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Beneficial Uses and Production of Isotopes

2004 Update

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The OECD is a unique forum where the governments of 30 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities takes part in the work of the OECD.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

This report is based on a study undertaken under the aegis of the OECD Nuclear Energy Agency (NEA) Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The study was carried out jointly by the NEA and the International Atomic Energy Agency (IAEA), with the assistance of a group of experts nominated by NEA member countries. The report is an update of the 2000 OECD publication entitled *Beneficial Uses and Production of Isotopes*. It includes statistical data on isotope production and demand as well as an analysis of key issues in the field of isotope supply and demand.

The main objectives of the study were to provide member countries with a comprehensive and up-to-date survey of isotope uses and production capabilities in the world, to analyse trends in the balance of supply and demand, and to draw findings and recommendations for the consideration of interested governments. Although their importance was recognised by the group, issues relating to regulation were specifically excluded since they are dealt with in a number of publications from the IAEA, the International Organization for Standardization (ISO) and the International Commission on Radiological Protection (ICRP). The production and use of isotopes for military and other classified uses were also excluded from the study.

Information on isotope production and use was collected via a questionnaire issued by the NEA and IAEA secretariats. Twenty-four countries responded to the questionnaire as did the European Commission Research Centre at Ispra, Italy. However, as a number of significant producers of isotopes did not respond to the questionnaire, the discussion and conclusions about isotope production must be considered indicative only. The information collected has been augmented by descriptions of uses of isotopes provided by members of the group of experts. This report is published under the responsibility of the OECD Secretary-General.

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EXECUTIVE SUMMARY

The use of isotopes[1] is an important and state-of-the-art practice in many sectors of the world economy. However, defining their precise role is difficult because there is a lack of comprehensive information on isotope production and demand, particularly quantitative data on the uses and economic impacts of isotope use in the various sectors and countries throughout the world. Therefore, a robust assessment of the overall economic importance of beneficial uses of isotopes was not possible. Additionally, the overview on isotope uses included in this report provides mainly qualitative information. While it was recognized by the Expert Group that a comprehensive quantitative review of isotope uses could prove to be quite valuable, the collection of reliable data proved difficult and revealed a number of issues such as consistency between sectors and countries, commercial confidentiality and national security. These issues remain beyond the scope of the Expert Group to resolve.

In 2002, isotopes were produced for domestic use and/or international markets in 26 countries (as reported in the survey responses) and more than 30 additional countries were likely producers of isotopes, although they did not respond to the questionnaire. Isotopes were mainly produced in multi-purpose research reactors, dedicated isotope production reactors and accelerators.[2] While most research reactors produce isotopes as a by-product to their primary mission, accelerators (except for a few high-energy research machines) are generally dedicated to isotope production. Research reactors are aging with around half of them more than 35 years old. There are, however, at least 11 reactors being built or projected to be built in a number of countries with high-flux reactors being planned for France, Germany, China and Russia. The number of accelerators producing isotopes, especially small dedicated facilities, is growing steadily with the majority of machines being of relatively recent vintage.

Public entities own and operate almost all the research reactors, large-scale accelerators and chemical separation facilities being used for isotope production. Historically, the very large capital requirements, extensive planning and licensing time demands, and additional operating expenses have made public ownership necessary in most cases. Through public-owned facilities, governments offer infrastructure for isotope production and provide for the education and training of the qualified manpower required in the field. These public-owned facilities also often play a critical role of supporting the initial production for research and clinical trials prior to the commercialisation of any promising application. There is, however, a continuing trend toward privatisation and, for example, two privately owned reactors dedicated to isotope production have been built in Canada and are expected to be operational in the near future. A number of medium-sized cyclotrons producing major isotopes for medical applications are owned and operated by private sector enterprises for their exclusive uses as well. Most small cyclotrons, dedicated to the production of medical isotopes, are owned and operated by private enterprises.

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1. Throughout this study the word “isotope(s)” is intended to mean radioactive isotopes except where specifically identified as stable isotopes.
2. Reactors are generally used to produce neutron-rich isotopes, whereas accelerators are generally used for neutron-deficient isotopes.

Trends in isotope production vary according to the various production facility types and to the geographic region being considered. In particular, trends appear to be different for facilities dedicated to isotope production, such as cyclotrons producing isotopes for medical applications, and for facilities that produce isotopes only as a side activity such as most research reactors. Recent additions to the isotope production capabilities in several regions show a trend to the emergence of private or semi-private producers in response to increasing demand, where this is commercially viable. The security of supply of the major isotopes used in the medical and industrial fields does not appear to be an issue for the short or medium term. However, the ageing infrastructure in a number of important areas such as high-flux research reactors, which are the sole means of production of certain types of isotopes, and the uncertainty for their replacement, leaves questions over the long-term. It is important to ensure a redundancy mechanism in order to secure the supply, in each country, of critical short half-life isotopes such as ^{99}Mo, irrespective of technical (e.g. facility failure), social (e.g. strike) or international (terrorist event closing borders) problems that procurers may encounter.

There are isotope uses in nearly every sector of the economy and in nearly all countries of the world. Isotopes have been used in nuclear medicine since 1946 (^{14}C at the University of Chicago) and routinely for several decades. Nuclear medicine is characterised by an ongoing evolution of techniques and the continued emergence of new procedures requiring the production of new isotopes or new applications for existing isotopes. Globally, the number of medical procedures involving the use of isotopes is constantly growing and these procedures require an increasing diverse spectrum of isotopes. In industry, isotope uses are very diverse and their relative importance in the various sectors differs greatly. However, in general, isotopes occupy niche markets where they are more efficient than alternatives or have no substitute. Non-nuclear alternatives are often preferred when they are economically comparable.

The information collected for this study underscores the critical role of governments and public sector entities in isotope production and use. Though the direct responsibilities of governments in the field of isotopes are normally limited to the establishment of safety regulations and the control of compliance with those regulations, national policy, on research and development and medical care, for example, remains a key driver for demand of isotopes and, although to a lesser extent, for their production. However, with the increasing involvement of private companies and the shift to more commercial management of the activities related to isotopes production and uses, governments may want to consider additional support to ensure the stable production of isotopes for research and non-commercial uses within the framework of their national policies, given the importance of beneficial uses of isotopes for science and human welfare.

A number of additional issues are of increasing importance to the application of isotopes. As the distribution of isotopes becomes more global, transportation issues become obvious. The limited number of back-up production facilities and the increasing use of short-lived isotopes demand an effective and secure international transportation infrastructure. Good practices should ensure that control and accountability of isotopes, especially long-lived sealed sources, receive particular attention. In addition, as the production and use of isotopes becomes more ubiquitous, it is becoming more evident that liability issues resulting from the accidental or malicious use or exposure may require additional attention and analysis.

Given the dynamic nature of isotope production and use and their importance in many sectors, it is recommended that the OECD and IAEA continue to monitor this field.

I. ISOTOPE PRODUCTION

The production of isotopes requires a series of steps leading to a product ready for end-uses (see Appendix 1). Generally, the entire process is not carried out in a single plant but rather in several different facilities. This report focuses on the nuclear part of the process, *i.e.* production of the desired isotope *per se*. Therefore, the isotope production facilities described below include only reactors, accelerators and separation facilities used to produce isotopes. Neither the upstream part of the process, i.e. selection and preparation of the target material, nor the downstream, i.e. chemical processing, packaging and control of the isotopes leading to a commercial product ready for final use, are described in this report.

Survey results show that the production of isotopes is a worldwide activity and isotope producing facilities exist all over the world. Broken down by region the fewest production facilities exist in Africa and Central and South America while the largest numbers of facilities are located in Western Europe, Scandinavia and North America (see Table 1.1).

Table 1.1 **Regional distribution of facilities producing isotopes** (as of 1 January 2003)

Region	**Heavy isotope facilities**	**Accelerators**	**Research reactors**	**Total**
Africa	0	2	4	**6**
Central and South America	0	6	3	**9**
Central, Eastern and South-eastern Europe	1	18	11	**30**
East Asia	0	53	8	**61**
Middle East, Central and Southern Asia	0	8	5	**13**
North America	3	84	9	**96**
South-eastern Asia and Pacific	0	9	5	**14**
Western Europe and Scandinavia	1	93	9	**103**
Total	**5**	**273**	**54**	**332**

Production in 2002

Twenty-five countries responded to a questionnaire seeking information on isotope production and demand (see Appendix 4).[3] The European Commission also reported isotope production at its accelerator facility in Ispra, Italy. Of those that responded, 23 reported production of isotopes in 2002 (see Table 1.2). Additional information from the IAEA indicates that 31 other nations produced isotopes that year. [1,2]

The five major isotopes produced in 2002 in terms of those produced in the greatest number of countries were ^{18}F (13 of the 23 respondents reporting isotope production),[4] ^{99}Mo/^{99m}Tc (10 of 23), ^{192}Ir

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[3] A number of significant producers of isotopes did not respond to the questionnaire. Therefore, all discussions and conclusions about isotope production should be considered indicative only.

[4] In addition to the production reported in survey responses, many additional countries likely produced ^{18}F (and other common isotopes) in 2002. For example, IAEA data indicates that 38 countries produced ^{18}F in 2002 (see Appendix 3).

(10 of 23) and ^{11}C and ^{131}I (each with eight countries). Ordering in terms of activity (TBq at the end of irradiation), the top five isotopes produced in 2002 were ^{99}Mo, ^{192}Ir, ^{60}Co, ^{131}I and ^{18}F (see Table 1.3).

Table 1.2 **Summary of reported isotope production in 2002**

Country	**Major isotopes produced in 2002**	**Amount produced in 2002 (EOI)**	**Other isotopes produced in 2002**	**Total amount produced in 2002 (EOI)**	**New isotopes planned to be produced 2003-2005**
Australia	^{192}Ir	1 074.5 TBq	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{51}Cr, ^{60}Co, ^{64}Cu, ^{67}Ga, ^{90}Y, ^{123}I, ^{131}I, ^{153}Sm, ^{201}Tl	1 551.9 TBq	^{76}Br, ^{124}I, ^{177}Lu
	^{99}Mo	453.6 TBq			
	^{169}Yb	17.8 TBq			
Austria	^{11}C, ^{13}N, ^{18}F	NR	NR	NR	NR
Belarus	NR	0	NR	0	^{99m}Tc
Belgium	^{99}Mo	30 170.0 TBq	^{11}C, ^{18}F, ^{90}Y, ^{103}Pd, ^{125}I, ^{153}Sm, ^{186}Re, ^{177}Lu, ^{203}Hg	47 515.9 TBq	^{188}Re
	^{192}Ir	15 000.0 TBq			
	^{131}I	2 220.0 TBq			
Brazil	^{18}F	3.0 TBq	^{35}S, ^{51}Cr, ^{60}Co, ^{82}Br, ^{123}I, ^{192}Ir, ^{203}Hg	7.9 TBq	^{99}Mo, ^{131}I, ^{201}Tl
	^{67}Ga	1.8 TBq			
	^{153}Sm	1.7 TBq			
Chile	^{99m}Tc	32.0 TBq	^{82}Br, ^{192}Ir	39.1 TBq	^{18}F, ^{67}Ga
	^{131}I	6.8 TBq			
	^{153}Sm	0.2 TBq			
Czech Republic	^{192}Ir	27.4 TBq	^{90}Y, ^{203}Hg	32.8 TBq	NR
	^{153}Sm	5.4 TBq			
	^{166}Ho	20 GBq			
Egypt	^{99m}Tc*	1.3 TBq	NR	1.7 TBq	^{99}Mo, ^{153}Sm, ^{188}Re, ^{188}W
	^{131}I	370 GBq			
	^{32}P	3.7 GBq			
European Commission	^{123}I	3.0 TBq	^{211}At	4.0 TBq	NR
	^{18}F	1.0 TBq			
	^{64}Cu	10 GBq			
Finland	^{15}O	23.7 TBq	^{24}Na, ^{41}Ar, ^{64}Cu, ^{82}Br, ^{123}I, ^{129}Cs, ^{132}Cs, ^{136}Cs, ^{140}La, ^{153}Sm, ^{198}Au	42.5 TBq	NR
	^{11}C	8.7 TBq			
	^{18}F	6.0 TBq			
France	^{99}Mo	4 000.0 TBq	^{11}C, ^{15}O, ^{18}F, ^{81m}Kr, ^{140}La, ^{169}Er, ^{186}Re	4 063.5 TBq	NR
	^{153}Sm	30.0 TBq			
	^{90}Y	13.0 TBq			
Germany	^{18}F	15.0 TBq	NR	30.0 TBq	^{211}Ac
	^{123}I	15.0 TBq			
India	^{60}Co	19 550.0 TBq	^{32}P, ^{46}Sc, ^{51}Cr, ^{82}Br, ^{131}I, ^{137}Cs, ^{153}Sm, ^{203}Hg	20 431.7 TBq	^{125}I, ^{177}Lu
	^{192}Ir	815.0 TBq			
	^{99}Mo	21.0 TBq			
Indonesia	^{153}Sm	9.7 TBq	^{32}P, ^{35}S, ^{46}Sc, ^{51}Cr, ^{65}Zn, ^{82}Br, ^{131}I, ^{141}Ce, ^{192}Ir	11.5 TBq	^{18}F, ^{54}Mn, ^{57}Co, ^{64}Cu, ^{103}Pd, ^{111}Ag, ^{165}Ho, ^{177}Lu
	^{99}Mo	0.6 TBq			
	^{186}Re	0.6 TBq			
Iran, Islamic Rep.	^{192}Ir	1 491.7 TBq	^{32}P, ^{67}Ga, ^{81m}Kr, ^{201}Tl	1 546.5 TBq	^{11}C, ^{18}F, ^{103}Pd, ^{123}I
	^{99m}Tc	39.9 TBq			
	^{131}I	14.8 TBq			
Japan	^{192}Ir	947.8 TBq	^{60} Co	982.4 TBq	NR
	^{169}Yb	27.7 TBq			
	^{198}Au	6.8 TBq			

Table 1.2 **Summary of reported isotope production in 2002** (cont'd.)

Country	Major isotopes produced in 2002	Amount produced in 2002 (EOI)	Other isotopes produced in 2002	Total amount produced in 2002 (EOI)	New isotopes planned to be produced 2003-2005
Korea	^{192}Ir	2 625.2 TBq	^{7}Li, ^{11}C, ^{18}F, ^{32}P, ^{41}Ar, ^{60}Co, ^{67}Ga, ^{79}Kr, ^{123}I, ^{166}Ho, ^{201}Tl	2 638.5 TBq	^{33}P, ^{75}Se, ^{89}Sr, ^{125}I, ^{125}Sb, ^{152}Eu, ^{169}Yb
	^{131}I	10.8 TBq			
	^{99}Mo	1.2 TBq			
Pakistan	^{131}I	3.7 TBq	NR	3.7 TBq	^{166}Ho, ^{177}Lu
	^{24}Na	19 GBq			
	^{153}Sm	10 GBq			
South Africa	^{99}Mo	NR	^{32}P, ^{35}S, ^{131}I, ^{137}Cs, ^{192}Ir	NR	NR
Spain	^{18}F	61 GBq	NR	61 GBq	NR
Switzerland	^{18}F	0.7 TBq	^{11}C	0.7 TBq	^{94m}Tc
	^{67}Cu	20 GBq			
Syria	^{99m}Tc*	2.0 TBq	NR	2.0 TBq	^{15}O, ^{18}F, ^{67}Ga, ^{103}Pd, ^{123}I, ^{201}Tl
Turkey	^{18}F	1.3 TBq	NR	1.3 TBq	NR
USA	^{192}I	7.0 TBq	^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{22}Na, ^{24}Na, ^{32}Si, ^{41}Ar, ^{44}Ti, ^{46}Sc, ^{49}V, ^{55}Fe, ^{60}Co, ^{60}Cu, ^{61}Cu, ^{64}Cu, ^{65}Zn, ^{66}Ga, ^{67}Cu, ^{68}Ge, ^{73}As, ^{76}Br, ^{77}As, ^{77}Br, ^{82}Br, ^{82}Sr, ^{85}Sr, ^{86}Y, ^{88}Y, ^{88}Zr, ^{94m}Tc, ^{95m}Tc, ^{109}Cd, ^{124}I, ^{194}Hg, ^{194}Sb, ^{198}Au, ^{207}Bi, ^{252}Cf	30.4 TBq	^{63}Ni, ^{57}Co, ^{75}Se, ^{177}Lu, ^{186}Re
	^{125}I	8.1 TBq			
	^{188}W	2.5 TBq			

* Produced locally using ^{99}Mo imported from South Africa. NR Not reported. EOI: End of irradiation.

