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PRACTICAL ASPECTS OF OPERATING A NEUTRON ACTIVATION ANALYSIS LABORATORY

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FOREWORD

This book is intended to advise in everyday practical problems related to operating a neutron activation analysis (NAA) laboratory. It gives answers to questions like "what to use NAA for", "how to find relevant research problems", "how to find users for the technique", "how to estimate the cost of the analysis and how to finance the work", "how to organize the work in a rational way" and "how to perform the quality control". It gives advice in choosing staff, equipment, and consumables and how to design facilities and procedures according to need and available resources.

The book is designed to discuss problems not dealt with in ordinary NAA textbooks, but also, in order to prevent it from being too voluminous, to avoid duplication of material described in normal NAA text books. Therefore, the reader will find that some material of interest is missing from this book and it is recommended that one or two of the textbooks listed in chapter 11 be read in addition to this one.

The authors represent a wide range of experience with biological, environmental, geological, and industrial samples, in contexts from basic research to commercial analytical service. Their backgrounds also range from university to governmental research institute and private enterprise. Their summed experience exceeds the time since Hevesy and Levy's first publication on activation analysis; nevertheless, other workers in the field may not agree with all the statements made herein. It is their hope that this publication will be of value, both in respect to practical aspects of running a modern NAA laboratory, and in recommending relevant applications in a time with abundant analytical techniques and a requirement for a well-founded cost/benefit ratio for all activities.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

Nuclear research reactors are commonly purchased by governments or universities to form the basis for multidisciplinary research institutes. In many countries there is only one research reactor and it is intended to support the scientific and technical development of the whole country. A research reactor is a major investment and it is also expensive to run. Therefore it is important to use it efficiently.

Analytical chemistry is an essential part of science and technology. In most cases an analytical chemistry laboratory is established and used in the institutes which use the results. Neutron activation analysis (NAA) is an exception to this. The expensive research reactor necessary to conduct NAA cannot be purchased by every analytical laboratory. Therefore NAA is commonly only performed at reactor laboratories although some laboratories without reactors simply buy the irradiations. When short-lived nuclides are used close access to the reactor is obligatory.

Although very sensitive and accurate non nuclear analytical techniques exist, NAA has several advantages which support its use as a complement to other techniques, as has been clearly shown on several occasions [1]. Therefore it is the duty of the institute running the reactor to make NAA available to users in the whole country. This is, however, not successful in all countries or reactor laboratories. Several NAA laboratories are run in a way that is far from optimum as regards the needs of the country. One or several of the following reasons can be identified.

- The NAA group has no motivation to make the technique available to outside users. The work is academically oriented. The group develops analytical methods to be published in scientific journals and only runs its own research projects.

- Co-operation with scientific institutions and industrial enterprises is limited. The NAA group is not aware of the needs of the country and the possible counterpart has no knowledge about the possibilities of using NAA to solve their analytical problems.

- There does not exist a mechanism that makes the NAA services available to outside users. The increased use of NAA requires manpower and instrumentation, the cost of which must somehow be covered.

- The laboratory does not have the capability for large scale work. Delivery time of results is long and only a limited number of samples can be analyzed annually, because of lack of skill, manpower, instrumentation or proper procedures. The cost of services may also be high for this reason.

- The quality of the work is not good enough. The end users of the analytical data cannot rely on the results and therefore do not use the NAA services.

- NAA is applied to elements and samples for which the techniques are not optimal compared to available non-nuclear analytical techniques.

The authors feel that the available articles and books on NAA do not deal with the problems outlined here. In this book the emphasis is not on theory or new techniques.

Radiochemical NAA is not dealt with because (1) radiochemical NAA, with the exception of some preirradiation applications, is not economically competitive with non-nuclear techniques, and (2) description of the numerous chemical separation techniques and radiochemical laboratory practices would enlarge the book too much.

This book addresses itself to scientists who are starting with NAA or who are establishing new NAA laboratories. It is, however, foreseen that it will also be useful to scientists who have already been working a few years with NAA.

2. PRINCIPLES OF INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS

2.1 HISTORICAL BACKGROUND

Neutron activation analysis (NAA) can be dated to the time of Hevesy and Levi [2], who published their first report of the method in 1936.

Following the development of nuclear reactors in the 1940s and sodium-iodide scintillation detectors in the early 1950s, the possibilities for applying NAA to trace element analysis of samples from many disciplines were recognized. Early development of NAA was rapid. The invention of high resolution solid-state Ge(Li) detectors in the 1960s and more recent advancements of computers and automation during the 1970s and 1980s have made possible application of NAA to research studies involving very large numbers of samples.

2.2 CHARACTERISTICS OF NEUTRON ACTIVATION ANALYSIS

Neutron activation analysis has become a mainstay of geochemical and biochemical trace element research because the technique possesses several important advantages.

(a) Substantial freedom from systematic errors. The physical processes involved are well understood. Radioactive growth and decay are rigorously exponential. The number of energetically possible nuclear reactions from a given target nuclide is small, and all possible reactions can be enumerated by inspection of a table of nuclides. High-resolution gamma-ray spectroscopy affords qualitative identification of the nuclides present as well as their quantitation. The density of known gamma-ray lines in energy space is small compared with the resolution of modern detectors, and not many analytically important decay gamma rays remain to be discovered. The presence of possible interferences may often be readily tested when multiple lines of either component are emitted.

(b) Complementarity to other methods. A different suite of elements is measurable by using nuclear rather than chemical reactions, and the detection limits are quantitatively different. Equally important, the kinds of errors to which nuclear methods are subject are due to different physical phenomena and are therefore likely to give a different bias in the results.

(c) Freedom from analytical blank and other problems related to dissolution. Except for pre-irradiation handling and packaging, there is no reagent blank in the usual sense. Analytical methods which require that the analyte be in solution call for chemical laboratory skills far beyond simple weighing and packaging. With some matrices (rocks containing complex silicates like chromite or zircon; fatty animal tissues), it is not easy to assure complete dissolution without using extreme conditions or multistep chemistry.

(d) Quantitatively known precision. The random process of radioactive decay gives an a priori estimate of the variation to be expected between samples. A simple T test shows immediately whether counting statistics is the limiting factor in precision. The accuracy can be comparable to the precision at levels well below 1%, even for a decaying source.

(e) Multi-element capability. Gamma-ray spectroscopy is inherently a multinuclide analytical process, the components of which add linearly. Radioactive decay adds the dimension of time, which can often act as a perfect separation chemist to resolve otherwise interfering components such as Cr-51 and Ti-51.

(f) Sensitivity. Neutron activation analysis has been shown to be applicable to the analysis of many elements at sub-picogram amounts. The option of chemical separation after irradiation is often available for the blank-free removal of interfering radioactivities.

(g) Results are independent of chemical state of elements. Neutron activation analysis is based on physical phenomena which take place in the nuclei of elements. As such, the chemical state as defined by the atomic binding, has no influence on the results. There are no chemical matrix effects as may occur in analytical techniques based on atomic properties and changes therein.

These characteristics of nuclear methods have been widely exploited, particularly in research into trace element analytical methodology. Fifty-six percent of all published analyses of NBS multielement SRMs have been performed by nuclear techniques, according to a recent survey [3]. Contemporary trace element geochemistry, from lunar sample and meteorite analysis [4/5/6] to mineral exploration, relies heavily on neutron activation analysis. Because of its freedom from blank, neutron activation is the most powerful technique available for the study of contamination in handling and sampling animal tissues [7/8].

The physical phenomena upon which NAA are based are the properties of the nucleus, radioactivity, and the interaction of radiation with matter. The sequence of events during a typical (n,γ) reaction are illustrated in Figure 1.1. When a neutron interacts with a target nucleus by a non-elastic collision, a compound nucleus is formed in a highly excited state. The high excitation energy of the compound nucleus 8 MeV on the average, is due to the high binding energy of the neutron with the nucleus. The lifetime of the compound nucleus is typically 10^{-16} to 10^{-14}s. This is long enough that no traces remain to identify the particular process of formation, but short enough that the nucleus can undergo a rapid de-excitation to a more stable configuration, in a number of different ways which usually involve emission of nuclear particles or prompt gamma rays. In most cases, the new nucleus is radioactive and will further de-excite by emitting decay gamma rays. The NAA method relies on the measurement of either these characteristic prompt or decay gamma rays for identifying elements and determining their amounts present in samples. About 70% of the elements have nuclides possessing properties suitable for NAA.

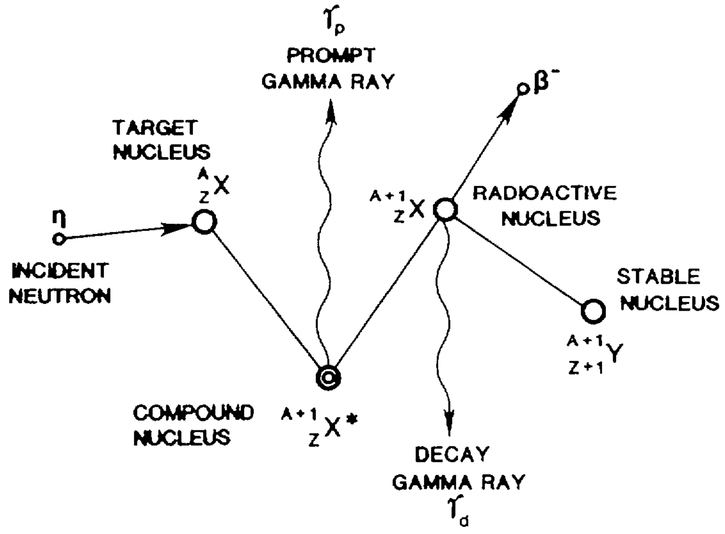


FIG. 1.1. Schematic diagram illustrating the sequence of events for a typical (n,γ) reaction.

2.2.1 NEUTRONS AND NUCLEAR REACTIONS

There are several types of neutron sources (reactors, accelerators and radioisotopic neutron emitters), but nuclear reactors with their high fluxes of neutrons from the fission of ^{235}U give the most intense irradiations and, hence, the highest available sensitivities for NAA. Fission-produced neutrons have energies ranging up to 15 MeV with an average energy of about 2 MeV. Through elastic collisions with moderator nuclei the fission neutrons rapidly become thermalized creating a broad energy distribution consisting of three principal components (thermal, epithermal and fast) as shown in Figure 1.2. The neutron energy distributions of different reactors vary considerably in relation to the type of reactor and between irradiation positions within a reactor.

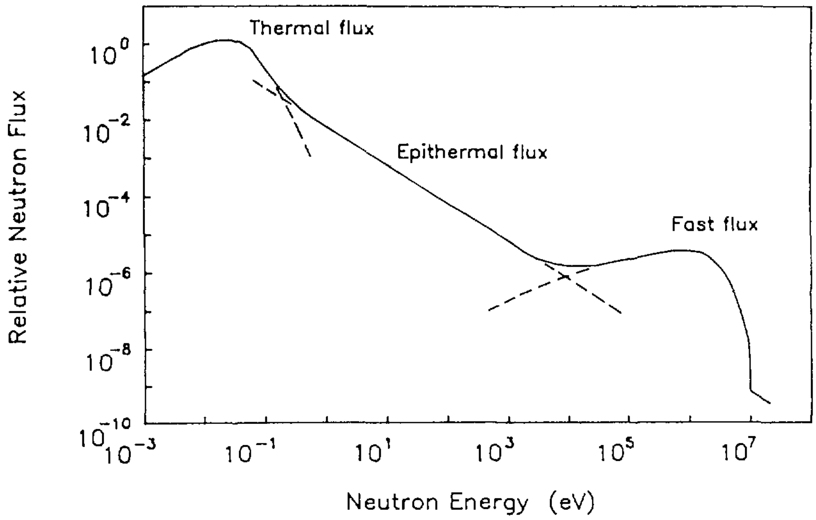


FIG. 1.2. A typical reactor neutron spectrum showing the various components used to describe neutron energy regions.

The thermal component consists of low-energy neutrons (below 0.5 eV) which have achieved thermal equilibrium with the atoms in the reactor moderator. At room temperature the energy spectrum of thermal neutrons can be described by a Maxwell-Boltzmann distribution with a mean energy of 0.025 eV and a most probable velocity of 2200 m/s. The flux of thermal neutrons, φ_{th}, is defined as the product of the most probable velocity v and the number density n of neutrons per unit volume. The upper energy limit is established by a cadmium foil 1 mm thick, which as a filter passes only those neutrons having energies above 0.5 eV. A nonresonant capture reaction has a cross section inversely proportional to the neutron velocity (a "1/v" excitation function).

The rate of such a reaction is thus proportional to nv/v or the neutron density, the proportionality constant being conventionally taken as the cross section at 2200 m/s. Measurements of thermal neutron flux are commonly carried out with flux monitors of cobalt by the $^{59}Co(n\gamma)^{60}Co$ reaction, which has a well-established cross section of 37.1 barns (1 barn = $10^{-24}cm^2$). A typical thermal neutron flux in the core of a one-megawatt research reactor is about $10^{-13}ncm^{-2}s^{-1}$.

The epithermal neutrons are those neutrons which have been only partially moderated. Their distribution can be approximately described by a 1/E slope beginning above the cadmium threshold and ranging up to about 1 MeV. The epithermal flux in a typical research reactor is usually about 2 percent of the thermal flux.

A non-rigorous but commonly used description of the total reaction rate per target atom for (n,γ) reactions induced by both thermal and epithermal neutrons is given by:

$$R = \varphi_{th}\,\sigma_{th} + \varphi_{epi}\,I \qquad (1)$$

where

φ_{th} = thermal neutron flux;

φ_{epi} = epithermal neutron flux;

σ_{th} = average thermal neutron cross section; and

I = effective resonance integral or epithermal cross section.

Because the cross-section curves for many nuclides are characterized by numerous resonance peaks in the epithermal neutron region, the effective resonance integral is defined by the expression:

$$I = \overset{\infty}{\underset{0.5\ \mathrm{eV}}{}}\ \sigma(E)\,dE/E \qquad (2)$$

In general, the thermal and epithermal neutrons in a reactor are the most widely used for NAA because their fluxes are greatest and the cross sections for (n,γ) reactions are the largest. Thus, neutrons from these energy regions offer the greatest analytical sensitivity available for NAA.

Although the epithermal neutrons represent only a small fraction of the total reactor neutrons, they are sometimes useful in NAA for several elements (e.g., Br, Rb, Sr, Mo, Ba, Ta, and U) which have higher relative reaction rates for epithermal neutrons than for thermal neutrons. The technique for taking advantage of those (n,γ) reactions with high resonance integrals by irradiating samples under a cadmium cover to shield out the thermal neutrons is commonly known as epithermal neutron activation analysis (ENAA). The reaction rate per atom R for ENAA is given by the expression:

$$R_{epi} = \varphi_{epi} I \qquad (3)$$

In general, calculation of effective cross sections for epithermal neutrons is made difficult by the large number of resonance peaks for most nuclides. However, the reaction $^{197}Au(n,)^{198}Au$ which has only a single resonance peak has been well investigated and its resonance integral is known to be 1550 barns. Therefore, the activity ratio for an infinitely thin gold foil or gold-alloy wire irradiated with and without cadmium covers is a frequently used method for measuring epithermal flux and as a calibration standard to measure the resonance integrals for other (n,γ) reactions. The equation describing this cadmium ratio (CR) is:

$$CR = \frac{R_{bare}}{R_{epi}} = \frac{\varphi_{th}\,\sigma_{th} + \varphi_{epi} I}{\varphi_{epi} I} \qquad (4)$$

A tabulation of both thermal neutron cross sections and resonance integrals for most (n,γ) reactions can be found in Table I of the Appendix.

The remaining component of the neutron spectrum from 1 to 15 MeV consists of the primary fission (or fast) neutrons which still have much of their original energy following the fission reaction. At high neutron energies the cross sections for (n,γ) reactions are very small and those nuclear reactions which result in ejecting one or more particles - (n,p), (n,γ) and (n,2n) reactions - become important. All of these reactions are known as threshold reactions because a minimum neutron energy, E_T, is necessary for the reaction to occur. Below E_T the cross section is zero and above this threshold the cross section is energy dependent. Because this energy dependence is not easily described, an average cross section is commonly used in calculations. The average cross section for a reaction induced by neutrons from a ^{235}U fission neutron spectrum is defined by:

$$\sigma_f = \frac{\int_{E_T}^{\infty} \sigma(E)\,\varphi(E)\,dE}{\int_{E_T}^{\infty} \varphi(E)\,dE} \qquad (5)$$

Using this average cross section the reaction rate for a fission neutron-induced reaction is given by the expression:

$$R = \sigma_f\,\varphi_f \qquad (6)$$

where φ_f represents the average fission neutron flux.

Measurements of fast neutron fluxes and calibration of cross sections for threshold reactions are most conveniently made by irradiation of a nickel flux monitor which has a cross section of 113 millibarns for the $^{58}Ni(n,p)^{58}Co$ reaction. Table II of the Appendix contains a compilation of many threshold reactions of interest in NAA.

2.2.2 ACTIVATION AND DECAY EQUATIONS

In NAA, the count rate, A, of decay gamma rays at the time of measurement being emitted by a particular radionuclide is dependent on the disintegration rate, D, at the end of irradiation, which is in turn directly proportional to the amount of target element present in the sample. The basic equations in NAA for the activation and decay of a radionuclide with a halflife of $t_{1/2}$ are as follows:

$$D = (NWF/M)\,R\,[1 - \exp(-\lambda T_i)] \qquad (7)$$

$$A = \varepsilon T D \exp(-\lambda T_d) \qquad (8)$$

where

N = Avogadro's number, 6.023×10^{23} atoms/mole;

W = weight of element irradiated in grams;

F = fractional abundance of target isotope;

M = atomic weight of element;

R = nuclear reaction rate per nucleus of target isotope;

λ = decay constant ($\ln 2/t_{1/2}$) of the radioisotope;

Γ = branching ratio of identifying gamma ray;

ε = detector photopeak efficiency;

T_i = length of irradiation; and

T_d = length of decay following irradiation.

Under certain irradiation conditions equation (7) can be simplified. For example, saturation occurs when the value of $T_i >> t_{1/2}$, causing the factor $[1 - \exp(-\lambda T_i)]$ to approximate a value of 1. On the other hand, if the irradiation time is short compared to the half-life, then $T_i << t_{1/2}$ and the factor $[1 - \exp(-\lambda T_i)]$ can be reduced to λT_i.

From equations (7) and (8), it is obvious that improved sensitivity can be achieved by increasing sample weight, detection efficiency, irradiation time, and nuclear reaction rate. Relative sensitivities are dependent on the nuclear properties of individual elements: (a) atomic weight, fractional isotopic abundance, and neutron reaction cross-section for the stable isotope of the element being irradiated; and (b) the half-life and decay scheme for the radioisotope being measured.

Prompt gamma rays are also being used for NAA at reactors which have external neutron beam facilities designed to permit simultaneous irradiation and counting of samples. The method is useful for elements with extremely high cross-sections or which do not produce nuclides that are radioactive after irradiation (e.g., H, B, Cd, Sm and Gd). In prompt gamma neutron activation analysis (PGNAA, section 6.2.), the activation equation (7) is continuously at saturation so the count rates for prompt gamma rays are constant during irradiation.

Among the tasks of anyone engaged in the application of NAA are the identification and quantification of gamma-rays in a collected spectrum. Occasionally, there is a need to correct the desired gamma ray for contributions from an interfering one. To facilitate these tasks a number of tables useful to gamma-ray spectroscopists have been included in the

Appendix. These tables include: Table III - a listing of radioisotopes, production modes, half-lives, gamma-ray energies and gamma-ray abundances; Tables IV and V - which list the gamma rays according to their increasing energies for short and long-lived nuclides, respectively; Tables VI, VII and VIII - present listings of gamma rays recommended for analysis and their most common interferences.

2.2.3 INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS

With the use of automated sample handling, gamma-ray spectrum measurement with solid-state detectors, and computerized data processing it is often possible to measure more than thirty elements without chemical separations. This application of purely instrumental procedures for trace element analysis is frequently called instrumental neutron activation analysis (INAA).

