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Beneficial Uses and Production of Isotopes

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FOREWORD

Radioactive and stable isotopes are used throughout the world and in many sectors, including medicine, industry, agriculture and research. In many applications isotopes have no substitute, and in most others they are more effective and cheaper than alternative techniques or processes.

While around 50 countries have significant isotope production or separation capacities, and many others have smaller capacities, a comprehensive survey and analysis of the trends in isotope production and use, and of the isotope supply/demand balance, has never been made. Therefore, in 1996 a study was initiated by the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), in co-operation with the International Atomic Energy Agency (IAEA), with the objectives of collecting and compiling information on isotope production and uses; analysing the status and trends in the sector; and identifying key issues of relevance for governments with regard to ensuring security of isotope supply for beneficial uses.

This report is the result of a collective effort of experts in the field, and does not necessarily represent the views of the participating countries or international organisations. The data and analyses are representative of the world situation, but are by no means exhaustive. The report is published on the responsibility of the Secretary-General of the OECD.

EXECUTIVE SUMMARY

The Nuclear Energy Agency (NEA) Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) approved the present study on beneficial uses and production of isotopes within the 1997-1998 programme of work. The main objectives of the study are to provide Member countries with a comprehensive and up-to-date survey of isotope uses and production capabilities in the world, and to analyse trends in demand and supply of isotopes in order to identify issues of interest to governments. Issues related to regulation are excluded, since they are dealt with in a number of IAEA, ISO or ICRP publications. The production of isotopes used for nuclear power plant fuels is also excluded. The study was carried out by the NEA Secretariat assisted by a consultant, in co-operation with the IAEA Secretariat. Information was collected and analysed by the Secretariat, under the guidance and supervision of experts from NEA Member countries.

There are many isotope applications in practically all sectors of economic activities and in most countries of the world. Although there is a great deal of literature on the uses of isotopes in different sectors, there is no comprehensive world-wide survey of isotope demand covering all the uses.

Many isotopes are produced with research reactors, others are produced with accelerators. While information on research reactors and accelerators in operation in the world is available, for example in IAEA publications, it is difficult to get hold of their real activities in isotope production. In research reactors, isotopes are obtained as by-products. Besides, the producers of isotopes are often independent of reactor operators. Also, accelerators, particularly of high energy, are devoted to scientific research, and isotope production is only a side activity on which comprehensive information is not readily available.

Public entities own and operate almost all the research reactors, large-scale accelerators and chemical separation facilities being used for isotope production, as well as facilities for extended uses of isotopes in medical and scientific fields. Governments fund infrastructures for effective production and beneficial uses of isotopes at those facilities, and provide education and training of qualified manpower required in the field. A number of medium-size cyclotrons producing major isotopes for medical applications are owned and operated by private sector enterprises for their exclusive uses. Regarding such facilities, the role of governments is limited to the implementation of safety regulations and controls.

For some isotopes, particularly of short lives or of special specifications, the supply demand balance is a regional issue. The isotopes of very short lives, such as those for PET, must be produced on the end-user's site. For other isotopes, that may be transported over long distances and require highly specialised facilities for their production, adequate supply may be ensured at world level. In most countries, domestic supply relies at least partly on imports. Some isotopes are supplied by a few producers to a number of users distributed world-wide. Furthermore, many isotope producers rely on target irradiation services provided by reactors operated in foreign countries.

At present, most of the isotope production facilities are operated in OECD countries and they also are the main users. Demand is increasing in non-OECD countries and their production capabilities might not increase as fast as their demand. Satisfying isotope demand requires exchanges, in particular between OECD and non-OECD countries, that are essential to ensure adequate supply. Therefore, the availability of comprehensive information on existing and projected production capabilities in the world is important. The need for international transport of irradiated targets and separated isotope products calls for international harmonisation of regulations on licensing and controls related to production, transport and uses of isotopes.

Isotope demand is evolving owing to the development of new applications on one side and to the progressive phase out of some uses on the other. As far as the production is concerned, most facilities require several years to be built and commissioned, so that it is essential to monitor projected demand and planned production capacities at world level to alleviate the risk of inadequate supply in the future. The demand for stable isotopes is increasing, as they are essential for some applications. The production of large quantities of economically interesting stable isotopes is likely to be ensured as long as industrial enrichment plants using gaseous centrifuge technology will continue to operate. It is, however, necessary to pursue the development of new technologies or plants in order to separate stable isotopes that cannot be obtained by the centrifuge technology.

Inadequate supply of major isotopes produced with reactors, such as molybdenum-99 and iridium-192, would have detrimental impacts in medical and industrial sectors. Although usually they are supplied on a commercial basis, it is important that governments keep interest in monitoring the supply of such important isotopes. It is essential to promote basic research in medical, physical and life sciences that require small quantities of diverse isotopes. Some isotopes useful in medical care are produced with high neutron flux reactors and/or special processing facilities, which are very limited all over the world today. Governmental policies are instrumental in maintaining adequate production capabilities for the isotopes used in those fields.

Recognising the great potential of isotopes in their beneficial uses for medical, industrial and scientific applications, governments should consider policy measures to ensure adequate supply of isotopes adaptable to the existing and foreseeable demand. International organisations, such as the NEA, should assist governments by compiling relevant data on isotope demand and supply and analysing trends in the field.

Government policies in the field of isotope production and uses are likely to be re-assessed in the context of economic deregulation and privatisation of industrial sectors traditionally under state control. It might be relevant to investigate whether changes in policies might affect the availability and competitiveness of isotopes and, thereby, the continued development of some isotope uses. In some areas and sectors where there is a regular and rather large demand to hold dedicated facilities, such as to supply some medical isotopes, market mechanisms are already in force and have proven to be effective. In many other cases, however, isotope production facilities are supported partly by governments in the framework of global scientific and social development policies. Full cost recovery applied to by-product isotope producing facilities might jeopardise the development of a number of beneficial uses of isotopes in particular in science and medicine. This could compromise the unique contribution of isotope technology to the advancement of human society.

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1. INTRODUCTION

1.1 Background

The present report is the result of a study carried out by the OECD Nuclear Energy Agency (NEA) in co-operation with the International Atomic Energy Agency (IAEA). This study was approved by the Nuclear Development Committee (NDC) within the 1997-1998 programme of work of the NEA. The Committee found it relevant for NEA to undertake an analysis of the beneficial uses and production of isotopes in view of both the importance of the subject matter for many, if not all, NEA Member countries, as well as the IAEA Member States, and the potential role of Governments in ensuring the continued supply of isotopes for a number of beneficial uses. In this regard, it should be noted that while isotopes are produced essentially in a relatively small number of facilities, the uses of isotopes are extremely numerous and constantly increasing with the development of new applications.

1.2 Objectives and scope

The main objectives of the study are: to provide Member countries with a comprehensive and up to date survey of isotope uses and production capabilities in the world; and to analyse trends in isotope demand and supply in order to draw findings and conclusions of interest to governments.

The study focuses on topics relevant to governments such as the role of the public sector in isotope production and use. Issues related to regulation are excluded from the study since they are comprehensively dealt with in a number of IAEA, ISO or ICRP publications. The production of isotopes used for nuclear power plant fuel fabrication is not dealt with either.

The report covers a survey of the main uses of isotopes in different sectors of the economy, and data on isotope production capacities in the world by type of facility and by region. Although efforts were made to obtain comprehensive and up to date information world-wide, the data and analyses presented in the report focus on some fifty countries that are major actors in the field. Issues relating to trends in the sector and supply demand balance are discussed. Finally, the report offers some findings, conclusions and recommendations, for consideration by governments, on ways and means to take advantage of international organisations (such as IAEA and NEA) for the enhancement of international information exchange and co-operation.

1.3 Working method

The study was carried out by the NEA Secretariat, in co-operation with the IAEA Secretariat, assisted by a NEA Consultant. Information on isotope production was collected through a questionnaire designed by the Secretariat under the guidance of experts from a number of Member countries. Responses to the questionnaire served as a basis to identify the main production facilities in operation around the world. Such data were supplemented with literature surveys and individual inquiries carried out by the Consultant. A non-exhaustive list of bibliographic references is given in Annex 1. Information on isotope uses was compiled by the Consultant through literature surveys, and direct contacts with some users. The report, drafted jointly by the Consultant and the NEA Secretariat, was reviewed and agreed upon by a Group of Experts (see Annex 2, list of contributors to the report).

2. ISOTOPE USES

World-wide, isotopes are used in many sectors including medicine, industry, agriculture and food processing, and science. The following chapter does not intend to provide an exhaustive list of isotope applications but rather to illustrate with a number of examples, some of the main uses of isotopes in different sectors. As pointed out above, isotopes used for nuclear reactor fuels (i.e., uranium and plutonium) are not covered in the present study.

2.1 Medicine and research in biology

There is a rather long history of isotope use in medicine and the number of applications in this field is increasing constantly with the development and implementation of new technologies and processes. Over 30 million medical procedures involving the use of isotopes are carried out every year. Radiopharmaceuticals account for the principal application of radioisotopes in the medical field. For the purpose of nuclear imaging for diagnosis, gamma rays emitted by radioisotopes are detected by means of gamma cameras or Positron Emission Tomography cameras (PET cameras). An overall feature of the radiopharmaceuticals market is the progressive merging of the companies involved. The world's leading five companies are responsible for around 80 per cent of the supply.

2.1.1 Nuclear imaging

2.1.1.1 Gamma imaging

Gamma imaging represents a turn-over of around 1 billion US$ in the world. The main radioisotopes used are ^{99m}Tc (60 per cent of the market), ^{201}Tl (20 per cent of the market) and, to a lesser extent, ^{123}I, ^{133}Xe, ^{111}In and ^{67}Ga. There are around 8 200 nuclear medicine departments in the world using gamma cameras to detect diseases of various organs including heart, bone, lung and the thyroid. Six isotopes cover most of the regular diagnostic needs. Three are produced by accelerators (^{201}Tl, ^{123}I and ^{67}Ga) and three are produced by reactors (^{99m}Tc, ^{131}I and ^{133}Xe). The main applications of gamma cameras are summarised in Table 1.

A total of some 17 000 gamma cameras are in use. The demand for isotopes in this sector is growing by about 5 per cent per year. The supply is ensured essentially by a dozen private companies and a few public bodies.

New applications are being developed. In the field of immuno-diagnosis, after a transition phase during which problems related to certain specific features were addressed, combinations of radioisotopes (essentially ^{99m}Tc) and monoclonal antibodies or peptides (7 products already marketed and 17 under development) are used in oncology, essentially in the United States.

Moreover, a number of companies are developing post-surgical probes used to verify the disappearance of cancer cells after surgery. These probes are used to monitor isotopic markers linked to these specific antibodies.

