyclotrons <5>, of compact "industrial" or "medical" design <6>.

In addition, the BLIP facility <7> at Brookhaven National Laboratory in the U.S., as well as other major accelerator laboratories, including LAMPF in the U.S.<8>, TRIUMF in Canada <9> and SIN in Switzerland <10>, engaged in significant radionuclide production.

The present chapter has been written with a view to providing the researcher with:

a) a listing of radionuclides which have been used or proposed for use in biomedical research
b) data on their major decay modes and how the nuclides are produced, with pertinent literature references
c) an overview of production techniques

The data place the emphasis on accelerator–produced radionuclides, and have been organised in tabular form; what was included and in which table reflects the authors' arbitrary choice. On production methods, it was tried, where possible, to list all proton–induced reactions (reflecting certain trends in the field) together with such different, more efficient methods as may exist.

Some nuclides have been arbitrarily omitted, which have fallen from usage or have not enjoyed wide–spread exploitation up to the present. On the other hand, others have been included (especially in the table of positron emitters) which show promise for applications in the future. The authors apologise to those whose favourite nuclide or reaction have been omitted, and would appreciate receiving corrective information.

Organization of tables

The data have been grouped as follows: In Table 1 are listed gamma–ray suitable for measurement via standard gamma–cameras. Table 2 contains radionuclides which decay by positron emission. With the needs of positron emission tomography in mind, the authors have generally excluded nuclides with half–lives greater than two hours (except for ^{61}Cu and ^{52}Fe), or with positron emission in less than 60 % of their decays (except for ^{120}I). Table 3 lists those particularly useful nuclides which are produced via generators. Generally, data on production of the parent nuclide are included, and for relatively new generator systems references are given on how they have been implemented. Table 4 contains miscellaneous data, on nuclides for example with very long half–lives, or which decay without gamma–emission. Table 5 lists the most important commercially available radionuclides.

In the tables, the yields for the accelerator–produced radionuclides are expressed as mCi/μA at saturation where possible. Otherwise they are expressed as mCi/μAh and designated by "/h". For radionuclides produced by reactors, the cross–section is given in barns (b) for thermal neutrons (t) or for reactor spectrum neutrons (s). Other symbols used are e (for enriched), f.p. (for fission product), g (for generator), D (for transition, due to decay of a daughter radionuclide), N.D. (for no data) and * (yields calculated by the authors from cross–section data in the literature).

Some of the references in the tables are not directly connected with the physical production data given therein, but rather with potentially useful radiochemical separations.

Production techniques

a) General:

The researcher has relatively little direct interest in radionuclide production via reactors, since most of the products are available from commercial suppliers. On the other hand, techniques reviewed below for production via accelerators will be of interest to research staff with their own in–house cyclotron.

A cyclotron for radionuclide production may be chosen with low projectile energy (typically 10–16 MeV protons and deuterons of about half that energy) if a limited range of positron emitters at low cost is the objective, or be chosen to produce higher energy projectiles (proton energies from 26 to 65 MeV) if a wider range of medical radionuclides is intended. All such cyclotrons, however, share one characteristic which sets them apart from the previous generation of accelerators built for physics research, namely production of much higher beam intensities (in the range from 50 to 200 microamperes).

This high beam intensity, coupled with the substantial reaction cross–sections characteristic of the subject low–energy nuclear reactions, leads to the necessary radionuclide production capacity; it does so at the expense of the high target power densities and attendant problems described below.

The four major intermediate–energy accelerator installations referred to above, also have the characteristics of high beam intensity. At their proton beam energies (ranging from 200 to 800 MeV) the reaction cross–sections are smaller by about an order of magnitude; however, this is more than compensated by the larger thickness of target material which can be penetrated by the beam, and hence from which radionuclide production takes place. Thus, these accelerators are, in principle, copious sources of radionuclides, via the spallation reaction. They do, though, produce a wider spectrum of product (and hence impurity) nuclides, distributed through a larger target mass. To cope with this, the separation and purification chemistry tends to be complex, large scale and slow.

The total beam power from these machines is an order of magnitude greater than that from the low–energy cyclotrons described above. On the other hand, this power is distributed at lower density through the larger mass of target material, and this is reflected in the details of the target engineering <7,11,12>.

Radionuclide production at these machines is generally parasitic on the physics program for which they were built. This often leads to scheduling, reliability and other problems for routine supply. They do, however, provide access to a wider range of radionuclides of demonstrated and potential usefulness in biomedical research.

b) Target Design Problems:

In principle, the beam from a cyclotron is available in two locations. The circulating beam is available to targets inserted into the vacuum tank of the cyclotron itself, while the external beam is available following its extraction into an external beam line system.

Utilization of the circulating beam poses a number of difficulties. In addition to the obvious ones of producing a target system which can be introduced through a vacuum lock and which can withstand irradiation without degrading the machine vacuum, strategies must be adopted to reduce the power density deposited in the target material to a value that the target structure can dissipate. Rotating target systems or targets which are oriented so that the beam strikes them at an oblique angle may be employed <13,14>.