The concentrations of trace elements in a sample can be calculated with equations (7) and (8) provided the reaction rates, detector efficiency curve, halflives, and decay schemes of the radionuclides are known. The reaction rates can be determined by measuring the neutron fluxes with monitor elements such as Co, Au, or Ni which are co-irradiated with the samples. If the nuclear parameters are precisely known, then this so called "parametric" or "absolute" method of NAA can yield accurate concentrations for elements in the sample. In practice, however, uncertainties in the nuclear parameters can easily affect the accuracy for determining the concentration of an element of interest.

In ideal cases where irradiation conditions do not change with time, a variation of the parametric method called the "semi-absolute" method may be used. Calibration coefficients are determined experimentally for all elements of interest by irradiating elemental standards at one time. The analyst relies on the constancy of the determined coefficients for subsequent irradiations and analysis of samples. The accuracy of the method is only limited by the long-term stability of the reactor. However, there is no positive control of individual irradiations and the accuracy of analytical results obtained by the semi-absolute method is difficult to establish.

The most common approach to NAA is the "comparator" method, which is generally accepted as the most accurate way to quantify element concentrations. In this method, samples are irradiated simultaneously with standards containing known amounts of the element(s). After irradiation, both samples and standards are measured under identical geometrical conditions with the same detector. This procedure eliminates uncertainties in the nuclear parameters, detector efficiencies, etc. and reduces the NAA equation for each element to its simplest form:

$$\frac{W_s}{W_{st}} = \frac{A_s \exp(+\lambda T_{Ds})}{A_{st} \exp(+\lambda T_{Dst})}$$

where

W_s = weight of element being sought in the sample;

W_{st} = weight of the element in the standard;

D_s = disintegration rate at the end of irradiation for radioisotope measured; and

D_{st} = disintegration rate in the standard at the end of irradiation.

In the multi-elemental analysis of a sample, the comparator method requires a large number of individual elemental standards or use of a well-characterized multi-element standard. Preparation and irradiation of individual standards for each element are time-consuming and expensive; and the use of reference materials is not always practical because of the limited accuracy for certain elements or the differences between sample and standard matrices. As a result, the k_o-method of standardization [9, 10] has gained popularity in recent years.

In the k_o-method, a composite nuclear constant is used, the k_o-factor, which contains the nuclear parameters for the element of interest, ratioed with the nuclear parameters for a single comparator element such as gold. By measuring the activities of the radioisotopes in the sample, the activity of the gold comparator, detector efficiencies and neutron fluxes and applying the k_o-factors, the element concentrations for most elements can be calculated with reasonably good accuracy.

2.3 SENSITIVITIES AVAILABLE WITH NAA

The sensitivities for NAA are primarily dependent on the nuclear parameters and reactor neutron fluxes as mentioned earlier. Table 1.1 lists approximate sensitivities for determination of elements in interference free spectra by using neutrons from a typical research reactor.

TABLE 1 1 DETECTION LIMITS FOR NAA WITH DECAY GAMMA RAYS USING A FLUX OF $\phi_{th} = 10^{-13}$ $n \cdot cm^{-2} \cdot s^{-1}$ [10]

Sensitivity (pg)	Elements
1	Dy, Eu
1 - 10	Mn, In, Lu
10 - 10^2	Co, Rh, Ir, Br, Sm, Ho, Re, Au
10^2 - 10^3	Na, Ge, Sr, Nb, Sb, Cs, La, Yb, U, Ar, V, Cu, Ga, As, Pd, Ag, I, Pr, W
10^3 - 10^4	Al, Cl, K, Sc, Se, Kr, Y, Ru, Gd, Tm, Hg, Si, Ni, Rb, Cd, Te, Ba, Tb, Hf, Ta, Os, Pt, Th
10^4 10^5	P, Ti, Zn, Mo, Sn, Xe, Ce, Nd, Mg, Ca, Tl, Bi
10^5 - 10^6	F, Cr, Zr, Ne
10^7	S, Pb, Fe

The sensitivity, accuracy, and simplicity of NAA have preserved its role as one of the most important "work-horse" techniques for a vast amount of analytical work. Application of NAA is so widespread that it can be reasonably estimated that several hundreds of thousands of samples are being analyzed by NAA each year in areas as diverse as: archaeology, biology, environmental studies, geochemistry, semi-conductor materials, and forensic applications. For greater detail about the basic theory of NAA and radiochemistry in general the interested reader should refer to the works listed in Chapter 11.

3. POTENTIAL APPLICATIONS OF ECONOMIC AND SOCIAL IMPORTANCE

3.1. MAJOR APPLICATIONS

During the past decades, bi-annual review articles have been published [11/12/13/14/15/16/] with new developments and applications of nuclear techniques, including activation analysis. In their article ,'Nuclear and Radiochemical Analysis [16], Ehmann and Yates give recent (1985-1987) references on application of INAA in:

- Archaeology (bone, ceramics, pottery, glass, jewelry, coins, metal sculpture, paintings, raw materials, clays, soils);
- Environmental science and related fields (animals, birds, insects, fish, atmosphere, dust, aerosols, food, crops, ground water, rain, melanins, plants, trees, seaweed, algae, tobacco);
- Forensics (shooter identification, shotgun pellets);
- Geology and geochemistry (fossil fuels, coal, coal products, petroleum, meteorites, minerals, ocean nodules, rocks, sediments, soils, glacial till);
- Industrial products and applications (electronic materials, fertilizers, fissile material detection, high purity materials, municipal waste, pharmaceutical products);
- Medicine, human tissue, dental specimens (blood, bone, brain, colon, dental fillings, fetus, hair, liver, lung, mineral availability, muscle, nails, placenta, urinary stones, urine);

Also in the survey articles on the status of activation analysis in Europe and the Americas [17/18] many examples of applications of INAA and corresponding references can be found.

INAA is not always the most appropriate technique for all these applied fields. As an example, in particular in the medical and biological sciences trace element concentrations might be so low that sometimes the ultimate is asked of the technique with respect to sensitivity and control of sources of errors. For these applications, often other analytical methods may be preferred, like RNAA (Radiochemical Neutron Activation Analysis) or ICPMS (Inductively Coupled Plasma Emission Mass Spectroscopy).

In general, INAA may be the first choice for materials from the applied fields

- which are difficult to convert into a solution for analysis, e.g., via AAS or ICPMS; and/or

- of which only milligram quantities are available.

It has been one of our starting points that the the scientific and technical community of a country might benefit from a NAA laboratory when it applies itself to problems which are of economical and social importance. Therefore, geochemistry and mineral exploration and environmental control have been selected to be discussed in the next chapters as major applications for INAA.

3.1.1. GEOCHEMISTRY AND MINERAL EXPLORATION

One of the major applications of the INAA technique has been and will continue to be in the field of geochemistry. There are three major groups of "users" of the INAA technique within the geochemistry group, each with different requirements. These subgroups are university researchers, government geological surveys and the mineral exploration industry. Each of these users has different requirements of the INAA technique which can be basically subdivided into three categories, price, turnaround time and quality of data. A number of background books or review articles are available on the applications of INAA to the geosciences [19/5/6/20/21].

A) UNIVERSITY

The university researcher generally wants the highest quality data but is still concerned with price (because of limited research funds). Turn-around time appears to be of the least importance. The research efforts of this group are devoted to solving petrogenetic problems using trace element geochemistry. The major application is the analysis of rare earth elements by INAA [22/23/24] and subsequent plotting of chondrite normalized diagrams [25/6/26]. Other trace elements which are generally considered immobile under geochemical alteration processes are also analyzed by INAA. Some of these elements include Sc, Hf, Ta, Th and Cs. The INAA techniques provide the reseacher with an analytical technique to detect these elements at background levels in most rock types.

Typical multi-element INAA groupings of elements are a compromise between detecting many elements versus obtaining the best possible detection limits for a particular element. An example of a compromise list of elements and detection limits achievable for most rock materials is shown in table 3.1.

TABLE 3.1. TYPICAL DETECTION LIMITS ACHIEVABLE ON A 1 GRAM SAMPLE SIZE OF ROCK POWDER WITH A ONE HOUR THERMAL IRRADIATION, (5×10^{12} n·cm^{-2}·s^{-1}) DECAY OF 7 DAYS AND A 2000 SECOND COUNT TIME ON A HIGH RESOLUTION GERMANIUM DETECTOR (EFFICIENCY: 12%) [27]

ELEMENT	DETECTION LIMIT		ELEMENT	DETECTION LIMIT	
Ag	2	PPM	Ir	1	PPB
As	1	PPM	Mo	2	PPM
Au	2	PPB	Na	10	PPM
Ba	20	PPM	Ni	50	PPM
Br	0.5	PPM	Rb	10	PPM
Ca	0.2	%	Sb	0.1	PPM
Co	0.1	PPM	Se	0.5	PPM
Cr	0.5	PPM	Sr	100	PPM
Cs	0.2	PPM	Ta	0.5	PPM
Fe	50	PPM	W	1	PPM
Hf	0.2	PPM	Zn	10	PPM
RARE EARTHS AND ACTINIDES.					
Sc	0.01	PPM	Tb	0.1	PPM
La	0.1	PPM	Yb	0.05	PPM
Ce	1	PPM	Lu	0.01	PPM
Nd	3	PPM	U	0.1	PPM
Sm	0.01	PPM	Th	0.2	PPM
Eu	0.05	PPM			

Analysis of all the platinum group elements (PGE) by using a nickel sulphide fire assay collection followed by INAA has increased rapidly over the last ten years. Many of the applications of PGE analysis relate to research into the mode of formation of platinum deposits and related nickel deposits. Some of the PGE methods [28/29/30] use a fire assay preconcentration process as a means of separating the PGE from the rock matrix and thus enable a lowering of sensitivity.

Detection limits for the PGE are in the low ppb to sub-ppb range. Other elements which are analyzed by sister techniques of INAA include boron determination by prompt gamma analysis [31] and uranium analysis by delayed neutron counting techniques described in Chapter 6.

Finally, the last major use of the INAA technique by the university subgroup would be for the multi-element capability where the researcher can obtain data on as many as 47 elements with several irradiation and count periods using thermal [23/32/33] or epithermal irradiation [34/35] and in some cases measurements with both a coaxial and a low-energy photon detector [34/36/37]. Examples of obtainable detection limits are given in Tables 3.2 and 3.3. The detection limits in Tables 3.1 and 3.2, 3.3 are not necessarily comparable because the definitions of detection limit vary and are not stated here. For that the reader should go to the references. The multielement capability is

TABLE 3.2. DETECTION LIMITS OF 31 ELEMENTS IN ROCKS DETERMINED BY INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS [21]

Element	Detection limit (ppm)	Element	Detection limit (ppm)
Na	90	Ba	160
Al	300	La	0.5
K	3000	Ce	2
Ca	10^5	Nd	5
Sc	0.06	Sm	0.06
Cr	5	Eu	0.05
Ti	6000	Gd	4
V	30	Tb	0.05
Mn	10	Dy	0.3
Fe	350	Yb	0.07
Ni	15	Lu	0.2
Co	0.3	Hf	0.6
Rb	20	Ta	0.02
Zr	200	Th	0.4
Sb	0.2	U	0.5
Cs	0.4		

TABLE 3.3. DETECTION LIMITS FOR 25 ELEMENTS IN ROCKS DETERMINED BY INSTRUMENTAL EPITHERMAL NEUTRON ACTIVATION ANALYSIS OF TILL. SAMPLES ARE MEASURED FOUR DAYS AFTER IRRADIATION [35]

Element	Detection limit (ppm)	Element	Detection limit (ppm)
Na	250	Sb	0.1
Sc	0.5	Cs	0.6
Cr	40	Ba	80
Fe	2500	La	1.5
Co	2.5	Sm	0.05
Ni	40	Eu	2
Zn	100	Lu	0.05
As	1	Ta	0.5
Br	0.6	W	2
Rb	15	Au	0.003
Mo	1.5	Th	0.4
Ag	3	U	0.3
Sn	100		

very advantageous when the amount of sample material available (i.e., lunar samples, meteorites or separated minerals) is limited. The INAA techniques also complement the XRF and ICP techniques in the elements that can be obtained and the sensitivities required for geological purposes. Although there are instances when it may be possible to obtain data on most of the major elements by INAA it will be much cheaper to obtain the same data using the XRF or ICP techniques if available.

B) MINERAL EXPLORATION

The extent of usage of the INAA technique by the mineral industry is directly a function of what element or group of elements this group is exploring for and the sensitivity of that element to the INAA technique. Of primary importance to this group is turn-around time or how quickly they can get analytical results. The reason for requiring this fast turn-around is that planning of future exploration is frequently determined by analytical results and it becomes very expensive to have men and equipment sitting idle while waiting for results from the laboratory. To be successful in serving this market it is important to understand the concerns of the geologist and the geochemical behaviour of the element being analyzed. At present 80% of all exploration effort worldwide is devoted to finding gold deposits. Gold frequently occurs very inhomogeneously distributed in most geological materials. In rocks, for example, gold may occur as discrete native gold particles. It is therefore important to take an adequately large analytical sample for analysis to obtain a representative result [38]. This could require modification of irradiation facilities if possible. Samples as large as 1 kilogram have been analyzed by INAA for gold by commercial activation laboratories but the largest samples analyzed recorded in literature are 500g [39]. In some kinds of sediment samples gold can be homogeneously distributed. The sensitivity of gold by INAA is generally unrivalled by other analytical techniques in many matrices. Sometimes however, a preconcentration technique like fire assay [40/41] may also be applied to separate the element from its matrix which may cause interference.

Biogeochemical samples (vegetation or decaying vegetation) provides an excellent sample media for location of mineral deposits like gold [42]. The sample media, being primarily organic, is very amenable to the INAA technique and allows detection of up to 35 elements simultaneously (Table 3.4.) with detection limits of as low as 0.1 ppb gold [43]. This type of analysis and

TABLE 3.4. DETECTION LIMITS BY INAA ON VEGETATION BY IRRADIATION OF 30 GRAMS OF MATERIAL AT A FLUX OF 5×10^{12} $n \cdot cm^{-2} \cdot s^{-1}$ FOR 30 MINUTES WITH A COUNTING TIME OF 500 SECONDS AFTER A DECAY OF 6 DAYS

ELEMENT	DETECTION LIMIT	ELEMENT	DETECTION LIMIT
Au	0.1 PPB	Rb	1 PPM
Ag	0.3 PPM	Sb	0.005 PPM
As	0.01 PPM	Sc	0.01 PPM
Ba	5 PPM	Se	0.1 PPM
Br	0.01 PPM	Sr	10 PPM
Ca	0.01 %	Ta	0.05 PPM
Co	0.1 PPM	Th	0.1 PPM
Cr	0.3 PPM	U	0.01 PPM
Cs	0.05 PPM	W	0.05 PPM
Fe	0.005 %	Zn	2 PPM
Hf	0.05 PPM	La	0.01 PPM
Hg	0.05 PPM	Ce	0.1 PPM
Ir	0.1 PPB	Nd	0.3 PPM
K	0.001 %	Sm	0.001 PPM
Mo	0.05 PPM	Eu	0.05 PPM
Na	0.5 PPM	Tb	0.1 PPM
Ni	5 PPM	Yb	0.005 PPM
		Lu	0.001 PPM

that of humus (decaying vegetation) has proven very popular and has been very successful in locating gold deposits.

Heavy mineral concentrates from drilling of overburden and from stream sediments also provide a unique opportunity for the INAA technique. These samples are very expensive to collect and yield very little sample material. Analysis of the entire sample by INAA by a non-destructive method allows maximum use of a limited amount of sample material when in a multi-element mode. It is generally not desirable to split the sample for analysis because of the previously mentioned problem [44/45] of gold nugget inhomogeneity in this type of material.

The primary metals of importance to the mineral exploration geologist which can be analyzed best by INAA as compared to other competitive analytical methods include gold and pathfinder elements like arsenic, antimony, and tungsten, the platinum group elements, tantalum, thorium, scandium, cesium, uranium, and the rare earth elements. In many instances the exploration geologist is only interested in one element, however, the increasing use of microcomputers has increased the usage of multi-element data and as the geologist develops applications for the multi-element data the advantage of using INAA will be enhanced over single-element techniques like atomic absorption. A single geochemical type survey may generate thousands of samples for analysis. The samples must be analyzed rapidly and at low cost.

Accuracy and precision are not as important because the mining exploration companies are interested more in anomalies rather than absolute values. In simple terms the mineral explorationist's main interest is not in whether the sample contains 2 or 3 ppb gold but whether it is 2, 20 or 200 ppb. This class of lower precision analytical requirements are termed geochemical analyses (+30%) as opposed to the higher cost assay analyses (+5% or better).

C) GOVERNMENT

This market sector is a hybrid of the university and mineral exploration groups. In many instances, high quality assay analyses are required for elements like rare earths while in other circumstances large volume regional survey goals are to obtain large amounts of multi-element data as cheaply as possible [46]. Turnaround time with this group is not as critical as with the mineral exploration sector. Many national geological surveys will tend to have their own analytical instrumentation and generally the best people to talk to are the end users, not the analyst.

3.1.2. ENVIRONMENTAL MEASUREMENTS

Instrumental neutron activation analysis (INAA) is very well suited for application in environmental research and monitoring. It has been discussed extensively in the literature [47/48/49/50/51/52] and at meetings such as the IAEA symposium 'Measurement, Detection and Control of Environmental Pollutants' [53] and the series of conferences on 'Nuclear Methods in Environmental and Energy Research', organized by the American Nuclear Society. At one of these conferences Steinnes [54] stressed the importance of nuclear analytical techniques in environmental research along with other techniques such as atomic absorption spectroscopy and emission spectroscopy. In this respect, INAA offers multi-element capability, a high sensitivity for many relevant elements and a high accuracy for many sample types.

The large number of elements determined simultaneously in an INAA procedure is becoming increasingly important for many environmental applications. As it is often unknown beforehand which elements are matter of environmental concern in a certain area, a 'broad spectrum' analysis covering a large part of the periodic table is of major importance for environmental monitoring. The elements determined include most of the relevant potentially toxic elements which actually determine if and to what extent an environmental problem occurs. Exceptions are Be, Tl, Pb and, in some materials, Cd. Many other elements are not directly of environmental interest, but may play an essential role in the identification of the nature and origin of the sources of the toxic elements [55]. A variety of statistical interpretation methods have been described [56/57/58/59/60/61/62/63/64/65], which can be fruitfully applied in this.

The sensitivity of INAA is lower than achievable by radiochemical NAA and for certain elements with other analytical techniques like the ones mentioned above, but many toxic elements can be determined in the environment far below detrimental concentration levels. Increases of heavy metal concentration levels can therefore be observed, and the necessary measures be taken, long before they have developed into an acute environmental problem.

Another favourable characteristic of INAA is the low risk of contamination or element loss. This is especially important as the concentrations of interest in environmental samples are mostly in the ppb to ppm-range. Equally important is the lack of matrix effects for a large variety of sample types; it makes it possible to obtain absolute and directly comparable concentration values for strongly differing materials such as surface water, air particulate matter, human and animal tissues, plant materials and soils. Moreover, the absence of a destruction step or chemical separation contributes favourably to the well-established high degree of accuracy of INAA.

Often large numbers of samples have to be analyzed, and the sample matrix may vary strongly when focusing on different parts of an ecosystem. Here again the non-destructive character of the technique favors the applicability, as laborious dissolution steps, varying from one sample type to another, can be avoided.

Useful applications of INAA in the fields of environmental monitoring and research can be found in :

* Atmospheric Pollution [66]

Examples of these studies deal with long-distance transport [67/68/69], precipitation, source identification [62/63/64/70], impacts of industrial activities [71/72/73]. Sample types involved vary from air particulate matter (sometimes even size-fractionated [74/75]) and wet or dry deposition [76] to mosses [77/78] and lichens [65/79/63] used as biological indicators. In some of these studies also analyses of soils is included to determine enrichment factors, and materials from known anthropogenic sources of pollution to determine inter-element relationships.

* Industrial Waste

The analysis of samples of industrial wastes usually is part of a broader study of the impact of these wastes on an ecosystem. Examples are ashes from refuse incinerators [80], coal-burning plants (fly-ash) [81/82/83/84/ 85], (heavy) metal works [86/87], and smelters [88]. In this area of application the non-destructive character of INAA can fully be exploited.