Table 1. **Isotopes used and diagnostic purposes**

Organs	Isotopes used	Disease investigated
Lung	^{99m}Tc, ^{133}Xe, ^{81}Kr	Embolisms, breathing
Bone	^{99m}Tc,	Tumours, infection
Thyroid	^{99m}Tc, ^{131}I, ^{123}I	Hyper/hypothyroidism
Kidney	^{99m}Tc, ^{111}In, ^{131}I	Renal fixation
Brain	^{99m}Tc, ^{133}Xe	Embolisms, blood flow, tumours
Liver, pancreas	^{99m}Tc, ^{51}Cr	Cirrhosis, necrosis
Abdomen	^{67}Ga ^{99m}Tc	Tumours
Blood	^{111}In, ^{99m}Tc	Leukocytes
Heart	^{201}Tl, ^{99m}Tc	Myocardial infarction
All	^{99m}Tc, ^{67}Ga, ^{111}In	

The addition of sealed gamma sources, with energy peaks remote from those of the radiopharmaceutical ones, compensates for the attenuation of the signal in the human body. Since 1995, the Food and Drug Administration (FDA) in the United States, and regulatory bodies in some other countries, have authorised systems incorporating one or two of those sources in gamma cameras. The radioisotopes used are ^{153}Gd, ^{57}Co and ^{241}Am.

Nuclear medicine departments also use other radioisotopes including ^{57}Co for calibration of the camera, and ^{57}Co, ^{137}Cs and ^{133}Ba as standard sources for activity meters or other instruments (marker pens, rigid or flexible radioactivity rules).

2.1.1.2 Positron imaging: Positron Emission Tomography (PET)

The main radioisotopes used are ^{18}F (90 per cent of the market) and, to a lesser extent, ^{11}C, ^{13}N and ^{15}O. There are about 150 PET centres in the world operating a total of 200 PET cameras. The annual turnover of this sector represent some 75 million US$ and is growing rapidly by about 15 per cent per year. Approximately 70 per cent of the sites produce their own radioisotopes. Only 30 per cent of the PET centres obtain their radioisotopes from other sites, three in Germany (the nuclear centres), ten in the United States and all those having a non-dedicated cyclotron.

PET cameras use other isotopes including ^{68}Ga as a calibration source and, like gamma cameras, ^{57}Co, ^{137}Cs and ^{133}Ba as calibration sources for the activity meters. Also, systems using $^{68}Ge/^{68}Ga$ sources may be added to PET cameras in order to obtain a correction for attenuation.

2.1.1.3 Bone density measurement

Systems to determine bone density are used in radiology centres. A total of some 500 units are in operation using ^{125}I, ^{153}Gd or ^{241}Am sources. This demand is decreasing because X-ray tube devices tend to replace isotope based systems and only existing machines are still in use. The sources are supplied by three private companies, including two European companies.

2.1.2 Radioimmunoassay

Radioimmunoassay tests are in vitro diagnostic methods including five technologies: microbiology; haematology; biochemistry; molecular biology; and immunology. In the later category, the high specificity of immunoassay reagents is provided by the use of immunoproteins called antibodies. The high sensitivity of these products results from the possibility to measure very low concentrations of radioactive tags combined with the advanced instrumentation used to measure the presence of such tags. Radioimmunoassay tests use immunoproteins with radioisotopic tags such as ^{125}I, ^{57}Co, tritium (^{3}H) and ^{59}Fe in Japan.

Radioimmunoassays are mainly used in laboratories conducting medical analysis, mostly for tumour markers or hormones. For this application – which represents an annual turnover of some 85 million US$ – isotopes are progressively replaced by alternative technologies, such as methods involving luminescence or fluorescence or enzymes. The main radioisotope concerned is ^{125}I (which is also used as a calibration source). To a lesser extent ^{3}H (steroids) and ^{57}Co (growth factors) are used too. This market involves about 100 private companies.

^{14}C is used for marking urea in order to detect Helicobacter Pylori which is responsible for gastric ulcers. This technique faces some competition from marking with a stable isotope, ^{13}C. This type of product is being developed by an American company. Non-radioactive technologies are strong competitors in the sector.

2.1.3 Radiotherapy with radiopharmaceuticals

Nuclear medicine centres use radiotherapy mainly for treating hyperthyroidism, synovitis and cancers. The radioisotopes concerned are ^{131}I for treating hyperthyroidism (accounting for 30 per cent of the market), ^{32}P, ^{186}Re and ^{169}Er. The demand is growing at a projected rate of 10 per cent per year. About ten companies and some major government authorities are involved.

The use of ^{89}Sr, ^{186}Re or ^{153}Sm for the palliative treatment of cancers is a new development that already represents an annual turnover of around 28 million US$. Other developments are considered using ^{117m}Sn, ^{166}Ho and ^{188}Re.

Only a few companies are involved in the development of therapeutic substances for radiotherapy with radiopharmaceuticals but many research organisations are active in the field. Clinical tests are performed using products that combine radioisotopes (mainly ^{131}I, ^{153}Sm, ^{90}Y and ^{213}Bi) with monoclonal antibodies or peptides.

2.1.4 Radiotherapy with sealed sources

2.1.4.1 Remotely controlled cobalt therapy

This application represents an annual turnover (in terms of value of cobalt sources) of around 35 million US$ but demand is declining since ^{60}Co is being replaced by electron accelerators. World-wide, some 1 500 units using ^{60}Co sources are in operation in about 1 300 radiotherapy centres for remotely controlled cobalt therapy aiming at destroying cancer cells. Around 70 new machines are installed every year, including the replacement of units that are shut-down. Some 85 “Gamma-Knife” systems (multi source devices dedicated to brain tumour treatment) are in service. Nine companies, including three in North America, are active suppliers in this sector.

2.1.4.2 Brachytherapy

Brachytherapy is a medical procedure for the treatment of diseases by local radiation therapy from sealed radioactive sources. It is mainly used in specialised oncology centres, around 3 000 world-wide, providing a total of 50 000 procedures every year. The annual turnover in the sector represents around 35 million US$ and the demand is growing steadily at about 10 per cent per year.

The radioisotopes used are ^{192}Ir, ^{137}Cs, ^{125}I, ^{198}Au, ^{106}Ru and ^{103}Pd. Recently the permanent implantation of brachytherapy sources has become extremely successful for early stage prostate cancer treatment with ^{125}I and ^{103}Pd. In the United States, a private company has announced the construction of 14 cyclotrons dedicated to ^{103}Pd production. In ophthalmology, ^{106}Ru is used for retinoblastoma. Remote afterloading techniques using ^{192}Ir are often employed for the treatment of a range of diseases.

2.1.5 Irradiation of blood for transfusion

About 1 000 irradiators are used in blood transfusion laboratories. Irradiation of blood pouches at very low dose is used to avoid possible immunological reactions following blood transfusions to immunodepressed patients in the case of organ transplants. It is carried out in self shielded irradiators using one to three ^{137}Cs sources of about ten TBq each. Doses of 25-75 Gy are delivered at a dose rate of 5 to 40 Gy per minute. The demand for new units is about 70 per year. They use ^{60}Co and ^{137}Cs sources. This is a stable market involving three main industrial firms that are supplying machines and sources directly to their clients. The volume of activity in this sector is around 25 million US$.

2.1.6 Endovascular radiotherapy

This application is under active development. A growing number of private companies and university teams are pursuing clinical tests aiming at the commercial development of radioactive stents (inserts positioned in blood vessels to prevent vessel collapse) or sources to prevent restenosis of blood vessels following balloon angioplasty. The radioisotopes being investigated include ^{192}Ir, ^{32}P and ^{90}Sr/^{90}Y and ^{188}W/^{188}Re.

2.1.7 Stable isotopes

Stable isotopes are used as precursors for the production of cyclotron and reactor produced radioisotopes. In this sector, demand requiring very high enrichment levels is growing. Table 2 illustrates by some selected examples the use of stable isotopes for producing radioisotopes in reactors or accelerators.

Table 3 provides a more detailed list of stable isotopes for medical applications including the direct use of stable isotopes, such as ^{10}B for Boron Neutron Capture Therapy (BNCT) in cancer treatment and the use of polarised ^{3}He and ^{129}Xe for magnetic resonance medical imaging.

Table 2. **Selected enriched stable isotopes and derived radioisotopes**

Stable Isotope Target	Radioisotope Product	
	Produced in reactors	Produced in accelerators
Cadmium-112		Indium-111
Carbon-13		Nitrogen-13
Chromium-50	Chromium-51	
Gadolinium-152	Gadolinium-153	
Germanium-76	Arsenic-77	
Lutetium-176	Lutetium-177	
Nickel-58	Cobalt-58	Cobalt-57
Nitrogen-15		Oxygen-15
Oxygen-18		Fluorine-18
Palladium-102	Palladium-103	
Platinum-198	Gold-199	
Rhenium-185	Rhenium-186	
Samarium-152	Samarium-153	
Strontium-88	Strontium-89	
Thallium-203		Thallium-201
Tungsten-186	Tungsten-188	Rhenium-186
Sulphur-33	Phosphorus-33	
Xenon-124	Iodine-125	Iodine-123
Yterbium-168	Yterbium-169	
Zinc-68		Gallium-67, Copper-67

2.2 Industrial sectors

Industrial use of radioisotopes 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. Stable isotopes are used in particular in nuclear power and laser industries.

The uses of radioisotopes in industry may be classified under three main technologies: nucleonic control systems or nucleonic instrumentation; irradiation and radiation processing; and technologies using radioactive tracers.

The first category of technologies includes analysis, measurement and control using sealed radioactive sources incorporated into instrumentation (called nucleonic or radiometric instrumentation or control system) and non-destructive testing equipment (gamma radiography apparatus). The sources used may be emitters of alpha or beta particles, neutrons or X or gamma photons. Typically, the sources used have activities varying from some 10 MBq to 1 TBq (1 mCi to 100 Ci). A relatively large number of radioisotopes is concerned by such techniques. Nucleonic instrumentation is the major world-wide application in terms of the number of industrial sectors concerned, the number of equipment in operation and of industrial companies manufacturing such equipment.

Radiation processing uses high intensity gamma photons emitting sealed sources (mainly ^{60}Co in industrial irradiators). Typically, the activity of those sources is in the 50 PBq (1 MCi) range. It is the major world-wide application in terms of radioactivity, yet a limited number of end users and manufacturers are concerned.

Radioactive tracers (mainly beta or gamma emitters), as unsealed sources under various chemical and physical forms, are used to study, inter alia, chemical reactions, industrial processes in various industrial plants, transfer of matter in agronomy, hydrology, water engineering, coastal engineering, oil and gas reservoirs, waste storage areas. Typically, the activity of those tracers range between some 50 Bq and 50 MBq (1 nCi to 1 MCi). This category is widely spread in a large number of sectors, including research and development laboratories in nuclear or non-nuclear organisations or industries, but has less economic significance than the two other categories.