Table 1.3 **Major isotopes produced in 2002**

Rank	By activity (TBq at the end of irradiation)	By number of countries producing
1	^{99}Mo	^{18}F
2	^{192}Ir	^{99}Mo/^{99m}Tc
3	^{60}Co	^{192}Ir
4	^{131}I	^{11}C
5	^{18}F	^{131}I

Isotope production by reactors

Reactors generally are used to produce neutron-rich isotopes by neutron irradiation. The great majority of the reactors used for producing isotopes are multi-purpose research reactors. However, some isotopes (mainly ^{60}Co) are produced in commercial nuclear power plants as an adjunct to the production of electricity. Two reactors dedicated solely to ^{99}Mo production have been built in Canada and are expected to be operational shortly.

Research reactors

As the name implies the main mission of research reactors is as a tool for use in scientific research. A significant number, though, produce isotopes as part of this mission and in many cases for industrial and medical purposes. The research reactors considered in this study are those that produce a significant amount of isotopes, i.e. in most cases devoting at least five percent of their capacity to isotope production or represent a significant isotope production resource in a particular country. Generally, those reactors have a thermal power level significantly above 1 MW. For the purpose of the present study, neutron activation analysis is not considered as isotope production. According to this definition, out of a total of about 270 research reactors in operation worldwide, 54 are considered as isotope production facilities for the purposes of this report (see Appendix 2).

Reactor power

The power of a research reactor gives something of an indication of its capacity to produce isotopes. Generally, the larger the power the greater the capacity to produce isotopes due to the greater availability of neutrons and the larger physical volume for target sites available. About 30% of the research reactors producing isotopes are in the power range between 1 and 5 MW, about 46% are in the range 5 to 30 MW and about 24% are above 30 MW (see Table 1.4).

Table 1.4 **Regional distribution of isotope producing research reactors by power level**
(as of 1 January 2003)

Region	**Number of reactors**			
	< 5 MW	5 to 30 MW	> 30 MW	**Total**
Africa	1	3	0	**4**
Central and South America	0	3	0	**3**
Central, Eastern and South-eastern Europe	0	8	3	**11**
East Asia	2	4	2	**8**
Middle East, Central and Southern Asia	1	3	1	**5**
North America	5	1	3	**9**
South-eastern Asia and Pacific	4	1	0	**5**
Western Europe and Scandinavia	3	2	4	**9**
Total	**16**	**25**	**13**	**54**

Reactor flux

Neutron flux is another key parameter that defines the isotope production capabilities of reactors. In general, neutron flux determines the types of isotopes that can be produced. Over one-third of the research reactors have a thermal neutron flux below 1×10^{14} n/cm^{2}s. They include mainly university and research centre machines operated primarily for scientific research that produce isotopes generally as a side activity and for in-house or domestic purposes. About one-half of the reactors have a thermal neutron flux in the range between 1×10^{14} and 5×10^{14} n/cm^{2}s (see Table 1.5).

High-flux reactors (i.e. with a maximum thermal neutron flux $\geq 5\times10^{14}$ n/cm^{2}s) are needed to produce certain isotopes with high specific activity such as ^{60}Co, ^{63}Ni, ^{75}Se, ^{188}W and ^{252}Cf. Seven high-flux reactors are in operation in Belgium, China, Russia and the United States (see Table 1.6).

All the isotope producing research reactors are owned by public entities (state-owned), with two exceptions. Private companies own and operate two research reactors producing isotopes, one in the Czech Republic and one in Sweden. In the Netherlands and the United States, private companies operate three state-owned reactors. There is a trend, in OECD countries in particular, towards more involvement of the private sector in isotope production. The two reactors dedicated to isotope production being commissioned in Canada are privately owned, but will be operated by the government.

Table 1.5 **Regional distribution of isotope producing research reactors by maximum thermal flux level** (as of 1 January 2003)

Region	**Number of reactors**			
	$\leq 1\times10^{14}$ n/cm^{2}s	Between 1-5$\times10^{14}$ n/cm^{2}s	$\geq 5\times10^{14}$ n/cm^{2}s	**Total**
Africa	1	3	0	**4**
Central and South America	1	2	0	**3**
Central, Eastern and South-eastern Europe	1	8	2	**11**
East Asia	4	3	1	**8**
Middle East, Central and Southern Asia	2	3	0	**5**
North America	5	1	3	**9**
South-eastern Asia and Pacific	4	1	0	**5**
Western Europe and Scandinavia	3	5	1	**9**
Total	**21**	**26**	**7**	**54**

Table 1.6 **High-flux research reactors** (as of 1 January 2003)

Country	**Name**	**Location**
Belgium	BR2	Mol
Russia	SM2	Dimitrovgrad
	MIR-M1	Dimitrovgrad
United States	ATR	Idaho Falls
	HFIR	Oak Ridge
	MURR	Columbia
China	HFETR	Chengdu

A majority of the research reactors producing isotopes are equipped with hot cells dedicated to the processing, conditioning and handling of the raw isotope material produced by the reactor, before its transportation and delivery to a processing facility or end-use customer. A large majority of research reactors producing isotopes have isotope storage capacities at or near the reactor site, as well as hot cells for processing and handling.

Nuclear power plants

Commercial nuclear power plants are not normally used to produce isotopes. However, in a few countries, e.g. Argentina, Canada, Hungary, India and Russia, some commercial nuclear power plants are utilised to produce certain isotopes. For example, commercial power plants in India are used to produce ^{60}Co. In Canada, tritium (^{3}H) is recovered from the heavy water coolant of the power plants.

Production by accelerators

Generally, accelerators are used to obtain neutron-deficient nuclei by proton, deuteron or alpha particle bombardment. These isotopes generally decay by positron emission or electron capture. Some accelerators, especially high-energy machines, are operated essentially for research purposes and produce isotopes only with excess beams or beam dumps. Other machines are dedicated to isotope production, mainly for the production of medical isotopes.

Available information shows that 273 accelerators produced isotopes in 2002 (see Appendix 3). It is likely that this number is significantly larger with the continued installation of small cyclotrons dedicated to producing PET isotopes.

As shown in Appendix 3, a wide range of isotopes were produced in 2002 but the most commonly produced isotopes were the isotopes used in PET cameras for medical diagnosis, i.e. ^{11}C, ^{13}N, ^{15}O and ^{18}F.

Based on the questionnaire responses, not including PET isotopes, the other isotopes most commonly produced in 2002 (in terms of the number of countries producing them) were ^{123}I, ^{67}Ga, ^{201}Tl and ^{64}Cu, which are also used in the medical sector.

Beam energy

A key parameter of an accelerator in defining the isotope production capability is the beam energy. Generally, the lower the beam energy the fewer types of isotopes can be produced by the accelerator. To some extent, beam energy also affects the production capacity as higher beam energies improve the production rate because capture cross-sections increase as beam energy increases.

Most of the accelerators in use worldwide are low-energy machines (< 25 MeV) used mainly to produce the isotopes used in PET cameras (see Table 1.7). These represented about 63% of the world's total. Medium energy machines (25-180 MeV) made up most of the remainder (about 32%).

Table 1.7 **Regional distribution of accelerators by beam energy**
(as of 1 January 2003)

Region	**Number of accelerators**				
	< 25 MeV	25-180 MeV	> 180 MeV	Information not available	**Total**
Africa	1	0	1	0	**2**
Central and South America	1	4	0	1	**6**
Central, Eastern & South-eastern Europe	8	9	0	1	**18**
East Asia	37	15	0	1	**53**
Middle East, Central and Southern Asia	3	5	0	0	**8**
North America	54	21	6	3	**84**
South-eastern Asia and Pacific	7	2	0	0	**9**
Western Europe and Scandinavia	60	32	1	0	**93**
Total	**171**	**88**	**8**	**6**	**273**

There are eight high-energy accelerators, i.e. capable of operating at energy levels above 180 MeV (see Table 1.8). Five of those machines are operated in the United States, one in Canada, one in South Africa and one in Switzerland. Though primarily dedicated to research, these accelerators occasionally produce isotopes. Generally, they produce only small quantities of isotopes for research not available through other means, although some, like ^{82}Sr and ^{68}Ge, are produced in commercial quantities.

Beam current

Another key parameter is beam current which affects the production capacity for a given beam energy. Together the beam energy and the beam current define what types of isotopes the machine can produce and at what capacity.

Table 1.8 **High-energy accelerators** (as of 1 January 2003)

Country	**Name of accelerator/Location**	**Maximum beam energy** (MeV)
Canada	TRIUMF, Vancouver	500
South Africa	National Accelerator Centre, Faure	200
Switzerland	Paul Scherrer Institute, Villigen	590
United States	Brookhaven Linac Isotope Producer, Upton	200
	Indiana University, Bloomington	205
	LANCSE, Los Alamos	800
	National Superconducting Cyclotron Laboratory, East Lansing	200
	Texas A&M, College Station	240

Most of the world's accelerators have beam currents of < 100 μA (about 62%), which corresponds to their function of producing the small range of isotopes used in PET cameras. The bulk of the remainder have beam currents between 100 and 500 μA (about 21%). Only 10 machines have maximum currents > 500 μA (see Table 1.9).

Table 1.9 **Regional distribution of accelerators by beam current**
(as of 1 January 2003)

Region	**Number of accelerators**				
	< 100 μA	100-500 μA	> 500 μA	Information not available	**Total**
Africa	0	2	0	0	**2**
Central and South America	2	2	1	1	**6**
Central, Eastern and South-eastern Europe	11	4	2	1	**18**
East Asia	42	10	0	1	**53**
Middle East, Central and Southern Asia	3	3	2	0	**8**
North America	41	21	2	20	**84**
South-eastern Asia and Pacific	4	0	0	5	**9**
Western Europe and Scandinavia	67	16	3	7	**93**
Total	**170**	**58**	**10**	**35**	**273**

Accelerators are not uniformly distributed in the world. The great majority are located in the OECD member countries of Western Europe and North America. The regions of Africa, Central and South America, Middle East, Central and Southern Asia and South-eastern Asia and Pacific together have less than 10% of the world's accelerators.

Separation of isotopes from fission products

The most important isotope produced by separation from fission products is ^{99}Mo, a parent isotope used to produce ^{99m}Tc, which is used widely in nuclear medicine procedures. Since today's users require high specific activity ^{99}Mo, its production is achieved mainly by separation from fission products resulting from the irradiation of ^{235}U-enriched targets in reactors. There are facilities in operation that produce ^{99}Mo from fission product on a large scale in Belgium, Canada, the Netherlands and South Africa, which then ship the ^{99}Mo to other countries for production of ^{99m}Tc generators. For example, Egypt and Syria reported the production of ^{99m}Tc using ^{99}Mo imported from South Africa. There are a number of other producers in Australia and non-OECD Europe that use imported fission-produced ^{99}Mo for production of ^{99m}Tc generators. Some of the facilities used for the production of high specific activity ^{99}Mo also produce other isotopes such as ^{131}I and ^{133}Xe. A facility for the production of ^{99}Mo has been constructed in the United States but remains in standby condition without having been commissioned.

Also, several facilities produce isotopes such as ^{85}Kr, ^{90}Sr and ^{137}Cs from irradiated (spent) fuel. Facilities are operated in Russia, India and the United States. Recently, in the United States, the production of ^{90}Y (derived from ^{90}Sr contained as a fission product in spent fuel) is gathering increasing attention and a stock of ^{90}Sr together with a production process has been transferred to a private company. Other companies elsewhere in the world have similar "^{90}Y generator" technology.

Other activities reported include:

- Belarus reported developing a capability to produce ^{99m}Tc using a Zr-Mo gel technology using ^{99}Mo from irradiated MoO$_3$ targets. Other technologies for the concentration of ^{99m}Tc from reactor-produced ^{99}Mo have also been developed in the United States.
- India is a major producer of ^{60}Co by irradiation in commercial nuclear power plants.
- Belgium reported the production of ^{90}Sr, ^{90}Y, ^{99}Mo and ^{131}I from the processing of irradiated uranium at an isotope production facility in Fleurus. ^{99}Mo was the main isotope produced in this facility using uranium irradiated at several research reactors in Europe.

Separation of transuranic elements and alpha-emitters

A number of facilities produce a variety of heavy isotopes for various applications. The technology required is rather complex and the volume of output is fairly low in comparison with the stocks treated. Their geographical distribution is given in Table 1.10.

Table 1.10 **Geographical distribution of facilities producing transuranic elements and alpha emitters** (as of 1 January 2003)

Country	Name of facility	Location	Main isotopes produced
Germany	Institute for Transuranium Elements	Karlsruhe	^{213}Bi, ^{225}Ac
United States	ORNL LANL AlphaMed (PNNL)	Oak Ridge, TN Los Alamos, NM Hanford, WA	^{224}Ra, ^{225}Ac, ^{229}Th, ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{249}Bk, ^{252}Cf
Russia Federation	Dmitrovgrad	Dmitrovgrad	^{235}U, ^{236}U, ^{252}Cf, ^{241}Am, ^{244}Cm

Stable isotope production

Approximately 300 different stable isotopes of some 60 elements have been produced by a number of separation technologies. Generally these stable isotopes are classified as either heavy (sulphur and above in atomic number) or light. Both the separation technologies and the financial and institutional barriers differ greatly for each of these groups. Separation technologies applicable to heavy stable isotopes can be used to separate fissile materials and thus are subjected to strict international controls. Technologies to separate light stable isotopes are easier to implement and less sensitive.

Heavy stable isotopes production

Three production technologies for heavy stable isotopes are currently in use. These are the highly versatile but older electromagnetic separation process, using dedicated mass spectrometers called Calutrons, the modern and more efficient gas centrifuge process and the newly commercialised Plasma Separation Process (PSP) installed by Theragenics in the United States. The gas centrifuge process can only be used for elements that form suitable gaseous compounds. All of these technologies are quite complicated and the entry barriers for potential new producers are very high. Thus, the number of heavy stable isotope producers is very limited. These are all government-owned facilities except for the enrichment plant in Netherlands, which does have some limited government investment and the privately-owned Theragenics facility in the United States. Table 1.11 presents the geographic distribution of the heavy isotope production facilities.

Table 1.11 **Geographical distribution of heavy stable isotope production facilities**
(as of 1 January 2003)

Country	Operator	Technology
Netherlands	Urenco	Centrifuge
United States	Oak Ridge Nat. Lab./DOE Theragenics	Electromagnetic separation Plasma separation
China	CIAE	Electromagnetic separation
Russia	Centrotech ECP, St. Petersburg ECP Zelenogorsk, Krasnoyarsk Kurchatov Institute, Moscow SCC Siberian Group, Tomsk EKPC, Sverdlovsk OKB GAZ, Nizny Novgorod VNIIEF, Nizny Novgorod	Centrifuge Centrifuge Electromagnetic sep., centrifuge Centrifuge Electromagnetic separation Centrifuge Centrifuge

The producers of stable isotopes using electromagnetic separation rely on relatively old and expensive to operate facilities with the associated risks related to reliability of supply. The producers who use centrifuge technology have the advantage of more modern, cheaper equipment. However, this technology is less versatile and cannot produce as broad a range of stable isotopes. Additional concerns are raised by the importance of Russian producers in the world supply since financial and organisational problems in that country create a potential risk regarding their ability to ensure adequate levels of production.

Other technologies for the production of heavy stable isotopes that have been, and are being explored include laser technologies, a variety of plasma separation processes, and a few chemical separation schemes.