* Soils and Sediments

The analysis of sewage sludge [89/90/91/92/93/94] has also to be considered. These studies are not restricted to polluted areas. From trace-element data of materials from 'unspoiled' areas [95/96], more insight is gained on the degree or elevated concentrations in suspected polluted areas [97].

* Plants, Man, Animal

Almost all environmental studies deal with the impact of pollution on living organisms. Whereas plant material can relatively easily be sampled [98/99/100] ,for man and animal, biological indicators like hair [101/102/103/104], blood [105/106], nails [107], urine [108], and eventually tissues [109/110] have to be sampled. For these samples INAA is useful to a large extent [111], but sometimes other techniques like radiochemical NAA, have to be preferred because of sensitivity or interferences [112].

* Aquatic Environment

INAA can be applied to a number of materials from the aquatic environment, such as aquatic water plants [113/114], fish, mollusc [115/116] and sediments [117/118/119]. For water analysis - although applications of INAA have been reported [120/121/122], with or without preconcentration techniques [123/124/125/126/127/128/129] - other analytical techniques may offer better characteristics, and, if accessible, have to be preferred [77].

One of the drawbacks of INAA, sometimes mentioned when considering its use in a monitoring program, is its relatively long turn-around time, when compared to other analytical techniques. Indeed, sometimes a 3 or 4-week decay period is required to obtain highest sensitivity. However, many elements can often be determined with adequate sensitivity after shorter decay times. Moreover, INAA with short-half life nuclides may also provide a very rapid answer. The other drawback of INAA, especially when environmental studies are involved, is its inadequacy of determining lead - often one of the prime elements of interest in pollution studies.

It is the expectation that because of its characteristics, INAA will remain a method of choice for many types of environmental samples. As the types of problems are often complex, and sample matrices may be varying, more satisfactory results and sensitivities can be expected when attacking these problems with INAA in combination with other analytical techniques [77/130]. For almost all application areas reference materials are available, thus enabling adequate quality assesment of the analysis procedure.

3.2. OTHER APPLICATIONS

MEDICAL, NUTRITIONAL AND OCCUPATIONAL HEALTH APPLICATIONS

The use of NAA for the analysis of biological samples is widespread, and is well documented in review articles and books [131/132/133] and in conference proceedings [134/135/136]. The excellent sensitivity of NAA for determining many biochemically important elements has made it an important contributor to research into the roles of inorganic elements in nutrition, physiology, pathology, and toxicology. Because INAA inherently free of analytical blank, it has been the technique of choice in studying the problems of sampling this difficult group of materials [8/137]. As many as thirty elements can be determined instrumentally in plants, animal tissue, or diet samples. In many cases the use of radiochemistry increases the number of measurable elements and improves the detection limits of most by many orders of magnitude, but at a commensurate increase in the cost of analysis.

MATERIALS SCIENCE

The importance of trace analysis in characterizing high-technology materials like semiconductors and ceramics is becoming appreciated. Electrical properties of metals, semiconductors, and insulators, and the mechanical and thermal properties of graphite and ceramics are affected by many trace impurities. Electronics encapsulants, catalytic substrates, crucibles, medical implants, and laboratory ware need to be free of contaminants that may compromise their use. Materials of current interest include carbon, aluminum, silicon, germanium, alumina, silica, zirconia, silicon nitride, silicon carbide, and carbon and silicon-based polymers.

Some of these materials are extremely difficult to dissolve, limiting the application of analytical techniques that rely on the sample being in solution. Some that are excellent insulators are difficult to study with electron or ion-bombardment methods because of substrate charging. The nondestructive nature of INAA is of advantage in the analysis of these materials. With no chemistry needed before irradiation, there is less concern with contamination than with most chemical methods. Most of these materials are made of elements which do not activate strongly with thermal neutrons or produce only short-lived activity, so trace analysis can often be performed down to very low concentrations. For example, the analysis of 'pure' rhodium metal is easy since the rhodium nuclides produced on irradiation decay quickly to allow the measurement of the other platinum group elements in nanogram concentrations.

NAA is used to monitor the level of electrically conducting impurities such as Au, Na, Cu, As, Ca and W in silicon ingots and wafers [138]. Many other elements, both impurities and dopants have been analyzed in silicon and other materials used in semiconductor manufacturing [139/140/141].

FORENSIC APPLICATIONS

INAA and RNAA have been successfully applied to investigate samples from forensic laboratories. In review articles [142/143/144] a variety of examples of such analyses and work is given. In most cases trace element concentration patterns are being used to establish whether there is a link between a suspect and physical evidence found at the scene of a crime. For instance, it can be determined whether a suspect has fired a weapon recently by searching for Ba and Sb in gunshot residues on the hands. Lead bullets or shotshell pellets can be fingerprinted by their content of deliberately added Sb and their pattern of As, Cu, Ag and other trace elements. But the sample variety may be much larger than gunshot residues: glass, paint, hair, metal, paper etc. Not only does each of these materials present its own difficulty and concern in analysis [143], but also it should be noted that sometimes only very small amounts of material are available which also have to be kept intact to serve as a court evidence. High demands are set to accuracy, precision and statistical interpretation of results.

Forensic application of INAA can be regarded as an interesting application; the laboratory may gain general respect and may demonstrate the social benefit of the technique. However, the number of samples to be analysed and the extent of work is usually limited and irregular, and this application can therefore be regarded as an optional side-activity of the laboratory.

ART AND ARCHAEOLOGY

"Fingerprinting" by elemental composition patterns is a well-established technique for the identification of pottery, stone, and metal artifacts. Applications have been made to the authentication of works of art and studies of material sources, manufacturing methods, and trading routes [145]. INAA is an important contributor to this work because it provides a useful set of elements (twenty to thirty in mineral materials) and is well-suited to the nondestructive analysis of large numbers of small samples.

Another application is the determination of the silver content of silver coins. Because of inhomogeneity and corrosion the analysis of the whole coin by INAA is often the only reliable way to do it [146]. The composition of copper and bronze objects can also conveniently be determined by NAA [147].

ACTIVABLE STABLE TRACERS

Activable stable tracers are used as alternatives to radiotracers where it would be unacceptable to use radioactivity, i.e., in the environment, in humans or in countries where legislative practices prevent it. The reason for using a stable tracer can also be that no radioactive tracer of suitable half-life exist. The purpose of the stable tracer is to provide an easily activated material, which is not found in the material to be studied and which is very sensitive to determination by NAA. Any suitable element may be used as tracer, preferably one which produces nuclides with a short half-life (for rapid irradiation and counting) and with a high sensitivity for activation. Gilat has reviewed the industrial applications of activable tracers [148].

An example of the use of a stable tracer is to measure the effectiveness of a spraying machine in agricultural use for treating crops with pesticides. A suitable element is dysprosium which is relatively rare in the environment, has a radionuclide with a half-life of 1.6 min which can be detected down to 10 ng. Stable tracers are also used in medical studies, for example to follow the absorption of iron through the human gut. In this case an enriched isotope, Fe-58, is fed in the diet and then the Fe 58 collected in the faeces is activated for analysis. In the study of water flow in lakes or the sea, indium has been favourably used as an activable tracer. When long transport distances over long time intervals need to be studied the use of a stable tracer is preferred over the use of a radioactive tracer, because of the high initial activity of a long-lived radionuclide needed.

4. IRRADIATION FACILITIES

4.1 RESEARCH REACTOR TYPES

The research reactor is the most widely used source of neutrons for INAA, particularly with respect to the number of samples processed and the number of elemental analyses performed.

Five general types of research reactors are described: Slowpoke, Argonaut, TRIGA, Pool, and Heavy Water. Within each group there are variations in design and power level. Furthermore, the groups are not mutually exclusive and overlap in some respect, e.g., TRIGA reactors are of the Pool type. In this publication, the research reactor types are categorized as follows:

1. Manufacturer's designations are used for the types of reactors for which large numbers were produced and the terminology widely understood, i.e., Argonaut, TRIGA, Slowpoke.

2. Heavy water moderated research reactors are designated as Heavy Water reactors. This class of reactors are usually heavy water reflected. The coolant may be either heavy or light water.

3. Pool reactors include a wide variety and variation of reactors. The characteristics of this class of reactors as described below are limited to plate type fueled reactors, light water cooled and moderated and of the swimming pool type.

The data presented for each reactor type are average values or a range of values as reported by different reactor owners [149]. These data should be viewed as only approximate values that would vary depending on the specific design of the reactor. Most research reactors are of the multipurpose type while others are designated for specific purposes such as fuel and materials testing, radioisotope production, neutron beam research or INAA. Therefore, within any type of reactor, wide variations in performance parameters could be possible. In addition, a research reactor converting from highly enriched uranium fuel to low enriched fuel with changes in core configuration will have a hardening of the neutron spectrum and a reduction in the maximum thermal flux of about 15%.

The following information on the different reactor types have been extracted from reports from reactor operators.

SLOWPOKE REACTOR

The Slowpoke is a low cost, low power reactor of the tank-in-pool type. It is beryllium reflected with a very low critical mass and provides neutron fluxes higher than available from small accelerators or radioactive sources. Most Slowpokes are rated at a nominal 20 kW although operation at higher power for shorter durations is possible. A Chinese version of the Slowpoke, designated the Miniature Neutron Source Reactor (MNSR), is nominally rated at 27 kW with similar characteristics and performance.

Up to 10 irradiation tubes may be installed in the reactor vessel, 5 inner (7 cm^3 capsules) and 5 outer (27 cm^3 capsules). The maximum available thermal flux at the inner tube is in the order of 1×10^{12} $n/cm^2/s$.

Power	Maximum Flux ($n/cm^2/s$)
20 kW	inner site 1×10^{12} (thermal) 1.8×10^{11} (fast) outer site 5.8×10^{11} (thermal)

Irradiation System		
Inner Site (small capsule)	diameter:	1.58 cm
	length:	5.4 cm
	capsule volume:	7 cm^3
Outer Site (large capsule)	diameter:	2.9 cm
	length:	5.4 cm
	capsule volume:	27 cm^3

ARGONAUT REACTOR

Argonaut reactors operate at power levels between 2 watts and 300 kW. Most operating Argonauts are rated at 100 kW. These reactors are graphite reflected, light water moderated and cooled and operate with high enriched uranium fuel. A variety of core configurations are possible ranging from one slab, two slabs (arc or straight slab) or annular core depending on the design and intended use:

Power	Maximum Flux (n/cm^2/s)
100 kW	1.3 - 2 x 10^{12} (thermal) 2.6 - 4.8 x 10^{12} (fast)

Research Facilities	Neutron flux (thermal/fast) (c/cm^2/s)	Gamma dose rate rad/hr
Face of Core	2 x 10^9/2 x 10^7	
Beam Ports	1-2 x 10^8/1-2 x 10^7	10^4
Pneumatic System	1-1.5 x 10^{12}/0.4-2 x 10^{11}	
Thermal Column	2 x 10^{11}/4 x 10^8	

TRIGA REACTORS

TRIGA reactors are a popular multi-purpose type with about 50 currently operating. They range in power levels from 18 kW to 3 MW with 250 kW and 1 MW being the most common operating levels. One special purpose test reactor is rated at 14 MW. These reactors operate with uranium-zirconium hydride homogeneous solid fuel with enrichment of either 10% or 70%. The reactors are light water cooled, graphite reflected and of the pool type. Most TRIGA reactors are capable of operating in the pulse mode and most have a rotary specimen rack (called Lazy Susan) containing 40 irradiation positions between the core and the reflector.

Power	Maximum Neutron Flux (n/cm^2/s)	
250 kW	0.5 - 1 x 10^{13} (thermal)	0.7 - 1.4 x 10^{13} (fast)

Research Facilities	Neutron Flux (thermal/fast) (n/cm^2/s)	Gamma Dose Rate (rad/hr)
Beam Ports	1 x 10^7/1 x 10^6	
Pneumatic System In Core	2.5-4.3 x 10^{12}/3.5-5 x 10^{12}	
1.5 x 10^4-5 x 10^7		
Lazy Susan	1.8 x 10^{12}/1.5 x 10^{12}	4 x 10^3

POOL REACTORS

This is the most numerous of the five reactor types described. The large variations in design make it difficult to reflect a standard. They operate with plate type fuel in a rectangular configuration, usually highly enriched uranium fuel, in a swimming pool. They may be forced cooled (power > 100 kW) or cooled by natural convection of light water. They may be water reflected or reflected by graphite (the majority) or by beryllium or by heavy water tanks or one or more sides. The operating power ranges from a few watts to several tens of megawatts.

Although most reactors in this category operate with rectangular cores (Plan view) several operate with different configurations. Pool reactors offer many possibilities for configuring the core for performance or economy reasons by moving or removing one or more fuel elements or reflector elements.

Power	Max Neutron Flux (n/cm^2/s)	
10 kW	4.3 x 10^{11} (thermal)	2.6 x 10^{11} (fast)
100 kW	1.4 x 10^{12} (thermal)	3.5 x 10^{11} (fast)
1000 kW	1.4 x 10^{13} (thermal	3.8 x 10^{13} (fast)
2000 kW	1.4 - 3 x 10^{13} (thermal)	1 - 3 x 10^{13} (fast)
5000 kW	1.4 x 10^{14} (thermal)	

Research Facilities	Neutron Flux (thermal/fast) (n/cm^2/5)	Gamma dose rate (rad/hr)
Pool		
10 kW	4.6 x 10^{10}/5.1 x 10^{9}	
2000 kW	1.3 - 4.5 x 10^{13}/1 x 10^{12}	10^{8}
Pneumatic System		
100 kW	1.2 x 10^{12}/2 x 10^{11}	
1000 kW	2.0 x 10^{12}/5.0 x 10^{11}	5 x 10^{7}
2000 kW	1.4 x 10^{12}/1.0 - 1.5 x 10^{12}	5 x 10^{7}
5000 kW	1 x 10^{14} -	
Beam Ports		
10 kW	1.25 x 10^{11}/4.8 x 10^{10}	core contact
100 kW	2.1 x 10^{8}/2.3 x 10^{7}	beam exit
2000 kW	1.0 x 10^{8}/1.0 x 10^{7}	beam exit 1 x 10^{4}
2000 kW	1.0 x 10^{7}/1.0 x 10^{6}	1 x 10^{4}

HEAVY WATER REACTORS

This type of reactor, as a group, are rated at higher power levels than the others, usually between 10 and 26 MW. They are tank types using highly enriched uranium fuel, heavy water moderated and cooled and heavy water and graphite reflected. They are characterized as having well thermalized neutron flux and large available irradiation volumes. The following data on a 10 MW Heavy Water Reactor characterise this class of reactors.

Neutron Flux ($n/cm^2/s$)	Average/Maximum (thermal)
Average/Maximum (fast)	
$1.0 \times 10^{14}/1.7 \times 10^{14}$	$1.0 \times 10^{14}/1.5 \times 10^{14}$
Pneumatic System	
$6.0 \times 10^{13}/5.0 \times 10^{13}$	
Reflector Position	
$3.0 \times 10^{13}/5.0 \times 10^{13}$	
Beam Ports	
$1.0 \times 10^{12}/5 \times 10^{13}$	

Gamma Dose Rate (rads/hr)	
Pneumatic System	9×10^8
Reflector Position	3×10^7

4.2 SAMPLE ENCAPSULATION

In NAA each sample has to be irradiated and measured in a container of its own. The container has the following requirements:

The size has to correspond to required sample size and size of irradiation position.

The material has to sustain the conditions in the irradiation position for the time needed for the irradiation. It has to stand the effects of radiation, heat and mechanical impact. A gamma dose rate of 10^9 Rad/h corresponds to a temperature of 80°C in the sample. Data for the gamma dose rate in different reactor types and irradiation sites can be found in chapter 4.1. When analyzing volatile compounds the container should also be hermetically sealable and sustain high pressure in some cases.

No interfering activities should be induced in the capsule during irradiation. In many cases the sample is irradiated and measured in the same container. The material has also to be pure enough not to contaminate the sample during irradiation.

The most commonly used materials for the irradiation capsules are polyethylene, quartz and aluminium. In some special cases graphite is used. When the flux needs to be modified the container can be lined with graphite, cadmium or boron. These are discussed separately in section 4.4.

In normal conditions the most favourable material is polyethylene. It is cheap and it can be easily fabricated in different sizes and forms. The material can be produced in high purity and thus the same capsules can often be used both for irradiation and measurement. Table 4.1 shows impurity concentrations of polyethylene.

TABLE 4.1. CONCENTRATION OF IMPURITIES IN POLYETHYLENE AND QUARTZ* (Values adopted from Refs [150–153])

	Polyethylene (ng/g)	Quartz (ng/g)
Ag		1-10
Al	80-10^5	
As		0.17-10
Br	100-10^4	10-100
Ca		1-10
Cd		1-10
Cl	100-3.10^4	100-10^4
Co	0.07-10	0.3-10
Cr	15-300	1.6-100
Cs	0.05	0.12
Cu	1-17	2-100
I	10-100	
Fe	100-10^4	100-10^4
Hg	1-10	0.03
K	100-10^4	100-10^4
Mg	80-1500	
Mn	10-100	1-10
Mo		10-500
Na	40-10^5	
Ni		10-500
Rb		2-20
Sb	0.18-10	0.4-10
Se	10-100	0.7-10
Sn	10-100	
Sr	100-10^4	
Ti	5.10^3	
Th	3	0.46-10
U	840	
Zn	28-10^4	20-40

* These ranges are shown to demonstrate the order of magnitude and great variability of impurity concentrations depending on the material. Because the original papers have different ways of presenting the data, the data presented in this table are not directly comparable with each other and only data presented in the original papers should be referred to.

Two kinds of polyethylene are commercially available. Conventional low-density polyethylene (CPE) is made by a high-pressure process which gives branched polymer chains, while high-density linear polyethylene (LPE) is made by catalytic polymerization at a lower pressure. LPE can be irradiated for a longer time than CPE before becoming brittle (which makes it useful for rabbits), but it may contain a microgram of chromium or other catalyst per gram. For other elements as well, LPE is generally less clean than CPE, and polypropylene contains more impurities than either. Polystyrene has excellent radiation resistance, and can also be very free of contaminants [151/154].

Several kinds of commercially available polyethylene containers are useful for packaging samples, and are made in large enough quantity to be inexpensive. Polyethylene bag stock is widely sold in the form of flattened tubing, in widths (half the circumference) from 2.5 cm up and in wall thicknesses from 25 to 150 microns. Containers are cut from the tubing and the ends made airtight with a thermal impulse sealer. The inside can be efficiently cleaned by filling with a small amount of 1:1 nitric acid (note nitric acid may contain bromine). A 700-m roll of 50-micron tubing will last most laboratories for years. Surgical or food grade polyethylene tubing is available in several diameters up to 10 mm. Polyethylene screw-cap bottles are useful for containing large or numerous samples. Capsules cut from polyethylene microcentrifuge tubes will hold 100 mg of rock powder, and can be conveniently bundled into a rabbit.

Polyethylene capsules and rabbits can be purchased from some manufacturers of research reactor research products. It might be cheaper to buy capsules made for other purposes, like medicine tubes, if the sizes are appropriate and a local manufacturer exists. If a manufacturer of plastic products exists in the country and the consumption of vials is high, it is better to use the local manufacturer. The cost of special molds needed to produce the vials may have to be borne by the user. Figures 4.1, 4.2 and 4.3 show examples of vials and rabbits intended for irradiation.

Polyethylene vials can be sealed in three different ways. For most applications it is enough to use a snap-on lid. In some cases heat sealing is needed. There are apparatus designed for this purpose. Especially for relatively large size rabbits lids with threads are used.

Polyethylene has only a limited lifetime in a reactor. The vials are useful for irradiations of 1-200 h duration, depending on the gamma and neutron flux and the temperature in the irradiation position. Irradiation in cadmium shortens the lifetime of polyethylene considerably. The lifetime of the capsules must be determined experimentally, before any real sample irradiations are performed. Some elements like mercury and halogens diffuse through polyethylene during long irradiations.