An important issue, regarding the first two categories, is the limited number of companies (generally called encapsulators) that maintain catalogues of sealed sources, in particular for alpha or neutrons emitters (such as ^{241}Am or ^{252}Cf) or fission products (such as ^{137}Cs or $^{90}Sr/^{90}Y$). Besides, concerns arise because some production facilities might not follow basic safety standards internationally agreed.

2.2.1 Nucleonic instrumentation

2.2.1.1 On-line control systems

Nucleonic control systems, or nucleonic instrumentation, or nucleonic gauges 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.

Physical measurement gauges

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 ^{137}Cs, ^{60}Co 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.

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 the following radioisotopes: ^{85}Kr, ^{241}Am, ^{147}Pm, $^{90}Sr/^{90}Y$ and ^{137}Cs. Demand in this sector is stable, but isotopes face competition with technologies based on the use of X-ray generators.

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

On-line analytical instrumentation

Sulphur analysers are used in oil refineries, power stations and petrochemical plants, to determine the concentration of sulphur in petroleum products. They involve ^{241}Am sources. The demand is stable.

Instrumentation for on-line analysis of raw mineral materials, mainly based on neutron-gamma reactions, is used for various ores, coal, raw mineral products, bulk cement and other products. The demand for those applications is relatively limited but growing. Such systems use ^{252}Cf sources. 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.

Pollution measuring instruments

The technology is based on beta particles absorptiometry of dust particles collected on air filters and permits to measure particulate concentration in air. The radioisotopes involved are ^{14}C and ^{147}Pm.

Security instrumentation

Systems generally based on neutron-gamma 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 governmental entities is expanding. Only a few companies are developing those systems. Luminous paint with tritium is used to indicate the emergency exit.

2.2.1.2 Laboratory or portable systems

There are three main types of applications in this field and the demands in these sectors are stable.

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. The radioisotopes used are ^{55}Fe, ^{109}Cd, ^{241}Am and ^{57}Co.

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).

Oil well-logging tools, mainly used by oil prospecting companies, are very important for oil and gas exploration. Parameters like density, porosity, water or oil saturation of the rocks surrounding the exploration wells can be determined. The sources involved are ^{241}Am-Be, ^{252}Cf and ^{137}Cs.

2.2.1.3 Smoke detectors

Smoke detectors are essentially used in public areas such as hospitals, airports, museums, conference rooms, concert halls, cinemas and aeroplanes. They are so widely used that they represent the largest number of devices based on radioisotopes used world-wide; each industrialised country has several million smoke detectors in operation. Demand is stable and ^{241}Am is the main radioisotope used.

2.2.2 Irradiation and radiation processing

Irradiation and radiation processing is one of the major uses of radioisotopes that requires high activity levels particularly of ^{60}Co.

Radiation processing includes three main types of applications:

- Radiation 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;
- 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); and
- Plastic curing, mostly in view of cross-linking.

There are few other treatments or activities related to radiation processing, such as irradiation for radiation damage study, or sludge irradiation. They have less economic significance than the former.

There are about 180 gamma irradiators in operation world-wide. 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.

Although ^{137}Cs could also be considered, low specific activity ^{60}Co is the only radioisotope used in practice for radiation processing. The activities of such industrial sources are very large, around 50 PBq (1 MCi); they use low specific activity ^{60}Co (around 1 to 4 TBq/g or 30 to 100 Ci/g) contrary to the sources for radiotherapy (specific activities around 10 TBq/g or 300 Ci/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 the pallet).

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 sterilisation and irradiation. 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 has a very large potential market for a broad variety and large quantities of products. At present, the quantities treated every year amount to about 0.5 million tonnes. A real breakthrough of this technology could lead to a demand exceeding the present capacities of ^{60}Co supply. The World Health Organisation (WHO) and the IAEA have stated that this process does not present health risk for consumers and a number of countries have authorised its use. Nevertheless, consumer acceptance seems to be lagging behind regulations. Therefore, demand growth is likely to be relatively slow in the short-term and a 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.

2.2.3 Radioactive tracers

A tracer or indicator 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:

- the 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 radioisotopes produced by reactors and accelerators in various chemical or physical forms are required to complete such studies.

These studies are R & D applications to check performance, optimise process, calibrate models or test pilot, prototype or revamped installations.

2.2.4 Non destructive testing

Gamma radiography is used for non-destructive testing in a variety of fields including petroleum and gas industry, boiler making, foundry, civil engineering, aircraft and automobile industries. More than 90 per cent of the systems use ^{192}Ir sources. The other radioisotopes concerned are ^{60}Co, ^{75}Se and ^{169}Yb. Demand is stable.

2.2.5 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 emitting neutrons like ^{252}Cf. The present demand is characterised by the number of reactors under construction, i.e., more than 50 units. There are five suppliers for those sources.

Radioisotopic power sources, called RTG (Radioisotopic Thermoelectric Generators) or SNAP (System of Nuclear Auxiliary Power) are now restricted to power supply for long term and long range space missions. They are based on heat thermoelectric conversion and use high activity sealed sources of ^{238}Pu. Russia and the United States are the only active countries in this area.

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 discharge static electricity.

2.2.6 Stable isotopes

Industrial applications of stable isotopes represent an annual turnover of around 30 million US$ per year. They usually require larger amounts, lower enrichment levels and are cheaper than biomedical applications. This means that gas centrifuge production is often the preferred production method for heavier isotopes, whilst distillation is preferred for lighter isotopes. Industries that use stable isotopes include nuclear power and laser industry.

The nuclear industry uses isotopes such as ^{10}B and ^{7}Li for neutron absorption and depleted ^{64}Zn as an additive to cool water of nuclear power plants to reduce radiation levels from unwanted radioactive isotopes of cobalt and zinc (^{67}Co and ^{65}Zn). These are large scale applications using up several tonnes of isotopes per year.

In the laser industry, even numbered cadmium isotopes are used for performance boosters in HeCd lasers. The quantities involved are in the range of some kilograms per year.

Other industries are currently investigating various uses of stable isotopes. For example, stable isotopes may be used to enhance thermal conductivity in semiconductor applications, to enhance efficiency in lighting, or as traceability tags in explosives.

2.3 Scientific applications

2.3.1 Biomedical research

The use of nucleic acids and labelled protein chromatographic detection through auto radiography is declining slightly owing to the development of alternative fluorescence technologies. The radioisotopes involved are ^{32}P (gradually being replaced by ^{33}P), ^{35}S (for nucleic acids), ^{125}I, ^{14}C and ^{3}H (for amino acids). Some ten companies are involved in this sector.

^{125}I is used in diagnostic kits for biological research.

^{14}C and ^{3}H are used for molecular biology and for toxicological examination in pharmaceutical industries and for transfer experiments in agro-chemical environmental research (pesticides).

Stable isotopes are extensively used in biomedical research, where demand is increasing. Table 3 provides selected examples of stable isotope use in biomedical research.

2.3.2 Materials research

Mössbauer spectroscopy employs ^{57}Co, ^{119m}Sn, ^{125m}Te and ^{151}Sm. Demand is low and stable, and there are only a few private suppliers along with governemental organisations involved. ^{22}Na is used as positron source for material science studies.

Table 3. Selected examples of stable isotope uses in biomedical research

Stable Isotopes	Uses
Boron-10	* Extrinsic food label to determine boron metabolism * Boron neutron capture therapy for cancer treatment
Calcium-42, 46, 48	* Calcium metabolism, bioavailability, and absorption parameters during bed rest, and space flight * Osteoporosis research and bone turnover studies * Role of nutritional calcium in pregnancy, growth and development, and lactation * Bone changes associated with diseases such as diabetes and cystic fibrosis
Carbon-13	* Fundamental reaction research in organic chemistry * Molecular structure studies * Fundamental metabolic pathway research, including inborn errors of metabolism * Extrinsic labelling of food for determination * Non-invasive breath tests for metabolic research and diagnosis * Biological substrate oxidation and turnover * Elucidation of metabolic pathways in inborn errors of metabolism * Amino acid kinetics * Fatty acid metabolism * Air pollution and global climatic changes effects on plant composition
Chlorine-35, 37	* Environmental pollutant toxicity studies
Chromium-53, 54	* Non-invasive studies of chromium metabolism and human requirements * Adult onset diabetes mechanism
Copper-63, 65	* Non-invasive studies of copper metabolism * Studies of congenital disorders and body kinetics in gastrointestinal diseases * Investigation of role in maintaining integrity of issue such as myocardium
Helium-3	* In vivo magnetic resonance studies
Hydrogen-2	* Vitamin research * Chemical reaction mechanisms
Iron-54, 57, 58	* Metabolism, energy expenditure studies * Conditions for effective iron absorption and excretion * Research to develop successful interventions for anaemia * Metabolic tracer studies to identify genetic iron control
Krypton-78, 80, 82, 84, 86	* Diagnosis of pulmonary disease

Table 3. Selected examples of stable isotope uses in biomedical research (cont.)

Stable Isotopes	Uses
Lead-204, 206, 207	* Isotope dilution to measure lead levels in blood
Lithium-6	* Sodium and renal physiology * Membrane transport * Psychiatric diseases
Magnesium-25, 26	* Non-invasive studies of human requirements, metabolism and absorption * Kinetic studies of heart disease and vascular problems
Molybdenum-94, 96, 97, 100	* Extrinsic labelling of food for determination of human nutrition requirements
Nickel-58, 60, 61, 64	* Non-invasive measurement of human consumption and absorption
Nitrogen-15	* Large-scale uptake studies in plants * Whole body protein turnover, synthesis, and catabolism * Amino acid pool size and turnover * Metabolism of tissue and individual proteins
Oxygen-17	* Studies in structural biology; Cataract research
Oxygen-18	* Non-invasive, accurate, and prolonged measurement of energy expenditures during everyday human activity * Lean body mass measurement * Obesity research * Comparative zoology studies of energy metabolism
Rubidium-85, 87	* Potassium metabolism trace * Mental illness research
Selenium-74, 76, 77, 78, 80, 82	* Bioavailability as an essential nutrient
Sulphur-33, 34	* Human genome research and molecular studies * Nucleotide sequencing studies
Vanadium-51	* Diabetes, bioavailability, and metabolism * Brain metabolism studies
Xenon-129	* Magnetic resonance imaging
Zinc-64, 67, 68, 70	* Non-invasive determination of human zinc requirements * Metabolic diseases, liver disease, and alcoholism * Nutritional requirements and utilisation studies

3. ISOTOPE PRODUCTION

The production of radioisotopes requires a series of steps leading to a product ready for end-uses (see Figure 1). Generally, the entire process is not carried out in a single plant but rather in several different facilities, as illustrated on Figure 1. This report focuses on the nuclear part of the process, i.e., production of the desired isotope per se. Therefore, the radioisotope production facilities described below include only reactors, accelerators and separation facilities used to produce radioisotopes. 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.