In the case of irradiation with an external beam, the power density can be manipulated by beam defocussing or scanning. An external beam is easier to steer and generally much more convenient to work with. These advantages may, however, be offset by a lower available external beam intensity, at least from a cyclotron accelerating positive ions.

In the case of a linear accelerator or of a negative ion cyclotron, the efficiency with which a beam can be brought out of the machine into an external beam line is close to 100 % <15>. Thus, there is no advantage in using the internal beam, and irradiations for isotope production are generally conducted external to the accelerator.

c) Power Dissipation.

Beam energies of tens of MeV, coupled with beam intensities of the order of 100 microamperes, lead to power dissipations in target structures of several kilowatts. Even with a defocussed beam incident on a few square centimeters of target surface, the power dissipation will take place in a few cubic centimeters. Thus, elaborate target cooling is required to avoid melting of target structures.

In addition, the target material must be chosen to resist radiolytic decomposition, evaporation and other processes leading to gas evolution or target disintegration. For safety, the target material may be separated from the machine or beam line vacuum by

means of a "window", consisting of a metal foil thick enough to resist the pressure differentials which may arise (for example) during target recovery. The passage of the beam through such a window also leads to heat deposition, and measures may be needed to remove this heat. At the highest beam currents, two windows with a helium gas coolant flow between them may be required.

d) Solid Targets:

Target materials are most commonly irradiated as solids and all or a major part of the target structure needs to be subsequently transported to the radiochemistry laboratory, to permit extraction and purification of the product radionuclide.

Many metals, particularly of intermediate melting point, are electro–plated onto a copper backing providing good heat contact to the cooling system <16>. The front surface of a metallic target material, such as Tl, Cd, or Zn, may be exposed directly to the beam within the accelerator vacuum system. This system is convenient, since no target de–encapsulation is subsequently required, and there is no beam energy loss in target foils. Glassy materials (such as TeO_2) can likewise be fused to a backing <17>, while salts and powders are commonly compressed to pellet form and irradiated within appropriate metallic encapsulation <12>.

If the target material is of natural isotopic composition, economy of material during target preparation and recovery during the processing of an irradiated target is not a problem. The reverse is true if expensive isotopically–enriched material is being used.

e) Liquid Targets

Liquids can be irradiated by charged particle cyclotron beams, to the limit permitted by power dissipation and radiolytic decomposition. Currents of 10 to 15 microamperes of 20–25 MeV protons can be delivered to (e.g.) water volumes of a few millilitres without boiling becoming a problem.

Water of natural isotopic composition is a source of ^{13}N via the $^{16}O(p,\alpha)$ reaction <18>, while water enriched in ^{18}O is a source of ^{18}F by means of the (p,n) reaction, the radiofluorine being recovered as fluoride <19>. Molten metals, inorganic and organic compounds have also been used as radionuclide production targets. For example, molten NaI has been used in the production of ^{123}I via ^{123}Xe produced by the ^{127}I (p,5n) reaction <20>, while iodine mixed with diiodomethane is used in a similar application at Harwell <21>. Likewise, molten cesium metal in a heat–pipe target system is used in the production of ^{123}I and ^{123}Xe via the spallation reaction <22>. In each case, the activity is conveniently recovered as a reaction product, by sparging the volume above the liquid target material with a suitable sweep gas, usually helium.

f) Gas Targets

Perhaps the most extensive use of gaseous target materials has been in the production of radionuclides of carbon, nitrogen, oxygen and fluorine for positron emission tomography. Centres well known for work on this topic are Hammersmith in the U.K. (which produced a textbook <23>), Brookhaven National Laboratory <24> and the University of Wisconsin <25> in the U.S.

Gas target systems have certain unique advantages and disadvantages to chemist. The loading and unloading of target materials are easily accomplished under remote control, and the recovered material may be subjected to gas chemistry processing on route to the laboratory. Thus, radioactivity in a desired inorganic form may be available very shortly

after the end of bombardment <26>. Manipulation of the target gas mixture itself also permits some control over the radionuclide product chemistry <27>.

There are, however, two significant problems. First, in order to have enough target material in the beam to produce enough radionuclide product, it is often necessary to use long target chambers or elevated gas pressures. This latter in turn necessitates windows strong enough to withstand the pressure differentials, in the face of beam irradiation, with some reliability. Increased foil thickness then increases power deposition in the foil material, with degradation and straggling of the beam energy reaching the target material.

Secondly, there is the phenomenon of the reduction of the gas density in the target region traversed by the beam, due to "beam heating" <28>. In a sealed target of fixed volume, the heat deposited causes a general increase in target gas pressure; however, there are also generated gas pressure inhomogeneities, and a gas target thick enough to stop a beam completely at low beam currents, will fail to do so at higher beam currents, even though the beam energy remains unchanged <29>. Such effects reduce product yields below those calculated, or extrapolated from low current values.

g) Chemical Separations.