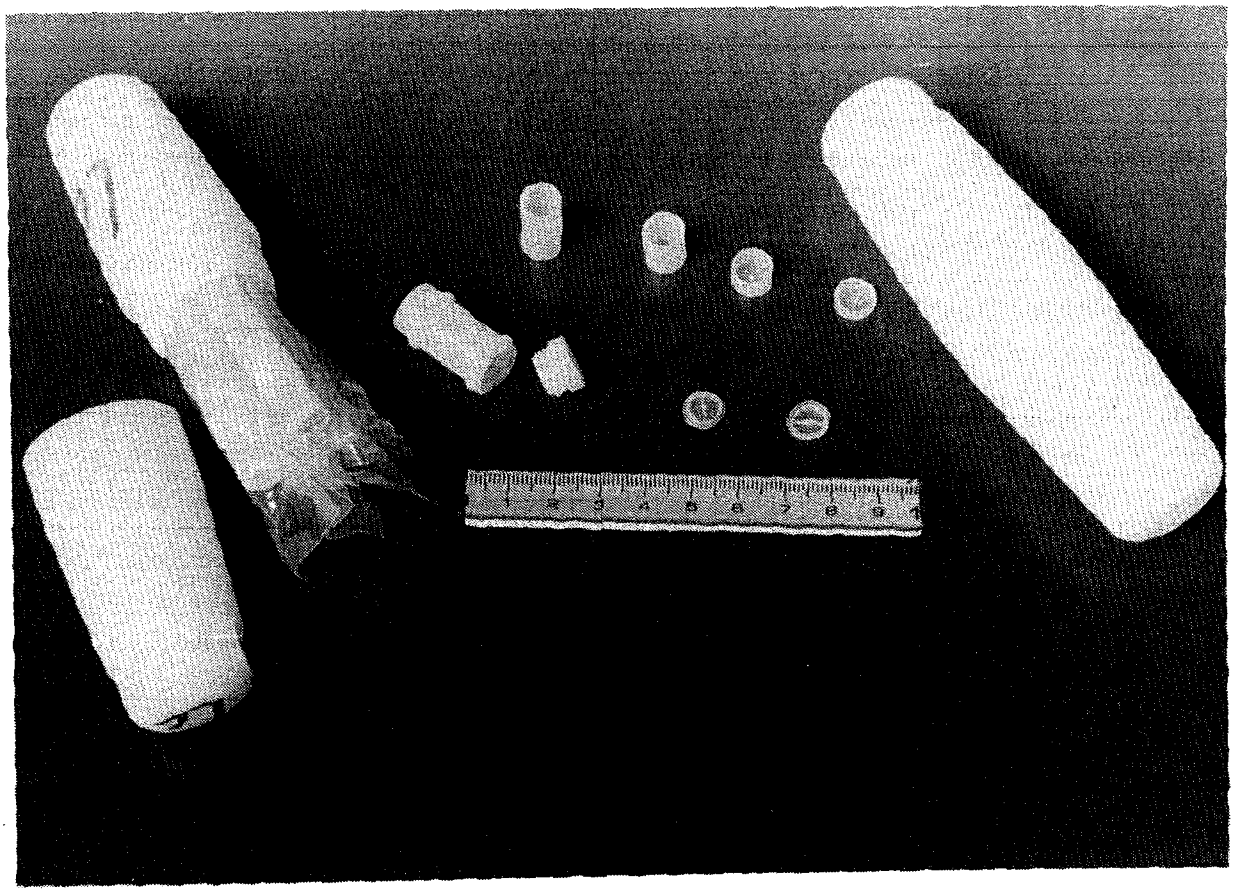


FIG. 4.1. Capsules and rabbits used for irradiation.

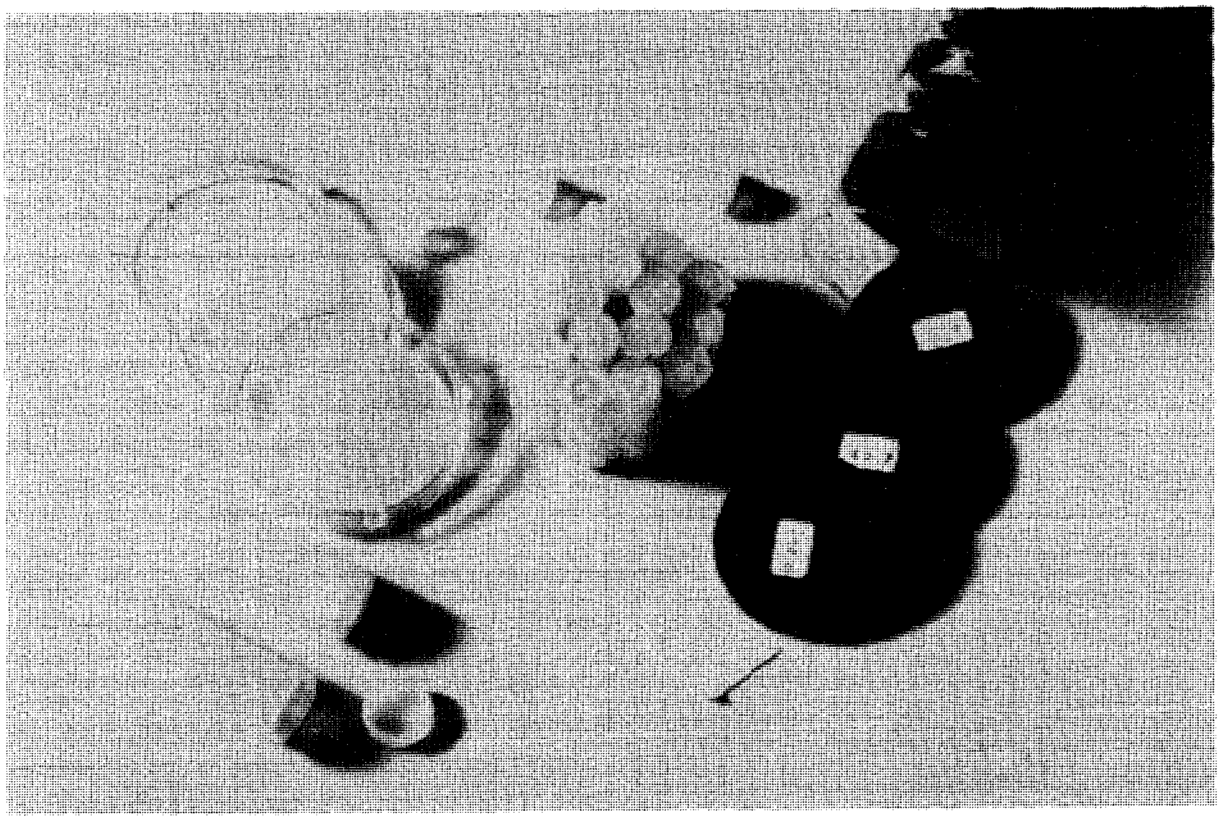


FIG. 4.2. Irradiation containers and pressed pellets of plant material.

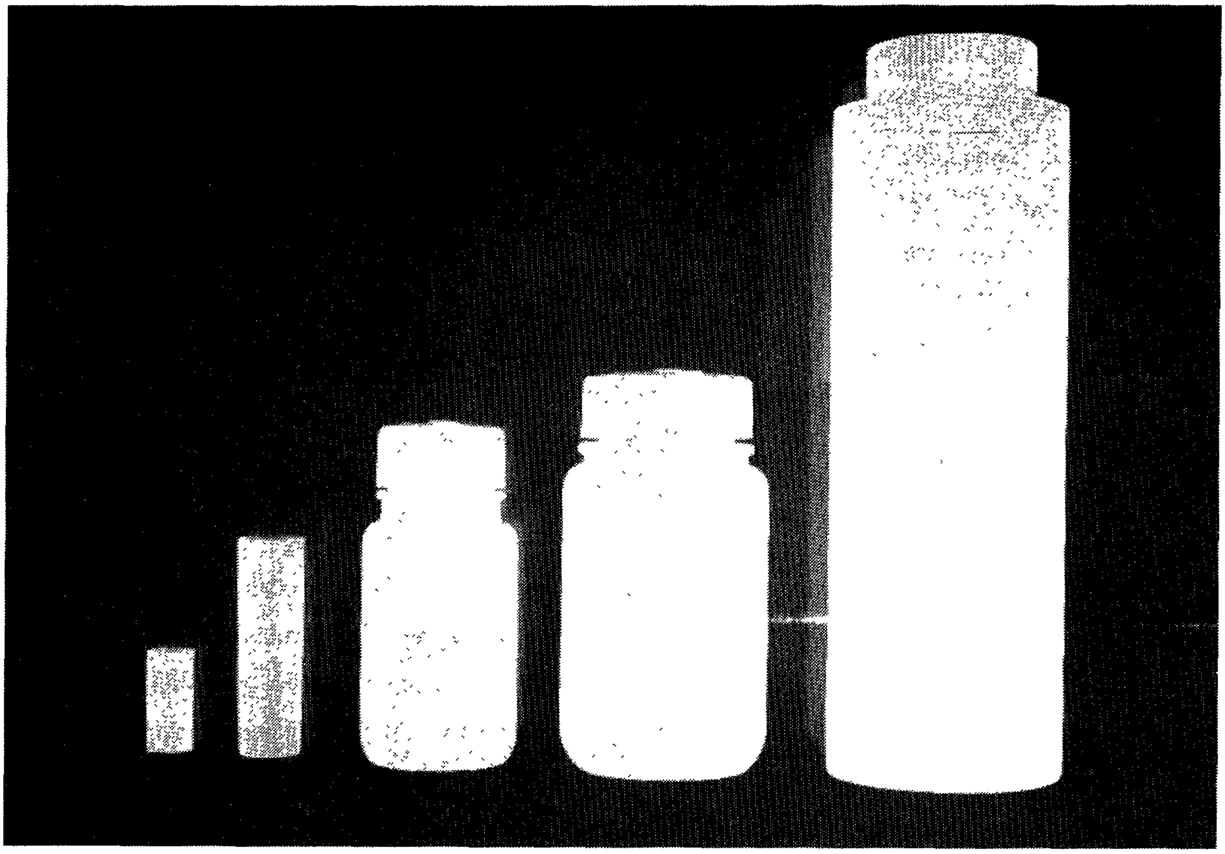


FIG. 4.3. Irradiation containers for different sizes of samples.

When polyethylene cannot be used quartz is usually the next choice. It is used for irradiating biological samples for prolonged periods in high flux. It is also always used for irradiation of fissionable materials. It can be obtained as tubing of different diameter, from which capsules can be prepared. Working quartz with a flame is more difficult than glass, so some laboratories have empty capsules prepared in quantity by a professional glassblower. Samples that char or evolve gases on heating may need a pre-necked ampoule in order to minimize the time in the flame. Sometimes capsules containing liquids are difficult to seal because of the pressure built up during the heating of the liquid. This can be avoided by cooling the closed end with liquid nitrogen.

Not all quartz is pure enough for irradiation containers. Mineral quartz is activated rather strongly and biological materials are difficult to transfer to a pure capsule for counting. This can be partly avoided by using the high-purity quartz. The quality of different products varies considerably. Table 4.1 shows impurity concentrations of some materials. High purity quartz is expensive.

If the samples are to be counted in the vials, care should be taken to avoid contamination during the sealing process. Some torch lighters generate sparks by creating copious quantities of small pyrophoric rare-earth metal particles; piezoelectric igniters or matches are preferable. When the quantity of analyte to be measured is very small, an all-quartz burner may be necessary to avoid contamination from metal torch tips [8].

A careful distinction needs to be made between quartz and Vycor. The latter is a glass which is interchangeable with quartz in most of its properties, but contains enough boron to cause problems during irradiation, both from neutron shielding and alpha particle heating.

High flux irradiation of many inorganic materials, like powdered rocks, can be made in pure aluminium foils. These are much easier to handle than quartz and the cost is lower. In this case the sample should not contain volatile compounds. The samples are inserted in pure polyethylene capsules for measurement, because the aluminium foil has always some ^{24}Na activity, produced by the (n,alpha) reaction from aluminium. The presence or absence of contamination, when irradiating in aluminium foil, or other kind of materials, can be investigated by irradiating pure quartz or cotton powder and measuring the induced activity after changing into a pure capsule.

When a pneumatic transfer system is used for irradiation in a very high flux, graphite rabbits are used. These can be obtained in high purity and resistance to strong mechanical impact, but the price is rather high. Therefore they are used in only very special cases.

Depending on vial material and concentration of elements to be analyzed it is sometimes necessary to clean the vials. The procedure is described in ref [151]. Normally a wash with acid followed by rinsing with demineralized water is used.

The vials have always to be marked in order to enable identification in different stages. Polyethylene vials and aluminium foils can be marked with waterproof ink from a pen intended for overhead transparencies. Quartz ampoules are permanently marked by an electrical engraving pen.

The sample vials have to be inserted in larger irradiation containers for insertion into the irradiation positions. These can be made of polyethylene or aluminium. The size depends on the size of the irradiation position which is usually made to fit. In special cases these containers have a lining for modification of the neutron flux. These are discussed in chapter 4.4.

4.3 IRRADIATION SITES

The irradiation position is evaluated according to its size, accessibility and the neutron flux, neutron energy distribution and homogeneity of the flux. The flux gradients both in respect to space and time are discussed in chapters 4.1. and 8.5. Also the gamma flux and temperature is of importance in many cases. Usually the transport of the sample is only a matter of safety and convenience, but when short-lived radionuclides are measured, other aspects like speed and reproducibility of the timing, have to be accounted for.

The highest fluxes are obtained in the core, but there the fast flux is also high. Commonly the irradiation positions are in the reflector or just outside of it in order to obtain a rather high but, at the same time, well thermalized flux. Radial and tangential beamports are used to extract a portion of the mixed flux and a thermal column is used for obtaining a well thermalized flux. These can be used for capture gamma analysis and also for insertion of pneumatic transfer systems. But mostly these beamports are used for neutron physical experiments or neutron or gamma radiography.

4.3.1 PNEUMATIC TRANSFER SYSTEMS

Sample containers with volumes from a fraction of a ml to a few hundreds of ml can be transported by pneumatic means. The use of a pneumatic transfer system allows short transfer times and convenient access to the irradiation position, especially if a reactor with a pressurized vessel is used. The only drawback is that the sample vials have to sustain mechanical impact and therefore quartz vials have to be especially packed, when irradiated with a pneumatic transfer system.

Several commercial pneumatic transfer systems are available but it is also quite common that laboratories build their own ones, which can be designed according to need.

In most pneumatic transfer systems the rabbit is transported with pressurized air. The system is simple and rather fast. A speed of 90 m/s can be reached. Figure 4.4 shows a rather complicated system with two irradiation and measurement positions [155]. Similar systems with only one irradiation and measurement position without sample changer or delay stack are still most commonly used. In order to reduce ^{41}Ar production nitrogen or carbon dioxide can be used instead of air.

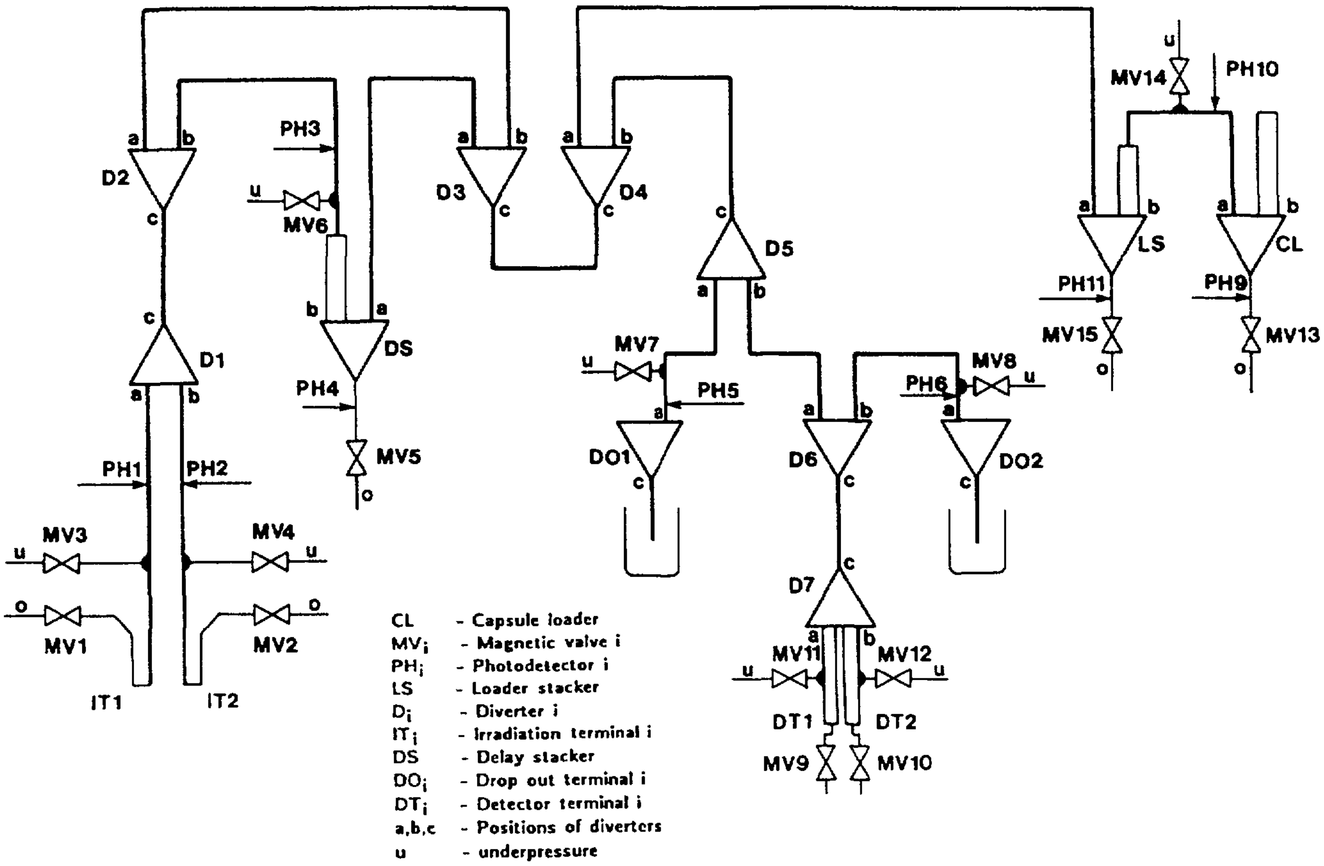


FIG. 4.4. Schematic diagram of a multipurpose pneumatic transfer system for research reactor application.

When speed is not a major goal, a system working by vacuum instead of the more common pressure can be used. Figure 4.5 shows the principle. A blower sucks air from either direction of a tube depending on the transport direction. The air is blown out in the ventilation system via a filter. Because underpressure is maintained the system is safe, but it is rather slow. If the irradiation position is punctured there is a risk that water will be sucked into the system. The transport time from the reactor core to the nearby room, about 10 m, is 3 seconds when the weight of the rabbit is 7 g. The time is reproducible within 1.2% when samples of similar weights are used [156]. When the transport distance is tens of meters and short irradiation times are used a sensor near the core is needed in order to measure the irradiation time. The reason for this is that the transport time varies considerably depending on the weight of the sample.