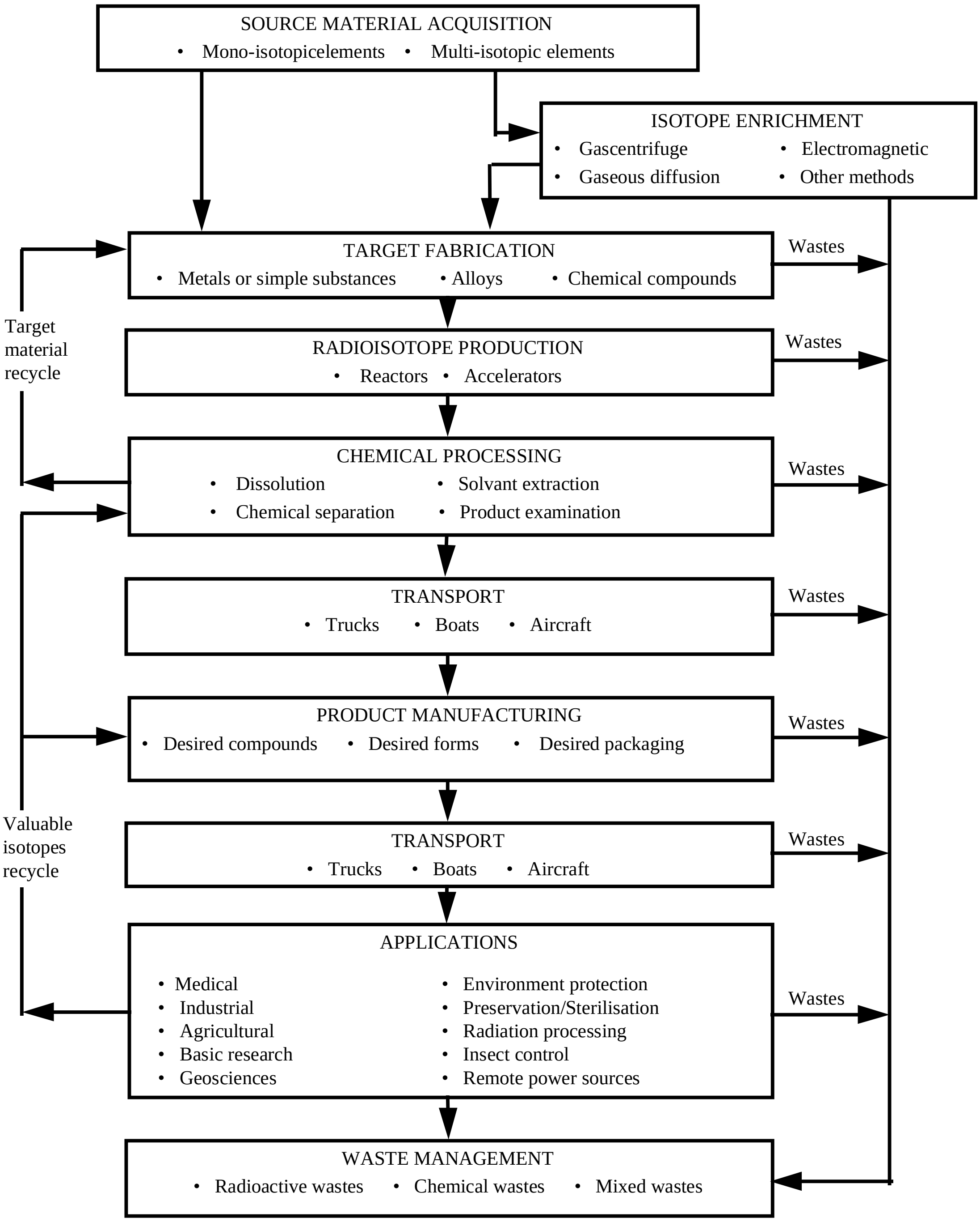
The most common radioisotope production facilities, i.e., reactors, accelerators and radioisotope separation facilities, are described in section 3.1, 3.2 and 3.3 respectively; stable isotope production is presented in section 3.4.

Table 4 summarises the main radioisotope production facilities included in the present survey and their geographic distribution. Annex 4 provides an overview of isotope production facilities in OECD Member countries.

Table 4. **Main isotope production facilities**

Type of facility	Number of units	
Reactors		
Research reactors	75	
of which high flux reactors		*6*
Fast neutron reactors	2	
Nuclear Power Plants (for ^{60}Co)	< 10	
Accelerators	188	
cyclotrons dedicated to medical isotopes		*48*
cyclotrons dedicated to PET		*130*
non-dedicated accelerators		*10*
Separation facilities	21	
Heavy stable isotope production facilities	9	
Numbers of producing countries	50	
Western Europe		*17*
Eastern Europe & FSU		*8*
North America		*3*
Asia & Middle East		*12*
Rest of the World		*10*

Figure 1. **Flow of radioisotope production, manufacturing, applications and waste management**



3.1 Reactors

Reactors generally are used to produce neutron-rich nuclei by neutron irradiation. Most of the reactors used for producing isotopes are research reactors, however, some radioisotopes are produced in power reactors (nuclear power plants). A list of the main isotopes produced by reactors is included in Annex 3.

3.1.1 Research reactors

The research reactors considered in this study are those that produce a significant amount of isotopes, i.e., in most cases devoting at least 5 per cent of their capacity to radioisotope production. Generally, those reactors have a power level 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 300 research reactors in operation world-wide[1], around 75 produce radioisotopes. Table 5 gives the geographic distribution[2] of the research reactors included in the present survey by range of power level. A detailed geographical distribution by country of research reactors producing isotopes is given in Annex 6.

Table 5. **Geographical distribution of research reactors producing isotopes**

Region (country)	**Number of reactors**			
	< 5 MW	5 to 30 MW	> 30 MW	Total
Western Europe	5	6	4	15
Eastern Europe & FSU	1	13	5	19
of which Russia	*0*	*7*	*5*	*12*
North America	2	3	3	8
of which United States	*1*	*2*	*2*	*5*
Asia & Middle East	10	10	4	24
of which Japan	*1*	*2*	*1*	*4*
Rest of the World	4	5	0	9
Total	**22**	**37**	**16**	**75**

Table 5 and Figure 2 show that, at present, research reactors producing isotopes are rather evenly distributed between Asia, Eastern and Western Europe and North America, although, in the power range below 5 MW, Asia has the largest share. However, the relative importance of Asia is likely to increase as new reactors are being built at a steady rate in this region while, in Western Europe and North America, ageing reactors tend to be shut down and are not always replaced by new units.

High neutron flux reactors (i.e., with a thermal neutron flux over 5×10^{14} neutron per cm^2 per second) are needed to produce some radioisotopes with high specific activity including ^{60}Co, ^{252}Cf, ^{192}Ir and ^{188}W. Six high flux reactors, included in the total numbers indicated in Table 5, are in operation in Belgium, Russia and the United Stated as shown in Table 6.

1. Source: IAEA, RDS n.° 3, Nuclear Research Reactors in the World, December 1996 Edition, Vienna (1996).

2. The list of countries included in each region is given in Annex 5.

Figure 2. Geographical distribution of research reactors producing isotopes (number of units)

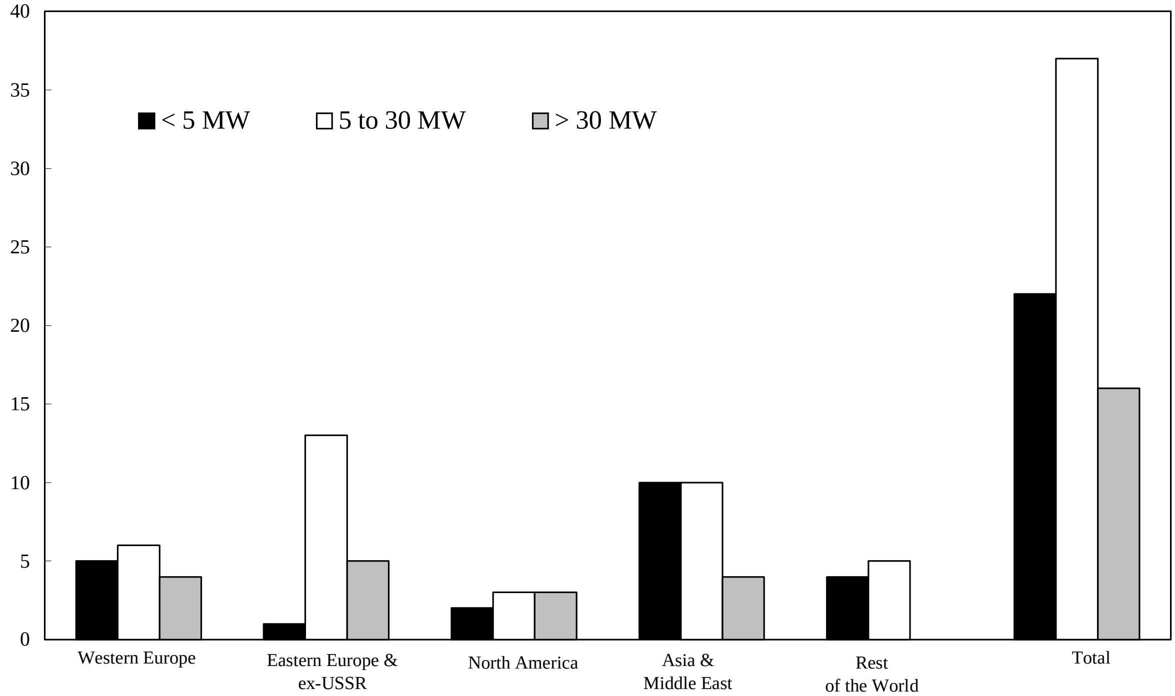


Table 6. **Geographical distribution of high flux reactors**

Region (country)	Number of units	Name (location)
Western Europe (Belgium)	1	BR2 (Mol)
Eastern Europe (Russia)	2	SM3 (Dimitrovgrad) MIR-M1 (Dimitrovgrad)
North America (United States)	2	ATR (Idaho Falls) HFIR (Oak Ridge)
Asia & Middle East (China)	1	HFETR (Chengdu)
Total	**6**	

In addition to the research reactors indicated above, there are two fast neutron reactors in operation in Russia that can produce ^{89}Sr.

All the isotope producing research reactors are owned and operated by public entities (state-owned) with the exception of one privately owned reactor in Sweden. In Canada, two reactors under construction, that will be dedicated to isotope production, are owned by a private company; they will be operated by a state-owned company.