Light stable isotopes production

A number of light stable isotopes (below sodium in the periodic table) have a wide range of applications in medicine and research. Various stable isotopes of oxygen, nitrogen, carbon and others are currently used. Different technologies may be used to separate stable isotopes. Electromagnetic separation, performed in the past for a number of such elements, is rather inefficient and tends to be replaced by more efficient methods including thermal diffusion and cryogenic distillation. Light stable isotopes are easier to produce than heavy stable isotopes and technological or institutional barriers to their production are minor. The main producers of light stable isotopes are the United States, Russia and Israel. The companies involved are mainly private. Facilities producing light stable isotopes are not covered in the report since there are no key supply issues.

Future production

Over the next few years the production of isotopes is projected to continue to increase. Of the 25 respondents to the questionnaire, 21 indicated that they plan on increasing either the amounts and/or the types of isotopes produced over the next three years. Significant increases in the production of ^{18}F, ^{60}Co, ^{99}Mo/^{99m}Tc, ^{103}Pd, ^{123}I, ^{131}I and ^{192}Ir are projected.

Eleven research reactors are either in commissioning, under construction or planned (see Table 1.12). These new reactors will improve the world's capability and capacity to produce isotopes.

Table 1.12 **Research reactors commissioning, under construction or planned**[5]
(as of 1 January 2003)

Country	**Reactor name**	**Power** (MWth)	**Maximum thermal flux** (n/cm^2s)	**Commissioning, planned or under construction** (C/P/UC)	**Projected operational date**
Australia	RRR	20	3×10^{14}	UC	2006
Canada	MAPLE I and II	10	2×10^{14}	C	2005
China	CARR	60	1×10^{15}	P	
France	JHR	100	7×10^{14}	P	2015
Germany	FRM II	20	8×10^{14}	C	
Indonesia	RIP	10	1×10^{14}	P	
Morocco	MA-R1	2	4.4×10^{13}	UC	
Russian Federation	PIK	100	4×10^{15}	UC	
Thailand	TRR-2	10	1×10^{14}	UC	2005
Tunisia	TRR	2	NA	P	

NA Not available.

The United States commissioned a major new accelerator facility for isotope production in January 2004. While allowing for the production of more than 30 different types of isotopes in significant quantities, the key isotopes projected to be produced initially are ^{67}Cu, ^{68}Ge, ^{73}As and ^{82}Sr.

While no specific figures are available it is expected that increasing numbers of PET cyclotrons will continue to be installed in hospitals and medical centres around the world as PET diagnostic techniques become more popular and widespread.

References

[1] IAEA, *Directory of Cyclotrons used for Radionuclide Production in Member States*, IAEA-CDRP/CD, ISBN 92-0-133302-1, Vienna, Austria, 2003.

[2] IAEA, *Research Reactors Database*, www.iaea.org/worldatom/rrdb, IAEA, Vienna, Austria.

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[5] Shaded cells indicate the reactor will be a high flux reactor with maximum thermal neutron flux $> 5\times10^{14}$ n/cm^2 sec.

II. ISOTOPE USES

Isotopes are used for many different purposes. These uses can be broadly grouped into three sectors, medicine, industry and research and development. The following chapter does not intend to provide an exhaustive list of isotope applications but rather to illustrate by way of examples, some of the main uses of isotopes in these different sectors. Isotopes used for nuclear reactor fuels (i.e. uranium and plutonium) or non-civil applications are not covered in the present study.

Medical applications

Isotopes have been used routinely in medicine for over 40 years and the number of applications in this field is increasing with the development and implementation of new technologies and processes. It is estimated that over 30 million critical medical procedures involving the use of isotopes are carried out every year. Isotope use in medicine can, for the most part, be divided into two broad categories, diagnostic uses and therapeutic uses.

Diagnosis of common diseases, such as heart disease and cancer, can be accomplished using gamma rays emitted by isotopes to produce images using cameras. Another technique called positron emission tomography (PET) uses cameras to detect the gamma emissions caused by positron annihilation.

Therapy is another field where the application of isotopes is rapidly increasing as the technique of choice for the treatment of some diseases, both benign and malignant. Targeted therapy using radiopharmaceuticals are used for the treatment of hyperthyroidism, synovitis and cancer as well as palliative care of pain associated with secondary cancers. Another form of therapy uses sealed radioactive sources to treat cancers by exposing the cancer cells to high-doses of targeted radiation to eliminate the cancer cells while avoiding damage to healthy tissue.

Generally, diagnostic isotopes other than ^{99m}Tc are produced using accelerators while therapeutic isotopes are mainly produced in research reactors (see Table 2.1). Common medical isotopes, their production methods and uses are provided in Appendices 5 (research reactors) and 6 (accelerators). Specific techniques and the isotopes used are discussed below.

Diagnostic techniques

Nuclear medicine diagnostic imaging is a unique technique that provides functional information about a range of important medical conditions. Nuclear imaging techniques are powerful non-invasive tools providing unique information about physiological and biochemical processes. They complement other imaging methods, such as conventional radiology (X-rays), nuclear magnetic resonance imaging (MRI) and ultrasound, which provide excellent physical and structural information. Additionally, nuclear diagnostic imaging is able to provide information at the cellular level reflecting the local biochemistry of diseased or damaged tissues.

Table 2.1 **Common medical isotopes sorted by use category and production method**

	Accelerator-produced	**Reactor-produced**
Diagnostic isotopes	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{55}Fe, ^{57}Co, ^{61}Cu, ^{64}Cu, ^{67}Ga, ^{74}As, ^{76}Br, ^{81m}Kr, ^{82m}Rb, ^{94m}Tc, ^{97}Ru, ^{111}In, ^{123}I, ^{124}I, ^{179}Ta, ^{201}Tl	^{3}H, ^{14}C, ^{51}Cr, ^{64}Cu, ^{97}Ru, ^{99m}Tc, ^{125}I, ^{131}I, ^{133}Xe, ^{153}Gd, ^{195m}Pt
Therapeutic isotopes	^{64}Cu, ^{67}Cu, ^{77}Br, ^{80m}Br, ^{88}Y, ^{89}Zr, ^{103}Pd, ^{111}In, ^{124}I, ^{186}Re, ^{211}At	^{32}P, ^{47}Sc, ^{60}Co, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{103}Pd, ^{103}Ru, ^{106}Ru, ^{109}Cd, ^{109}Pd, ^{117m}Sn, ^{115}Cd, ^{125}I, ^{131}I, ^{137}Cs, ^{145}Sm, ^{153}Sm, ^{165}Dy, ^{166}Dy, ^{166}Ho, ^{169}Er, ^{169}Yb, ^{170}Tm, ^{175}Yb, ^{177}Lu, ^{186}Re, ^{188}Re, ^{192}Ir, ^{195m}Pt, ^{198}Au, ^{199}Au, ^{213}Bi, ^{241}Am

Nuclear diagnostic imaging has an important role in the identification and management of conditions such as heart disease, brain disorder, lung and kidney functions, and a broad range of cancers. The high sensitivity and specificity of nuclear diagnostic imaging techniques offer the important advantages of being able to identify diseases at an early stage, to track disease progression, to allow for accurate disease staging and to provide predictive information about likely success of alternative therapy options.

In the case of cancers for example, nuclear diagnostic imaging is effective in assessing responses to treatment and detecting at an early stage any recurrence of the disease. Such information allows a precise and accurate management of the disease and may significantly alter medical decisions, for example surgical intervention.

Gamma imaging

Gamma cameras are used to detect diseases of various organs including heart, brain, bone, lung and the thyroid. The great majority of gamma imaging procedures rely on the use of ^{99m}Tc. Other isotopes used are ^{201}Tl, ^{67}Ga, ^{81m}Kr, ^{111}In, ^{123}I, ^{131}I and ^{133}Xe. These isotopes are produced either by reactors (^{99m}Tc, ^{131}I and ^{133}Xe) or by accelerators (^{67}Ga, ^{81m}Kr, ^{111}In, ^{123}I and ^{201}Tl). The main applications of nuclear diagnostic imaging using gamma cameras are summarised in Table 2.2.

Table 2.2 **Main isotopes used for gamma imaging**

Organs	**Isotopes used**	**Disease investigated**
Lung	^{99m}Tc, ^{133}Xe, ^{81m}Kr	Embolisms, breathing disorders
Bone	^{99m}Tc	Tumours, infection, bone fracture
Thyroid	^{131}I, ^{99m}Tc, ^{123}I	Hyper/hypothyroidism, tumours
Kidney	^{99m}Tc, ^{111}In, ^{131}I	Renal function
Brain	^{99m}Tc, ^{123}I, ^{133}Xe	Embolisms, blood flow, tumours, neurological disorders
Liver, pancreas	^{99m}Tc, ^{111}In	Tumours
Abdomen	^{99m}Tc, ^{67}Ga	Tumours
Blood	^{99m}Tc, ^{111}In	Infection, blood volume and circulation
Heart	^{99m}Tc, ^{201}Tl, ^{82}Rb	Myocardial function and viability
All	^{67}Ga, ^{99m}Tc, ^{111}In, ^{201}Tl	Tumours

A number of modality-specific immuno-diagnostic agents are in various phases of development. Combinations of isotopes (essentially ^{99m}Tc) and monoclonal antibodies or peptides for use in oncology, infection imaging, movement disorders and detection of deep vein thrombosis are under development. Radiosynoviorthesis is emerging as a complimentary option for the treatment of rheumatoid arthritis by loco-regional administration of radiopharmaceuticals, labelled with beta-emitting isotopes such as ^{90}Y, ^{188}Re, ^{32}P, ^{166}Ho, etc., in the affected joints. Also, a number of companies are developing intra-operative probes for isotope guided surgery (RIGS) to locate isotopic markers linked to specific antibodies or other biomolecules as a means to help in the effective removal of cancer cells during surgery.

The calibration of nuclear imaging instruments is based on the use of sealed gamma sources, with energy peaks similar to those of the isotopes used in radiopharmaceuticals, these sources include large area flood sources, point sources and anatomical phantoms.

Additionally, a recent new development has been the use of a transmission source fitted to the gamma camera that compensates for the attenuation of the radioactive signal in the body tissue; this technique of so called "attenuation correction" can provide improved image quality. Since 1995, the Food and Drug Administration (FDA) in the United States, and regulatory bodies in some other countries, have authorised systems incorporating a number of attenuation correction sources in gamma cameras. The isotopes used are ^{57}Co, ^{153}Gd and ^{241}Am.

Other applications in this field include the use of ^{57}Co, ^{133}Ba and ^{137}Cs as standard sources for activity meters or other instruments. Marker pens, rigid or flexible radioactivity rulers are used for delineating the anatomy of the patients.

Positron emission tomography (PET)

PET cameras are used mainly for the diagnosis and staging of cancer. The most commonly used radiopharmaceutical in clinical PET is the ^{18}F-labelled compound fluoro-deoxy-glucose (FDG) which behaves in a similar way to ordinary glucose in its initial metabolism in the body. About 90% of the PET procedures use FDG and this application is growing very rapidly in particular for detecting cancer cells metabolism. Many more ^{18}F-labelled molecules that have specific uptake in cancer tissues are being developed and clinically used. The radiolabelling of drugs or biologically active molecules with PET isotopes such as ^{11}C, ^{13}N and ^{15}O are used to a lesser extent.

PET imaging is characterised presently by the very short half-lives of the isotopes that require use within close proximity of the point of production. The maximum distribution range is of the order of two hours. Consequently, most users produce their own isotopes. Accelerators, specifically designed to produce PET isotopes, are commercially available and their use is increasing rapidly in Australia, Europe, Japan and the United States.

PET cameras use isotopes such as ^{68}Ga as a calibration source. Systems using ^{57}Co, ^{68}Ge/^{68}Ga, ^{133}Ba and ^{137}Cs sources may be added to PET cameras for attenuation correction. The PET technology is evolving rapidly and most manufacturers now make machines that are capable of simultaneously performing computerised tomography (CT) using X-rays while performing PET. The CT/PET gives excellent imagery combining functional and anatomical information.

The development of other PET isotopes, such as ^{64}Cu, ^{86}Y and ^{124}I is underway as potential diagnostic agents and markers of disease.

Bone density measurement

Systems to determine bone density are used in radiology centres. These units use ^{125}I, ^{153}Gd or ^{241}Am sources. This demand is decreasing because X-ray tube devices are replacing isotope-based systems and only existing machines are still in use. The sources are supplied by three private companies, of which two are in Europe.

Gastric ulcer detection

Urea labelled with ^{14}C is used as a marker for the presence of *helicobacter pylori* that can be responsible for gastric ulcers. This technique is growing rapidly but faces some competition from the alternative approach using a stable isotope, ^{13}C, combined with mass spectrometry. This type of product was initially developed by an Australian scientist and has been commercialised by private companies.

Radioimmunoassay

Radioimmunoassay is a technique used in medicine and biochemistry for quantifying very small amounts of biological substances such as hormones, enzymes and vitamins in blood, urine, saliva or other body fluids. Radioimmunoassay is commonly used in hospitals to help diagnose diseases such as thyroid disorders, reproductive problems, diabetes and hypertension. Radioimmunoassay is also finding application in non-clinical areas such as food safety and environmental monitoring due to its high sensitivity, specificity and ability to handle large number of samples at a time.

Radioimmunoassay requires a radioactive tracer of the antigen to be measured and a specific antibody to that antigen. The high specificity and sensitivity of immunoassay, which is provided by the use of the specific antibody in combination with the radioactive tracer, allows the measurement of very low concentrations of analytes present in complex matrices. Radioimmunoassay use antigens or antibodies labelled with the isotope ^{125}I or at times ^{3}H or ^{57}Co.

Alternative technologies, such as methods involving chemiluminescence, fluorescence or enzymes are progressively replacing the use of isotopes for diagnostic immunoassay tests.

Therapeutic techniques

Radiopharmaceutical applications

Radiopharmaceuticals are medical compounds that contain radioactive isotopes. Radiopharmaceuticals labelled with particle (e.g. alpha, auger electrons, beta) emitting isotopes are used for the treatment of hyperthyroidism, synovitis and cancer. Palliative care of pain associated with secondary cancers are also done using bone-seeking radiopharmaceuticals.

^{131}I is used for the post-surgery ablation of thyroid tissue in treatment of hyperthyroidism or thyroid cancer. Other isotopes, ^{32}P, ^{90}Y, ^{188}Re and ^{169}Er are used for the treatment of synovitis and arthritic conditions.

An increasing number of commercial companies are involved in the development of therapeutic substances for radiotherapy with radiopharmaceuticals and also many research organisations are active in the field. Development is targeted at the treatment of various cancers that have poor prognosis and are difficult to treat and cure by other techniques. Clinical tests are performed using products that combine isotopes, such as ^{90}Y, ^{177}Lu, ^{131}I, ^{153}Sm and ^{213}Bi, with monoclonal antibodies, antibody fragments and smaller molecules such as peptides.

Palliative care

Recent developments for the care of pain arising from bone metastasis derived from spread of breast, prostate and lung cancers include the use of ^{32}P, ^{89}Sr, ^{153}Sm and ^{186}Re labelled bone-seeking radiopharmaceuticals. The use of such techniques is growing steadily because of the improvements provided to the patients in the quality of life. Other agents based on ^{117m}Sn, ^{166}Ho, ^{177}Lu and ^{188}Re are under development.

Radiotherapy with sealed sources

Remote-controlled cobalt therapy

^{60}Co sources are used for remote-controlled cobalt therapy aiming at destroying cancer cells but demand is declining since ^{60}Co is being replaced by electron accelerators.

Gamma-Knife surgery is a relatively recent development of cobalt therapy. The Gamma-Knife is used to control benign and malignant brain tumours, obliterate arteriovenous malformations and relieve pain from neuralgia.

Brachytherapy

Brachytherapy is a medical procedure for the treatment of tumours by internal radiation therapy with sealed radioactive sources using an implanted radioactive material placed directly into or near the tumour. The brachytherapy implant is a small radiation source that may be in the form of thin wires, capsules or seeds. An implant may be placed directly into a tumour or inserted into a body cavity with the use of a catheter system. Sometimes, the implant is placed in the area left empty after a tumour has been removed by surgery, in order to kill any remaining tumour cells. The main isotopes used for brachytherapy are ^{137}Cs, ^{192}Ir, ^{103}Pd, ^{125}I and to a lesser extent ^{106}Ru and ^{198}Au.