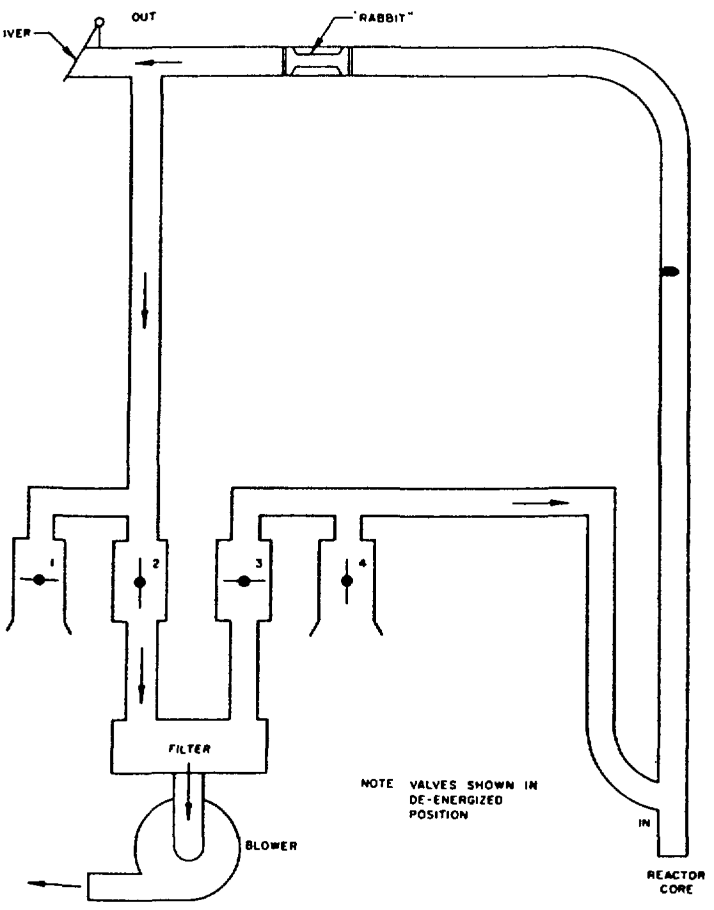


FIG. 4.5. Pneumatic transfer system.

Especially in the last few years a number of very fast pneumatic transfer systems have been described using very short-lived isotopes in activation analysis. The transportation from the irradiation position to the measurement station is performed by pressurized air, nitrogen, or even helium and varies between 30 ms and 500 ms depending on the circumstances. These very fast systems are only needed in very few applications.

4.3.2 ROTARY SPECIMEN RACK (LAZY SUSAN)

In the Triga reactors samples can be irradiated in the reflector, in the "rotary specimen rack" (Lazy Susan) (Fig. 4.3), in which there are 40 locations which can hold capsules 3 cm in diameter and 25 cm long. This rack can be rotated. In some laboratories the rack is rotated during irradiation in order to get a homogeneous flux for all samples. When samples with high absorption cross sections, or cadmium capsules are inserted in some of the positions, rotation is not possible because they would cause difficulties for the control of the reactor. Normally irradiation capsules are inserted manually, or using a "lift" working with electricity (Fig. 4.6), but pneumatic or hydraulic sample loading devices have also been constructed.

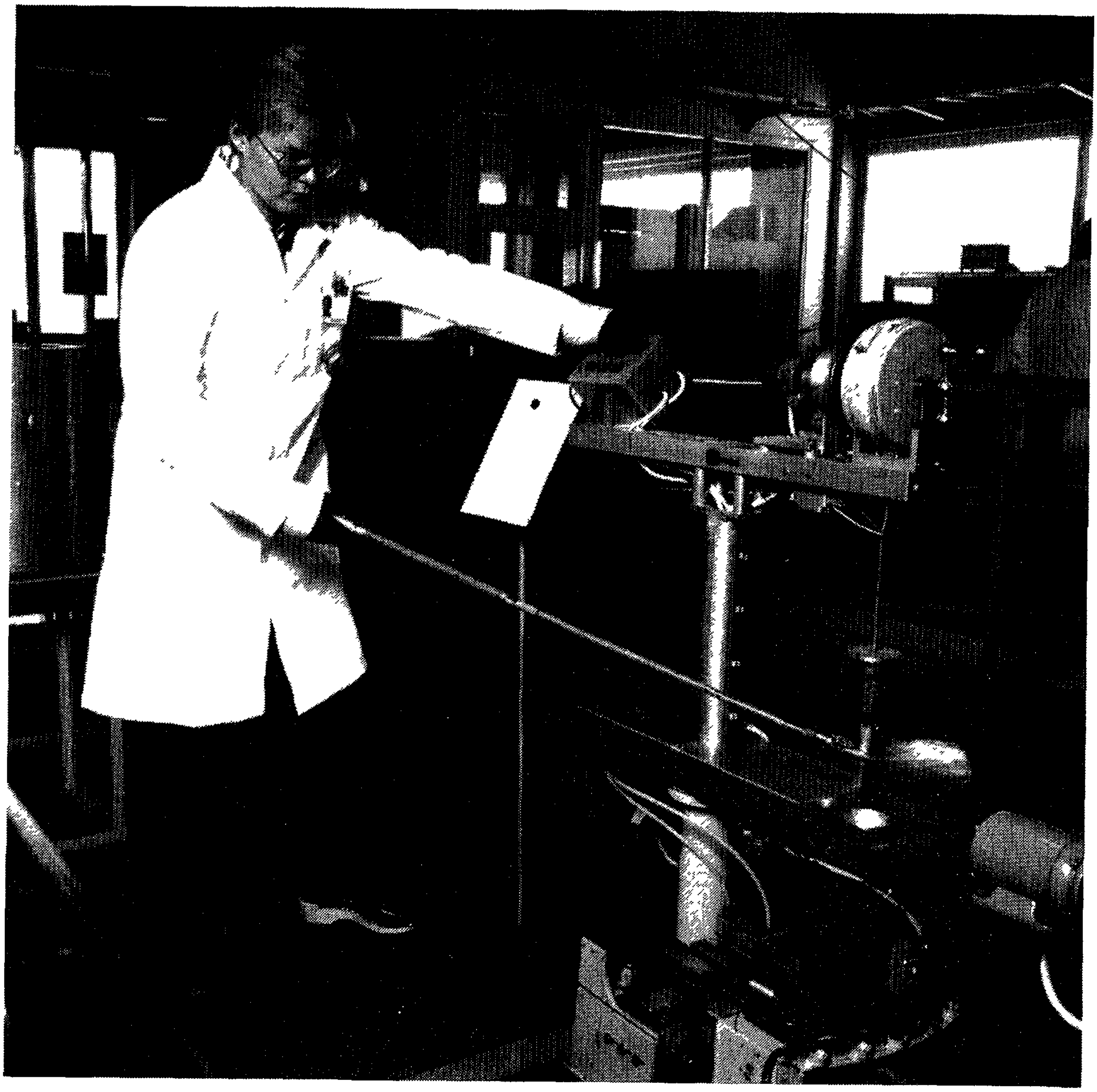


FIG. 4.6. Samples are inserted into the Lazy Susan using an electric lift.

4.3.3 OTHER MANUALLY LOADED SITES

Manually or mechanically loaded irradiation sites in the core or the reflector can be obtained by replacing fuel or reflector elements. Thus the size of the position is determined by the size of the element. In Triga reactors containers, approx. 3 cm in diameter, can be inserted. Usually the central core, with the highest flux, is used for irradiations. In other types of reactor positions up to 8x8 cm can be created this way. In some cases rotating irradiation devices are used to obtain a homogeneous flux [157]. Especially in the core of small reactors high flux gradients are common. Large irradiation positions with diameter up to 25 cm can be constructed inside or outside the reflector of a pool type reactor. Outside the reflector the flux decreases rapidly.

4.4 IRRADIATION IN MODIFIED FLUX

4.4.1 THERMALIZED FLUX

In some cases the thermal column is used for irradiation in order to get a well thermalized flux. Because of the low flux obtained compared with positions in or near the core, it is applied for very special reasons only, or in high-flux reactors. A pneumatic transfer system or a manually loaded position of almost any size can be constructed. In practice, the thermal column is very seldom used for NAA.

4.4.2 EPITHERMAL IRRADIATION FACILITIES

Epithermal NAA is very commonly used and a number of different applications have been reported. In principle, there are two main approaches with some modifications. One is to use an irradiation container made of cadmium metal or boron. The other possibility is to make a cadmium or boron-lined irradiation position. Cadmium is easily fabricated to any form. The cut off energy of 1 mm of cadmium is 0.5 eV. Boron, in the form of nitride or boric acid, is more difficult to fabricate, but it is less heavy and does not produce radioactivity, making it feasible to use in rabbits for pneumatic transfer systems. Its cuto-ff energy is approximately 280 eV, but depends on the thickness of the absorbing layer. Heating from the (n,α) reaction can be considerable and often cooling is needed. A special application is to mix high purity boron carbide with the sample [158].

In the Reactor Laboratory of the Technical Research Center of Finland the Lazy Susan of a Triga reactor is used to irradiate 600 half-gram samples in cadmium. That is accomplished by using 20 aluminium containers, inserted in the rotary specimen rack of the Triga MkII reactor. The dimensions are: diameter 30 mm x 250 mm, lined with 1 mm of cadmium and 0.2 mm of aluminium again (Fig. 4.7). The containers are kept in the reactor all the time. They are only lifted up when samples are inserted or removed. Most epithermal irradiation positions are made from cadmium. Boron can also be used. For example, at Los Alamos an irradiation facility is made by pressing sleeves of 50% elemental boron and 50% aluminium [159]. The wall thickness is 2.5 cm containing 2.3 g/cm^2 boron. The facility is cooled with water because of the considerable heat generated in the boron.

The benefits of using epithermal NAA are discussed in chapters 2 and 8.5.

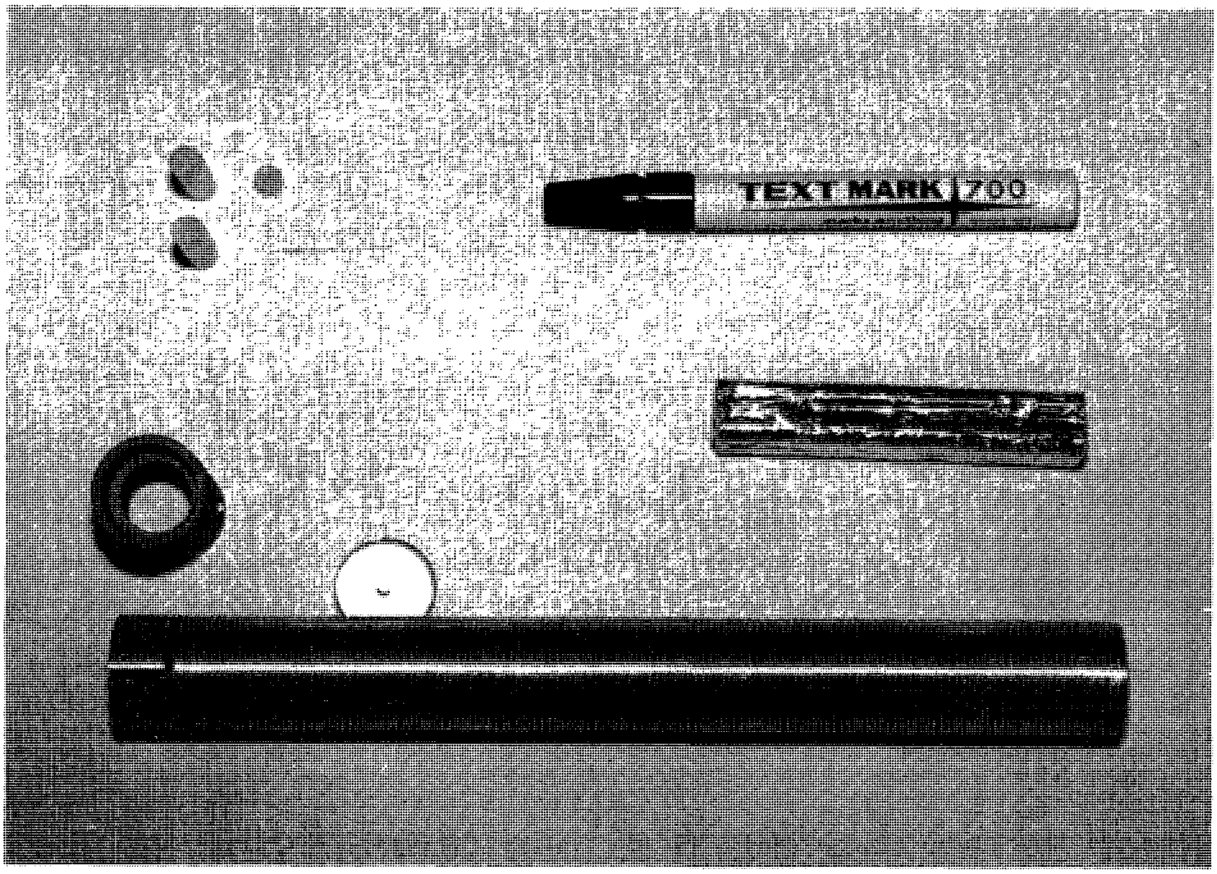


FIG. 4.7. Polyethylene capsules wrapped in aluminium foil, ready for irradiation in cadmium containers also shown in the figure.

4.4.3 FAST NEUTRON IRRADIATION FACILITIES

In principle a pure fast flux can be obtained using shields of ^{235}U or LiD which both absorb thermal neutrons and generate more fast neutrons, ^{235}U by fission and LiD by the reactions $^{6}Li(n,alpha)T$, $^{2}H(T,n)^{4}He$. Because of the high threshold energies of most fast neutron reactions the production of 14 MeV neutrons using LiD is more popular. Conversion rates between 2.10^{-4} and $9.6.10^{-4}$ fast neutrons per thermal neutron have been reported [160/161]. The heat produced in the containers and the high proportion of epithermal neutrons restricts its usefulness and therefore it has not found many applications.

5. COUNTING AND DATA PROCESSING FACILITIES

5.1 TYPICAL COUNTING SYSTEMS

One of the steps of every INAA procedure is the measurement of induced radioactivity which, with a very few exceptions, is being done by gamma-ray spectrometry. The basic set-up of a gamma-ray spectrometer for use in INAA is shown in Figure 5.1. It consists of:

- a semiconductor detector with associated preamplifier,
- a high-voltage power supply, a spectroscopy amplifier,
- an analog-to-digital converter (ADC),
- a multi-channel pulse height analyzer (MCA), and
- a computer-system with input/output facilities.

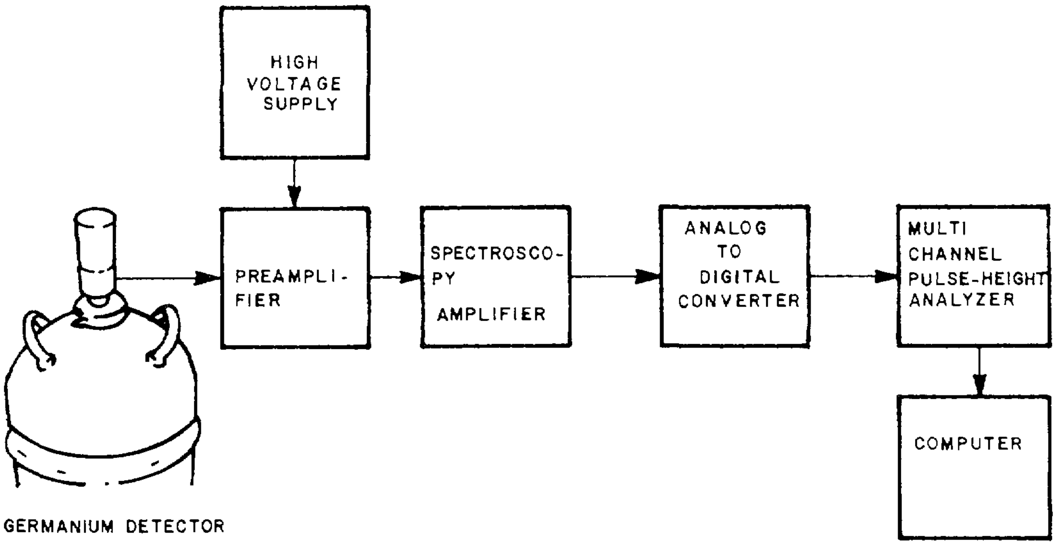


FIG 5 1 Schematic set-up of gamma ray spectrometer for use in INAA

Sometimes two or more of these functions are combined, e.g., ADC and MCA, or MCA and a computer system. Both integral apparatus and modular build-up apparatus exist. Modular systems are more complicated than integral ones, and require more technical expertise to set it up, to interface the different parts, and to operate it properly. The main advantages are flexibility and interchangeability; malfunctioning units can be more easily located, replaced and repaired; and the system can continuously be upgraded, changed or extended when new or more advanced units are released, or when applications change or grow. Spectrometers built with modular systems will initially be more expensive, but turn out to be over the years often more economical than integral systems. For this reason mainly modular spectrometers are in use nowadays .

Modular units are built to be put into a rack containing a number of interconnections and a power supply. In 1964, the Nuclear Instrumentation Module (NIM) Standard was accepted. The NIM standard is primarily suitable for processing analog signals, and less suitable for executing complex digital functions. For this the CAMAC-standard was especially designed, but has found most of applications in linking analog systems to larger computer systems.

In several INAA laboratories, more advanced and special purpose γ-ray spectrometers are in use than the set-up described above. Examples are Camac-linked spectrometers [162] , spectrometers with computer controlled amplifiers, anti-Compton spectrometers [163/164]. There are few basic differences, however, between some of the function units used in these spectrometers, and the ones of a simpler spectrometer.

It is not within the scope of this book to go into the fundamentals of the different parts of a γ-ray spectrometer. The presently most common available type of equipment will be introduced, together with some characteristics and practical aspects when applied in INAA.

5.2 SEMICONDUCTOR DETECTORS

The basic element of a semiconductor detector is a single crystal of semiconductor material with a P-I-N diode structure. [N- and P- refers to the nature of the impurities in the crystal. N-impurities are pentavalent atoms, thus acting as electron donors; P-impurities are trivalent atoms, acting as electron acceptors; I = intrinsic layer]. For application in INAA, only germanium detectors are of importance. Germanium semiconductor detectors exist in two versions:

- Lithium drifted germanium detectors, or Ge(Li) detectors
- Hyperpure (HP-) or intrinsic germanium detectors

In a Ge(Li) detector, lithium ions have been drifted into the crystal structure, thus compensating for impurity centers and forming an intrinsic or active region. High-purity germanium crystals may be of P-type (most common) or N-type; for use as γ-ray detectors in INAA there are no basic differences in characteristics between these detector types. Ge(Li) detectors are not being made any more by the leading detector manufacturers. However, detectors of this type are still widely in use at many laboratories.

Coaxial and planar germanium detector configurations exist (Fig. 5.2). The coaxial geometry makes possible detectors with large volumes, which can be used for detecting high energy gamma-rays. Detectors made in the planar configuration are small with low capacitance and low noise levels, and hence very high resolutions can be obtained. This detector type is primarily used for detection of low energy photons.

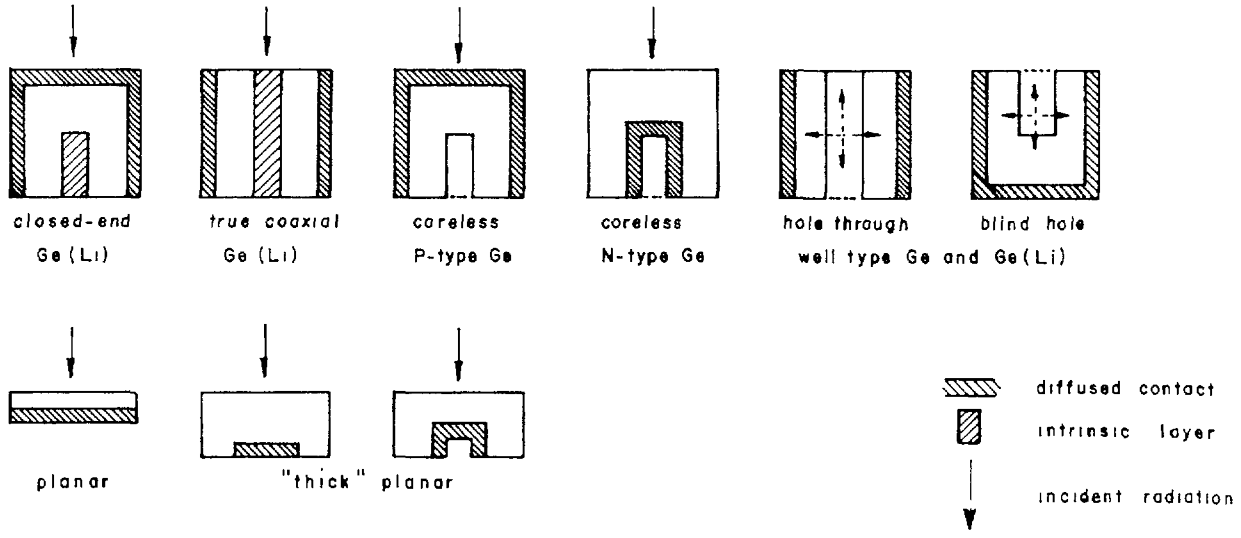


FIG. 5.2. Crystal configuration of germanium semiconductor detectors.