3.1.2 Nuclear power plants

Nuclear power plants are used to produce radioisotopes in some countries, including Argentina, Canada, Hungary and Russia. The main, almost only, isotope produced in power plants is ^{60}Co. Besides, in Canada, tritium is produced from heavy water, used as coolant for heavy water reactors.

3.2 Accelerators

Generally, accelerators are used to obtain neutron deficient nuclei by proton bombardment and produce mainly positron emitting isotopes. Some accelerators, including high energy machines, are operated essentially for research purposes and produce isotopes only with excess beam or beam dumps. Other machines are dedicated to isotope production. Annex 7 provides details on the main isotopes producing accelerators, listed by category and by country of location.

3.2.1 Dedicated accelerators

Some accelerators (mostly cyclotrons) are constructed and operated exclusively for the production of radioisotopes mainly for medical applications. In particular, some cyclotrons are dedicated to the production of isotopes for PET cameras and operated in connection with PET centres.

3.2.1.1 Cyclotrons producing isotopes for medical applications

There are some 50 cyclotrons dedicated to the production of radioisotopes for medical applications. These machines are operated mainly in North America, Asia and Western Europe (see Table 7 and Figure 3). Some countries have chosen to build and operate such machines owing to the size of their domestic demand and/or their distant location from foreign supply sources concerning radioisotopes required in the medical sector. The main isotope produced by those cyclotrons is ^{201}Tl. Other products include ^{123}I, ^{67}Ga, ^{111}In, ^{57}Co and ^{103}Pd.

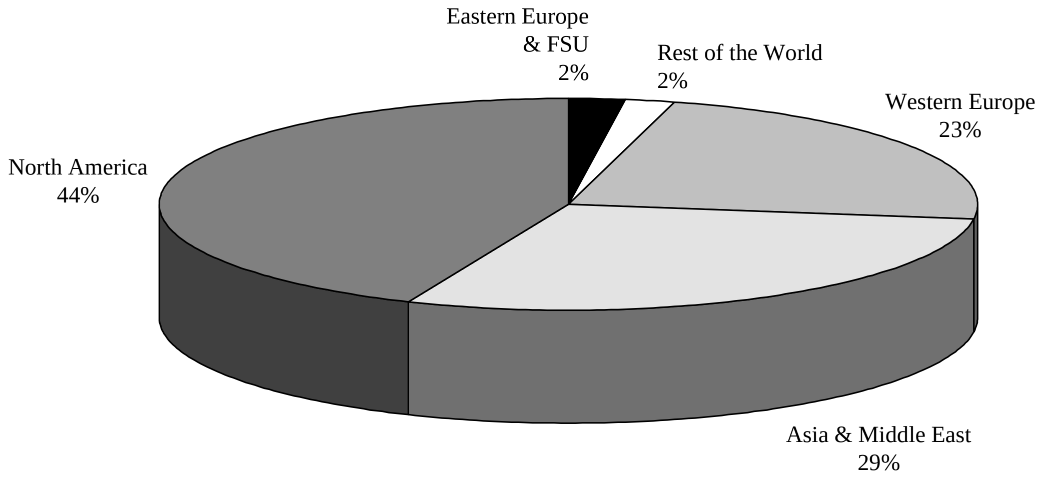
Practically, all the cyclotrons producing isotopes for medical applications are built by a single manufacturer. About 75 per cent of those machines are operated by private companies and five companies control half of the total. However, nine countries have public-owned machines.

The demand for classic cyclotrons is reaching a plateau. However, there are needs owed to the replacement of ageing machines; it is estimated that one to three classic cyclotrons are built every year. There is an increasing demand for cyclotrons dedicated to the production of ^{103}Pd.

Table 7. **Geographical distribution of cyclotrons dedicated to medical applications**

Region (country)	Number of machines		
	Total	**Private**	**Public**
Western Europe	11	10	1
Eastern Europe & FSU (Russia)	1	0	1
North America	21	21	0
of which United States	*19*	*19*	*0*
Asia & Middle East	14	6	8
of which Japan	*6*	*6*	*0*
Rest of the World	1	0	1
Total	**48**	**37**	**11**

Figure 3. **Geographical distribution of cyclotrons dedicated to medical applications**



3.2.1.2 Cyclotrons for positron emission tomography (PET)

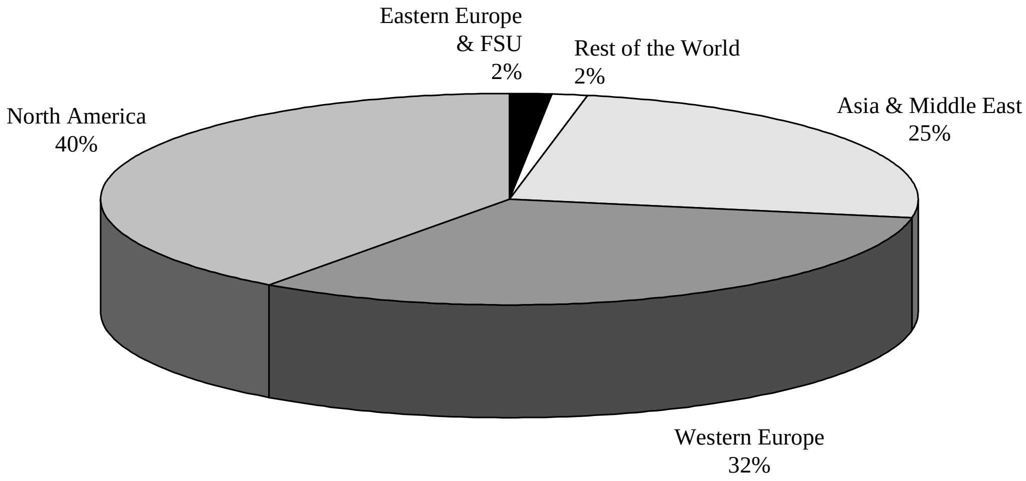
Cyclotrons producing isotopes for positron emission tomography are built and operated in connection with PET centres. The cyclotrons have to be close to PET facilities owing to the short half-lives of the isotopes used by PET cameras. The main radioisotopes produced by those cyclotrons are those needed to operate PET cameras, i.e., ^{11}C, ^{13}N, ^{15}O and ^{18}F.

There are some 130 machines of this type in operation in the world; their geographical distribution is shown on Table 8 and Figure 4.

Table 8. **Geographical distribution of PET cyclotrons**

Region (country)	Number of units
Western Europe	42
Eastern Europe & FSU (Russia)	2
North America	52
of which United States	*47*
Asia & Middle East	32
of which Japan	*25*
Rest of the World	2
Total	**130**

Figure 4. **Geographical distribution of PET cyclotrons**



Like the PET centres to which they are associated, cyclotrons producing isotopes for PET cameras are mostly owned and operated by public entities. However, technological, financial and institutional barriers to the implementation of these machines are somewhat minor and, therefore, the role of governments is not essential in this field. Some ten to fifteen cyclotrons for Positron Emission Tomography are built annually in the world. The demand for this type of machine is expected to increase significantly over the next few years.

3.2.2 Non-dedicated accelerators

3.2.2.1 High energy accelerators

There are four high energy accelerators, operating at energy levels ranging between 180 and 800 MeV, that are used mainly for ^{67}Cu, ^{64}Cu and ^{82}Sr production, because they offer the most effective means of producing those isotopes. Two of those machines are operated in the United States, one in Canada and one in Switzerland. A list of the main isotopes produced by high energy accelerators is included in Annex 3.

3.2.2.2 Medium energy accelerators

Although dedicated mainly to research activities, a number of cyclotrons rated between 25 and 130 MeV, produce isotopes (see list of main isotopes produced by those accelerators in Annex 3). The geographical distribution of those cyclotrons is given in Table 9. The cyclotron in operation in South Africa produces essentially isotopes for medical uses.

Table 9. **Geographical distribution of medium energy accelerators producing isotopes**

Region (Countries)	Number of units
Western Europe (Belgium, Finland, Germany, Italy, Netherlands, Norway)	6
Eastern Europe & FSU (Russia, Kazakhstan)	2
Asia (India)	2
Rest of the World (South Africa)	1
Total	**10**

3.3 Radioactive isotope separation

3.3.1 Separation of isotopes from fission products

The most important isotope produced by separation from fission products is by far ^{99}Mo serving for the manufacture of ^{99m}Tc generators which are used in about 80 per cent of some 30 million nuclear medicine procedures performed each year world-wide. Since today's technology requires high specific activity ^{99}Mo, its production can be achieved only by separation from fission products resulting from the irradiation of small ^{235}U targets in research reactors. There are five facilities in operation world-wide that produce ^{99}Mo from fission product on a large scale: one in Belgium; one in Canada; one in Indonesia, one in the Netherlands; and one in South Africa. Those facilities also produce other isotopes such as ^{133}Xe and ^{131}I. A new large facility for the production of ^{99}Mo is currently under testing in the United States; its commissioning is scheduled by the end of 1999.

There are also about a dozen small conversion plants including two in Russia, and one in Argentina, one in Australia and one in Norway, that produce isotopes extracted from fission products. In addition, seven facilities including hot cells produce ^{137}Cs and ^{85}Kr from nuclear power plant irradiated fuel. Five of those facilities are operated in Russia, one in India and one in the United States. Moreover, in the United States, the production of ^{90}Y (derived from ^{90}Sr contained in fission products) is gathering increasing attention.

Facilities for separation of isotopes from fission products are owned and operated essentially by public entities.

3.3.2 Separation of transuranium elements and alpha emitters

These plants produce a number of heavy radioisotopes 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 10.

Table 10. **Geographical distribution of plants producing transuranium elements and α emitters**

Region (countries)	Number of Facilities	Main Isotopes produced
Western Europe (Germany, United Kingdom)	2	^{244}Cm, ^{241}Am, ^{243}Am, ^{213}Bi, ^{225}Ac
Eastern Europe & FSU (Russia)	4	^{241}Am, ^{244}Cm, ^{235}U, ^{236}U, ^{252}Cf
North America (United States)	3	^{225}Ac, ^{241}Am, ^{243}Am, ^{249}Bk, ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{252}Cf
Total	**10**	

The demand for alpha emitting isotopes, in particular the ^{225}Ac/^{213}Bi and ^{212}Bi systems, is likely to increase as they may be used in a number of promising applications. Their production currently does not require the availability of existing research reactors, but is limited by the availability of starting source materials. In the case of the ^{225}Ac/^{213}Bi, it is the supply of the source material ^{229}Th, derived from ^{233}U or produced by the irradiation of ^{226}Ra, that is a limiting factor. For the ^{212}Bi system, the supply of the parent material ^{228}Th (derived from ^{232}U) determines the availability of the desired isotope. Limited quantities of source materials for those two systems are currently available and additional quantities will be necessary to ensure future security of supply.