Brachytherapy implants may be either low dose rate (LDR) or high dose rate (HDR) implants. HDR implants are normally removed after a few minutes whereas LDR implants are left in place for at least several days and, for some cancer sites, permanently. HDR can be referred to as remote after-loading brachytherapy since the radioactive source is guided by a computer through a tube to a catheter placed near the tumour. One of the advantages of HDR remote therapy is that it leaves no radioactive material in the body at the end of the treatment. It has been used to treat cancers of the cervix, uterus, breast, lung, pancreas, prostate and oesophagus.

The permanent implantation of LDR brachytherapy seeds (^{125}I and ^{103}Pd) has become extremely successful for early stage prostate cancer treatment. Consequently, the demand for the miniature radiation sources using the above isotopes has increased at a rapid rate.

Irradiation of blood for transfusion

Irradiating blood is recognised as the most effective way of reducing the risk of an immunological reaction following blood transfusions called Graft-Versus-Host Disease (GVHD). Blood irradiated at very low dose is used for immuno-depressed patients, as is the case for organ transplants or strong chemotherapy. It is carried out in self-shielded irradiators using, for example, ^{137}Cs sources. ^{60}Co can also be used for this purpose, but the irradiator will have shorter useful life and will need more frequent source changes. The radiation dose inactivates the lymphocytes in the blood prior to transfusion. Other methods presently available in blood banks that physically remove the lymphocyte cells through washing or filtration do not provide effective protection against GVHD.

Industrial applications

Industrial use of isotopes covers a broad and diverse range of applications relying on many different radionuclides, usually in the form of sealed radiation sources. Many of these applications use small amounts of radioactivity and correspond to “niche” markets. However, there are some large market segments that consume significant quantities of radioactivity, such as radiation processing and industrial radiography.

The uses of isotopes in industry may be classified under four main types of applications: nucleonic instrumentation systems; radiation processing, including sterilisation and food irradiation; technologies using radioactive tracers; and non-destructive testing (see Table 2.3).

Table 2.3 **Common industrial isotopes and their uses**

Isotope	Half-life	Production method	Uses
^{3}H	12.3 y	Reactor	Radioactive tracer, luminous paints
^{14}C	5730 y	Reactor	Nucleonic instrumentation, radioactive tracer
^{55}Fe	2.7 y	Reactor	Nucleonic instrumentation (industrial imaging)
^{57}Co	271.8 d	Accelerator	Nucleonic instrumentation (industrial imaging)
^{60}Co	5.3 y	Reactor	Sterilisation, food irradiation, nucleonic instrumentation, non-destructive testing (gamma radiography)
^{63}Ni	100 y	Reactor	Nucleonic instrumentation (e.g. explosives detectors)
^{75}Se	119.8 d	Reactor	Non-destructive testing (gamma radiography)
^{85}Kr	14.7 h	Reactor	Nucleonic instrumentation
^{90}Sr/^{90}Y	28.8 y/64 h	Reactor	Nucleonic instrumentation
^{109}Cd	462 d	Reactor	Nucleonic Instrumentation (industrial imaging)
^{137}Cs	30 y	Reactor	Sterilisation, nucleonic instrumentation
^{147}Pm	2.6 y	Reactor	Nucleonic instrumentation
^{169}Yb	32 d	Reactor	Non-destructive testing (gamma radiography)
^{192}Ir	73.8 d	Reactor	Non-destructive testing (gamma radiography)
^{204}Tl	3.78 y	Reactor	Nucleonic instrumentation
^{210}Po	138.4 d	Reactor	Static electricity elimination
^{238}Pu	87.7 y	Reactor	Spacecraft power source
^{241}Am	432.2 y	Reactor	Nucleonic instrumentation (e.g. smoke detectors)
^{252}Cf	2.65 y	Reactor	Nucleonic instrumentation (e.g. explosives detectors), neutron radiography

Nucleonic instrumentation includes analysis, measurement and control using sealed radioactive sources (incorporated into instrumentation) and non-destructive testing equipment (gamma radiography apparatus). The sources used may be emitters of alpha or beta particles, neutrons, or X-ray or gamma photons. A relatively large number of isotopes are used for these technologies that constitute the major worldwide application of isotopes in terms of the number of industrial sectors concerned, the number of equipment in operation and the number of industrial companies manufacturing such equipment.

Radiation processing uses high-intensity, gamma-emitting sealed sources, e.g. ^{60}Co in industrial irradiators. Typically, the activity of these sources is very large, in the 50 PBq range. This is the largest worldwide application of isotopes, in terms of total radioactivity involved. However, a limited number of users and manufacturers are involved.

Radioactive tracers (mainly beta or gamma emitters), as unsealed sources in various chemical and physical forms, are used to study various chemical reactions and industrial processes. This category is widely spread in a large number of sectors, including agronomy, hydrology, water and coastal engineering, and oil and gas industry. Radioactive tracers are used also in research and development laboratories in the nuclear or non-nuclear fields. However, this type of application has less economic significance than the nucleonic instrumentation or radiation processing.

Nucleonic instrumentation

Nucleonic instrumentation systems are integrated as sensors and associated instrumentation in process control systems. The major fields of application are physical measurement gauges; on-line analytical instrumentation; pollution measuring instruments and security instrumentation.

Gauges of density, level and weight, by gamma absorptiometry, are employed in most industries for performing on-line non-contact and non-destructive measurement. They incorporate ^{60}Co, ^{137}Cs or ^{241}Am sealed sources. For those applications, isotopes are in competition with non-ionising technologies such as radar, and their market share tends to decrease. However, emerging applications include multi-flow metering in oil exploration.

Gauges of thickness and mass per unit area, by beta particle or gamma photons absorptiometry, are used mainly in steel and other metal sheet making, paper, plastics and rubber industries. They use isotopes such as ^{85}Kr, ^{90}Sr/^{90}Y, ^{137}Cs, ^{147}Pm, and ^{241}Am. Isotopes face competition in these uses from technologies based on the use of X-ray generators.

Gauges for measuring thickness of thin coatings, by beta particles back-scattering, incorporating ^{14}C, ^{90}Sr/^{90}Y, ^{147}Pm or ^{204}Tl sealed sources are used essentially for measurements on electronic printed circuits, precious metal coatings in jewellery or electrical contacts in the electromechanical industry.

Different sealed sources are incorporated into various on-line analytical instruments. Sulphur analysers with ^{241}Am sources are used in oil refineries, power stations and petrochemical plants, to determine the concentration of sulphur in petroleum products. Systems with ^{252}Cf sources are used in instrumentation for on-line analysis of raw mineral materials, mainly based on neutron-gamma reactions. Such systems are used for various ores, coal, raw mineral products and bulk cement. Very few manufacturing firms are involved. Some chemical products, like pollutants, pesticides and PCBs may be detected by gas phase chromatography, coupled with electron capture sensors incorporating ^{63}Ni beta sources.

One of the applications in the field of pollution measuring instruments is the use of beta particles for absorptiometry of dust particles collected on air filters in order to estimate particulate concentration in air. The isotopes involved are ^{14}C and ^{147}Pm.

Security instrumentation systems generally based on neutron-gamma (n.γ) reactions using ^{252}Cf sources are used to detect explosives and/or drugs mainly in airports, harbours and railway stations. Those systems are very reliable and demand from public security authorities is expanding. Only a few companies are developing those systems. ^{3}H is used to make luminous paints for emergency exit signs.

Laboratory or portable systems, including X-ray fluorescence analysers, sensors and well-logging tools, constitute a stable demand for various isotopes. X-ray fluorescence analysers are used in mines and industrial plants to analyse ores, to determine the nature of alloys and for inspecting or recovering metals (for example, they are used for analysing old painting aiming at finding traces of heavy metals). The isotopes used are ^{55}Fe, ^{57}Co, ^{109}Cd, and ^{241}Am. Humidity/density meters for on-site measurements are used in agronomy and civil engineering. Humidity meters are also used in steel making. These sensors, based on neutron diffusion, sometimes coupled with gamma diffusion, may use ^{241}Am-Be sources (and sometimes ^{137}Cs and ^{252}Cf). Well-logging tools, used by oil and gas prospecting companies for example, are very important in those sectors of activity. Sources of isotopes such as ^{137}Cs, ^{241}Am-Be, and ^{252}Cf are used for measuring parameters like density, porosity, water or oil saturation of the rocks surrounding the exploration wells.

Smoke detectors using ^{241}Am sources in general are installed in a large number of public areas such as hospitals, airports, museums, conference rooms, concert halls, cinemas and aeroplanes as well as in private houses. They are so widely spread that they represent the largest number of devices based on isotopes in use worldwide.

Irradiation and radiation processing

Irradiation and radiation processing is one of the major uses of isotopes that requires high activity levels particularly of ^{60}Co. Radiation processing includes three main types of applications:

- *Sterilisation* of medical supplies and related processes such as sterilisation of pharmaceutical or food packaging. These processes are by far the most important uses of dedicated and multipurpose ^{60}Co irradiators. Bulk sterilisation of mail is increasing in response to security concerns.
- *Food irradiation*, mainly to improve the hygienic quality of food. Currently most treated food is in the dry state (e.g. spices, dried vegetables) or in the deep frozen state (e.g. meat, fish products).
- *Material curing*, mostly plastic.

There are a few other treatments or activities related to radiation processing, such as irradiation for radiation damage study, or sludge irradiation, which have a rather limited economic significance. There are about 180 gamma irradiators in operation worldwide. Some of them are dedicated to radiation sterilisation while others are multipurpose facilities dealing mostly with radiation sterilisation yet irradiating food or plastics as complementary activities.

In practice, high-intensity, low specific-activity ^{60}Co is the only isotope used for radiation processing although ^{137}Cs could also be considered. Typically, ^{60}Co sources for industrial applications have low specific activities, around 1 to 4 TBq/g, and very large total activities, around 50 PBq. In this regard, they differ from ^{60}Co sources used for radiotherapy that have higher specific activities, around 10 TBq/g.

^{60}Co gamma irradiators offer industrial advantages because they are technically easy to operate and able to treat large unit volumes of packaging (up to full pallets). Such gamma irradiators are in competition with electron accelerators using directly the electron beam or via a conversion target using Bremstrahlung X-rays. Currently, ^{60}Co source irradiators represent the main technology for food irradiation and sterilisation. On the other hand, most plastic curing involving large quantities of product and high power is carried out with accelerators.

Radiation sterilisation is growing slowly but steadily. The technical difficulty in controlling the alternative process (ethylene oxide sterilisation) and the toxicity of the gas involved in that process are incentives for the adoption of radiation sterilisation. However, the cost of the radiation sterilisation process (investment and validation) is a limiting factor for its deployment.

Food irradiation

Food irradiation has a very large potential market for a broad variety and large quantities of products. Food irradiation has been endorsed as a means to improve the safety and nutritional quality of food available by reducing bacterial contamination levels and spoilage. Food irradiation has been endorsed by a number of international governmental organisations such as the World Health Organisation (WHO), the Food and Agriculture Organisation (FAO) and the International Atomic Energy Agency (IAEA), and by national organisations such as, in the United States, the Food and Drug Administration.

Worldwide, an increasing number of food suppliers are seriously considering the use of food irradiation in their processes and the number of countries allowing food irradiation is growing continuously (see Table 2.4). Nevertheless, growth in demand for ^{60}Co is likely to be relatively slow in the short-term and a market penetration breakthrough might not occur for some years.

In the future, competition from accelerator facilities will become stronger and stronger, owing to both technical and economic progress of accelerator technology, and because accelerators (and the products processed by accelerators), that do not involve radioactivity, are accepted better by the public than isotopes and irradiated products.

Radioactive tracers

A tracer is a detectable substance, for instance labelled with a beta or gamma emitter, which has the same behaviour in a process (e.g. chemical reactor, ore grinder, water treatment plant) as the substance of interest.

The main areas of use are to study:

- Mode and the efficiency of chemical reactions (in chemical synthesis research laboratories).
- Mass transfer in industrial plants (e.g. chemistry, oil and gas, mineral products transformation, metallurgy, pulp and paper, water treatment, waste treatment).
- Behaviour of pollutants (dissolved or suspended) in rivers, estuaries, coastal shores, aquifers, waste dumping sites, oil, gas or geothermal reservoirs.

A large number of isotopes produced by reactors and accelerators in various chemical or physical forms are required for such applications and studies to check performance, optimise process, calibrate models or test pilot, prototype or revamped installations. Also, tracers are increasingly used in the oil exploration and exploitation industries.

Non-destructive testing

Gamma radiography is used for non-destructive testing in a variety of fields including the petroleum and gas industry, boiler making, foundry, civil engineering, aircraft and automobile industries. The value of this type of non-destructive testing is principally to ensure the safety and security of critical structures, e.g. the integrity of an aircraft turbine blade or the quality of a weld in a pipe. Most systems use ^{192}Ir sources. Other isotopes used are ^{60}Co, ^{75}Se and ^{169}Yb. Neutron radiography is also applied using ^{252}Cf.

Table 2.4 **Cobalt-60 food irradiation facilities**

Country	Number of facilities (End of 2002)	IAEA International Consultative Group on Food Irradiation
Argentina	2	✓
Australia	2	
Bangladesh	1	✓
Belgium	1	✓
Brazil	3	✓
Bulgaria	1	✓
Canada	1	✓
Chile	3	
China	15	✓
Cuba	1	✓
Czech Republic	1	✓
Denmark	2	✓
Egypt	1	✓
France	4	
Hungary	1	✓
India	2	
Indonesia	1	✓
Iran, Islamic Republic	1	✓
Israel	1	✓
Japan	1	
Korea, Rep.	1	
Mexico	1	✓
Netherlands	1	✓
Norway	1	✓
Pakistan	1	✓
Russian Federation	3	✓
Spain	1	✓
South Africa	5	✓
Syria	1	✓
Thailand	2	✓
Turkey	2	
Ukraine	1	✓
United Kingdom	1	✓
United States	20	✓
Yugoslavia	1	✓
OECD	41	
TOTAL	**87**	

Other industrial uses of radioactive isotopes

The start-up of nuclear reactors, for power generation, research or ship propulsion, necessitates the use of start-up sources like ^{252}Cf that emits neutrons.

Radioisotopic power sources, called RTG (Radioisotopic Thermoelectric Generators) are used as power supplies for long-duration space missions. They are based on heat thermoelectric conversion and use high-activity sealed ^{238}Pu sources. Russia and the United States are the only current producers of these sources.

Calibration sources are required for nuclear instrumentation including all health physics instrumentation, nuclear detectors and associated electronics, and instrumentation used in nuclear medicine. Those sources include a large number of isotopes with small activities adapted to the different measurement conditions. The various users of these sources are the manufacturers of nuclear instruments, nuclear medicine and radiotherapy departments of hospitals, nuclear research centres, the nuclear fuel cycle plants and the operators of power producing reactors.

Paper, plastic, graphic, magnetic tape and paint industries are the principal users of systems using ^{210}Po to eliminate static electricity that builds up during the process.

Scientific/research applications

Three types of unique characteristics come into play when isotopes are used in research work:

- Isotopes emit a range of particles with varying characteristics (types of interaction, penetration, flux etc.). The way in which they interact with matter gives information about the latter. This means that a range of radiometric instruments can be used which improve the way in which various phenomena are observed.
- Isotopes, whether radioactive or stable, exhibit the same chemical and physical properties as the natural elements to which they correspond. In the case of radioactive isotopes, detection is possible in the absence of any contact and at extremely low concentrations, making them unrivalled tools as tracers.
- The particles emitted by isotopes make it possible to deposit energy in matter in a highly controlled manner and to make chemical and biological alterations that would be impossible using any other method.

A rapid survey of current or recent research work involving isotopes, or results which were only made possible by the use of isotopes, points to the wide variety of isotopes used and to the uncertain and ever-shifting boundary between R&D and applications, particularly in the medical field.