The variety of radiochemical procedures employed to separate the product nuclide from the residual target material is as wide as the diversity of chemical species dealt with. The procedures do, however, have some characteristics in common.

a)   Shielding and some degree of remote control is often needed <1,2>. The production of patient doses of 10 millicuries and more at the end of synthetic organic chemistry and radiopharmaceutical procedures necessitates the separation of quantities ranging from 100 millicuries to 1 curie or more from the irradiated target. Quantities at the lower end of this activity scale may be handled in a radiochemical fume hood with demountable lead brick shielding. In general, quantities more than about 1 curie require proper hot cell facilities with substantial shielding and remote manipulation facilities <30>. Semiautomated chemical systems for the production of radiogases in particular chemical forms, or for the synthesis of routine scanning agents, continue to be developed <31,32,33>.

b)   The radionuclide mixture produced by low energy nuclear reactions generally will contain the desired product as the dominant component, with impurity nuclides (particularly those isotopic with the desired product) being present only in minor proportions if the incident projectile energy is properly controlled. This is particularly true if half–life differences or parent–daughter activity relationships can be exploited, in addition, to minimise the yield of such impurities. On the other hand, the products of the spallation reaction at intermediate energies will produce larger quantities of more impurity nuclides, for all except the lightest target nuclides.

The procedures used for the separation and purification of radionuclides are generally adaptations of classical techniques. Thorough, useful compilations have been published <1,2,34>.

For further data on nuclear reactions, the interested reader is referred to the BNL compilation <35> and for more data on radioisotope production to the compilation by Christman and Karlstrom <36>.

References 161–182 contain information on nuclear decay data, medical cyclotrons, reaction compilations, gas target handling and other information that may prove useful to the researcher on medical isotopes.

TABLE I

RADIONUCLIDES USED IN SINGLE PHOTON EMISSION STUDIES.

Nuclide	$T_{1/2}$	Principal Decay Mode.	$E\gamma(I)$ [MeV(%)]	Reaction	Yield (E) [mCi/μA(MeV)]	Ref
^{7}Be	53.3d	e.c.	0.477(10)	^{7}Li(p,n)	0.166/h(20)	37
^{28}Mg	21.1h	β^-	0.401(36)	^{26}Mg(α,2p) ^{27}Al(α,3p)	0.155/h(140)0.3/h e 0.02-0.04/h(140)	38,39
^{28}Al	2.2m	β^-	1.779(100)	^{28}Mg g	see above	
^{38}Cl	37.2m	β^-	1.642(31) 2.167(42)	^{37}Cl(d,p)	0.5/h (20)	40
^{43}K	22.2h	β^-	0.373(22) 0.617(81)	^{40}Ar(α,p)	0.1/h (25) 0.12/h(30)	41,42
^{47}Sc	3.41d	β^-	0.159(73)	^{47}Ca g	see table IV	
^{48}Cr	21.6h	e.c.	0.308(99)	^{51}V(p,4n) ^{nat}Ti(^{3}He,xn)	0.004/h(45-40)* 0.035/h(36)	43,44
^{51}Cr	27.7d	e.c.	0.320(10)	^{50}Cr(n,γ) ^{51}V(p,n)	16b (t) 0.6/h(17)	1,2,45
^{54}Mn	312d	e.c.	0.835(100)	^{56}Fe(d,α)	0.001/h(15)	37
^{52}Fe	8.3h	e^+	0.169(100) 0.378(20)	see table II		
^{59}Fe	44.6d	β^-	1.099(57) 1.292(43)	^{58}Fe(n,γ)	1.1b (t)	1,2
^{55}Co	17.5h	β^+	0.477(16) 0.931(73)	^{56}Fe(p,2n)	11/h(22)	14
^{57}Co	271d	e.c.	0.122(85) 0.136(11)	^{56}Fe(d,n) ^{58}Ni(p,2p)	0.009/h(15) 0.1/h(27) e	37,176
^{62}Cu	9.8m	β^+	1.173(0.3)	^{62}Zn g	see below	
^{64}Cu	12.7h	β^+,β^-	1.346(0.6)	^{63}Cu(n,γ) ^{64}Zn(n,p)	4.4b (t)	1,2,46-48
^{67}Cu	61.9h	β^-	0.185(40) 0.093(16)	^{68}Zn(p,2p) ^{68}Zn(γ,p)	0.02/h(40-30)* 0.03/h(500) 0.01/h(50MeV brem. on 1g e target)*	48-51,122
^{62}Zn	9.15h	β^+	0.597(24) 0.508(13)	^{63}Cu(p,2n)	2.3/h(22-16)	52
^{69}Zn^m	13.9h	β^-,IT	0.493(95)	^{69}Ga(n,p)		
^{66}Ga	9.5h	β^+	1.039(37)	^{66}Zn(d,2n)	1.5/h(16-10)	53
^{67}Ga	78.3h	e.c.	0.093(38) 0.185(24)	^{68}Zn(p,2n)	4.5/h(26-18)	16,48,49
^{72}As	26h	β^+	0.834(80) 0.630(8)	^{72}Ge(p,n)	2.1/h(22) 10/h(15-14) e	14,54
^{74}As	17.8d	β^-,β^+	0.569(59) 0.634(15)	^{74}Ge(p,n)	0.17/h(15)	37,54,55
^{72}Se	8.5d	e.c.	0.046(59)	^{70}Ge(α,2n)	0.037/h(34-20)	54,56
^{73}Se	7.1h	β^+	0.067(99) 0.361(97)	^{nat}Ge(α,xn)	0.22/h(26)	57
^{75}Se	120d	e.c.	0.136(56) 0.265(58)	^{74}Se(n,γ)	50b (t)	
^{77}Se^m	17.5s	IT	0.162(100)	^{77}Br g	see below	

TABLE I(cont'd.)   RADIONUCLIDES USED IN SINGLE PHOTON EMISSION STUDIES.