3.4 Stable isotope production

3.4.1 Heavy stable isotopes

Two production technologies for heavy stable isotopes are in use: the highly versatile but old electromagnetic separation process, using dedicated mass spectrometers called calutrons, and the modern and more efficient process of gas centrifuges. The latter can only be used for elements that form suitable gaseous compounds. Both technologies are quite complicated and the entry barriers for potential new producers are very high.

The number of heavy stable isotope producers is very limited as shown in Table 11; these are public companies except for the enrichment plant in the Netherlands.

Table 11. **Geographic distribution of heavy isotope production facilities**

Country	Electromagnetic Separation	Gas Centrifuge	Total
United States	1		1
The Netherlands		1	1
Russia	2	5	7

The electromagnetic producers of stable isotopes rely on relatively old, expensive to operate, facilities with the associated risks related to reliability of supply. The centrifuge producers have the advantage of more modern, cheaper equipment. However this technology is less versatile and cannot produce a broad 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 risk regarding their ability to ensure adequate levels of production.

3.4.2 Light stable isotopes

A number of light isotopes (below Na in the periodic table) have a wide range of applications in medicine and research. Various 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 isotopes are easier to produce than heavy 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.

4. TRENDS IN ISOTOPE USES AND PRODUCTION

4.1 Trends in isotope uses

Demand for isotopes and its evolution vary from sector to sector. In the medical field, the use of isotopes is increasing on the whole. The development of new applications may create additional demand for isotopes currently used and for new isotopes. Nuclear imaging, especially positron emission tomography, and radiotherapy are the sectors were the highest demand growth is expected. The future demand for medical applications, however, will depend on government policies regarding social security, i.e., public support medical care expenses. In industry as a whole, isotope demand is relatively stable. The demand of isotopes for food preservation could increase dramatically if national regulations would authorise the distribution and consumption of irradiated food products in a larger number of countries. Demand for other industrial applications is likely to remain stable owing to regulation restrictions and competition with other techniques such as X-rays, ultra-sound, laser and radar. As regards scientific applications, demand is linked to research programmes. This sector is characterised by diversity and frequent changes in the type of isotopes required, as well as by the small volumes needed; the future demand is, therefore, difficult to predict. Still, the involvement of the public sector (governments) is very important. The demand for enriched stable isotopes for biomedical, industrial and scientific uses is growing and could increase further for already existing and new emerging or "dormant" applications.

4.2 Trends in isotope production

Trends in isotope production vary according to the type of production facility and the region. In particular, trends are different for facilities dedicated to isotope production, such as cyclotrons producing isotopes for medical applications, and for facilities, such as some research reactors, that produce isotopes only as a side activity. As far as research reactors are concerned, since generally they are operated for scientific purposes and isotopes are only "by-products", the trends mainly result from policies on nuclear research. Also trends depend on the degree of governmental involvement in the construction and operation of various isotope production facilities.

Production of some radioisotopes require specific facilities that are operated in a limited number of countries and their production trend depends mainly on policies in those countries, upon which the world's supply relies. It is the case of ^{252}Cf and high specific-activity ^{60}Co for medical applications, produced only in high neutron flux reactors. ^{67}Cu and ^{64}Cu can also be obtained in some cyclotrons or linear accelerators. The two countries at stake are the United States and Russia but other countries, such as Canada, China and Switzerland, might become suppliers. The tritium production programme of the United States ensures short-term security of supply with regards to isotopes produced by linear accelerators if the accelerator route is chosen as the preferred option. Also, tritium can be obtained in bulk from a Canadian facility processing heavy water used as coolant for Candu reactors. However, the production of high specific activity ^{60}Co for medical applications might become a problem as the three production facilities in operation in Western Europe and North America are expected to be shut down shortly (within the next three years).

As regards to neutron rich isotopes produced in reactors, trends and issues are regional. Some regions, such as Africa, rely generally on dedicated production facilities. In Asia, where demand is growing, new reactors are being built and commissioned. However, those reactors are multi-purpose machines and cannot be expected to produce large quantities of isotopes on a regular basis. Therefore, they are likely to provide supply only in the country where they are operated or at most in the region. In North America, on one hand, while old reactors are being shut down, new production units are being built for ^{99}Mo production, and one old reactor is being refurbished. Those units will ensure adequate supply in the future. In Western Europe, on the other hand, three reactors (Astra, in Austria, Osiris, in France and FRM in Germany) will be shut down in the next decade and it is not clear whether they will be replaced. Generally, in OECD countries, new research reactors are designed mainly for scientific research and/or for technical research on components and fuel for future nuclear power plants. Therefore, they are not adapted very well to isotope production. The trend in Eastern Europe and the Former Soviet Union is difficult to assess. In Russia, a third of the reactors producing isotopes at present is likely to be shut down by 2005 and it is not clear whether new investments will be made for isotope production in the region.

The size of domestic demand is a key factor for investors in production facilities concerning isotopes for medical applications produced by cyclotrons. The demand, in turn, depends on the health care system in place in each country (social security coverage). In many industrialised countries, where nuclear imaging is reimbursed by health insurance, the demand is growing steadily and production increases accordingly as cyclotrons can be operated on a commercial basis by private enterprises. In other countries, the construction of cyclotrons may depend essentially on the implementation of health care programmes covering medical procedures relying on the use of radiopharmaceuticals. In the field of PET, production trends are in line with demand growth itself depending mainly on governmental policies regarding research in the medical field and social security. Further developments would be necessary in order to go beyond the present research and prototype level and bring PET cameras to the level of commonly used medical practices.

The production of some isotopes, such as ^{137}Cs and ^{90}Sr, that are obtained by separation from fission products, raise important concerns regarding access to source materials, i.e., dedicated separation processes of high level waste at spent fuel reprocessing plants.

5. FINDING, CONCLUSIONS AND RECOMMENDATIONS

5.1 Findings

The present study has shed light on a number of issues in the field of isotope uses and production. In particular, the inquiries and literature survey carried out to prepare this report have revealed the lack of comprehensive, harmonised and reliable information covering all the aspects of beneficial uses of isotopes. Furthermore, the study highlighted the important role played by governments, national policies and international co-operation, in the field. In this context, it was found that international governmental organisations could assist both in ensuring adequate information exchange and strengthening international co-operation. It is necessary to transport regularly irradiated targets and separated isotope products world-wide. Regulations and controls applicable to the transportation of radioactive materials may differ from country to country.

5.1.1 Isotope uses

There are a large number of isotope applications in various sectors of economic activities. This survey has shown a steady and continuous use of isotopes, indicating that they remain among the best technologies available and an economically attractive option in many cases. Although there is a great deal of literature on the use of isotopes in different sectors, no comprehensive survey of isotope demand covering all uses exists, with the exception of Japan. It is, therefore, difficult to have a robust assessment of the overall economic importance of beneficial uses of isotopes.

Uses of isotopes evolve continuously. Some applications are declining due to the replacement of isotopes by other technologies that prove to be more efficient and/or cheaper. However, new applications are emerging as science and technology progress. Trends vary from sector to sector and should be assessed on a case by case basis.

5.1.2 Isotope production

Information on research reactor activities is available particularly through IAEA databases and publications. However, it is difficult to assess actual isotope production, since isotopes are by-products of reactor activities. Moreover, the isotope producer is often independent of the reactor operator, and may receive services, (i.e., target irradiation for isotope production), from different reactors. Therefore, while collecting information on research reactors producing isotopes proved to be reasonably easy, assessing the actual isotope production level of those reactors has been less straightforward.

Likewise, high energy accelerators are used mainly for research purposes and information on their isotope production, being a secondary activity, is generally not easily available. Still, low and medium energy accelerators, mostly cyclotrons, are dedicated exclusively to isotope production. Nevertheless, since they are operated essentially on commercial bases, commercial confidentiality makes it hard to get data.

Data are published by some countries on national isotope production annually. These publications may serve as a basic framework for collecting similar data world-wide through an international inquiry and by compiling the results.

5.1.3 Role of governments

The information analysed in the study highlights the important role of the public sector in isotope production and, although to a lesser extent, in isotope uses. Also, in all countries, governments are responsible for establishing regulations and norms regarding production, transport and uses of isotopes.

Public entities own and operate almost all the research reactors, large-scale accelerators and chemical separation facilities for isotope production as well as 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. They provide opportunities for education and training of qualified manpower required for these activities.

Concerning the production of major isotopes used in medical applications, a number of medium-size cyclotrons are owned and operated by private companies for their exclusive uses. The role of governments in such cases is to ensure that activities are carried out in compliance with safety regulations.

5.1.4 Role of international exchanges

Nearly all countries depend on imports at least for some isotopes that are not domestically produced, though half lives of some isotopes limit their distribution globally. Many isotope producers rely on target irradiation services provided by reactors operated in foreign countries. Some isotopes are supplied only by a few producers serving a large number of foreign users. Therefore, international exchanges are essential to ensure adequate supply, together with the availability of comprehensive information on existing and projected production capabilities.

At present, most of the isotope production facilities are operated in OECD countries and they also are the main users. Demand is increasing in non-OECD countries and their production capabilities might not increase as fast as their demand.

5.1.5 Costs and prices

Facilities dedicated to isotope production, such as cyclotrons producing isotopes for medical applications, are managed on a commercial basis and prices in that case reflect full cost recovery. For research reactors and high energy accelerators that are not dedicated to isotope production, only the marginal additional cost associated to isotope production per se is generally accounted for in prices of isotopes from these sources. In this case, the overall cost of the facilities, including investment, safety, maintenance, fuel, waste management and decommissioning are borne by the main users, i.e., research programmes.

Since economic conditions differ according to region, costs and prices for isotopes produced with the same technology may vary depending on the country where they are produced. This has led users to seek supply preferably from some regions where prices tend to be low. Recently, supply of isotopes as raw materials has shifted progressively from North America and Western Europe to Eastern Europe and China, because of the lower costs/prices prevailing in those regions.

5.2 Conclusions

The present report offers a general survey on isotope uses and production in the world. It is the first international compilation and data analysis on the subject. However, it should be pointed out that the information collected is not fully comprehensive and that the rapid evolution in the sector calls for regular update. The lack of detailed up-to-date information on isotope production and uses may lead to gaps in supply for a given application and to over capacity of production for some isotopes.

It might be difficult to collect reliable data on isotope demand covering all sectors and countries concerned. However, the regulatory framework in place in each country for licensing isotope uses may offer the opportunity to access information. On the supply side, existing databases on research reactors and accelerators in operation provide a significant share of the information required. However, additional data and evaluations are needed to provide a full overview of isotope production capabilities.