The very wide range of isotopes involved makes it difficult to group them into general homogeneous categories. Furthermore, there are examples of one isotope being used for a unique application, e.g. ^{51}Cr as a reference source for the emission of neutrinos. The shift from R&D to application may be illustrated by PET procedures that currently are used routinely for medical care in some hospitals but remain a tool for research in the fields of neurology and psychiatry.

Medical research

Medical research is of strategic social and economic importance. It has an impact on the long-term performances of national health systems, including quality of life and life expectancy, and health care efficiency and costs. The outcomes of medical research may have significant economic consequences in the medical sector (manufacture of equipment and products). In this domain, isotopes and stable isotopes have a unique and often irreplaceable role.

The boundary between research and application is evolving very rapidly in the medical field and the need for isotopes is changing rapidly also. It should be stressed that differences between countries are very significant in this area.

Current research in this field falls roughly into the following areas aiming primarily to enhancing medical care procedures already used:

- Radiotherapy, where an isotope is associated with an antibody or biological molecule with a specific affinity for the cancerous cells to be destroyed.
- Metabolic radiotherapy, characterised by the injection of a radiopharmaceutical which selectively focuses on the target tissue and irradiates it *in situ*.
- Treatment of pain caused by cancers.
- Brachytherapy for the treatment of prostate and ocular cancer using ^{103}Pd and ^{125}I.
- Functional imaging using ^{18}F labelled molecules such as fluoro-deoxy-glucose, fluro-thymidine, etc.

Finally, endovascular radionuclide therapy (EVRT) is potentially a very effective preventive treatment of coronary artery restenosis. This application is under active clinical development. A large number of private companies and university teams are developing radioactive stents (devices positioned in blood vessels to prevent vessel collapse) for permanent implant or radioactive sources for short irradiation to prevent restenosis of blood vessels following percutaneous transluminal coronary angioplasty (PTCA), commonly known as balloon angioplasty. The isotopes being investigated include ^{32}P, ^{90}Y, ^{188}Re, ^{166}Ho and ^{192}Ir. However, drug coated stents capable of preventing restenosis are becoming a preferred choice.

Research in the field of industrial processes

Radioactive tracers continue to be a powerful tool for developing and improving processes in the field of process engineering. They are used to closely monitor the behaviour of solid, liquid and gaseous phases *in situ*. This makes it possible to optimise the operation and validate operational models for a wide range of equipment. It should be remembered that until a model has been validated, it is no more than a working hypothesis.

In the field of mechanical engineering, radioactive techniques are the most effective and accurate way of measuring wear phenomena *in situ*, without having recourse to dismantling. It is also used to devise the most appropriate technical solutions to ensure that an item of equipment complies with its specification. In most cases, the source is generated by irradiation of parts of the component to be studied in a cyclotron.

Research on materials uses Mössbauer spectroscopy that employs ^{57}Co, ^{119m}Sn, ^{125m}Te and ^{151}Sm. ^{22}Na is used as a source for material science studies in a technique called positron annihilation spectroscopy (PAS).

Research in the field of environmental protection

Some characteristics of isotopes make them among the most effective tracers for studies involving the environment. The period during which a isotope can be detected depends on its half-life and the choice of the isotope can be adapted to the specific problem investigated. The isotope and its chemical form can be selected from a wide range of elements and compounds. The detection of isotopes is possible at very low concentrations.

Isotopes constitute the perfect tool for carrying out a whole range of environmental studies including:

- Subterranean and surface hydrology studies: measurement of velocity, relative permeability and pollutant migration, identification of protection boundaries around lines of catchment and location of leaks from dams.
- Dynamic sedimentology studies: the transfer of sediment in the marine environment, studies of catchment areas.

The most common isotopes used in this field of applications are ^{46}Sc, ^{51}Cr, ^{113}In, ^{147}Nd, ^{182}Ta, ^{192}Ir and ^{198}Au.

However, society has been less and less willing to accept the use of isotopes in the natural environment and their use now tends to be limited to cases where there is practically no alternative. Hydrology and river sedimentology studies almost exclusively make use of chemical or fluorescent tracers, or even tracers which can be made radioactive, with the exclusion of those occurring naturally.

Biotechnologies

Isotopes continue to be a reference tool for a large range of research work in the fields of biology and biotechnology, from the most fundamental research to developments that can practically be classed as industrial research. This work includes plant biology and research into photosynthesis, agronomy (studies of fertilisers containing nitrogen) and biochemistry. The main isotopes used are ^{3}H, ^{14}C, ^{32}P, ^{33}P and ^{35}S.

III. ISSUES RELATED TO ISOTOPE PRODUCTION AND USE

Transportation

Recent events have engendered concerns about the ability to transport isotopes around the world. Certain isotopes have relatively few producers but have worldwide application, e.g. ^{99}Mo, that given its relatively short half-life demands air transport. However, as currently structured and regulated, the transportation of isotopes is subject to a number of inefficiencies that can cause delays or present barriers to transportation.

The new IAEA *Code of Conduct on the Safety and Security of Radioactive Sources* (Code of Conduct)[6] can serve as a good resource for appropriate regulatory authorities and industry to harmonise activities with respect to the safety and security of radioactive sources. Consideration should be given to the development of a common international approach to regulating and managing these sources. Making more effective use of typical radioactive source manufacturers' data including tracking, packaging type and certification of compliance with regulations should be considered.

Regulations and practices could also be modified to permit the worldwide transport of radioactive sources after the producer has demonstrated compliance with all relevant labelling and packaging regulations thereby obviating compliance inspections at each stage in the transport sequence. This could include blanket import-export approvals for radioactive sources from certified vendors in countries with established regulatory authorities in order to ensure compliance with regulations of radioactive materials. Current practices, which permit aircraft commanders to refuse shipments of isotopes that meet regulatory requirements, may also need to be reconsidered.

Improved training of "non-nuclear" personnel involved in the transport of isotopes may be considered as a means to minimising delays and barriers through better understanding of the requirements and risks involved.

Sealed source accountability

Security is recognised as an emerging issue of great importance with respect to the transport and distribution of isotopes. Since considerable effort is underway on this issue, comments regarding these concerns have not been included in the present study. However, one aspect, control and accountability of radioactive sources merits mention.

Of the millions of licensed radioactive sources worldwide, the great majority pose very little safety or security risks if they are lost, stolen, or misused. However, some types of radioactive sources could present unacceptable risks, if they are involved in an incident. These types of sources include

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[6] IAEA (2003), *Measures to Strengthen International Cooperation in Nuclear, Radiation and Transport Safety and Waste Management. Revision of the Code of Conduct on the Safety and Security of Radioactive Sources*. Vienna, Austria. See http://www.iaea.org/About/Policy/GC/GC47/Documents/gc47-9.pdf

those containing large amounts radioactivity, are portable, contain readily dispersible radioactivity, and/or contain long-lived isotopes. In particular, sources that contain the reactor-produced isotopes ^{60}Co, ^{137}Cs, ^{90}Sr, ^{192}Ir, ^{226}Ra, ^{241}Am, ^{238}Pu and ^{252}Cf are of the greatest concern.

Member countries should be able to identify and locate all significant radioactive sources in use in their country. Therefore, they should, as appropriate, have policies to define the types of radioactive sources that should be monitored and the processes to identify and track these sources.

Policies and regulations should also define the responsibilities and financial accountability for the management of radioactive sources throughout their useful lives and, after their useful lives, for their disposal. As far as possible, these policies, standards and regulations should be normalised between member countries to facilitate trade and transport while maintaining adequate safety and security. As a minimum, these controls should encompass all new radioactive sources. Additional efforts should also be considered to re-instate control over lost, abandoned, or improperly discarded radioactive sources.

Often, recovery of older sources may involve technical difficulties for handling, transport and disposal as well as administrative or legal difficulties in defining accountability and liability. Each member country should maintain or have access to a technical capability to handle, treat and store and dispose of every type of source that has been used or is in use in that country.

The IAEA revised Code of Conduct should be referenced by policy makers when addressing the above issues.

Maintaining governmental role

Public entities own and operate almost all the research reactors, large-scale accelerators and chemical isotope separation facilities for isotope production as well as the facilities for extended uses of isotopes in medical and scientific fields. Governments perform the role of funding an infrastructure for effective isotope production and their beneficial uses. In particular, many isotopes used in R&D are not being produced in sufficient quantity or at a sufficient number of production sites to ensure their availability if they prove to be successful in future applications. Thus, governments have an important role to play in ensuring availability at reasonable cost of new isotopes desired by the research community that cannot be or will not be supplied by commercial producers. Governments also provide opportunities for education and training of qualified personnel for these activities. Thus, it is critical to address these concerns that governments endeavour, either directly, or through government-backed programmes, to:

- *Provide strong management and leadership.* Only governments can provide the effective management and coordination of the efforts of various organisations within a country. This leadership would also monitor universities and commercial production of isotopes in order to influence these organisations to act for the common good and to garner the broad-based support needed.
- *Facilitate collaboration among all interested parties.* A successful isotope programme is possible only if all organisations involved in the production and use of isotopes routinely communicate to shape policy. Governmental entities must interact with the various organisations representing the commercial and research user communities and the various university programmes.
- *Provide adequate resources for the production of R&D isotopes.* Isotopes used in research are usually unavailable from commercial suppliers due to insufficient revenues and are typically

very expensive due to high unit cost associated with smaller quantities. Government subsidies (either direct or indirect) are needed to ensure their availability to researchers. This may require direct support for the construction of new facilities or expansion of existing ones in order to ensure adequate supply.

- *Continuously monitor the needs of researchers and clinicians.* Governmental agencies should ensure that all reactors, accelerators, and other resources are optimally used to meet the needs of researchers and clinicians. In the short term, this requires coordinating the efforts of existing governmental resources. In the long term, this may involve the possible construction of reactors or accelerators. Governments should also ensure that the necessary infrastructure will be maintained for the isotope production facilities.
- *Facilitate the transfer of commercially viable isotope programmes to the private sector.* Normally, governments should not be in the business of commercially supplying isotopes. However, there can be significant barriers to the commercialisation of isotope production, particularly the high capital costs of production facilities, and government support may be required to overcome these barriers.
- *Address dependence on foreign suppliers where impacts of supply interruptions are unacceptable.* The continuing globalisation and generalisation of isotope supply could lead to incidents where the supply of specific isotopes may be interrupted by circumstances beyond the control of any one government. Governments should understand the nature of the supply of critical of isotopes in their country and have mechanisms in place to address shortfalls or disruptions, as appropriate.

Third-party liability concerns

Given that sources of ionising radiation are ubiquitous, highly mobile, and located in environments far less secure than nuclear installations, there is a risk of exposure due to an accident or malicious act. Liability for damage resulting in death or personal injury to individuals and the general public, as well as damage to the environment, presents concerns for policy makers, industry and insurers. Among these concerns is discerning the parties liable to compensate damaged parties when the radioactive source causing damage is an orphan source. Another concern is whether manufacturers, vendors and users who may be held liable to third parties have the means to compensate victims. Insurance practices or other forms of financial guarantee for this type of liability vary throughout OECD countries.

The revised IAEA Code of Conduct aims to strengthen protection of the public through recommendations on the management and control of specific sources of ionising radiation. Although it does not possess legally binding force, the Code seeks a commitment from IAEA member states to implement its terms without necessarily creating a legal obligation to do so. However, it contains no specific provision on liability for damage(s) caused by exposure to the radioactive sources within its scope, nor does it recommend subscription of liability insurance cover or other financial security for such damage(s). Further, the damage(s) caused by radioactive sources, as defined by the Code, do not fall within the scope of application of either the Paris Convention or Vienna Convention insofar as the damage(s) occurs outside of a nuclear installation.

At the request of the Nuclear Law Committee, NEA is investigating the applicable rules of liability and practices of insurance cover in OECD countries for damage(s) resulting from exposure to radioactive sources. The results of initial inquiries will be discussed in the Nuclear Law Committee, which will then decide whether a group of technical and legal experts should undertake a study to address the following points:

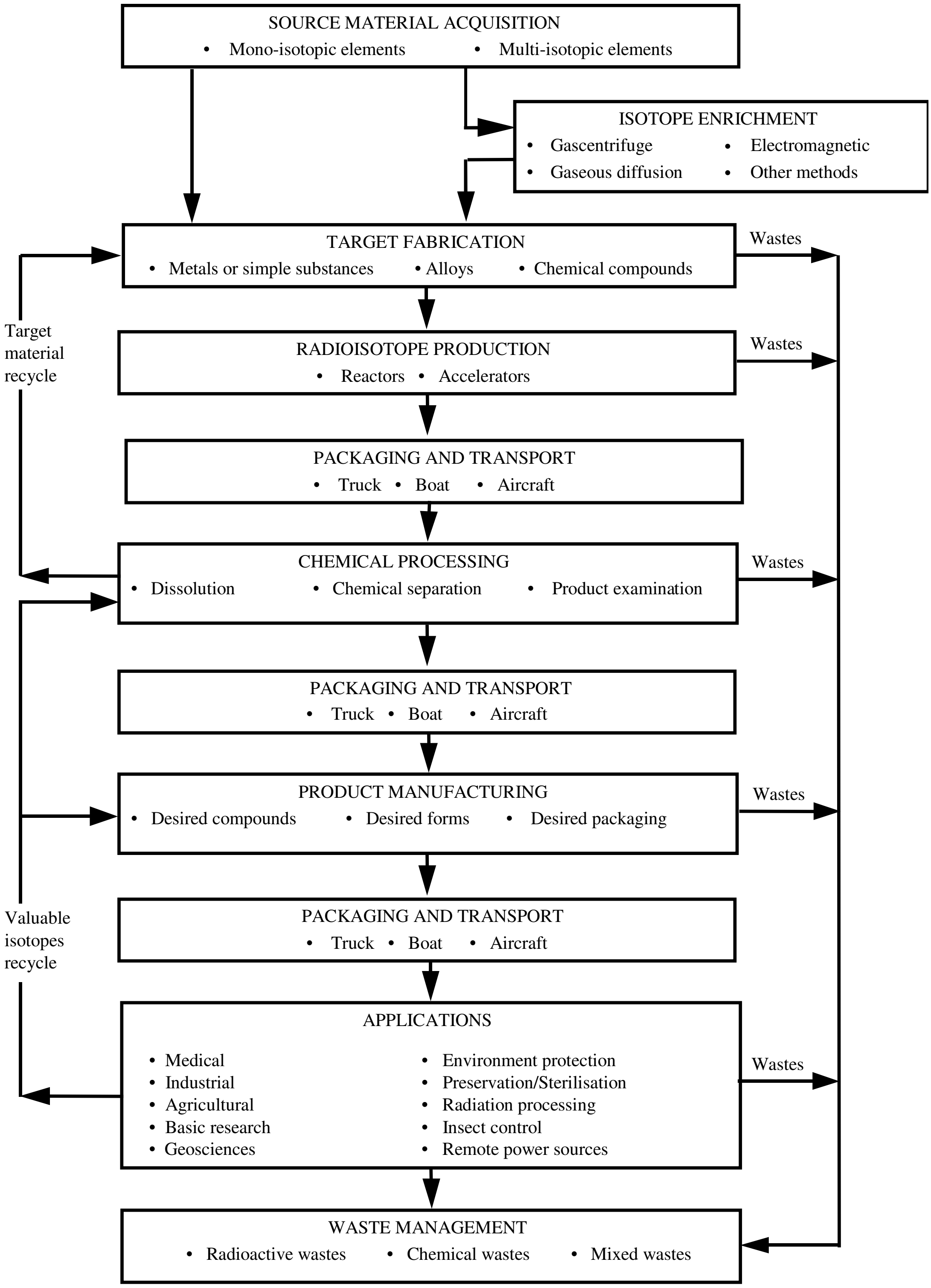
- The nature of the risks presented by radioactive sources as well as the potential damage(s) caused by such sources.
- Identification of the parties potentially liable for such damage(s) (manufacturers, wholesalers, distributors, users, retrievers, etc).
- Conditions for providing insurance coverage in respect of damage(s) caused by radioactive sources, the criteria used to assess risk and the possibility of rationalising/ harmonising these practices.
- Practices regarding the assumption of costs for retrieval and disposal of radioactive sources at the end of their useful life, including retrieval of orphan sources.