One of the advantages of HP-germanium is that well-type detectors can be more easily fabricated and repaired than ever was attainable with Ge(Li) material, resulting also at more practical large well-diameters (up to 25 mm have been reported), and at highly competitive prices.

Semiconductor detectors are operated at liquid nitrogen (LN2) temperature (77 K). The crystal is mounted in a vacuum cryostat, thermally connected to a copper rod, the 'cold finger' (Fig.5.3a). This cold finger transfers the dissipated heat from the crystal to the cooling medium. Ge(Li) detectors have always to be stored at LN2-temperature; warming up leads to almost irreparable damage. HP-Ge detectors can be stored at room temperature without damaging the crystal as long as the HV bias is removed.

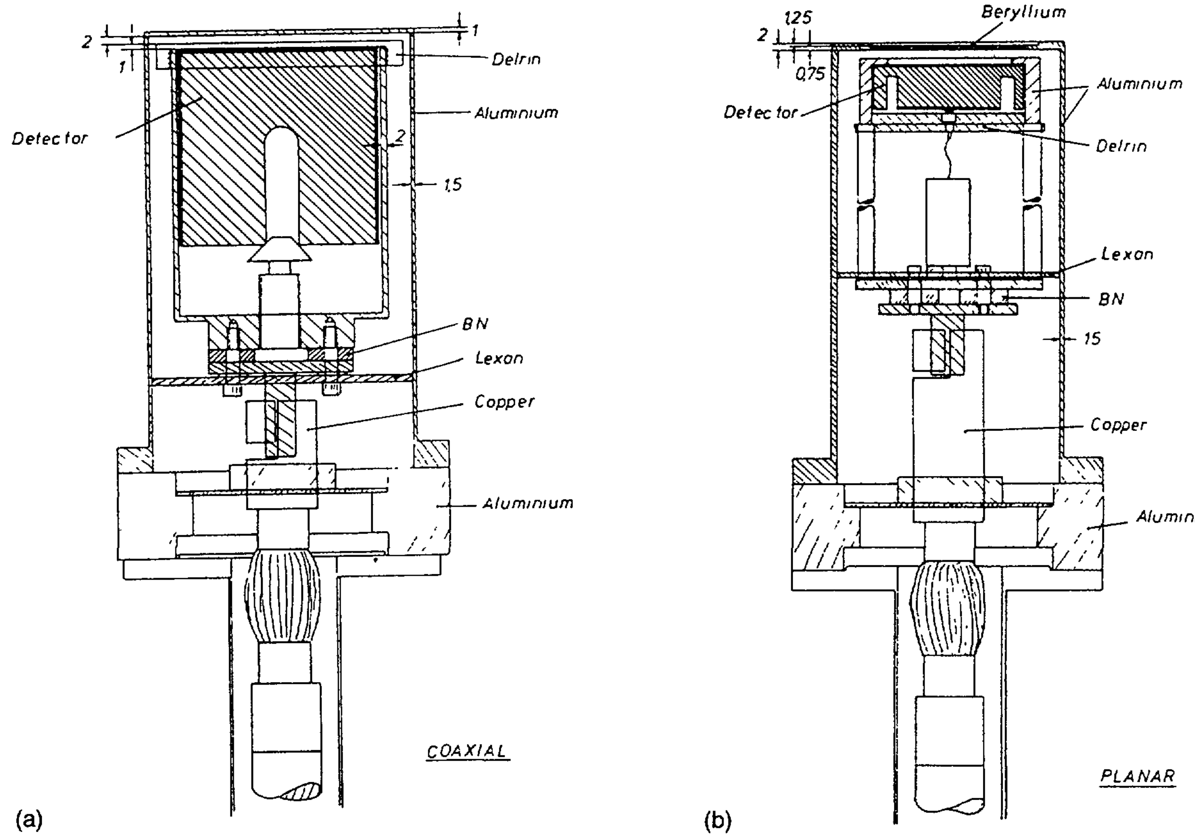


FIG. 5.3. Mounting (schematic) of (a) coaxial and (b) planar germanium detector (from PGT).

Detailed information on the physics of semiconductor detectors can be found in the literature [165/166/167/168] and to some extent in catalogues of detector manufacturers.

5.2.1. COAXIAL DETECTORS

The most generally applicable detector type is the coaxial detector. The majority of coaxial Ge-detectors have P- and N-contacts on a outer surface of the cylindrical crystal and on an axial hole drilled in the bottom of the cylinder. Some Ge(Li) detectors do not have this coreless geometry but a closed-end geometry, or are of the true-coaxial type. The N-contact is a relatively thick (0.5 - 1 mm) diffused layer, whereas the P-contact is ion-implanted, and therefore very thin. Two different detector configurations exist :

a. N-contact on the outside of the crystal, and P-contact on the inside of the drilled core;

b. P-contact on the outside of the crystal, and N-contact on the inside of the drilled core.

a. N-CONTACT ON THE OUTSIDE OF THE CRYSTAL

This is the detector geometry for Ge(Li) detectors, and at present the majority of the HP-Ge-detectors. As the thick N-contact is facing the cryostat's entrance window, and no electrical signals are produced by interaction of the photons within the contact layers, low energy photons are strongly absorbed before reaching the active region. In practice, this detector type can be applied in INAA for measurement of photons with energies higher than 60 keV. For HP-detectors, the starting material is usually of P-type.

b. P-CONTACT ON THE OUTSIDE OF THE CRYSTAL

The HP-Ge crystal is mounted in the vacuum cryostat with the very thin P-contact facing the entrance window. Because of the near absence of absorbing material the detector can be used to measure photons with energies as low as 10 or even 3 keV, depending on the type of window (aluminium or beryllium). The absence of absorbing layers also result in a flat and high efficiency curve for photons with energies lower than 100 keV. Starting material usually is N-type germanium, though some manufacturers also use P-germanium crystals for such a geometry.

When considering an application of a semi-conductor detector in an anti-Compton spectrometer, there are no differences in timing properties between P-type and N-type Germanium detectors [169]. Timing resolution gets poorer with increasing size of the crystal. For capture gamma-ray spectroscopy systems, N-type crystals have the advantage of higher resistance against neutron radiation.

5.2.2. PLANAR DETECTORS

In the planar configuration a germanium P-type crystal of small thickness is used. The crystal is mounted in the cryostat with the thin P-contact facing the cryostat's beryllium entrance window (Fig. 5.3b.). Absorption of low energy photons is thus minimized, and a detector type is created with performance optimized for X-rays and γ-ray energies from 5 keV to 200 keV. Because of the small size, the capacitance of the diode is considerably lower than for a coaxial detector, resulting in a lower noise level and a higher resolution.

Some manufacturers also developed detector types in geometries which resemble both planar and coaxial geometry using a thick slice of detector material. Being a compromise, a detector of this configuration might have a higher efficiency shared by a lower resolution than a true planar detector. Moreover, because of the enhanced efficiency to high energy radiation this detector type also has a higher response to Compton scattered radiation.

At first sight, the coaxial detector-type with thin P-type entrance contact (referred to as 'extended-range coaxial') may seem more useful for application in INAA than the commonly used coaxial detector, because of its extended dynamic range. However, a few practical aspects of extended range γ-ray spectroscopy in INAA should not be overlooked :

a. There are only very limited analytical advantages in INAA of γ-ray spectroscopy with photons of energies as low as 5 keV. For most applications, a lower energy cut-off at 40 or 50 keV is sufficient. Moreover, many spectra will show a complex variety of X-ray peaks and γ-ray peaks in the energy range below 100 keV. To keep this part of the spectrum analyzable, high demands are set to low-energy resolution of the detector, and to analysis software. Gain settings of 250 eV/channel or less may be required resulting in 8192 or even 16384 channels for spectra covering the energy range up to 2000 keV.

b. Coaxial detectors have a high efficiency for high energy γ- rays. In spectra of actual samples the peaks of X-rays and low energy γ- rays will be measured at a high Compton background level of simultaneously interacting high energy photons.

The only real advantage of extended range coaxial detectors when compared to other coaxial detectors for INAA is higher efficiency for 60 - 100 keV photons. The expected analytical merit of measuring peaks in this region has to balance against the higher cost of these detectors.

The ideal approach for measurement of photons in the energy range from 5 - 2000 keV would therefore be a twin detector spectrometer. Here the sample is faced by simultaneously measuring planar and coaxial detectors (Fig. 5.4.), each having optimal performance for a specific energy range, in resolution and in efficiency.

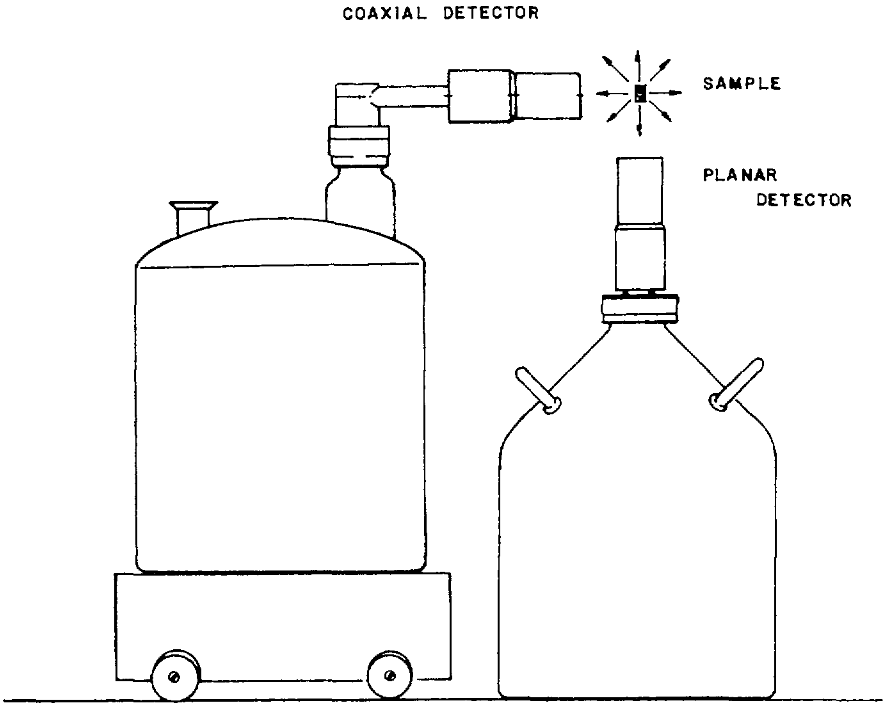


FIG. 5.4. Example of twin-detector spectrometer.

Although each of the detector types has specific advantages, the coaxial detector is a general purpose detector, widely applicable in INAA. For low sample activities (small samples, low concentrations, low neutron fluxes) a well-type detector should considered. A planar detector can be useful for measuring specific radionuclides emitting low-energy gamma-rays and X-rays (REE) or to reduce interferences from high energy radiation. But the applicability is limited compared to coaxial and well-type detector due to the low absolute photopeak efficiency and the necessary correction for self absorption at these low energies.

5.2.3. PERFORMANCE OF GERMANIUM DETECTORS

In Table 5.1 a survey is given of detector types, crystal configurations, practical energy ranges, sensitivities and resolutions for semiconductor detectors, used in γ-ray spectrometers for INAA.

TABLE 5.1 SURVEY OF SOME CHARACTERISTICS OF CURRENT DETECTOR TYPES

DETECTOR TYPE	CRYSTAL CONFIGURATION	CRYSTAL DIMENSIONS, RELATED REL.EFFICIENCIES		TYPICAL P/C-RATIO	TYPICAL RESOLUTION IN keV (FWHM) AT			APPLICABLE FOR ENERGY RANGE (keV-keV)
					5.9 keV(^{55}Fe)	122 keV(^{57}Co)	1332 keV(^{60}Co)	
PLANAR	NORMAL	area 25-1000 mm^2 thickness 5-15 mm		- -	0.150-0.350	0.450-0.650	-	3-200
	THICK	area 500-2500 mm^2 thickness 15-25 mm		- -	0.350-0.500	0.650-0.750	-	5-500
COAXIAL	TRUE COAXIAL Ge(Li)	50-175 cm^3	10-40%	35:1-50:1	-	0.8-1.2	1.7-2.2	>30
	CLOSED-END Ge(Li)	50-175 cm^3	10-40%		-	0.8-1.2	1.7-2.2	>40
	P-TYPE Ge	50-200 cm^3*	10-50%	35:1-60:1	-	0.8-0.95	1.75-2.2	>40
	N-TYPE Ge	50-175 cm^3*	10-40%	35:1-50:1	0.600-0.700	0.8-0.95	1.8-2.2	>5
	WELL-TYPE Ge	70-150 cm^3 cryostat well diameter 10 mm - 25 mm		-	-	1.2-1.5	2.1-2.4	>30

* Detectors with rel. efficiencies as high as 80-90% have recently been constructed; these detectors are not yet considered here as standard types.

When selecting a semiconductor detector, the following characteristics play an important role :

- energy resolution and peak shape,
- peak to-Compton ratio,
- efficiency,
- crystal or well dimensions, and
- price (not discussed here).

a. ENERGY RESOLUTION AND PEAK SHAPE

The resolution of a detector is a measure for the ability to separate closely spaced peaks in the spectrum. Resolution is a function of γ-ray energy and is specified in terms of Full Width at Half Maximum (FWHM) of the 122 keV photopeak of ^{57}Co and the 1332 keV photopeak of ^{60}Co for coaxial detectors; for the 5.9 keV photopeak of ^{55}Fe and the 122 keV photopeak of ^{57}Co for planar detectors . For most applications in INAA energy resolutions as good as 1.8 keV at 1332 keV and 1.0 keV at 122 keV are sufficient. Resolution depends on the size of the detector, and in particular on its capacitance. The larger the detector - and its photopeak efficiency - the higher its capacitance will be, resulting in a slightly poorer energy resolution. For the same reason (higher crystal capacitance) well-type detectors always will have poorer resolutions (e.g. 2.2 keV at 1332 keV and 1.4 keV at 122 keV) than coaxial detectors of comparable size. When using a planar detector, resolution in the low energy range (< 250 keV) depends on detector size, and type of preamplifier (see paragraph 5.3.1.). In order to get a sufficient separation of the lines, resolutions as good as 300 eV at 5.9 keV and 700 eV at 122 keV are a necessity.

However, not only the FWHM has to be considered when selecting a detector, but also the actual shape of the measured peaks. An indication of the quality of a detector to produce peaks with (semi) Gaussian shapes is obtained from the ratio of the Full Width at Tenth of the Maximum (FWTM), and the Full Width at Fiftieth of the Maximum (FWFM) to the FWHM-value. Theoretical values for a Gaussian peak are FWTM/FWHM =1.83, and FWFM/FWHM = 2.38; these values should be approached at least as close as 1.9 and 2.7, respectively.

b. PEAK-TO-COMPTON RATIO

The Peak-to-Compton (P/C) ratio is a measure of the detector's ability to distinguish low-energy peaks in the presence of high energy sources. P/C ratios are specified for the ^{60}Co spectrum as the ratio between the height of the 1332 keV peak and the number of counts per channel in the 1040-1096 keV region.

In the low-energy region of the γ-ray spectrum (below 150 keV) the photoelectric interaction is dominant, and because of the limited sensitivity of planar detectors for high energy photons the contribution of Compton interaction in the detector to the total of interaction processes is rather small and normally neglected (cf. Fig 5.5.). As a result, a planar detector has certain advantages for measurement of radiation of intermediate energy (up to 300 keV) in the presence of high intensities of high energy radiation, e.g., from ^{24}Na, ^{46}Sc, ^{38}Cl or ^{60}Co.

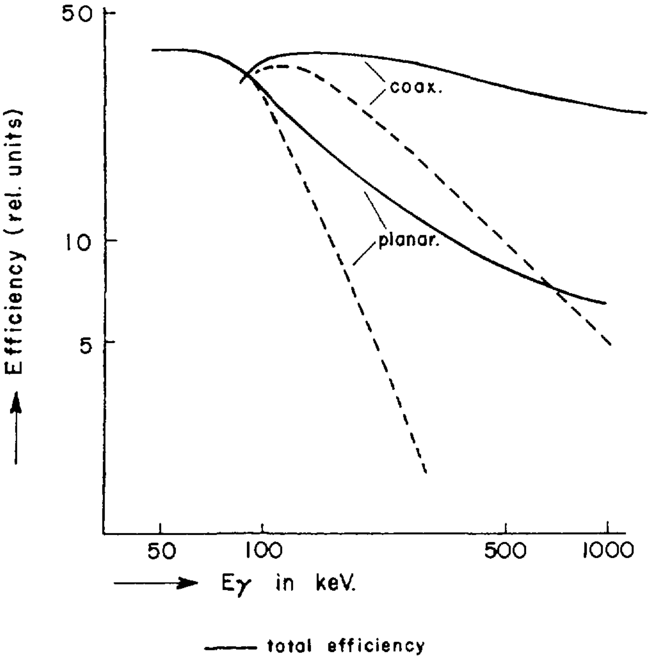


FIG. 5.5. Photopeak efficiency and total efficiency of planar and coaxial detectors.

c. DETECTOR EFFICIENCY

Detector efficiency depends on energy of the radiation, position of the sample relative to the detector, thickness and composition of the detector window and dimensions and composition of the active volume of detector material. The photopeak efficiency of coaxial detectors is measured according to an IEEE-standard and is specified for the 1332 keV photopeak of ^{60}Co by the ratio between the measured absolute photopeak efficiency of the semiconductor, and the absolute photopeak efficiency at the same sample-detector distance (25 cm) of a 3" x 3" NaI(Tl) detector, which is defined to be 1.2 x 10^{-3} counts per photon. The efficiency of a well-type detector is measured according to a different standard protocol, leading to a value for the absolute photopeak efficiency of a single line source measured inside the detector's well (section 8.7).

For most INAA applications in which moderate or high induced activities have to be measured (e.g., > 10^3 - 10^4 Bq), coaxial detectors with relative efficiencies in the range 10 - 20 % will suit.

When there is a need for measuring low or very low activities, or natural radioactivity, price and performance of large Ge-detectors and well-type detectors have to be compared. As an example, Fig. 5.6. shows absolute photopeak efficiencies of equal volume coaxial and well-type detectors, under practical counting conditions.

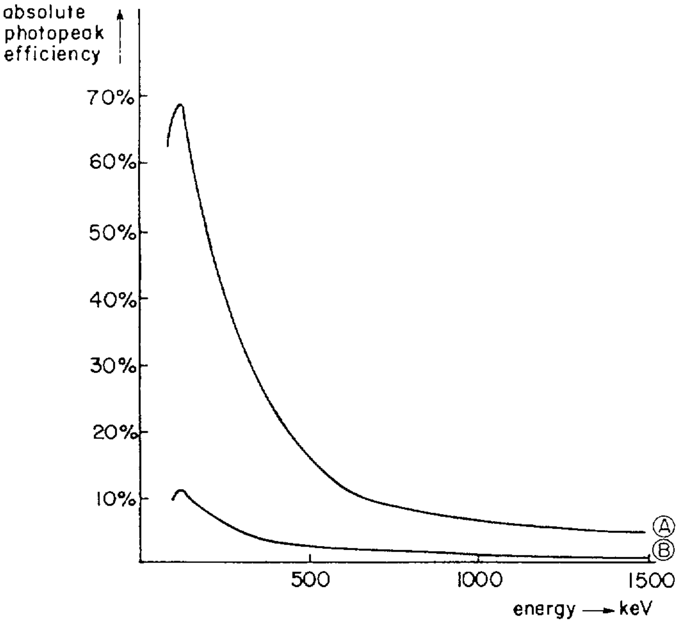


FIG. 5.6. Absolute photopeak efficiency of 125 cm^3 well-type and coaxial detectors, measured respectively inside cryostat well and at source-end cap distance of 2 cm.