For some isotopes, particularly those with short lives or with special types of specifications, the supply demand balance is a regional issue. Production capabilities of very short life isotopes must match demand at regional level. It is the case of PET isotopes that have to be produced on the end-user's site. For other isotopes, that may be transported over long distances and require highly specialised machines and/or facilities for their production, world supply may be ensured by a limited number of facilities located in a few countries. International co-operation and exchanges are important for adequate security of supply. In all countries, domestic supply relies at least partly on imports. In particular, supply demand balance at national level requires exchange between OECD and non-OECD countries.

Owing to the development of new applications on the one side and to the progressive phase out of some uses on the other, radioactive isotope demand is evolving. On the production side, adaptation to demand requires rather long lead-times. Most production facilities require several years to be built and commissioned (e.g., around three years for dedicated cyclotrons and eight years for research reactors). Monitoring projected demand and planned production capacities at world level is essential to alleviate the risk of inadequate supply in the future. The demand for stable isotopes is increasing as they are essential for some applications. The production of economically attractive stable isotopes in large quantities is likely to be ensured as long as industrial enrichment plants using gaseous centrifuge technology will continue to operate. However, the continued production of stable isotopes that cannot be produced by gas centrifuge and of those used for scientific (R & D) applications may raise concerns.

The study has shown that beneficial uses of isotopes are important for economic and social welfare world-wide. Its findings and conclusions highlight the role of governments in the field and the need for enhanced information exchange and international co-operation to ensure adequate supply of all the isotopes needed in various sectors. International organisations, such as the NEA and the IAEA, could assist in enhancing international information exchange and co-operation.

5.3 Recommendations

Recognising both the importance of isotopes for medical, industrial and scientific applications and the present and potential future roles that they could play in enhancing welfare world-wide, it is recommended that governments consider maintaining or implementing policies favouring adequate supply of isotopes taking into account present and foreseeable future demands. Intergovernmental organisations, such as the NEA and the IAEA, could assist in this process by collecting and compiling in a database relevant information on demand and supply of isotopes and by providing analyses, including projections, on supply and demand issues.

In the light of the expected changes in isotope uses and geographic distribution of production capabilities, it would be useful to analyse regional trends in order to assess whether adequate supply could be ensured in the short, medium and long term. In particular, the analysis could identify specific actions and measures that governments might consider to facilitate international exchange of isotopes between OECD and non-OECD countries and to optimise production capabilities globally.

Establishment, regular update, and dissemination of databases on isotope uses and production would be a relevant means to make the information widely available. Therefore, it is recommended to undertake a systematic collection of isotope production data country by country through an annual questionnaire. The questionnaire, designed by experts in the field, would be circulated among producers by international organisations such as the NEA and the IAEA. The results would be made available in an annual publication and/or in an electronic database accessible on the Internet. To undertake a regular review of isotope uses could also be considered starting from a survey of existing files established by regulatory bodies in charge of licensing isotope uses, focusing first on some countries selected in view of their importance in the field. As for production data, the survey may be undertaken under the auspices of international organisations such as the NEA and the IAEA with the assistance of national experts in the field, and the results would be made available in paper or electronic publications with periodical update.

It is recommended that governments consider adequate policy measures to guarantee continued supply of isotopes, essential in medical and industrial applications such as molybdenum-99 and iridium-192. Although the production of those isotopes is generally ensured by the private sector and large government owned authorities, the consequences of supply shortages would have drastic consequences that call for governments' attention.

To obtain some isotopes especially useful in medical care, high neutron flux reactors and/or special facilities are required. There are several reactors either in operation or planned. It is recommended both to maintain in operation the existing reactors and facilities that can be used for this purpose and to make plans for their replacement at the end of their lifetime.

Small quantities of diverse isotopes are necessary in basic medical, physical and life science research, crucial for progress. It is important to make sure that adequate supply of such isotopes continues to be ensured at the regional level, to enable an efficient health care service.

The demand for stable isotopes is increasing, as they are essential for some applications. Although the production of most stable isotopes is likely to be ensured as long as industrial enrichment plants using gaseous centrifuge technology will continue to operate, it is recommended that countries, in particular OECD countries, pursue the development of new technologies and plants to separate stable isotopes that cannot be obtained from centrifuge technology.

Given the importance of international exchanges in ensuring adequate isotope supply world-wide, it is recommended that governments endeavour to harmonise regulations and norms for isotope production, transport and uses, in order to facilitate these exchanges.

Government policies in the field of isotope production and uses are likely to be re-assessed in the context of economic deregulation and privatisation of industrial sectors traditionally under state control. It might be relevant to investigate whether changes in policies might affect the availability and competitiveness of isotopes and, thereby, the continued development of some isotope uses. In some areas and sectors where there is a regular and rather large demand to hold dedicated facilities – such as the supply of medical isotopes – market mechanisms are already fully in force and have proven to be effective. In many other cases, however, isotope production facilities are partly supported by governments in the framework of global scientific and social development policies. This has been crucial in promoting the unique isotope technology and making it available for the advancement of human society. While it would be fair to consider pricing policies reflecting marginal costs of isotope production, full cost recovery applied to facilities producing isotopes as a by-product might jeopardise the development of a number of beneficial uses of isotopes in particular for science and medicine.

Annex 1

BIBLIOGRAPHY

1. US Department of Energy (1994), *National Isotope Strategy,* Prepared by the Isotope Production Program, Washington DC, USA.

2. Management Information Services, Inc. (1994), *Economic and employment benefits of the use of radioactive materials,* Washington DC, USA.

3. *Nuclear Engineering International* (1997), vol. 2, n.° 515, n.° 516, n.° 517.

4. Nuclear Engineering International (1995), *World Nuclear Industry Handbook*.

5. *Nuclear News Buyers Guide* (1998), American Nuclear Society, vol. 41.

6. *Nuclear Physics News International* (1996) – NuPECC, vol. 5, n.° 4, vol. 6, n.° 1 and 4, vol. 7, n.° 1.

7. *Applied Radiation and Isotopes* (1996), vol. 46, n.° 1.

8. Institute of Medicine (1995), *Isotopes for Medicine and the Life Sciences*, National Academy Press, Washington DC, USA.

9. Umezawa, H. (1997), *Radioisotope Production and Quality Control, Nuclear Technology*, Japan.

10. Umezawa, H. (1997), *The Use of Radioisotopes and Radiation: Today and Future*, Annals of Nuclear Medicine and Sciences, vol. 10, n.° 2, Chinese Taipei.

11. International Atomic Energy Agency (1998), *Directory of cyclotrons used for radionuclide production in Member States*, IAEA-TECDOC-1007, Vienna, Austria.

12. Taylor, G.M. (1998), *Henkin: An overview of nuclear medicine in the United States,* Nuclear News, vol. 41, n.° 2, pp. 30-34.

13. Lennox, A. J. (1998), *Medical applications of accelerators,* Nuclear News, vol. 41, n.° 2, pp. 38-41.

14. Hladik III, W. B. (1998), *New radiopharmaceuticals used in medicine*, Nuclear News, vol. 41, n.° 2, p. 44.

15. Ripon, S. (1998), *Neutron therapy at Germany's oldest and newest reactors*, Nuclear News, vol. 41, n. ° 2, pp. 50-52.

16. Sauerwein, W., et al. (1998), *European clinical trials of boron neutron capture therapy for glioblastoma*, Nuclear News, vol. 41, n. ° 2, pp. 54-56.

17. Garnett, H. (1998), *Radiopharmaceutical usage – Asia/Pacific trends*, Proceedings of PNBC'98, Banff, Canada.

18. Malkoske, G. (1998), *MDS-Nordion – A Canadian radioisotope success story, science advancing health*, Proceedings of PNBC'98, Banff, Canada.

19. Banditsing, C. (1998), *Irradiation of food and industrial products*, Proceedings of PNBC'98, Banff, Canada.

Annex 2

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Annex 3

MAJOR RADIOISOTOPES PRODUCED IN REACTORS AND ACCELERATORS

Reactor produced radioisotopes	Accelerator produced radioisotopes	High energy accelerator produced radioisotopes
Molybdenum-99	Thallium-201	Strontium-82
Cobalt-60	Iodine-123	Magnesium-28
Iridium-192	Gallium-67	Copper-67
Phosphorus-32	Indium-111	Aluminum-26
Phosphorus-33	Rubidium-81	Silicon-32
Xenon-133	Sodium-22	Gadolinium-148
Iodine-131	Cobalt-57	Hafnium-172
Iodine-125	Palladium-103	Lead-200
Strontium-89	Fluorine-18	
Carbon-14	Carbon-11	
Californium-252	Nitrogen-13	
Sulphur-35	Oxygen-15	
Gold-198		
Chromium-51		
Rhenium-186		
Thallium-204		
Samarium-153		
Gadolinium-159		
Iron-59		
Copper-64		
Hydrogen-3		

Annex 4

ISOTOPE PRODUCTION IN OECD COUNTRIES

Country	Research reactor	Cyclotrons for medical applications	Cyclotrons for PET	Others
NORTH AMERICA	**8**	**21**	**52**	
Canada	2	2	5	+ 1 cyclotron
Mexico	1	0	0	–
United States	5	19	47	transuranium + 2 linear accelerators
PACIFIC	**6**	**8**	**28**	
Australia	1	1	1	–
Japan	4	6	25	–
Korea (Republic of)	1	1	2	–
EUROPE	**15**	**11**	**42**	
Austria	1	0	0	–
Belgium	1	2	5	+ 1 cyclotron
Czech Republic	1	1	0	–
Denmark	1	0	2	–
Finland	0	0	1	+ 2 cyclotrons
France	1	2	3	–
Germany	1	1	12	transuranium
Greece	1	0	0	–
Hungary	1	0	0	–
Italy	1	0	0	+ 1 cyclotron
Netherlands	2	3	2	+ 1 cyclotron
Norway	1	0	0	+ 1 cyclotron
Portugal	1			–
Spain	0	0	2	–
Sweden	1	0	2	–
Switzerland	0	0	2	+ 1 cyclotron
Turkey	1	0	0	–
United Kingdom	0	2	6	transuranium

Annex 5

COUNTRIES AND REGIONAL GROUPINGS

WESTERN EUROPE		
Austria	France	Portugal
Belgium	Greece	Spain
Czech Republic	Hungary	Sweden
Denmark	Italy	Switzerland
Germany	Netherlands	Turkey
Finland	Norway	United Kingdom

EASTERN EUROPE AND FORMER SOVIET UNION		
Bulgaria	Romania	Ukraine
Kazakhstan	Russia	Uzbekistan
Latvia	Slovenia	Yugoslavia
Poland		

NORTH AMERICA		
Canada	Mexico	United States

ASIA AND THE MIDDLE EAST		
Bangladesh	Indonesia	Malaysia
China	Iran	Pakistan
Chinese Taipei	Israel	Saudi Arabia
Democratic Rep. of Korea	Japan	Vietnam
India	Korea (Republic of)	