Nuclide	$T_{1/2}$	Principal Decay Mode.	$E\gamma(I)$ [MeV(%)]	Reaction	Yield (E) [mCi/μA(MeV)]	Ref
^{77}Br	56h	e.c.	0.239(26) 0.521(23)	^{75}As(α,xn) ^{nat}Se(p,xn) ^{79}Br(p,3n)^{77}Kr ^{nat}Mo(p,spall)	0.9/h(40-15) 1.2/h(20-2) 0.36/h(50-30)	58-61
^{81}Kr^m	13s	IT	0.190(100)	^{81}Rb g	see below	
^{85}Kr^m	4.5h	β^-,IT	0.151(80) 0.305(20)	^{84}Kr(d,p)	0.79(15)	62
^{81}Rb	4.6h	β^+	0.446(23) 0.457(3)	^{79}Br(α,2n) ^{nat}Kr(p,xn) ^{82}Kr(p,2n)	2/h(30-14) 11.6/h(32-16) 15/h(22-14) e	63-65
^{85}Sr	65.2d	e.c.	0.514(100)	^{85}Rb(p,n)	0.06/h(22)	14
^{87}Sr^m	2.8h	IT	0.388(100)	^{87}Rb(p,n)	16/h(22)	14
^{89}Y^m	16.1	IT	0.909(100)	^{89}Zr g	see table IV	
^{90}Nb^m	18.8s	IT	0.122(64)	^{90}Mo g	see table IV	
^{95}Tc	20h	e.c.	0.766(94) 1.074(4)	^{96}Mo(p,2n)	7/h(20-15)*	66
^{97}Tc^m	90d	IT	0.096(100)	^{97,98}Mo(p,xn)	0.011/h (22)	67
^{99}Tc^m	6.0h	IT	0.140(89)	^{99}Mo g	see table IV	
^{97}Ru	2.89d	e.c.	0.216(89) 0.324(11)	^{96}Ru(n,γ) ^{nat}Mo(α,xn)	0.25b (t) 0.069-0.075/h(30)	68,69
^{103}Rh^m	56m	IT	0.040(100)	^{103}Pd g	see table IV	
^{109}Ag^m	39.6s	IT	0.088(3.6)	^{109}Cd g	see table IV	
^{111}In	2.83d	e.c.	0.172(100) 0.247(100)	^{112}Cd(p,2n)	6/h(26-18)	70-73, 176
^{113}In^m	1.66h	IT	0.392(100)	^{113}Sn g	see table IV	
^{115}In^m	4.5h	IT	0.336(94)	^{115}Cd g	see table IV	
^{117}Sn^m	14d	IT	0.159(86)	^{121}Sb(p,2p3n)	0.015/h(60-27)	82
^{117}Sb	2.8h	β^+	0.158(86)	^{117}Sn(p,n)	1.6(7-5)*	74
^{118}Sb	3.5m	β^+	1.230(3)	^{118}Te g	see table IV	
^{121}Te	17d	e.c.	0.573(80) 0.508(18)	^{121}Sb(p,n) ^{121}Sb(d,2n)	0.081/h(22) 0.25/h(22)	75
^{123}Te^m	120d	IT	0.159(84)	^{123}Sb(p,n)	0.018/h(22)	14,75
^{123}I	13.1h	e.c.	0.159(83) 0.529(1)	^{124}Te(p,2n) ^{127}I(p,5n)^{123}Xe ^{133}Cs(p,spall)^{123}Xe	20/h(26.5-21)* 20/h(65-50) 10/h(500)	76-82
^{131}I	8.0d	β^-	0.364(84) 0.080(7)	^{130}Te(n,γ)^{131}Te f.p.	0.2b (t) 17b (t)	1,2
^{132}I	2.3h	β^-	0.668(99) 0.773(77)	^{132}Te g	see table IV	
^{127}Xe	36.4d	e.c.	0.203(76) 0.172(30)	^{133}Cs(p,spall) ^{127}I(p,n) ^{133}Cs(p,2p5n)	0.07/h(500) 0.07/h(20) 0.11/h(174-77)	51,82-83