In the low energy part of the gamma spectrum, detector efficiency is more determined by absorption cross-section than by total detector volume. Therefore, with planar detectors no efficiencies are specified; instead, sensitivity has to be derived from detector thickness and surface area. A choice depends strongly on the energy range of interest, as the lower the photons to be measured, the higher the resolution has to be. In reported applications of planar detectors in INAA [34/24/37/36/170/171/172] detectors are used with areas varying from 50 mm^2 to 500 mm^2 and with thicknesses from 5 to 10 mm.

d. CRYSTAL DIMENSIONS AND CRYSTAL WELL DIMENSIONS

From crystal dimensions an impression can be get about the relative efficiency for γ-ray energies lower than 1332 keV [173]. Best performance for the energy region below about 1 MeV is obtained when detectors have a crystal diameter which exceeds their length.

Sensitivity increases roughly with the square of the distance between sample and crystal. But as also geometric errors increase strongly when counting close to the crystal, information on the precise position of the crystal in the cryostat is important. Such distances may vary from a few mm to about 1 cm. It should be noted here that geometric errors are to a large extent absent when measuring inside the well of a well-type detector [174].

For well-type detectors, usually only the dimensions of the 'room-temperature well', or cryostat well are given. The exact location of the crystal with respect to the cryostat well should also be known. Blind-hole or hole-through configurations exist (Fig. 5.2.); detectors with blind-hole, or single open-ended configuration generally will show somewhat poorer resolution, as the complex mounting of contacts and wires introduces enhanced noise levels. The advantage of the blind-hole configuration is that the active material at the bottom leads to a higher efficiency. This is especially of importance for large well configurations, in which for a hole-through type the solid-angle losses would lead to a reduction in efficiency. The hole-through detector type has the advantage of higher resolution; when the cryostat well is completely penetrating through the active volume large sample volumes can be surrounded by detector material.

f. CRYOSTATS AND DEWARS

Although for most INAA applications, detectors both vertical and horizontal dipstick cryostats are used, vertical dipstick configurations have the additional advantage of placing samples on top of the end cap (e.g., Marinelli beakers). The development of streamlined cryostats with preamplifier mounted in a more or less extended end cap, and the availability of cryostats with extended 'necks' make possible to shield these types of detectors relatively easily.

In an alternative design the entire end cap assembly, including preamplifier, can be disconnected from the cold finger part, without disturbing the vacuum. By this approach the detector configuration can be altered from horizontal into vertical dipstick, without the high cost of remounting the crystal. For special purposes, e.g., very low level counting or measurement of natural radioactivity, some manufacturers have detector cryostats in which all construction materials have been carefully selected for the absence of traces of natural radioactivity.

In the cryostat a thermal insulation shield is often mounted around the crystal. In a well-type configuration such a shield is absent between cryostat well and crystal well. As a result, the cryostat well will always have a lower temperature because of the large temperature gradient, and condensation of moisture may occur. There are no rules of thumb on the lifetime of the molecular sieve inside the cryostat; the only practical measure one has is the weekly LN2 consumption. Experience showed that lifetimes as long as 10 years or more are very normal. Molecular sieves tend to vent gas when detectors are warmed-up to room temperature, which may lead to pressure build-up in the cryostat. In manuals of planar detectors and N-type detectors with Be-windows extensive attention is paid to how such a warm-up has to be carried out with a minimum of risk for explosion of the window. Although the sieve tends to restore vacuum when cooled down again, continuous storage at LN2-temperature is probably more safe. It should be noted that some detectors have always to be kept upright to keep the sieve in place in the cryostat.

5.2.4. LIQUID NITROGEN SUPPLY

Because of the heat dissipation in the crystal, and the imperfect insulation of both cryostat and dewar, LN2 is consumed at a normal rate of 5 - 10 L/week, depending on crystal size. Theoretical holding time for a 30 L dewar is therefore about 3 weeks under normal laboratory conditions. When considering the purchase of a Ge(Li) detector, one should be sure that LN2- supply is regular, at least on a weekly basis.

Safety precaution systems like LN2-level indicators, alarms, high-voltage shut-off systems, and automatic filling devices are available. However, these systems may go off during the night or in weekends or even may not work at all when needed. The proven safest way of maintaining a detector system is to set up a regular manual filling scheme. By filling a detector once a week (by preference on a fixed day), there is never any doubt whether there is enough LN2 in the Dewar. It is important to train as many employees in a group as possible in this procedure, so that no situations may occur in which the person-in-charge is absent and nobody knows what to do.

Filling LN2 dewars can be done with self-pressurized LN2 containers (volumes 50 - 300 l), or using a spare 30 L Dewar as supply and pressurized nitrogen gas. This has to be done at low overpressure (less than 1 atmosphere, 10 - 15 psi). Also LN2-pumps are available. When applying the tubing between detector dewar and supply container, PVC-tubes, when cooled down and under mechanical tension, may 'explode' into many very sharp pieces; better cryogenic resistance is shown by polyethylene or silicone tubing. Attention has also to be paid to the gas-exhaust tube, which has to be led sufficiently far away from the cryostat and preamplifer. During filling, check regularly that there is no spilling of LN2 in the vicinity of the cryostat. Although LN2-drops evaporate quickly, a regular spill may eventually lead to cracks in the vacuum seal rings of the cryostat.

Some detectors show excessive microphonics during the filling process. In such a case data accumulation can be interrupted for a few minutes to prevent distortion of the measured spectrum.

There are some developments going on in mechanical, electrical and He gas cooling systems for semi-conductor detectors. Such detector systems certainly have advantages when working in remote areas, or in field laboratories. For INAA laboratories, the use of such detectors should only be considered when LN2 supply is highly irregular. Maintenance, like absorber change or vacuum restoration has to be done about once or twice a year when the detector is used continuously. The resolution of such detector systems is worse than for LN2-cooled systems, and the price is considerably higher.

5.2.5. SELECTING A DETECTOR

Several questions have to be asked before a detector can be selected from a catalogue or a stock list. First, what is the type of work it will be used for? Do you expect to use it solely for measurements of moderate and highly active samples (i.e. > 10^3 - 10^4 Bq) , or can it be foreseen that in the future also measurements have to be done of samples of somewhat lower activity? This may help to choose between a 10 % or 20 % coaxial detector. But if only low or very low induced activities are expected, or measuring natural activities is or will be one of your tasks, the purchase of a well-type detector should be considered.

Try to define which elements will be of importance, their related radionuclides, and γ-ray energies. It may contribute to making a choice between a planar, an extended range coaxial or a normal coaxial detector. When type and size (efficiency) are known, the next thing is to try to find a detector with a peak-to-Compton ratio as high as you can afford. The P/C ratio ultimately defines sensitivity for many nuclides. Detectors with a high P/C ratio are of particular importance when the detector is needed for measurements of short half-life nuclides, as in many cases sensitivity is influenced by the high Compton continuum from ^{28}Al. Note that detectors from different manufacturers, though of comparable size (efficiency) and resolution, may have different P/C ratios. You will also see that the higher the P/C ratio, the better the resolution (and, usually, the higher the price).

It has been stated before that a resolution of 1.8 keV for ^{60}Co is sufficient for most applications. Remember that to exploit better resolution, you have to spread your 2 MeV spectrum over at least 8192 and maybe even 16384 channels to get analyzable peaks (i.e., peaks which are spread-out over more than 1 channel). Almost all manufacturers are capable now in specifying peak shapes in terms of FWHM, FWT(tenth or twentieth)M, or FWF(fiftieth)M.

With well-type detectors there will always remain the limitation of the usable cryostat-well dimensions related to the sample containers you want to use. Ask the different manufacturers for accurate information on size and position of the crystal in the cryostat, and make scale drawings to get an idea how your sample will be located in the cryostat well with respect to the active region of the detector. It appears that for well-type detectors, most manufacturers are willing to make custom-made detectors.

When high humidity occurs in your counting room, or when high count rate experiments are expected, it may be worthwhile to discuss this with the manufacturers; some have possibilities to treat the preamplifier for this. Choice of preamplifier is the next step. Check with the manuals of the other spectrometer parts you already may have or which you selected whether the main amplifier and ADC are able to process reset pulses.

Sometimes a stainless steel end cap may be preferred above the standard Al end cap (better rigidity and better resistance in corrosive atmospheres); decide also whether you really need a fragile, expensive Be-window, or if an Al-window will do. Horizontal cryostats have the advantage of easier shielding, especially if the detector comes with an offset-port Dewar; the advantage of vertical cryostats is the possibility of placing the sample on top of it (e.g., Marinelli beakers).

Finally, if you start negotiating with one or more manufacturers, never tell them beforehand your budget. Select a detector which comes close to your demands and budget, and then start negotiating the price.

5.3 BASIC ELECTRONICS

In the following paragraphs the basic system parts of a γ-ray spectrometer will be briefly described, with the emphasis on the existing differences related to application in INAA. Detailed information on specifications and conditions for use can be found in catalogues and manuals.

5.3.1. PREAMPLIFIERS

The preamplifier has the following functions :

- impedance matching
- conversion of an input charge pulse into an output voltage pulse
- signal amplification

Several components of the preamplifier have been carefully selected to meet the detector's electronic characteristics; to reduce noise, some circuits are built into the cryostat (cooled input Field Effect Transistor or FET). This input FET can easily be damaged by improper use or treatment. Both AC-or DC-coupled systems exist. With a very few exceptions, DC-coupling is standard as it offers better resolution, and less probability of FET breakdown.

Three different types of preamplifiers are of importance for detector systems in INAA :

a. resistor feedback preamplifiers
b. pulsed optical feedback preamplifiers
c. transistor reset preamplifier

The resistor feedback preamplifier is the most commonly applied, and coaxial detectors are usually so equipped. The pulsed optical feedback preamplifier (POFB) is used in systems where very high resolutions are required (e.g., with planar detectors). The transistor reset preamplifier has advantages in systems where high energy, high count rates have to be processed without spectrum distortion. However, this goes at the cost of increased main amplifier dead-time. It should be noted that the reset pulse in these systems set requirements to the type of main amplifier or ADC (inhibit connections, high shaping times). Moreover the principles of the applied reset system should be studied carefully, as it has been shown that sometimes circuits have been incorrectly designed, leading to erroneous results [175/176/177/178].

The high-voltage loops in the preamplifier make necessary to protect them against moisture, e.g., condensation due to the LN2-vent. The best solution is to lead the exhaust away from the preamplifier. In humid atmospheres it can be necessary to cover the preamplifier with a bag filled with some silica gel. Repairing a damaged FET has to be done by the detector manufacturer to match the new FET optimally with the detector's characteristics. Sometimes, when the FET is not cooled, disconnecting the preamplifier may be considered because of easier transportation. However, one should be aware that any soldering at the cryostat's feedthrough has to be done with great care and many precautions. If inevitable, soldering has to be done by preference at the preamplifier end. Especially when the preamplifier has been repaired, instructions from the manufacturer are needed to prevent the new FET from being damaged again when soldering during remounting. The best solution to have a preamplifier repaired is to send the entire detector assembly to the manufacturer. HP-germanium detectors have the advantage that they can be warmed up for this; transportation of a Ge(Li) detector system always is more difficult because of the LN2-requirements. If the damaged FET is in a cooled section of a Ge(Li) detector, it should seriously be considered to purchase a new detector, as repair - if possible anyhow - presumably will be very costly.

5.3.2. NIM-BIN AND POWER SUPPLY

The NIM-bin is the supporting rack for 12 modules made in the NIM-standard; the power supply provides the necessary DC-voltages on the connectors in the bin. Most bins supply the standard DC-voltages ±24 V, + and -12 V; taking into account the power requirements of some newer NIM modules, it is recommended to purchase only bins which also provide ±6 V. When all the positions in the bin are expected to be used, it might be sensible to consider a rack with higher output power, especially +6V, than the standard model. Most NIM-bins have front panel control, and indicator and monitoring positions for DC output. It is required to place the bin in such a way that a good air circulation takes place through the module. Sometimes mounting feet are available when used as a tabletop rack. Large rubber stoppers make convenient feet.

5.3.3. HIGH VOLTAGE POWER SUPPLY

NIM high voltage power supplies for semi-conductor detectors have typical output characteristics of 3 - 5000 Volts, at low currents and with a low noise level. The increasing quality of semi-conductor detector elements have made it possible to operate them at increasing maximum high voltage levels. When selecting a new high voltage power supply it might be considered to purchase one with a higher maximum output voltage than necessary for the present detector in use, especially when this detector is relatively old and may be replaced in forthcoming years. Most units have built-in dV/dt networks. In case of an electricity failure, output voltage drops off slowly in time and is also restored slowly to the preset value when the interruption is over. In older detector systems, abrupt changes of the high voltage may damage the FET. In modern detectors, often HV filters directly connected to preamplifier are applied, with built-in HV time constants varying from 5 - 10 seconds.

Before applying high voltage, be sure the polarity is set correctly for the detector.

5.3.4. SPECTROSCOPY AMPLIFIER

The spectroscopy or main amplifier is a key unit in the γ-ray spectrometer. Its functions are :

- linear amplification of the pulses from the preamplifier to levels suitable for pulse height analysis (0 - 10 V);

- improvement of signal-to-noise ratio by shaping of the signal pulses;
- DC power supply to the preamplifier.

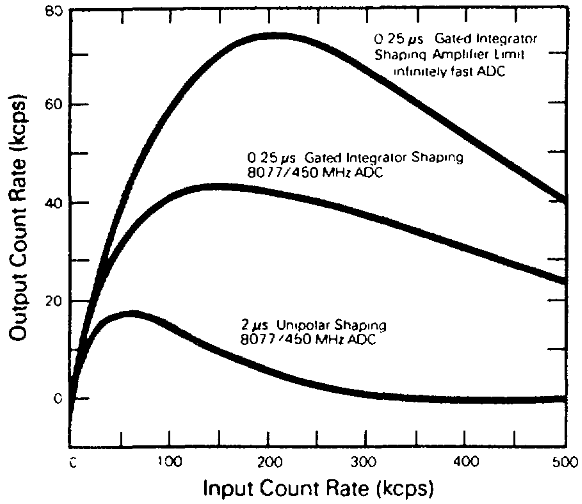
The performance of spectroscopy amplifiers is defined by energy resolution at low count rate and by gain and resolution stability as function of count rate. There are no great differences in specifications of the top models of different manufacturers. In practice, some differences in performance may occur due to the combination with other parts of the spectrometer. A try-out of several models before purchasing is therefore very valuable. There is no reason in trying to save money by buying the second best spectroscopy amplifier from a series or when balancing between manufacturers. Price differences are not large, and in fact almost negligible in the total cost of the spectrometer. For use in INAA where high performance, high stability and reliability over many years is a necessity, premium amplifiers offer best value for money.

As the shape of pulses may affect the signal-to-noise ratio, energy resolution and dead-time of an entire system, much attention has been paid to these networks. The following methods of pulse shaping are being applied :

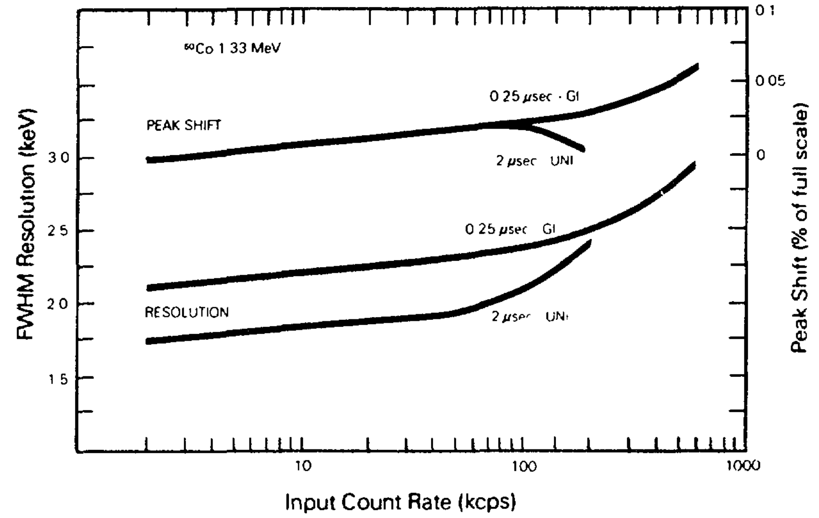
a. (Semi) Gaussian shaping,
b. Triangular shaping,
c. Gated integrated pulse shaping.

For a long time (semi) Gaussian shaping has been the only pulse shaping method, and is still the most common. On a theoretical basis it was known that a triangular shaping network would not only lead to an even better signal-to-noise ratio, but would also permit higher pulse processing rates. Only recently have amplifiers with such networks become available. Especially for high count rate spectroscopy systems the gated integrated pulse shaping network can be used. The advantage of this pulse shaping method lies in higher system throughput; however, this goes at the cost of about 10-15% loss of energy resolution for high-resolution detectors (Fig. 5.7.).

All shaping networks have selectable time constants. Choosing a time constant has to be done by experiment, observing the system resolution and the count rate effect of the setting. From the detector specification sheet, some indication can be observed on the time constant to be chosen; as a rule of thumb, for Ge(Li) detectors 2-3 μs, HP-Ge detectors 3-6 μs and planar detectors 6-8 μs are nearly optimum settings for Gaussian shaping networks.



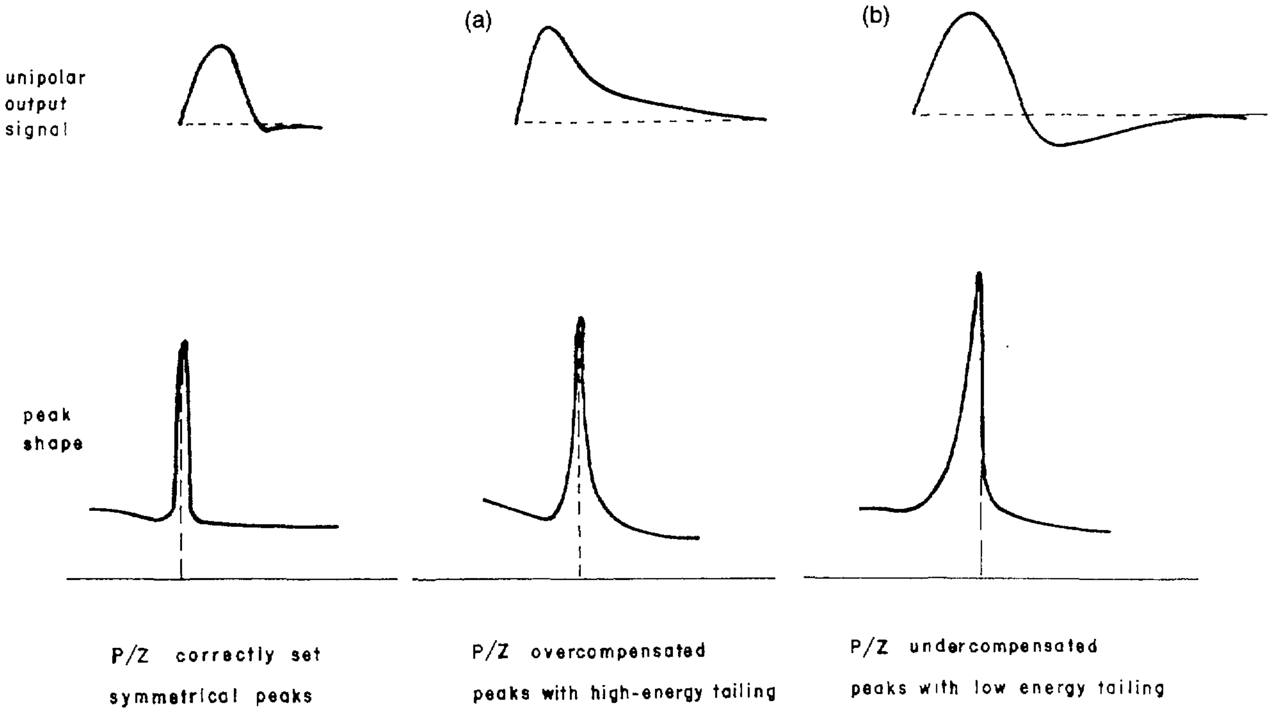
Throughput for 2 μs Unipolar and 0.25 μs Gated Integrator Outputs: 5 V Average Input Pulse Height and 4k ADC Conversion Gain



Resolution and Peak Shift Stability vs. Counting Rate and Shaping, AUTO Restorer Threshold, ASYM Restorer Mode and a 1.33 MeV ^{60}Co Gamma Peak

FIG. 5.7. Comparison of effect of unipolar and gated integrated pulse shaping networks on performance of spectrometers.