REST OF THE WORLD		
Algeria	Brazil	South Africa
Argentina	Chile	Zaire
Australia		

Annex 6

GEOGRAPHICAL DISTRIBUTION OF RESEARCH REACTORS PRODUCING ISOTOPES

Western Europe

Country	Reactor name	Location	Power (MW)	Main producers
Austria	ASTRA	Seibersdorf	10	
Belgium	BR 2	Mol	100	**X**
Czech Republic	LWR-15 REZ	Rez	10	
Denmark	DR-3	Roskilde	10	
France	OSIRIS	Saclay	70	**X**
Germany	FRM	Garching	4	
Greece	DEMOKRITOS (GRR-1)	Attiki	5	
Hungary	BRR	Budapest	10	**X**
Italy	TRIGA RC-1	Santa Maria di Galeria	1	
Netherlands	HOR	Delft	2	
	HFR	Petten	45	**X**
Norway	JEEP II	Kjeller	2	
Portugal	RPI	Sacavem	1	
Sweden	R-2	Nyköping	50	**X**
Turkey	TR-2 TURKISH REACTOR 2	Istanbul	5	

Eastern Europe & Former Soviet Union

Country	Reactor name	Location	Power (MW)	Main producers
Bulgaria	IRT	Sofia	2	
Latvia	IRT	Riga	5	
Poland	MARIA	Swierk	30	**X**
Romania	TRIGA II	Pitesti	14	
Russia	SM-3	Dimitrovgrad	100	**X**
	MIR/M1	Dimitrovgrad	100	**X**
	RBT-6	Dimitrovgrad	6	
	RBT-10	Dimitrovgrad	10	
	BOR-60	Dimitrovgrad	60	
	WWR-TS	Obninsk	12	
	AM-2	Obninsk	10	
	BR-10	Obninsk	10	
	WWR-M	Gatchina	18	
	IR-8	Moscou	8	**X**
		Mayak	> 30	**X**
		Mayak	> 30	**X**
Ukraine	WWR-M	Kiev	10	
Uzbekistan	WWR-CM	Tashkent	10	
Yugoslavia	RA	Belgrade	6.5	

North America

Country	Reactor name	Location	Power (MW)	Main producers
Canada	NRU	Chalk River	135	**X**
	MNR McMaster University	Hamilton	5	**X**
Mexico	TRIGA MARK III	Salazar	1	
United States	ATR	Idaho Falls ID	250	**X**
	HFBR	Upton NY	30	**X**
	HFIR	Oak Ridge TN	100	**X**
	ACRR	Albuquerque NM	2	**X**
	MURR Univ. of Missouri RR	Columbia MO	10	**X**

Asia & Middle East

Country	Reactor name	Location	Power (MW)	Main producers
China	HWRR-II	Beijing	15	**X**
Bangladesh	TRIGA MARK II	Dhaka	3	
	HFETR	Chengdu	125	**X**
	SPR IAE	Beijing	3.5	
	SPRR-300	Chengdu	3.7	
	MJTR	Chengdu	5	
Chinese Taipei	THOR	Hsinchu	1	
DPRK	IRT- DPRK	Pyongyang	5	
India	APSARA	Trombay	1	
	CIRUS	Trombay	40	
	DRHUVA	Trombay	100	
Indonesia	TRIGA II	Bandung	1	
	GA SIWABESSY MPR	Serpong	30	**X**
Iran	TRR	Teheran	5	
Israel	IRR-1	Yavne	5	
Japan	KUR	Osaka	5	
	JRR-3M	Ibaraki-ken	20	**X**
	JRR-4	Ibaraki-ken	3.5	**X**
	JMTR	Ibaraki-Ken	50	**X**
Korea (Rep. of)	HANARO	Taejeon	30	**X**
Malaysia	TRIGA PUSPATI (RTP)	Kajang	1	
Pakistan	PARR-1	Islamabad	9	
Philippines	PRR-1	Diliman	3	
Thailand	TRR-1/M1	Bangkok	2	

Rest of the World

Country	Reactor name	Location	Power (MW)	Main producers
Algeria	ES-SALAM	W. Djelfa	15	
Argentina	RA-3	Buenos Aires	2.8	**X**
Australia	HIFAR	Menai	10	**X**
Brazil	IEA-R1	Sao Paulo	2	
Chile	RECH-1	Santiago	5	
Egypt	ETRR-1	Cairo	2	
Peru	RP-10	Lima	10	
South Africa	SAFARI-1	Pelindaba	20	**X**
Zaire	TRICO II	Kinshasa	1	

Annex 7

GEOGRAPHICAL DISTRIBUTION OF ACCELERATORS PRODUCING ISOTOPES

CYCLOTRONS DEDICATED TO MEDICAL APPLICATIONS

Western Europe (Total 11)

Country	Operator	Type	Number of units
Belgium	Nordion Nordion	CGR 930 S CYCLONE 30	2
Czech Republic	NRI	U-120	1
France	CIS BIO	CGR 40 MeV CYCLONE 30	2
Germany	FZK	TCC-CP-42	1
Netherlands	Vrije Amsterdam University Mallinckrodt Mallinckrodt	PHILIPS PHILIPS CYCLONE 30	3
United Kingdom	Amersham Amersham	TCC-CP-42 MC-40	2

Eastern Europe & Former Soviet Union (Total 1)

Country	Operator	Type	Number of units
Russia	Radium Institute	MGC-20	1

North America (Total 21)

Country	Operator	Type	Number of units
Canada	Nordion Nordion	TCC-CP-42 TR-30	2
United States	Amersham Amersham Amersham Amersham Dupont Dupont Dupont Dupont Mallinckrodt Mallinckrodt Mallinckrodt Theragenics	CGR 70 MC-40 (2 units) TCC-CS-22 CYCLONE 30 TCC-CS-22 TCC-CS-30 (3 units) MC-35 CYCLONE 30 MC-40 Cyclone 30 ? (2 units) CYCLONE 18 (4 units)	19

Asia & Middle-East (Total 14)

Country	Operator	Type	Number of units
China	IAE INR IMP	CYCLONE 30 CYCLONE 30 69 MeV	3
Chinese Taipei	INER	TR 30/15	1
Indonesia	Batan	TCC-CS-30	1
Iran	NRC	CYCLONE 30	1
Japan	Daiichi Daiichi Nihon Medi-Physics Nihon Medi-Physics	CYCLONE 30 MC-40 CYCLONE 30 (2 units) TCC-CS-30 (2 units)	6
Korea (Republic of)	IRI/KAERI	MC-50	1
Saudi Arabia	King Faisaal	TCC-CS-30	1

Rest of the World (Total 1)

Country	Operator	Type	Number of units
Australia	NMC/ANSTO	CYCLONE 30	1

CYLOTRONS DEDICATED TO PET

Western Europe (Total 42)

Country	Operator	Type	Number of units
Belgium	Liege University (Ulg)	CGR-520	5
	VUB	CGR-520	
	Erasmus (ULB)	CYCLONE 30	
	Gasthuisberg (KUL)	CYCLONE 10/5	
	UCL	CYCLONE 30	
Denmark	RIGS Hospital	MC-32N	2
	Aarhus Hospital	PETRACE	
Finland	Turku University	CYCLONE 3	1
France	SHFJ	CGR-30	3
	CERMEP	CYPRIS 325	
	CYCERON	CYPRIS 325	
Germany	FZJ	PETTRACE	12
		JSW BC 1710	
	UKRV	CYCLONE 3	
	Bonn University	RDS-112	
	Tübingen	PETTRACE	
	Ulm	CYCLONE 18/9	
	Humbolt	RDS-112	
	Tech. University Munich	RDS-112	
	Heidelberg	PC 2048	
	Cologne	MC-17	
	Bad Oyenhausen	CYCLONE 18/9	
	Hannover	MC-17	
Italy	Istituto S. Raffaele Milano	RDS-112	5
	Ospedale Castelfranco	RDS-112	
	Veneto	MC-17F	
	Istituto Naz. Tumori Milano	PETTRACE	
	CNR-ICP Pisa	MC-17	
	Istituto Naz. Tumori Napoli		
Netherlands	Univ. Hospital Groningen	MC-17	2
	Vrije Amsterdam Univ.	CYCLONE 18/9	
Spain	Clinic Univ. Navarre	CYCLONE 18/9	2
	Madrid	ISOTRACE	
Sweden	Karolinska Institute.	MC-17	2
	UN. PET CENTRE	MC-17	
Switzerland	HCU Geneva	CYCLONE 18/9	2
	USZ Zurich	PETTRACE	
United Kingdom	Hammersmith	CYCLONE 30	6
	Hammersmith	MC-40	
	St. Thomas Hospital	RDS-112	
	London Inst. of Neurology	CYCLONE 3	
	Cambridge University	PETTRACE	
	Aberdeen University	TCC-CS-30	

Eastern Europe & Former Soviet Union (Total 2)

Country	Operator	Type	Number of units
Russia	Inst. Human Brain Bakulev Institute	MC-17 DRS-111	2

North America (Total 52)

Country	Operator	Type	Number of units
Canada	McMaster Clark Institute McGill University McGill University Heart Institue	RDS-112 MC-17 JSW BC 107 CYCLONE 18/9 RDS-111	5
United States			47

Asia & Middle East (Total 32)

Country	Operator	Type	Number of units
China	Boshnan Zibo Xuan Wu Hospital INR	PETTRACE RDS-111 8 MeV	3
Chinese Taipei	VET's General Hopital	MC-17	1
Israel	Hadassah University	CYCLONE 18/9	1
Japan			25
Korea (Republic of)	Samsung Medical Centre Seoul National University	PETTRACE PETTRACE	2

Rest of the World (Total 2)

Country	Operator	Type	Number of units
Argentina	CNEA	RDS-112	1
Australia	Austin Hospital	CYCLONE 10/5	1

Western Europe (Total 8)

Country	Operator	Type	Number of units
Belgium	UCL Gent University (RUG)	CYCLONE CGR-520	2
Finland	Jyvaskyla University ABO. AKAD	K-130 MGC-20	2
Hungary	ATOMKI	MGC-20E	1
Italy	JRC-AMI	MC-40	1
Norway	Oslo University	MC-35	1
Switzerland	PSI	SIN	1

Eastern Europe & Former Soviet Union (Total 2)

Country	Operator	Type	Number of units
Russia	CYCLOTRON	U-150-1	1
Kazakhstan	INP	KVEIC	1

North America (Total 3)

Country	Operator	Type	Number of units
Canada	TRIUMF	TRIUMF	1
United States	LANL/DOE BNL/DOE	LAMPF BLIP	2

Asia & Middle East (Total 1)

Country	Operator	Type	Number of units
India	VECC	SSC	1

Rest of the World (Total 1)

Country	Operator	Type	Number of units
South Africa	NAC-FRD	SSC	1

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