Nuclide	$T_{1/2}$	Principal Decay Mode.	Eγ(I) [MeV(%)]	Reaction	Yield (E) [mCi/μA(MeV)]	Ref
^{133}Xe	5.3d	β^-	0.081(37)	f.p.	38b (t)	84,85
^{128}Cs	3.8m	β^+	0.443(26)	^{128}Ba g	see table IV	
^{129}Cs	32.3h	e.c.	0.373(43)	^{127}I(α,2n)	0.7/h(45)	86
			0.040(53)			
^{133}Ba^m	38.9h	IT	0.276(18)	^{133}Cs(d,2n)	1.1/h(16)	87
^{137}Ba^m	2.6m	IT	0.662(89)	^{137}Cs g	see table IV	
^{134}La	6.7m	β^+	0.605(5)	^{134}Ce g	see table IV	
^{139}Ce	138d	e.c.	0.166(79)	^{139}La(p,n)	0.006/h(15)	37
^{140}Pr	3.4m	e.c.	1.596(0.5)	^{140}Nb g	see table IV	
^{144}Pr	17.3m	β^-	0.696(1.5)	^{144}Ce g	see table IV	
^{157}Dy	8.1h	e.c.	0.326(93)	^{156}Dy(n,γ)	36b (t)	88–90
			0.060(4)	^{159}Tb(p,3n)	0.023/h(30)	
				^{155}Gd(α,2n)	0.08/h(30)	
^{167}Tm	9.3d	e.c.	0.208–D(42)	^{168}Er(p,2n)	0.3/h(22)	14
^{169}Yb	31d	e.c.	0.063(96)	^{169}Tm(p,n)	0.08/h(22)	14
			0.110(60)			
^{172}Lu	6.7d	e.c.	1.094(64)	^{172}Hf g	see table IV	
^{178}Ta	9.3m	e.c.	0.093(6)	^{178}W g	see table IV	
^{183}W^m	5.2s	IT	0.108(18)	^{183}Ta g	see table IV	
			0.099(9)			
^{191}Ir^m	4.9s	IT	0.129(26)	^{191}Os g	see table IV	
^{195}Pt^m	4.1d	IT	0.130(3)	^{197}Au(p,3n)	N.D.	
			0.099(11)	^{194}Pt(n,γ)	1.2b (t)	
^{195}Au^m	30.5s	IT	0.057(100)	^{195}Hg^m g	see table IV	
			0.262(97)			
^{197}Au^m	7.8s	IT	0.279(72)	^{197}Hg^m g	see below	
			0.130(3)			
^{198}Au	2.7d	β^-	0.411(100)	^{197}Au(n,γ)	100b (t)	1,2
			0.676(1)			
^{197}Hg^m	23.8h	IT	0.134(34)	^{197}Au(p,n)	0.23/h(18)	2,92
			0.279(4)	^{196}Hg(n,γ)	500b (t)	
^{203}Hg	46.6d	β^-	0.279(82)	^{202}Hg(n,γ)	5b (t)	2
^{199}Tl	7.4h	e.c.	0.455(12)	^{200}Hg(p,2n)	6.6/h(22)	14
			0.208(12)			
^{201}Tl	73h	e.c.	0.167(9)	^{203}Tl(p,3n)^{201}Pb	1.5/h(29–21) e	93–98
			0.135(2)			
^{203}Pb	52.1h	e.c.	0.279(80)	^{203}Tl(p,n)	0.22/h(22)	14
			0.401(3)	^{205}Tl(p,3n)	3.5/h(28)	97,98
^{204}Bi	11.3h	e.c.	0.899(99)	^{206}Pb(p,3n)	2/h(32)	89
			0.375(75)			
^{206}Bi	6.2d	e.c.	0.803(99)	^{207}Pb(p,2n)	0.7/h(22)	99
			0.881(42)			