Concluding remarks

Isotopes are widely used and important to the economies and welfare of NEA member countries. Governmental involvement is essential for the safe, secure supply of isotopes. In light of the dynamic nature of isotope production and use, their importance in many sectors of member state economies and welfare endeavour, it is relevant that the OECD and IAEA continue to monitor this field on a periodic basis.

Appendix 1

Flow diagram of isotope production, manufacturing, applications and waste management



Appendix 2. **Research reactors producing isotopes**

Country	Reactor Name	Location	Start-up year	Planned for S/D by 2008	Power (MW)	Maximum thermal flux (n/cm^{2}s)	Isotopes produced in 2002	New isotopes planned for 2003-2005
Australia	HIFAR	Menai	1958	Yes[1]	10	1.4×10^{14}	^{51}Cr, ^{60}Co, ^{90}Y, ^{99}Mo, ^{131}I, ^{192}Ir, ^{192}Yb	^{177}Lu
Bangladesh*	TRIGA Mk II	Savar	1986	NR	3	5.6×10^{13}	NR	NR
Belgium	BR2	Mol	1961	No	100	1×10^{15}	^{99}Mo, ^{125}I, ^{131}I, ^{133}Xe, ^{153}Sm, ^{177}Lu, ^{186}Re, ^{192}Ir, ^{203}Hg	NR
Brazil	IEA-R1	Sao Paulo	1957	No	5	1.2×10^{14}	^{35}S, ^{51}Cr, ^{60}Co, ^{82}Br, ^{153}Sm, ^{192}Ir, ^{203}Hg	^{99}Mo, ^{131}I
Canada*	NRU	Chalk River	1957	NR	135	4×10^{14}	^{14}C, ^{60}Co, ^{99}Mo, ^{125}I	NR
Chile	RECH-1	Santiago	1974	No	5	7×10^{13}	^{82}Br, ^{99}Mo, ^{131}I, ^{153}Sm, ^{192}Ir	NR
Chinese Taipei*	THOR	Hsinchu	1961	NR	2	3.6×10^{13}	^{131}I	NR
China*	HFETR	Chengdu	1979	NR	125	6.2×10^{14}	^{60}Co, ^{99}Mo, ^{131}I, ^{153}Sm, ^{192}Ir	NR
	MJTR	Chengdu	1991	NR	5	8×10^{13}		
Czech Republic	LWR-15	Rez	1957	No	10	1.5×10^{14}	^{90}Y, ^{153}Sm, ^{166}Ho, ^{192}Ir, ^{203}Hg	NR
Egypt	ETRR-1	Cairo	1962	Yes	2	1.5×10^{13}	^{32}P, ^{131}I	^{153}Sm, ^{188}Re, ^{188}W
	ETRR-2	Cairo	2003	No	22	2.8×10^{14}		
France	ORPHEE	Saclay	1980	No	14	3×10^{14}	^{90}Y, ^{99}Mo, ^{131}I, ^{133}Xe, ^{140}La, ^{153}Sm, ^{169}Er, ^{186}Re	NR
	OSIRIS	Saclay	1966	No	70	2.7×10^{14}		
Germany*	FRJ-2	Jülich	1962	NR	23	2.5×10^{14}	^{99}Mo	NR
Hungary*	BRR	Budapest	1959	NR	10	2.5×10^{14}	^{32}P, ^{125}I, ^{131}I, ^{153}Sm*	NR
India	DRHUVA	Trombay	1985	No	100	1.8×10^{14}	^{32}P, ^{46}Sc, ^{51}Cr, ^{60}Co, ^{82}Br, ^{99}Mo, ^{131}I, ^{137}Cs, ^{153}Sm, ^{192}Ir, ^{203}Hg	^{125}I, ^{177}Lu
Indonesia	TRIGA Mk II	Bandung	1964	NR	2	5.1×10^{13}	^{32}P, ^{35}S, ^{51}Cr, ^{65}Zn, ^{82}Br, ^{99}Mo, ^{131}I, ^{192}Ir	^{166}Ho

Appendix 2. **Research reactors producing isotopes** (cont'd)

Country	**Reactor Name**	**Location**	**Start-up year**	**Planned for S/D by 2008**	**Power** (MW)	**Maximum thermal flux** (n/cm^2s)	**Isotopes produced in 2002**	**New isotopes planned for 2003-2005**
Iran	Nuclear Research Centre	Tehran	1967	No	5	3×10^{13}	^{32}P, ^{99}Mo, ^{131}I, ^{192}Ir	NR
Italy*	TRIGA RC-1	Santa Maria di Galeria	1960	NR	1	2.7×10^{13}	^{166}Ho	NR
Japan	JMTR	Ibaraki-ken	1968	No	50	4×10^{14}	^{60}Co, ^{169}Yb, ^{192}Ir, ^{198}Au	No
	JRR-3M	Ibaraki-ken	1990	No	20	3×10^{14}		
	JRR-4	Ibaraki-ken	1965	No	3.5	7×10^{13}		
	KUR	Osaka-fu	1964	No	5	8.15×10^{13}	^{59}Fe, ^{169m}Te, ^{24}Na, ^{58}Co, ^{60}Co, ^{31}Si, ^{27}Mg, ^{28}Al, ^{198}Au, ^{56}Mn, ^{99}Mo, ^{140}La, ^{65}Zn, ^{46}Sc	
Korea, Rep. of	HANARO	Daejeon	1995	No	30	4.5×10^{14}	^{7}Li, ^{32}P, ^{41}Ar, ^{60}Co, ^{79}Kr, $^{99}Mo/^{99m}Tc$, ^{131}I, ^{166}Ho, ^{192}Ir	^{33}P, ^{75}Se, ^{89}Sr, ^{125}I, ^{125}Sb, ^{152}Eu, ^{169}Yb
Libya*	IRT-1	Tajoura	1981	NR	10	2×10^{14}	NR	NR
Malaysia*	TRIGA PUSPATI	Bangi	1982	NR	1	2×10^{13}	NR	NR
Netherlands[2]	HFR	Petten	1961	NR	45	2.7×10^{14}	^{89}Sr, ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, ^{166}Ho, ^{177}Lu, ^{192}Ir	NR
Norway*	JEEP II	Kjeller	1966	NR	2	2×10^{13}	^{60}Co, ^{82}Br, ^{153}Sm	NR
Pakistan	PARR-1	Islamabad	1965	No	10	1.7×10^{14}	^{24}Na, ^{32}P, ^{59}Fe, ^{99}Mo, ^{111}Au, ^{131}I, ^{153}Sm	^{166}Ho, ^{177}Lu
Peru*	RP-10	Lima	1988	NR	10	1.2×10^{14}	^{32}P, ^{99}Mo, ^{131}I	NR
Poland*	MARIA	Swierk	1974	NR	30	4.5×10^{14}	^{32}P, ^{35}S, ^{131}I	NR
Portugal*	RPI	Sacavem	1961	NR	1	3.6×10^{13}	NR	NR
Romania*	TRIGA Mk II	Pitesti	1979	NR	14	3.3×10^{14}	^{131}I	NR

Appendix 2. **Research reactors producing isotopes** (cont'd)

Country	Reactor Name	Location	Start-up year	Planned for S/D by 2008	Power (MW)	Maximum thermal flux (n/cm^2s)	Isotopes produced in 2002	New isotopes planned for 2003-2005
Russian Federation*	BOR-60	Dimitrovgrad	1969	NR	60	2×10^{14}	^{33}P, ^{99m}Tc, ^{131}I, ^{182}Ta, ^{192}Ir, ^{197}Hg, ^{198}Au	NR
	IR-8	Moscow	1981	NR	8	2.5×10^{14}		
	MIR-M1	Dimitrovgrad	1966	NR	100	5×10^{14}		
	RBT-10/2	Dimitrovgrad	1984	NR	7	7.4×10^{13}		
	SM-3	Dimitrovgrad	1961	NR	100	5×10^{15}		
	WWR-M	Gatchina	1959	NR	18	4×10^{14}		
South Africa	SAFARI-1	Pretoria	1965	NR	20	2.4×10^{14}	^{99}Mo, ^{131}I	NR
Sweden*	R-2	Nyköping	1960	NR	50	4×10^{14}	NR	NR
Thailand*	TRR-1/M1	Bangkok	1977	NR	2	3.1×10^{13}	^{131}I	NR
Ukraine*	WWR-M	Kiev	1960	NR	10	1.6×10^{14}	NR	NR
United States	ATR	Idaho Falls, ID	1967	No	250	8.5×10^{14}	^{24}Na, ^{41}Ar, ^{46}Sc, ^{55}Fe, ^{60}Co, ^{77}As, ^{82}Br, ^{125}I, ^{188}W, ^{192}Ir, ^{194}Sb, ^{198}Au, ^{252}Cf	^{63}Ni, ^{75}Se, ^{177}Lu
	HFIR	Oak Ridge, TN	1965	No	85	2.1×10^{15}		
	MNRC	McClellan AFB, CA	1990	No	2	4×10^{13}		
	MURR	Columbia, MO	1966	NR	10	6×10^{14}		
	NSCR	College Station, TX	1962	No	1.0	2×10^{13}		
	OSTR	Corvallis, OR	1967	No	1.1	1×10^{13}		
	TRIGA II	Austin, TX	1992	No	1.1	2.7×10^{13}		
	WSUR	Pullman, WA	1961	No	1.0	7×10^{12}		
Uzbekistan*	WWR-CM	Tashkent	1959	NR	10	2.3×10^{14}	^{32}P, ^{33}P, ^{99m}Tc, ^{125}I, ^{131}I, ^{198}Au	NR
Vietnam*	DRR	Dalat	1963	NR	0.5	2.1×10^{13}	^{32}P, ^{99}Mo, ^{131}I	NR

Source: IAEA Research Reactor Database and questionnaire responses.

* Reported in IAEA Research Reactor Database.

1. A replacement reactor is under construction and planned to be operational in 2006.
2. Source: Nuclear Research and Consultancy Group, 2002 Annual Report, Petten, Netherlands (www.nrg-nl-com)

NR Not reported.

Shaded cells indicate the reactor is a high flux reactor with maximum thermal neutron flux > 5×10^{14} n/cm^2sec.

Appendix 3. **Accelerators producing isotopes**

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Argentina (2)	CNEA	Buenos Aires	^{1}H	42	^{18}F, ^{201}Tl	^{11}C, ^{15}O, ^{123}I
	Fundacion Ecuela de Medicina Nuclear	Mendoza	^{1}H	11		
Australia (7)	Global Medical Solutions (Syncor)	Brisbane	^{1}H	10	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{64}Cu, ^{67}Ga, ^{76}Br, ^{123}I, ^{124}I, ^{201}Tl	NR
	Cyclotek	Bundoora	^{1}H	16		
	Peter MacCallum Cancer Institute	East Melbourne	^{1}H	12		
	Austin and Repatriation Medical Centre	Heidelberg	^{1}H, ^{2}H	10, 5		
	ANSTO NMC	Sydney	^{1}H	30		
	Royal Prince Alfred Hospital	Sydney	^{1}H	16		
	Sir Charles Gairdner Hospital	Perth	^{1}H	18		
Austria (4)	ARGOS Zyklotron	Klagenfurt	^{1}H, ^{2}H	17, 8.5	^{11}C, ^{13}N, ^{18}F	NR
	ARGOS Zyklotron	Linz	^{1}H, ^{2}H	17, 8.5		
	ACRS Seibersdorf	Seibersdorf	^{1}H, ^{2}H	17, 8.5		
	Universitätsklinik NEUBAU AKH	Vienna	^{1}H, ^{2}H	17, 8.5		
Belgium (11)	Erasme Hospital	Brussels	^{1}H	30	^{11}C, ^{18}F, ^{103}Pd	NR
	Vrije Universiteit Brussels	Brussels	^{1}H, ^{2}H, ^{3}He, ^{4}He	42, 22, 50, 43		
	IBA Isotopes	Fleurus	^{1}H	14		
	MDS Nordion	Fleurus	^{1}H	30		
	University of Gent	Gent	^{1}H, ^{2}H, ^{3}He, ^{4}He	24, 14.5, 32, 29		
	University of Leuven	Leuven	^{1}H, ^{2}H	10, 5		
	University of Liège	Liège	^{1}H, ^{2}H	18, 9		
	Catholic University of Louvain	Louvain-la-Neuve	^{1}H	30		
	Catholic University of Louvain	Louvain-la-Neuve	^{1}H, ^{2}H, ^{3}He, ^{4}He	85, 55, 145, 110		
	IBT	Nivellas	^{1}H	14		
	IBT	Nivellas	^{1}H	14		

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Brazil (3)	IEN	Rio de Janeiro	^{1}H, ^{2}H, ^{3}He, ^{4}He	24, 14, 36, 28	^{18}F, ^{67}Ga, ^{123}I	^{201}Tl
	IPEN/CNEN-SP (CV-28)	Sao Paulo	^{1}H, ^{2}H, ^{3}He, ^{4}He	24, 14, 36, 28		
	IPEN/CNEN-SP (Cyclone 30)	Sao Paulo	^{1}H, ^{2}H	15, 30		
Canada (9)	Cross Cancer Centre	Edmonton	^{1}H, ^{2}H	19, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{94m}Tc, ^{103}Pd, ^{111}In, ^{123}I, ^{124}I, ^{201}Tl	NR
	Hamilton Health Sciences Corp.	Hamilton	^{1}H	10		
	Montreal Neurological Institute	Montreal	^{1}H, ^{2}H	18, 9		
	University of Ottawa	Ottawa	^{1}H	11		
	Clark Institute of Psychiatry	Toronto	^{1}H, ^{2}H	17, 8.5		
	TRIUMF (520 MeV)	Vancouver	^{1}H	500		
	TRIUMF (CP42)	Vancouver	^{1}H	42		
	TRIUMF (TR30)	Vancouver	^{1}H	30		
	UBC/TRIUMF PET Programme	Vancouver	^{1}H	13		
Chile (1)	Comision Chilena de Energia Nuclear	Santiago	NR	NR	NR	^{67}Ga, ^{18}F
China (9)	China Institute of Atomic Energy	Beijing	^{1}H	30	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{111}In, ^{201}Tl	NR
	Institute of Applied Chemistry (CS22)	Beijing	^{1}H, ^{2}H, ^{3}He	22, 11, 29		
	Institute of Applied Chemistry (CS30)	Beijing	^{1}H, ^{2}H, ^{4}He	26, 15, 30		
	Peking Union Medical College	Beijing	^{1}H	11		
	The PLA General Hospital	Beijing	^{1}H	11		
	Guangdong Province People's Hospital	Guangzhou	^{1}H	11		
	Hong Kong Sanatorium & Hospital	Hong Kong	^{1}H	11		
	Zibo Wanjie Hospital	Shangdong	^{1}H	16.5		
	Shanghai Institute of Nuclear Research	Shanghai	^{1}H	30		
Czech Republic (2)	Nuclear Physics Institute	Rez	^{1}H, ^{2}H, ^{3}He, ^{4}He	38, 20, 53, 40	^{15}O, ^{18}F, ^{67}Ga, ^{201}Tl, ^{211}At	NR
	Nuclear Research Institute	Rez	^{1}H, ^{2}H	18, 9		
Denmark (2)	Aarhus University Hospital	Aarhus	^{1}H, ^{2}H	17, 8	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{123}I, ^{124}I, ^{111}In, ^{211}At	NR
	University Hospital of Copenhagen	Copenhagen	^{1}H, ^{2}H, ^{4}He	32, 16, 32		
Egypt (1)	Atomic Energy Authority	Cairo	^{1}H, ^{2}H, ^{3}He, ^{4}He	18, 10, 24, 20	NR	NR