TABLE II | POSITRON EMITTING RADIONUCLIDES

Nuclide	$T_{1/2}$	Branch %β^+	Eγ(I) [MeV(%)]	Reaction	Yield (E) [mCi/μA(MeV)]	Ref
^{11}C	20.3m	99.8	no γ	^{10}B(d,n)	10(7.0)	100-103
				^{11}B(p,n)	40(7.5)	
				^{14}N(p,α)	97(12)	
^{13}N	9.97m	99.8	no γ	^{12}C(d,n)	50(7)	104-106
				^{13}C(p,n)	155(15)	
				^{16}O(p,α)	65(23)	
^{15}O	2.03m	100	no γ	^{14}N(d,n)	50(8-1)*	26,107-109
				^{15}N(p,n)	47(8-6)	
				^{16}O(p,pn)	25(26.5-25)	
^{18}F	109.8m	96.9	no γ	^{16}O(^{3}He,p)	6/h(23)	24,110-113
				^{16}O(α,pn)	27(40)	
				^{18}O(p,n)	170(11-2)	
				^{20}Ne(d,α)	82(14-2)	
^{19}Ne	17.4s	99	no γ	^{16}O(α,n)	1.2/min @ 2L/min	114,115
				^{19}F(p,n)	N.D.	
				^{20}Ne(d,dn)	1/min @ 1L/min(14-9)	
^{30}P	2.50m	100	2.235(0.06)	^{27}Al(α,n)	4.74(28-10)	116
				^{31}P(p,pn)	18.7(35-19)	
^{34}Cl^m	32.2m	53	2.128(42)	^{31}P(α,n)	N.D.	
				^{35}Cl(p,pn)	0.9/h(20)	
^{38}K	7.6m	99.5	2.168(99)	^{35}Cl(α,n)	0.58(15-6)	117,118
				^{40}Ar(p,pn)	4.4(32-29.8)	
^{49}Cr	42.0m	93.2	0.091(54)	^{51}V(p,3n)	37(45-30)*	43
^{51}Mn	46.2m	97.2	0.749(26)	^{50}Cr(d,n)	N.D.	25,118
				^{52}Cr(p,2n)	35/h(26)	
^{52}Mn^m	21.1m	98.5	1.434(98)	^{52}Fe g	see below	118
				^{52}Cr(p,n)	50/h(12.3) e	
^{52}Fe	8.3h	56.5	0.169(99)	^{50}Cr(α,2n)	0.003/h(30)	82,119-122
				^{55}Mn(p,4n)	0.16/h(65)	
				^{nat}Ni(p,spall)	8.3Ci(.5sat)(800,μA?)	
^{60}Cu	23.4m	93.6	1.332(88)	^{60}Ni(p,n)	16(12-10)*	123
^{61}Cu	3.4h	62.2	0.283(13)	^{61}Ni(p,n)	25(12-10)*	123,124
				^{64}Zn(p,α)	10(18-12)*	
^{62}Cu	9.8m	97.8	1.173(0.33)	^{62}Zn g	see table I	
^{63}Zn	38.1m	93	0.670(8.4)	^{63}Cu(p,n)	38(15-10)*	125
^{68}Ga	68.1m	87.5	1.077(3.3)	^{68}Ge g	see table IV	
^{75}Br	97m	75.5	0.285(92)	^{75}As(α,4n)	7.5(64-54)	59,126,127
				^{75}As(^{3}He,3n)	6(34-24)	
				^{76}Se(p,2n)	118(28-22) e	
				^{77}Se(p,3n)	50(38-28)) e	
				^{nat}Br(d,xn)^{75}Kr	0.21(90-68)	
				^{79}Br(p,5n)^{75}Kr	N.D.	
				^{78}Kr(p,α)	N.D.	
^{77}Kr	1.24h	80	0.130(84)	^{79}Br(p,3n)	48-75(45-25)	59,60
^{82}Rb	1.25m	96.2	0.776(13)	^{82}Sr g	see table IV	
^{87}Zr	1.6h	83	1.228(100)	^{89}Y(p,3n)	50(45-35)*	128
^{94}Tc^m	52m	72	0.871(94)	^{96}Mo(p,3n)	46(35-27)*	66
^{110}In	69m	72	0.658(98)	^{110}Cd(d,2n)	29(24-11)*	129
				^{111}Cd(d,3n)	10(28-21)*	
				^{109}Ag(α,3n)	1.5(40-30)*	
^{120}I	1.35h	46	0.560(73)	^{127}I(p,8n)^{120}Xe	N.D.(>100 MeV)	131
				^{133}Cs(p,spall)^{120}Xe	N.D.	
^{122}I	3.6m	77	0.564(18)	^{122}Xe g	see table IV	132