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
European Commission (1)	EC Joint Research Centre	Ispra	^{1}H, ^{2}H, ^{3}He, ^{4}He	40, 20, 40, 40	^{18}F, ^{64}Cu, ^{67}Ga, ^{111}In, ^{123}I	NR
Finland (4)	University of Helsinki	Helsinki	^{1}H, ^{2}H	10, 5	^{11}C, ^{15}O, ^{18}F, ^{24}Na, ^{41}Ar, ^{64}Cu, ^{82}Br, ^{123}I, ^{129}Cs, ^{132}Cs, ^{136}Cs, ^{140}La, ^{153}Sm, ^{198}Au	NR
	University of Jyväskylä	Jyväskylä	^{1}H, ^{2}H, ^{3}He	70, 65, 168		
	Turku University Central Hospital	Turku	^{2}H	7		
	Turku University Central Hospital	Turku	^{1}H, ^{2}H, ^{3}He, ^{4}He	20, 10.5, 28, 21		
France (7)	CERMEP	Lyon	^{1}H, ^{2}H	16, 8	^{11}C, ^{15}O, ^{18}F, ^{81m}Kr	NR
	CERMEP-Hospital Neurocardiologique	Lyon	^{1}H, ^{2}H	18, 9		
	Centre Antoine Lacassagne	Nice	^{1}H, ^{2}H, ^{3}He, ^{4}He	65, 65, 65, 65		
	CIS BIO	Saclay	^{1}H	40		
	CIS BIO	Saclay	^{1}H	30		
	CNRS-CERI	Orléans	^{1}H, ^{2}H, ^{3}He, ^{4}He	35, 25, 60, 50		
	Service Hospitalier Frédéric Joliot	Orsay	^{1}H, ^{2}H, ^{3}He, ^{4}He	20, 14.5, 30, 29		
Germany (29)	Rheinisch Westfälische Technische Hochschule	Aachen	^{1}H	11	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{64}Cu, ^{86}Y, ^{94m}Tc, ^{123}I, ^{124}I, ^{211}At	^{211}Ac
	Zentralklinik Bad Berka GmbH	Bad Berka	^{1}H	11		
	Herz und Diabeteszentrum	Bad Oynhausen	^{1}H, ^{2}H	18, 9		
	Rudolf Virchow Krankenhaus	Berlin	^{2}H	3.5		
	EUROPET Cyclotron	Berlin	^{1}H, ^{2}H	16.5, 8.4		
	Charite	Berlin	^{1}H	11		
	Westdeutsche Cyclotron GmbH	Bonn	^{1}H	11		
	Forschungszentrum Rossendorf	Dresden	^{1}H, ^{2}H	18, 9		
	Forschungszentrum Rossendorf	Dresden	^{1}H, ^{2}H, ^{4}He	7, 14, 28		
	PET-NET	Erlangen	^{1}H	11		
	Institute for Medical Radiation Physics	Essen	^{1}H, ^{2}H, ^{3}He, ^{4}He	24, 14, 36, 28		

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Germany (29) (cont'd.)	Universitätsklinikum Essen	Essen	^{1}H, ^{2}H	18, 9		
	Insitute of Radiology & Nuclear Medicine	Frankfurt am Main	^{1}H	11		
	Euro-PET GmbH	Freiburg	^{1}H, ^{2}H	16.5, 8.4		
	German Cancer Research Centre	Heidelberg	^{1}H, ^{2}H	32, 16		
	Forschungszentrum Jülich GmbH	Jülich	^{1}H, ^{2}H	16.5, 8.4		
	Forschungszentrum Jülich GmbH	Jülich	^{1}H, ^{2}H	17, 10		
	Forschungszentrum Jülich GmbH	Jülich	^{1}H, ^{2}H, ^{3}He, ^{4}He	22, 14, 36, 28		
	Forschungszentrum Karlsruhe	Karlsruhe	^{1}H	42		
	Forschungszentrum Karlsruhe	Karlsruhe	^{1}H, ^{2}H, ^{4}He	26, 52, 104		
	Universitätsklinikum Hamburg	Hamburg	^{1}H, ^{2}H, ^{3}He, ^{4}He	30, 16, 42, 36		
	Medizinische Hochschule	Hannover	^{1}H, ^{2}H, ^{3}He, ^{4}He	35, 18, 47, 35		
	Max Planck Institut	Köln	^{1}H, ^{2}H, ^{3}He, ^{4}He	17.2, 8.3, 12.4, 16.5		
	Universitätsklinikum Leipzig	Leipzig	^{1}H, ^{2}H	16, 8.4		
	Technische Universität	Munich	^{1}H	11		
	Westfälische Wilhelms Universität	Münster	^{1}H	11		
	Universitätsklinikum Regensburg	Regensburg	^{1}H	11		
	Eberhard Karls University	Tübingen	^{1}H, ^{2}H	16.5, 8.4		
	Universitätsklinikum Ulm	Ulm	^{1}H, ^{2}H	16.5, 8.4		
Hungary (1)	Institute of Nuclear Research	Debrecen	^{1}H, ^{2}H, ^{3}He, ^{4}He	20, 10, 26, 20	^{18}F, ^{67}Ga, ^{123}I	NR
India (2)	Variable Energy Cyclotron Centre	Calcutta	^{1}H, ^{2}H, ^{4}He	6.3, 12.3, 25.8	^{18}F	NR
	Radiation Medicine Centre	Trombay	^{1}H, ^{2}H	16.5, 8.5		
Indonesia (1)	National Atomic Energy Agency	Serpong	^{1}H	27	^{46}Sc, ^{99}Mo, ^{141}Ce, ^{186}Re	^{18}F, ^{54}Mn, ^{57}Co, ^{64}Cu, ^{103}Pd, ^{111}Ag, ^{177}Lu
Iran (1)	Nuclear Research Centre for Agriculture and Medicine	Karaj	^{1}H, ^{2}H	30, 15	^{67}Ga, ^{81m}Kr, ^{201}Tl	^{11}C, ^{18}F, ^{103}Pd, ^{123}I

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Israel (2)	Hadassah Medical Organization	Jerusalem	^{1}H, ^{2}H	18, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F	NR
	Soreq NRC	Yavne	^{1}H, ^{2}H	10, 5		
Italy (9)	Azienda Ospedaliera di Bologna	Bologna	^{1}H, ^{2}H	16.5, 8	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{64}Cu, ^{94m}Tc, ^{123}I, ^{124}I	NR
	Ospedale Civile	Castelfranco Veneto	^{1}H	10		
	Ospedale Maggiore	Milan	^{1}H, ^{2}H	16.5, 8.4		
	Ospedale San Raffaele	Milan	^{1}H, ^{2}H	18, 9		
	Instituto Nazionale per lo Studio e la Cura dei Tumori	Milan	^{1}H, ^{2}H	17, 8.5		
	Instituto Scientifico H. San Raffaele	Milan	^{1}H	11		
	CNR Institute Pascale	Naples	^{1}H, ^{2}H	17, 8.5		
	CNR Institute of Clinical Physiology	Pisa	^{1}H, ^{2}H	16.7, 8.4		
	Azienda Ospidaliera 5 Maria Nuova	Reggio Emilia	^{1}H	9.6		
Japan (38)	Research Institute for Brain & Blood Vessels	Akita City	^{1}H, ^{2}H	16, 8	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{48}V, ^{52}Mn, ^{52}Fe, ^{62}Cu, ^{64}Cu, ^{62}Zn, ^{67}Cu, ^{67}Ga, ^{76}Br, ^{77}Br, ^{81}Rb, ^{111}In, ^{123}I, ^{201}Tl	NR
	Daiichi Radioisotope Laboratories	Chiba	^{1}H	30		
	Daiichi Radioisotope Laboratories	Chiba	^{1}H	30		
	Fukui Medical University	Fukui	^{1}H	12		
	Kyushu University	Fukuoka	^{1}H, ^{2}H	17, 10		
	JAERI	Gunma	^{1}H, ^{2}H, ^{4}He	90, 50, 100		
	Gunma University School of Medicine	Gunma-ken	^{1}H	18		
	Nikko Memorial Hospital	Hokkaido	^{1}H	11		
	Hyogo Institute for Ageing Brain and Cognitive Disorders	Hyogo	^{1}H	12		
	National Research Institute for Metals	Ibaraki	^{1}H, ^{2}H, ^{3}He, ^{4}He	17, 10, 26, 20		
	National Institute for Radiological Sciences	Inage-ku	^{1}H, ^{2}H	18, 10		

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Japan (38) (cont'd.)	National Institute for Radiological Sciences	Inage-ku	^{1}H, ^{2}H	20, 10		
	National Institute for Radiological Sciences	Inage-ku	^{1}H, ^{2}H, ^{3}He, ^{4}He	90, 55, 145, 110		
	Kanazawa Cardiovascular Hospital	Ishikawa	^{1}H, ^{2}H	NR		
	Chiba University School of Medicine	Chiba	^{1}H, ^{2}H	18		
	National Cancer Center Hospital East	Chiba	^{1}H, ^{2}H	12		
	Osaka University School of Medicine	Osaka	^{1}H, ^{2}H	18		
	Nishina Memorial Cyclotron Centre	Iwate	^{1}H, ^{2}H	17, 8		
	Kyoto University Hospital	Kyoto	^{1}H, ^{2}H	16, 8		
	Nishijin Hospital	Kyoto	^{1}H, ^{2}H	17, 10		
	HIMEIC Imaging Centre	Minamitsuru-gun	^{1}H, ^{2}H	18, 10		
	Nagoya City Rehabilitation and Sports Centre	Nagoya	^{1}H, ^{2}H	18, 10		
	Medical School of Nagoya University	Nagoya City	^{1}H, ^{2}H	22, 11		
	National Institute for Longevity Sciences	Obu	^{1}H, ^{2}H	18, 10		
	Institute for Biofunctional Research	Osaka	^{1}H, ^{2}H	18, 10		
	National Cardiovascular Centre	Osaka	^{1}H, ^{2}H	18, 10		
	Osaka City University Medical School	Osaka	^{1}H	12		
	Nihon Medi-Physics Co., Ltd.	Sanda City	^{1}H	30		
	Nihon Medi-Physics Co., Ltd.	Sanda City	^{1}H	30		
	Hokkaido University	Sapporo	^{1}H, ^{2}H	18, 10		
	Tohohu University	Sendai	^{1}H, ^{2}H, ^{3}He, ^{4}He	40, 25, 65, 50		
	International Medical Centre of Japan	Shinjaku-ku	^{1}H, ^{2}H	20, 1		
	Nihon Medi-Physics Co., Ltd.	Sodegaura	^{1}H	30		
	Nihon Medi-Physics Co., Ltd.	Sodegaura	^{1}H	28		
	National Centre of Neurology and Psychiatry	Tokyo	^{1}H	12		

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Japan (38) (cont'd.)	Nishidai Clinic	Tokyo	^{1}H, ^{2}H	18, 10		
	Tokyo Metropolitan Institute of Gerontology	Tokyo	^{1}H, ^{2}H, ^{3}He, ^{4}He	18, 10, 24, 18		
	University of Tokyo	Tokyo	^{1}H, ^{2}H	18, 10		
Kazakhstan (1)	Institute of Nuclear Physics	Almaty	^{1}H, ^{2}H, ^{3}He, ^{4}He	30, 25, 62, 50	^{18}F, ^{67}Ga, ^{111}In, ^{201}Tl	^{57}Co, ^{85}Sr, ^{88}Y, ^{109}Cd
Korea, Republic of (6)	Asan Medical Centre	Seoul	^{1}H, ^{2}H	18, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{123}I, ^{201}Tl	^{45}Ti, ^{124}I, ^{211}At
	Korea Insitute of Radiological and Medical Sciences (Cyclone 30)	Seoul	NR	NR		
	Korea Insitute of Radiological and Medical Sciences (KIRAMS-13)	Seoul	^{1}H	13		
	Korea Insitute of Radiological and Medical Sciences (MC-50)	Seoul	^{1}H, ^{2}H, ^{4}He	50, 25, 50.5		
	Samsung Medical Centre	Seoul	^{1}H, ^{2}H	16.5, 8.4		
	Seoul National University Hospital	Seoul	^{1}H	13		
Mexico (1)	Universidad Nacional Autonomade Mexico	Ceidad Universitaria	^{1}H	11	^{11}C, ^{13}N, ^{15}O, ^{18}F	NR
Netherlands (8)	Vrije Universiteit	Amsterdam	^{1}H, ^{2}H	18, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{111}In, ^{201}Tl	NR
	Vrije Universiteit	Amsterdam	^{1}H, ^{2}H, ^{3}He, ^{4}He	28, 16, 45, 32		
	Accrec B.V. Eindhoven University of Technology	Eindhoven	^{1}H	30		
	Accrec B.V. Eindhoven University of Technology	Eindhoven	^{1}H	3		
	Accrec B.V. Eindhoven University of Technology	Eindhoven	^{1}H, ^{4}He	30, 20		
	Groningen University Hospital	Groningen	^{1}H, ^{2}H	17, 8.5		
	Mallinckrodt Medical	Petten	^{1}H	30		
	Mallinckrodt Medical	Petten	^{1}H	30		

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Norway (1)	University of Oslo	Oslo	^{1}H, ^{2}H, ^{3}He, ^{4}He	35, 17, 47, 35	^{18}F	NR
Philippines(1)	St. Luke's Medical Center	Quezon City	^{1}H	9.6	^{18}F	NR
Poland (3)	Henryk Niewodnicanczanski Insitute of Physics	Krakow	^{1}H, ^{2}H, ^{4}He	60, 30, 60	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{111}In, ^{211}At	NR
	Henryk Niewodnicanczanski Insitute of Physics	Krakow	^{1}H, ^{2}H, ^{4}He	60, 30, 60		
	Warsaw University	Warsaw	^{1}H	NA		
Romania (1)	National Institute for Physics and Nuclear Engineering	Bucharest	^{1}H, ^{2}H, ^{4}He	15, 13, 27	^{18}F, ^{67}Ga, ^{103}Pd, ^{111}In, ^{123}I	NR
Russian Federation (9)	Central Research Institute of Roentgenology and Radiology	St-Peterburg	^{1}H, ^{2}H, ^{3}He, ^{4}He	18, 10, 28, 20	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{57}Co, ^{67}Ga, ^{68}Ge, ^{85}Sr, ^{103}Pd, ^{109}Cd, ^{123}I, ^{124}I, ^{201}Tl	NR
	Bakoulev Scientific Centre for Cardiovascular Surgery	Moscow	^{1}H	11		
	Kurchatov Institute of Atomic Energy	Moscow	^{1}H, ^{2}H, ^{3}He, ^{4}He	32, 30, 70, 60		
	Cylotron Co., Ltd.	Obninsk	^{1}H	14		
	Cylotron Co., Ltd.	Obninsk	^{1}H, ^{3}He	22, 22		
	Institute of Human Brain RAS	St. Petersburg	^{1}H, ^{2}H	17, 8.5		
	St. Petersburg Technical University	St. Petersburg	^{1}H, ^{2}H, ^{3}He, ^{4}He	18, 10, 27, 20		
	V.G. Khlopin Radium Institute	St. Petersburg	^{1}H, ^{2}H, ^{3}He, ^{4}He	18, 10, 24, 20		
	Tomsk Polytechnic University	Tomsk	^{1}H, ^{2}H, ^{3}He, ^{4}He	15, 14, 30, 28		
Saudi Arabia (1)	King Faisal Specialist Hospital and Research Centre	Riyadh	^{1}H, ^{2}H, ^{3}He, ^{4}He	28.5, 15, 38, 30	^{13}N, ^{18}F ^{67}Ga, ^{111}In, ^{123}I, ^{124}I, ^{201}Tl, ^{203}Pb	NR
Slovak Republic (1)	Slovak Office for Standards, Metrology and Testing	Bratislava	^{1}H, ^{2}H	18, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F	NR
South Africa (1)	National Accelerator Centre	Faure	^{1}H	200	^{18}F, ^{67}Ga, ^{123}I	NR

Appendix 3. **Accelerators producing isotopes** (cont'd)