TABLE III

GENERATOR SYSTEMS

Daughter Nuclide	$T_{1/2}$	Principal Decay Mode	$E\gamma(I)$ [MeV(%)]	Parent	$T_{1/2}$	Reaction (see table)	Ref
^{28}Al	2.3m	β^-	1.78(100)	^{28}Mg	21.2h	I	
^{38}Cl	37.3m	β^-	2.17(42) 1.60(31)	^{38}S	2.9h	IV	
^{47}Sc	3.4d	β^-	0.159(68)	^{47}Ca	4.5d	IV	
^{52}Mn^m	21.1m	β^+	0.511(196) 1.43(98)	^{52}Fe	8.2h	II	121
^{62}Cu	9.8m	β^+	0.511(194)	^{62}Zn	9.1h	I	52,133
^{68}Ga	68.1m	β^+	0.511(176) 1.08(3.3)	^{68}Ge	287d	IV	
^{72}As	1.1d	β^+	0.511(150) 0.835(80)	^{72}Se	8.4d	I	
^{77}Se^m	17.5s	IT	0.162(54)	^{77}Br	56h	I	134,135
^{81}Kr^m	13.3s	IT	0.190(67)	^{81}Rb	4.6h	I	
^{83}Kr^m	1.86h	IT	0.009(5)	^{83}Rb	83d	IV	
^{82}Rb	1.25	β^+	0.511(192) 0.777(13.4)	^{82}Sr	25d	IV	51,135-139
^{87}Sr^m	2.81h	IT	0.388(82)	^{87}Y	3.3d	IV	140,141
^{89}Y^m	16.1s	IT	0.909(99)	^{89}Zr	78.5h	IV	
^{90}Nb^m	18.8s	IT	0.122(64)	^{90}Mo	5.7h	IV	
^{99}Tc^m	6.0h	IT	0.140(89)	^{99}Mo	2.78d	IV	135
^{103}Rh^m	56m	IT	0.040(.07)	^{103}Pd	17.0d	IV	135
^{109}Ag^m	39.6s	IT	0.088(3.6)	^{109}Cd	464d	IV	
^{111}Cd^m	48.7m	IT	0.150(30) 0.245(94)	^{111}In	2.83d	I	
^{113}In^m	1.66h	IT	0.392(64)	^{113}Sn	115d	IV	135
^{115}In^m	4.49h	IT	0.336(46)	^{115}Cd	53.4h	IV	142
^{118}Sb	3.5m	β^+	0.511(150) 1.23(5)	^{118}Te	6.0d	IV	
^{122}I	3.6m	β^+	0.511(130) 0.564(18)	^{122}Xe	20.1h	IV	132
^{132}I	2.29h	β^-	0.668(99) 0.73(76)	^{132}Te	3.24d	IV	143
^{128}Cs	3.6m	β^+	0.511(102) 0.441(27)	^{128}Ba	2.43d	IV	143
^{137}Ba^m	2.55m	IT	0.662(89)	^{137}Cs	30y	IV	143
^{134}La	6.8m	β^+	0.511(124) 0.605(5)	^{134}Ce	73h	IV	
^{140}Pr	3.4m	β^+	0.511(50) 1.60 (0.5)	^{140}Nd	3.4d	IV	
^{144}Pr	17.3m	β^-	0.696(1.5) 2.186(0.8)	^{144}Ce	284d	IV	144
^{172}Lu	6.7d	e.c.	1.094(64) 0.901(29)	^{172}Hf	1.87y	IV	145
^{178}Ta	9.3m	e.c.	0.093(7)	^{178}W	21.5d	IV	146
^{183}W^m	5.3s	IT	0.108(18)	^{183}Ta	5.0d	IV	
^{191}Ir^m	4.9s	IT	0.129(26)	^{191}Os	15.3d	IV	147
^{195}Au^m	30.6s	IT	0.261(68)	^{195}Hg^m	1.67d	IV	135
^{197}Au^m	7.8s	IT	0.130(3) 0.279(72)	^{197}Hg^m	23.8d	I	143
^{211}At	7.2h	α, e.c.	0.669(0.3)	^{211}Rn	14.6h	IV	148

TABLE IV

MISCELLANEOUS RADIONUCLIDES

Nuclide	$T_{1/2}$	Principal Decay Mode	$E\gamma(I)$ [MeV(%)]	Reaction	Yield(E) [mCi/μA(MeV)]	Ref
^3H	12.3y	β^-	noγ	$^6Li(n,\alpha)$	940b (t)	
^{14}C	5730y	β^-	noγ	$^{14}N(n,p)$	1.8b (s)	149
^{22}Na	2.6y	β^+	1.275(100)	$^{24}Mg(d,\alpha)$	0.002/h(15)	14
^{24}Na	15h	β^-	1.368(100) 2.75(100)	$^{23}Na(n,\gamma)$	0.43b (t)	
^{32}P	14.3d	β^-	noγ	$^{32}S(n,p)$	0.07b (s)	1,2
^{35}S	87.2d	β^-	noγ	$^{35}Cl(n,p)$	0.49b (t)	1,2
^{38}S	2.84h	β^-	1.942(83)	$^{37}Cl(\alpha,3p)$ $^{40}Ar(p,3p)$	N.D. N.D.	
^{36}Cl	3×10^5y	β^-,β^+	noγ	$^{35}Cl(n,\gamma)$	43b (t)	
^{47}Ca	4.54d	β^-	1.297(75) 0.808(7)	$^{46}Ca(n,\gamma)$	0.7b (t)	
^{55}Fe	2.7y	e.c.	noγ	$^{55}Mn(p,n)$	0.014/h(20)	45
^{58}Co	70.8d	β^+	0.811(99)	$^{59}Co(p,pn)$ $^{60}Ni(p,2pn)$	0.066/h(30-20)* 0.028/h(40-30)*	150,151
^{60}Co	5.3y	β^-	1.173(100) 1.332(100)	$^{59}Co(n,\gamma)$	37b (t)	
^{65}Zn	244d	e.c.	1.115(49)	$^{65}Cu(p,n)$	0.015/h(20)	37
^{68}Ge	287d	e.c.	1.077-D(3.3)	$^{69}Ga(p,2n)$ Ga(p,xn) As(p,spall) RbBr(p,spall)	0.012/h(19), 0.028/h(26) 0.009/h(55-10) 0.004/h(500) 0.002/h(500)	51,82,152
^{82}Br	35.4h	β^-	0.776(85) 0.554(71)	$^{81}Br(n,\gamma)$	2.7b (t)	
^{83}Rb	86d	e.c.	0.521(46) 0.530(30)	$^{nat}Kr(p,xn)$	0.007/h(22)	153
^{82}Sr	25.0d	e.c.	0.776-D(13)	$^{nat}Mo(p,spall)$ $^{nat}Rb(p,xn)$	0.060/h(500) 0.18/h(60)	51, 135-139
^{87}Y	3.3d	e.c.	0.485(91)	$^{87}Sr(p,n)$ $^{nat}Rb(\alpha,xn)$	0.008/h(23) 0.059/h(35)	140,141
^{90}Y	64h	β^-	1.761(<.02)	^{90}Sr g/$^{89}Y(n,\gamma)$	1.3b (t)	154
^{89}Zr	78.5h	e.c.	0.909-D(99)	$^{89}Y(p,n)$	0.8/h(21-10)*	155
^{90}Mo	5.7h	e.c.	0.257(78) 0.203(6)	$^{93}Nb(p,4n)$	N.D.	
^{99}Mo	2.78d	β^-	0.140-D(88)	$^{98}Mo(n,\gamma)$ f.p.	0.14b (t) 35b (t)	1,2
^{103}Pd	17.0d	e.c.	0.040-D(0.07)	$^{103}Rh(p,n)$	0.52/h(22)	155
^{109}Cd	464d	e.c.	0.088-D(3.6)	$^{108}Cd(n,\gamma)$ e $^{109}Ag(d,2n)$ In(p,spall) $^{115}In(p,2p5n)$	1.2b (t) 0.008/h(16) 0.018/h(500) 0.025/h(200-177)	51,82,156
^{115}Cd	53.4h	β^-	0.336-D(46)	$^{114}Cd(n,\gamma)$	0.3b (t)	
^{113}Sn	115d	e.c.	0.392-D(64) 0.255(2)	$^{112}Sn(n,\gamma)$	1b (t)	1,2
^{118}Te	6.0d	e.c.	1.229-D(5)	$^{121}Sb(p,4n)$	N.D.	
^{132}Te	3.24d	β^-	0.228(88)	f.p.		
^{124}I	4.2d	e.c.	0.603(61) 1.691(11)	$^{124}Te(p,n)$	0.093/h(26-12)	77
^{125}I ^{128}I	60d 25m	e.c. β^-	0.035(6) 0.443(16)	$^{124}Xe(n,\gamma)^{125}Xe$ I(n,)	120b (t) 6b (t)	1,2