Country	**Operator**	**Location**	**Beam type**	**Beam energy** (MeV)	**Isotopes produced in 2002**	**New isotopes planned for production 2003-2005**
Spain (5)	Barnatron (CADISA)	Barcelona	^{1}H	16.4	^{13}N, ^{18}F	NR
	Centro PET Complutense	Madrid	^{1}H	12		
	Clinica Lopez Ibor	Madrid	^{1}H	9.6		
	Clinica Universitaria de Navarra	Pamplona	^{1}H, ^{2}H	18, 9		
	Centro Andaluz de Diagnostico	Sevilla	^{1}H	16.5		
Sweden (1)	Uppsala Universitet	Uppsala	^{1}H, ^{2}H	17, 17	^{11}C, ^{15}O, ^{18}F	NR
Syria (1)	Atomic Energy Commission of Syria	Damascus	^{1}H	30	^{18}F, ^{67}Ga, ^{201}Tl	^{15}O, ^{103}Pd, ^{123}I
Turkey (1)	Monrol Isotopes Services	Gebze Kocaeli	^{1}H	11	^{18}F	NR
Switzerland (5)	University Hospital of Geneva	Geneva	^{1}H, ^{2}H	18, 9	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Cu, ^{123}I, ^{201}Tl	^{64}Cu, ^{86}Y
	University Hospital of Geneva	Geneva	^{1}H, ^{2}H	18, 9		
	Paul Scherrer Institute	Villigen	^{1}H	72		
	Paul Scherrer Institute	Villigen	^{1}H	590		
	University Hospital Zürich	Zürich	^{1}H, ^{2}H	16.5, 8.5		
United Kingdom (6)	John Mallard Scottish PET Centre	Aberdeen	^{1}H	11	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I	NR
	University of Cambridge	Cambridge	^{1}H, ^{2}H	16, 8.5		
	Imaging Research Solutions Ltd	London	^{2}H	3.8		
	Imaging Research Solutions Ltd	London	^{1}H, ^{2}H, ^{3}He, ^{4}He	40, 20, 53, 40		
	St. Thomas Hospital	London	^{1}H	11.5		
	Douglas Cyclotron Unit Clatterbridge for Oncology	Wirral	^{1}H	62		
United States (74)	74 accelerators produced isotopes	Various	Various	Various up to 800 MeV	^{7}Be, ^{22}Na, ^{44}Ti, ^{49}V, ^{60}Cu, ^{64}Cu, ^{65}Zn, ^{67}Cu, ^{68}Ge, ^{73}As, ^{76}Br, ^{77}Br, ^{82}Sr, ^{85}Sr, ^{86}Y, ^{88}Y, ^{88}Zr, ^{94m}Tc, ^{95m}Tc, ^{109}Cd, ^{124}I, ^{194}Hg, ^{207}Bi	NR

Source: IAEA Directory of Cyclotrons used for Radionuclide Production in Member States, October 2002.
NR Not reported.

Appendix 4

Countries that responded to the questionnaire*

Australia	Austria
Belarus	Belgium
Brazil	Chile
Czech Republic	Egypt
Finland	France
Germany	India
Indonesia	Iran, Islamic Republic of
Japan	Korea, Republic of
Pakistan	Slovak Republic
South Africa	Spain
Switzerland	Syria
Turkey	Ukraine
United States	

* The European Commission Research Centre at Ispra, Italy, also responded to the questionnaire.

Appendix 5

Common medical isotopes produced in reactors and their uses

Isotope	Half-life	Production route	Use category*	Uses
H-3	12,3 y	Li-6(n, alpha)H-3	D	Biochemistry research tracer, Radioimmunoassay
C-14	5730 y	N-14(n,p)C-14	D	Gastric ulcer detection
Na-24	14.9 h	Na-23(n, gamma)Na-24	R	Hypertension research
P-32	14.3 d	S-32(n,p)P-32	T	Therapy for bone cancer, arthritis and synovitis therapy
S-35	87.2 d	Cl-35(n, p)S-35	R	Radiolabeled biomedical compounds, biochemical and biomedical research
Ca-45	162.7 d	Ca-44(n, gamma)Ca-45	R	Biochemistry research tracer
Sc-46	83.8 d	Sc-45(n, gamma)Sc-46	R	Biochemistry research tracer and liquid flow tracer
Ca-47	4.5 d	Ca-46(n, gamma)Ca-47	R	Biochemistry research tracer
Sc-47	3.3 d	Sc-45(n, gamma)Sc-46(n, gamma)Sc-47	T	Radioimmunotherapy
Cr-51	27.7 d	Cr-50(n, gamma)Cr-51	D	Diagnosis of blood cell volume, biochemistry research tracer
Fe-55	2.7 y	Fe-54(n, gamma)Fe-55	R	Biochemistry research tracer
Fe-59	44.5 d	Fe-58(n, gamma)Fe-59	R	Biochemistry research tracer
Co-60	5.3 y	Co-59(n, gamma)Co-60	T	Cancer therapy
Cu-64	12.7 h	Cu-63(n, gamma)Cu-64	D/T	Cancer diagnosis and therapy
Zn-65	243.8 d	Zn-64(n, gamma)Zn-65	R	Biochemistry research tracer
Cu-67	2.6 d	Zn-67(n, p)Cu-67	T	Cancer therapy, biochemistry research tracer
Se-75	119.8 d	Se-74(n, gamma)Se-75	R	Gamma radiography, biochemistry research tracer
Sr-85	64.8 d	Sr-84(n, gamma)Sr-85	R	Biomedical tracer
Rb-86	18.6 d	Rb-85(n, gamma)Rb-86	R	Biochemistry research tracer
Sr-89	50.5 d	Sr-88(n, gamma)Sr-89 ou Y-89(n, p)Sr-89	T	Bone cancer therapy
Sr-90	28.8 y	U-235 fission product	T	Cancer therapy
Y-90	64 h	Y-89(n, gamma)Y-90 ou Sr-90 (bêta moins)Y-90	T	Cancer therapy, arthritis and synovitis therapy
Tc-99m	6.01 h	Mo-99(bêta moins)Tc-99m[1]	D	Diagnosis
Pd-103	17 d	Pd-102(n, gamma)Pd-103	T	Prostate cancer therapy
Ru-103	39.3 d	U-235 fission product	T	Prostate cancer therapy
Ru-106	1 y	U-235 fission product	T	Brachytherapy
Cd-109	462 d	Cd-108(n, gamma)Cd-109	T	Therapy for cancer
Pd-109	13.5 h	Pd-108(n, gamma)Pd-109	T	Therapy for cancer
Sn-117m	13.6 d	Sn-116(n, gammaSn-117m ou Sn-117(n,n)Sn-117m	T	Bone cancer therapy
Cd-115	44.6 d	Cd-114(n, gamma)Cd-115	T	Arthritis therapy
Te-123m	119.7 d	Te-122(n, gamma)Te-123m	R	Lung, heart research
I-125	59.4 d	Xe-124(n, gamma)Xe-125(beta-minus)I-125	D/T	Brachytherapy, cancer therapy, bone density measurement, radioimmunoassay
I-131	8 d	Te-130(n, gamma)Te-131(bêta minus)I-131 or U-235 fission product	D/T	Gamma imaging, thyroid therapy, cancer therapy
Xe-133	5.2 d	U-235 fission product	D	Gamma imaging of lung functions
Cs-137	30 y	U-235 fission product	T	Brachytherapy
Sm-145	340 d	Sm-144(n, gamma)Sm-145	T	Cancer therapy
Sm-153	1.9 d	Sm-152(n, gamma)Sm-153	T	Bone cancer therapy
Gd-153	241.6 d	Gd-152(n, gamma)Gd-153	D	Osteoporosis diagnosis
Dy-165	2.3 h	Dy-164(n, gamma)Dy-165	T	Arthritis therapy
Dy-166	3.4 d	Dy-164(n, gamma)Dy-165(n, gamma)Dy-166	T	Cancer therapy
Ho-166	1.1 d	Ho-165(n, gamma)Ho-166	T	Cancer therapy, palliative care
Er-169	9.4 d	Er-168(n, gamma)Er-169	T	Arthritis and synovitis therapy
Yb-169	32 d	Yb-168(n, gamma)Yb-169	T	Palliative care
Tm-170	128.6 d	Tm-169(n, gamma)Tm-170	T	Leukemia therapy
Yb-175	4.2 d	Yb-174(n, gamma)Yb-175	T	Cancer therapy
Lu-177	6.7 d	Lu-176(n, gamma)Lu-177	T	Cancer therapy
Re-186	3.8 d	Re-185(n, gamma)Re-186	T	Bone cancer therapy
Re-188	16.9 h	W-186(n, gamma)W-187(n, gamma) W-188(bêta minus)Re-188 ou Re-187(n, gamma)Re-188	T	Cancer therapy, palliative care, antirestenosis
Ir-192	73.8 d	Ir-192(n, gamma)Ir-192	T	Cancer therapy, brachtherapy, anti-restenosis
Pt-195m	4 d	Pt-195(n, gamma)Pt-195m	D/T	Cancer diagnosis and therapy
Au-198	2,7 d	Au-197(n, gamma)Au-198	T	Cancer therapy, brachytherapy
Au-199	3,1 d	Pt-198(n, gamma)Pt-199(bêta minus)Au-199	T	Cancer therapy
Bi-213	45,6 m	Derived from decay of U-233	T	Alpha-emission cancer therapy
Am-241	432,2 y	Multiple neutron absorptions starting with U-238	T	Bone density measurement
Cf-252	1,65 y	Multiple neutron absorptions starting with U-238	T	Cervical cancer therapy

* D = diagnostic T = therapeutic R = research n = neutron
d = day m = minute h = hour y = year

1. Mo-99 is produced as a U-235 fission product or by the reaction Mo-98(n)Mo-99

Appendix 6

Common medical isotopes produced in accelerators and their uses

Isotope	Half-life	Production route	Use category*	Uses
Be-7	53.3 d	Li-7(p,n)Be-7	R	Berylliosis studies
C-11	20.3 m	B-11(p,n)C-11	D	Positron Emission Tomography (PET) diagnosis
N-13	10 m	C-13(p,n)N-13	D	Positron Emission Tomography (PET) diagnosis
O-15	122.3 s	N-15(p,n)O-15	D	Positron Emission Tomography (PET) diagnosis
F-18	1.8 h	O-18(p,n)F-18	D	Positron Emission Tomography (PET) diagnosis
Mg-28	21 h	P-31(p,4p)Mg-28	R	Magnesium tracer
V-48	16 d	Ti-48(p,n)V-48	R	Nutritional studies
Fe-52	8.3 h	Mn-55(p,4n)Fe-52	D/R	Positron emission diagnosis, iron tracer
Co-57	271.8 d	Fe-57(p,n)Co-57	D	Radioimmunoassay
Cu-61	3.4 h	Ni-61(p,n)Cu-61 ou Zn-64(p,alpha)Cu-61	D	Positron emission diagnosis
Cu-64	12.7 h	Ni-64(p,n)Cu-64 ou Cu-65(p,pn)Cu-64	D/T	Positron emission diagnosis, radioimmunotherapy
Cu-67	2.6 d	Zn-68(p,2p)Cu-67	T	Radioimmunotherapy
Ga-67	3.3 d	Zn-67(p,n)Ga-67	D	Gamma diagnostics
As-74	17.8 d	Ge-74(p,n)As-74	D	Positron emitting analog of phosphorus
Br-77	2.4 d	Se-77(p,n)Br-77	T	Radioimmunotherapy
Br-80m	4.4 h	Se-80(p,n)Br-80m	T	Radioimmunotherapy
Kr-81m	13.1 s	Br-81(p,n)Kr-81m	D	Gamma diagnostics
Rb-82m	6.3 h	Sr-82(ec)Rb-82	D	Cardiac imaging
Y-88	106.6 d	Sr-88(p,n)Y-88	T	Radioimmunotherapy
Zr-89	3.3 d	Y-89(p,n)Zr-89	D/T	Positron emission diagnosis, radioimmunotherapy
Ru-97	2.9 d	Rh-103(p,alpha3n)Ru-97	D	Hepatobiliary function; tumor and inflammation localisation
Pd-103	17.0 d	Rh-103(p,n)Pd-103	T	Prospate cancer therapy
In-111	2.8 d	Cd-111(p,n)In-111	D/T	Radioimmunotherapy, gamma imaging
I-123	13.2 h	I-127(p,5n)Xe-123(ec)I-123	D	SPECT brain-imaging emitter
I-124	4.2 d	Te-124(p,n)I-124	D/T	Radioimmunotherapy, positor emitter
Xe-127	36.4 d	I-127(p,n)Xe-127 ou Cs-133(p,2p5n)Xe-127	D/R	Lung diagnosis and ventilation studies
Tl-201	3.0 d	Tl-203(p,p2n)Tl-201	D	Cardiac imaging
Bi-205	15.3 d	Pb-207(p,3n)Bi-205	D/R	Bismuth biological distribution
Bi-206	6.2 d	Pb-207(p,2n)Bi-206	D/R	Bismuth biological distribution
At-211	7.2 h	Bi-209(alpha,2n)At-211	T	Alpha-emitting cancer therapy

* D = diagnostic   T = therapeutic   R = research

ec = electron capture
p = proton
n = neutron
d = day

h = hour
m = minute
s = second

Appendix 7

List of non-governmental organisations relevant to the production and use of isotopes

American Society for Therapeutic Radiology and Oncology (ASTRO)
12500 Fair Lakes Circle Suite #375, Fairfax, VA 22033-3882, USA
Website: www.astro.org

Council on Radionuclides and Radiopharmaceuticals, Inc. (CORAR)
3911 Campolindo Drive, Moraga, CA 94556-1551, USA
Website: www.corar.org

European Association of Nuclear Medicine (EANM)
EANM Executive Secretariat, Hollandstrasse 14 Mezzanine, A-1020 Vienna, Austria
Website: www.eanm.org

European Society for Therapeutic Radiology and Oncology (ESTRO)
Avenue E. Mounierlaan 83, B-1200 Brussels, Belgium
Website: www.estro.be

International Isotope Society (IIS)
Website: www.intl-isotope-soc.org

Joint Accelerator Conference Website (JACoW)
Website: www.JACoW.org

Society of Nuclear Medicine (SNM)
1850 Samuel Morse Dr. Reston, VA 20190, USA
Website: www.snm.org

Appendix 8

Working group members

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Czech Republic	
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France	
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Italy	
Mr. G. CAPANNESI	ENEA
Mr. M. PAGANINI FIORATI	APAT
Turkey	
Ms. B. ONAT	
United States of America	
Mr. J. KLEIN (**Chairman**)	Oak Ridge National Laboratory
International Atomic Energy Agency	
Mr. N. RAMAMOORTHY	Director, Division of Physical and Chemical Sciences Department of Nuclear Sciences and Applications
Mr. M. HAJI-SAEID	Head, Industrial Applications and Chemistry Section Division of Physical and Chemical Sciences
Mr. M.R.A. PILLAI	Industrial Applications and Chemistry Section
OECD Nuclear Energy Agency	
Mr. R. PRICE (**Scientific Secretary**)	Nuclear Development Division

Appendix 9

Grouping of countries and areas

The countries and geographical areas referenced in this report are listed below. Countries followed by "**" are members of OECD.

1. North America

Canada**
Mexico**
United States of America**

2. Central and South America

Argentina
Brazil
Chile
Cuba
Peru

3. Western Europe and Scandinavia

Austria**
Belgium**
Denmark**
Finland**
France**
Germany**
Italy**
Netherlands**
Norway**
Portugal**
Spain**
Sweden**
Switzerland**
United Kingdom**

4. Central, Eastern and South-eastern Europe

Belarus
Czech Republic**
Hungary**
Russian Federation
Romania
Poland**
Slovak Republic**
Turkey**
Ukraine

5. Africa

Egypt
Libya
South Africa

6. Middle East, Central and Southern Asia

Bangladesh
India
Iran, Islamic Republic of
Israel
Kazakhstan
Pakistan
Saudi Arabia
Syria
Uzbekistan

7. South-eastern Asia and Pacific

Australia**
Indonesia
Malaysia
Philippines
Thailand
Vietnam

8. East Asia

China
Chinese Taipei
Japan**
Korea, Republic of**

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