TABLE IV (cont'd.)   MISCELLANEOUS RADIONUCLIDES

Nuclide	$T_{1/2}$	Principal Decay Mode	$E\gamma(I)$ [MeV(%)]	Reaction	Yield(E) [mCi/μA(MeV)]	Ref
^{122}Xe	20.1h	e.c.	0.564-D(18) 0.350(8)	^{127}I(p,6n)	1/h(70-53)	132
^{137}Cs	30y	β⁻	0.662(85)	f.p.		
^{128}Ba	2.43d	e.c.	0.273(15)	^{133}Cs(p,6n)	0.69/h(54-30)	82
^{134}Ce	76h	e.c.	noγ	^{139}La(p,6n)	N.D.	
^{144}Ce	284d	β⁻	0.134(11)	f.p.		
^{140}Nd	3.4d	e.c.	1.596-D(0.5)	^{141}Pr(p,2n)	3.4/h(33-12)	157
^{165}Er	10.4h	e.c.	noγ	^{165}Ho(p,n)	N.D.	158
^{172}Hf	1.87y	e.c.	0.024(20)	^{181}Ta(p,spall)	N.D.	145
^{179}Ta	600d	e.c.	noγ	^{180}Hf(p,2n)	0.005/h(22)	14
^{183}Ta	5.0d	β⁻	0.246(27) 0.354(11)	^{181}Ta(nn,γ)	N.D.	
^{178}W	21.5d	e.c.	0.093-D(7)	^{181}Ta(p,4n)	0.045/h(38-31)	82,146
^{181}W	122d	e.c.	Ta X-rays	^{181}Ta(d,2n)	0.005/h(15)	37,91
^{191}Os	15.3d	β⁻	0.129-D(26)	^{190}Os(n,γ)	11b (t)	
^{195}Hg^{m}	40h	IT,e.c.	0.262(33)	^{197}Au(p,3n)	N.D.	
^{211}At	7.2h	α	0.669(0.3)	^{209}Bi(α,2n)	0.4/h(28-26)	159,160
^{211}Rn	14.6h	e.c.	0.674(44) 1.363(32)	^{209}Bi(^{7}Li,5n)	0.26/h(60-38)	148

TABLE V.   MAIN COMMERCIAL RADIONUCLIDES

Nuclide	$T_{1/2}$	See Table	1982 LIFE-SCIENCE RETAIL CONSUMPTION (~Ci/year, time of end-use)
^{3}H	12.3y	IV	>1000
^{14}C	5730y	IV	600
^{32}P	14.3d	IV	700
^{51}Cr	27.7d	I	150
^{67}Ga	78.3h	I	800
^{99}Mo/^{99}Tc^{m}	66h/6h	IV	100000 (^{99}Mo)
^{111}In	68h	I	150
^{113}Sn/^{113}In^{m}	115d/99m	IV	40 (^{113}Sn)
^{123}I	13.2h	I	75
^{125}I	60d	IV	1500
^{131}I	8.0d	I	10000
^{127}Xe	36.4d	I	100
^{133}Xe	5.2d	I	25000
^{201}Tl	73h	I	500

150