Modern amplifiers are equipped with built-in baseline restorer and pole-zero network, to achieve a proper return of the tail edge of the pulse to the baseline, and to remove any under or overshoot (Fig. 5.8). Correct setting of the BLR and P/Z control requires some experience, but manuals are well documented. A recent development in amplifier technology is the automatic adjustment of P/Z networks. Most top models in a series of spectroscopy amplifiers have also an integrated pileup rejecting network (PUR). Due to pile up, system dead-time increases, spectrum distortion occurs (introduction



P/Z correctly set symmetrical peaks

P/Z overcompensated peaks with high-energy tailing

P/Z undercompensated peaks with low energy tailing

FIG. 5.8. Effect on peak shape of (a) wrongly set pole-zero network and (b) pile-up.

of unwanted peaks, peak-shifts) and resolution degrades. The PUR network of an amplifier recognizes pulses subject to pileup, prevents their processing by gating off the ADC, and simultaneously controls the live-time correction when the ADC has been integrated with a MCA. The choice of making the PUR-network active strongly depends on the counting conditions, and has to be determined by experiment. In this, also attention can be paid to the effects observed when using the pulser method for dead-time correction in combination with a PUR-active network in the amplifier [179].

The correct matching of DC output level of the amplifier and the DC input level of the ADC is often overlooked. Some amplifiers provide control trimpotmeters for this. An incorrect setting leads to improper functioning of BLR, and to count-rate dependent shifts of all peaks in the spectrum. Finding the optimal setting of a spectroscopy amplifier is a matter of experiment. It can easily be carried out using a ^{60}Co source of moderate strength at a fixed position to the detector, and a more active ^{137}Cs source which can be placed at different distances to the detector in order to alter the total count rate. The position and width of the ^{60}Co peaks is then observed as a function of changing count rates for different settings of time constant, BLR, threshold etc. (see also paragraph 5.3.7.). Also the degree of pile up and system throughput can be observed as function of time constant and count rate (Figs. 5.9 and 5.10 from [180]). Such an adjustment experiment however requires that amplifier gain and ADC conversion gain and offset are thus chosen that peaks are measured with, e.g., 0.15 eV/channel.

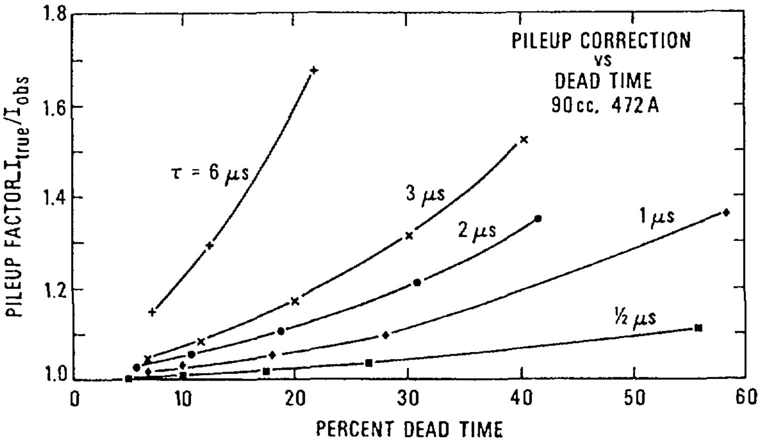


FIG. 5.9. Dependence of pile-up correction factor on dead time. The reference source is ^{60}Co, with varying amounts of ^{137}Cs to change the counting rate.

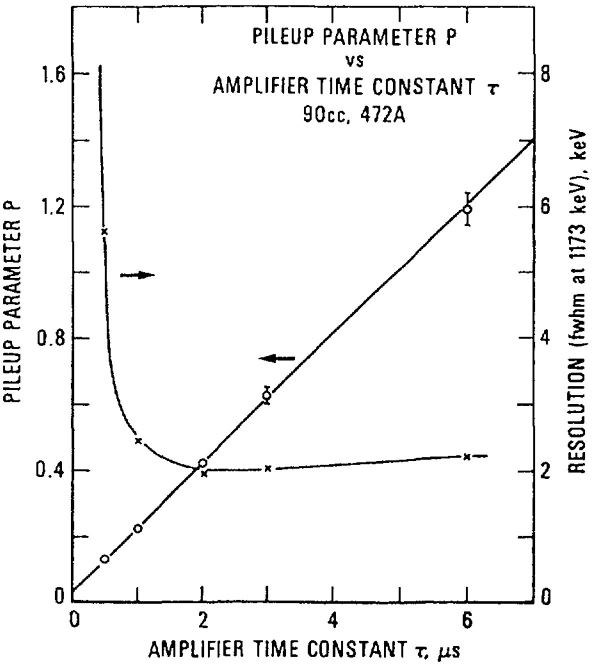


FIG. 5.10. Pile-up parameter P derived from the data set of Fig. 5.9. The optimum balance between small pile-up correction and good resolution is reached for a time constant of 1–2 μs.

5.3.5. A.D.C.

Analog-to-Digital Converters convert the pulse height of the amplifier output signal into digital information for storage in an address or channel number in a memory. ADCs often form an integrated part of multi-channel analyzers; NIM ADCs sometimes offer more flexibility and control options. For the conversion of the analog signals into digital information, two approaches exist :

- the linear approximation approach which has lead to the Wilkinson type ADC;
- the successive approximation approach resulting in the fixed conversion or fixed dead-time type ADC.

In the conversion process of a Wilkinson type ADC, high frequency clock pulses are employed; the higher the clock frequency (50, 100, 200 or even 450 MHz) the faster the analog signals are digitized, and the lower the dead time per event. The dead time per event of such an ADC consists of a fixed dead time per conversion (e.g., 2 µsec for a 100 MHz version), and a variable dead time per conversion, depending on the converted ADC address (for a 100 MHz ADC : 0.01 * channel number). Therefore, a twice as high clock frequency does not necessarily imply half the dead time at a given count rate. Successive approximation ADCs exist with fixed dead times varying from 1.5 to 20 µsec. As a rough comparison, a fixed dead-time ADC with a conversion time of about 5 µsec has at a conversion address of 2048 about the same processing rate as a 450 MHz Wilkinson ADC.

For application in INAA there is no specific preference for any of these types. Wilkinson ADC's are the more common and may show better linearity, but fixed dead-time ADC's have certain advantages at high count rate spectroscopy. The selection of an ADC also has to be done on the basis of input characteristics (important when the amplifier has to be operated at long time constants), several output options like dead time, busy, inhibit signals (required for hardware dead-time and pile-up corrections), and setting options like channel offset (important in many adjustment experiments with low energy/channel settings), conversion range , zero level control, gating, and options for interfacing with MCAs or computer systems.

5.3.6. AUXILIARY ELECTRONICS

a. PULSE GENERATORS

When during the measurement the count rate does not change due to decay, dead time can be corrected for using the pulser method [181/182]. Pulses from a constant frequency tail pulse generator are fed into the test input of the preamplifier. The pulses thus follow the same signal processing as the detector signals, and are subject to the same total system dead time. In the γ-ray spectrum a peak will be observed, which area can be used to calculate the live time. Of course, the amplitude of the pulser is thus chosen that the peak shows up in the spectrum in a region which is not crowded by γ-ray lines (e.g., between 1900 and 2000 keV).

It is important that the pulses from the pulse generator have shapes which are very similar to the detector signals, in particular fall times have to match to prevent large undershoots in the output signal of the main amplifier. As an example, for coaxial detector systems, fall times as large as 1000 - 2000 µsec are required. Many commercially available pulse generators provide pulses with shorter maximum fall times. In some models this value can sometimes be enlarged somewhat by increasing the output capacitance in the module. Pulses from a pulse generator will slightly degrade the total system resolution; therefore any spectrometer setting or resolution check should be done with the pulse generator disconnected.

Another advantage of applying pulses from a pulse generator to a γ-ray spectrometer is that a small increase in system noise by electronic interferences more easily be observable from an increase in the narrow pulser peak width than from variations in the width of the γ-ray lines.

b. SPECTRUM STABILIZERS

Digital spectrum stabilizers may be useful for applications in which high accuracy measurements are required over long counting times (e.g., as they occur when measuring natural radioactivity). The stabilizer functions by monitoring two naturally occurring peaks in the spectrum, by preference a low and a high-energy peak. After the initial peak positions have been set, the stabilizer continuously will alter ADC conversion gain and zero level in order to keep the two peaks at the preset positions, in order to correct any drift in the electronics. Application in INAA depends on stability requirements, and applied counting times, while always the same two peaks have to be present in all samples. It is possible to introduce two extra peaks in the spectrum by fixed sources attached to the detector, but this implies, for a high energy gamma-ray, also an extra associated Compton background, affecting sensitivity. Pulser peaks are not suited for stabilization, as drifts in the position of such peaks not only originate from instability of the spectrometers' amplification section, but also may be due to instability of the pulse generator itself. As a result, the change in position of the pulser peak does not always reflect changes in position of the γ-ray lines.

c. LOSS FREE COUNTING

Loss-free-counting (LFC) is a statistical method of correcting for losses of pulses in the electronics when it is busy. The technique is well described in the literature [183/184/185/186] and NIM-modules operating on these principles are available to be added to a spectroscopy system. With such a module, which operates closely in connection with the ADC, a real-time correction for dead time is achieved; the pulses lost because of the finite resolving time of the system are in real time mode to the acquired data in the same way they were initially lost, instead of increasing the data acquisition time as occurs in live-time mode. This method is particularly useful for applications of INAA in which high to very high count rates occur, very short counting times (which make dead-time correction by the pulser method almost impossible), and alteration of count rates due to decay during measurement. Moreover, no dead-time corrections are required as under all conditions live time equals clock time. It is important to bear in mind that counting statistics are disturbed by this artificial increase of the number of counts in the channels, and it may be necessary to acquire an uncorrected spectrum simultaneously so that the statistics can be computed.

5.3.7. ELECTRONIC PROBLEMS

Trouble-shooting, often initiated by uncommon spectrum analysis results, belongs to the daily tasks of the activation analyst. The operating manuals of the different units of the spectrometer sometimes contain extended paragraphs on trouble-shooting, on symptoms of malfunctioning parts and suggestions to overcome the problems. The most common problems will be briefly mentioned here.

Detector Microphonics

Every semiconductor detector has a certain response to vibration, mechanical shocks or sounds. If this response is excessive, the detector is said to be microphonic; as a result energy resolution will deteriorate. Detectors equipped with cooled FETs are less sensitive to microphonics because of the shortened connections between crystal and electronics. Noise due to microphonic behaviour becomes visible as low-frequency signals in the main amplifier's output in the 100 Hz - 5 kHz range. (Fig. 5.11a.). The effect can be enhanced by clapping your hands close to the end-cap, or by gently tapping your finger against the cryostat. Microphonics due to vibrations can be solved using shock-absorbing material under the Dewar; sensitivity to sounds is more difficult to solve, and often requires assistance from the detector's manufacturer. As lead is a good acoustic damping material, sometimes surrounding the detector by a lead shield may help to decrease the sensitivity to sounds. Another source of vibrations causing microphonic behaviour may be found in the LN2 Dewar. In some Dewars the cold-finger tip of the cryostat fits into and touches a recess on the bottom of the Dewar. The detector crystal mounted on the other end of the coldfinger may then strongly experience any vibrations in the Dewar. The presence of such a construction can be checked without emptying the Dewar. Carefully lift the cryostat 5 - 10 cm, and even more carefully lower it again to its original position. Little shocks will be noticed when the coldfinger tip finds the hole. If such a construction is suspected to cause microphonics, either another Dewar can be chosen or the cryostat has to be lifted permanently a little using some extra collars. The bubbling of the liquid nitrogen in the Dewar can also act as a source of microphonics; this may be due to an insufficient insulation of the Dewar (in other words, the Dewar's vacuum mantle is leaking). Another Dewar should be tried first before the detector manufacturer is contacted.

Shorter pulse shaping time constants, the use of the main amplifier's bipolar output with longer shaping time constant, a lower main amplifier gain in combination with a higher ADC conversion gain or a baseline restorer operating in the symmetric mode may eliminate to some extent the deteriorating effect of microphonics.

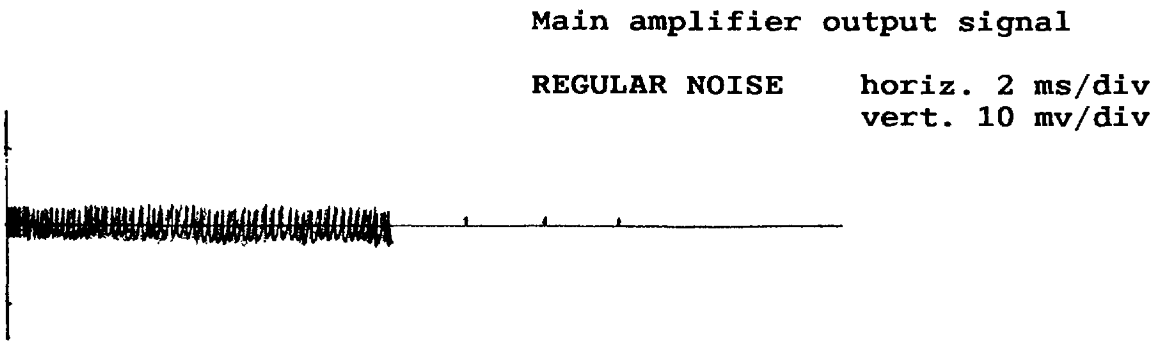


FIG. 5.11. Regular noise.

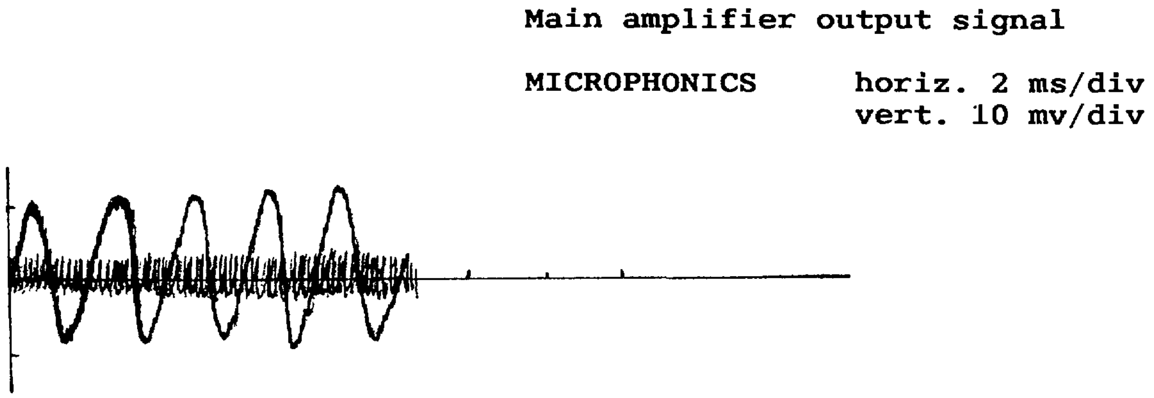


FIG. 5.11(a). Effect of microphonics.

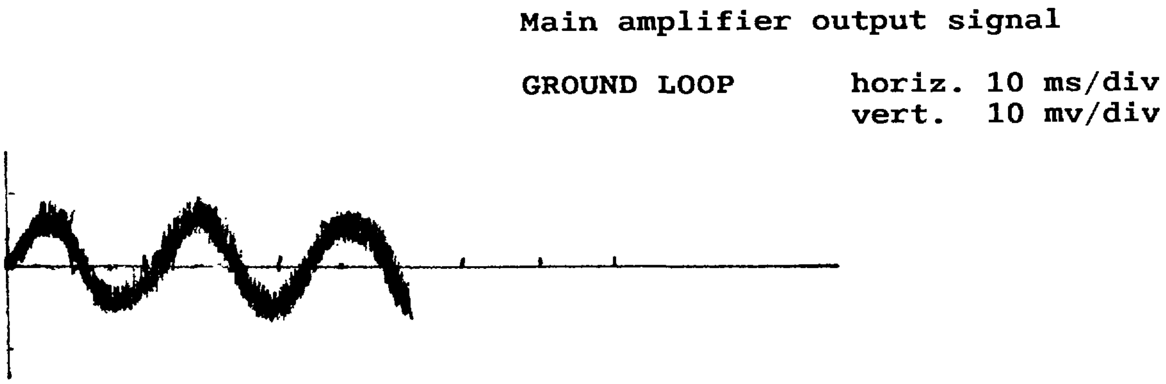


FIG. 5.11(b). Effect of ground loops.

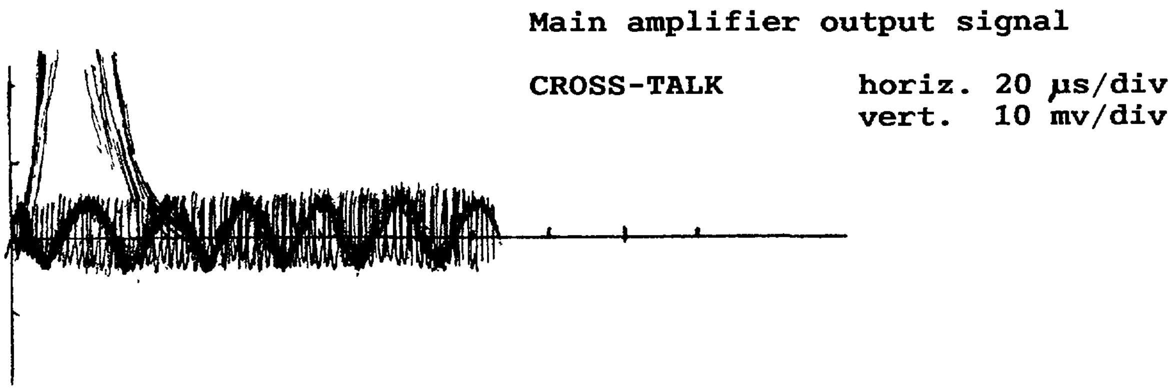


FIG. 5.11(c). Effect of cross-talk.

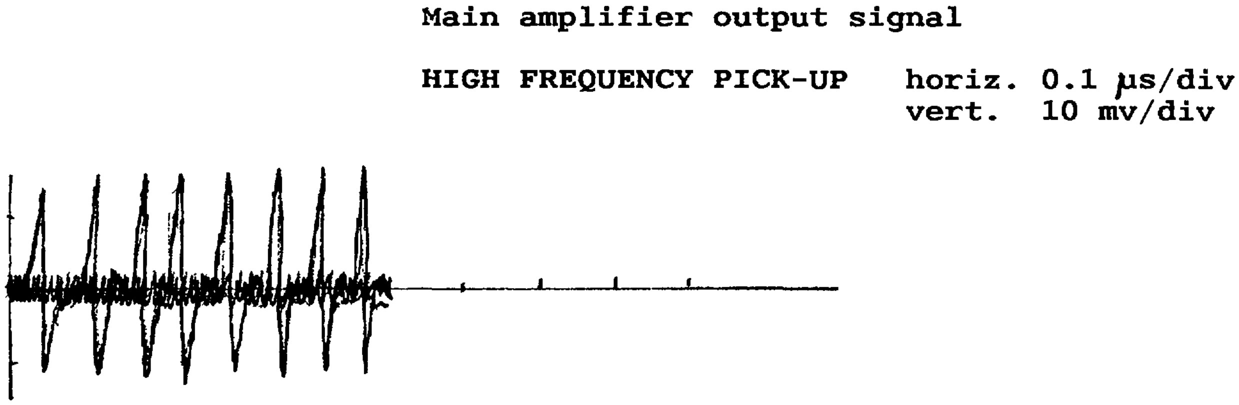


FIG. 5.11(d). Effect of high frequency electromagnetic radiation.

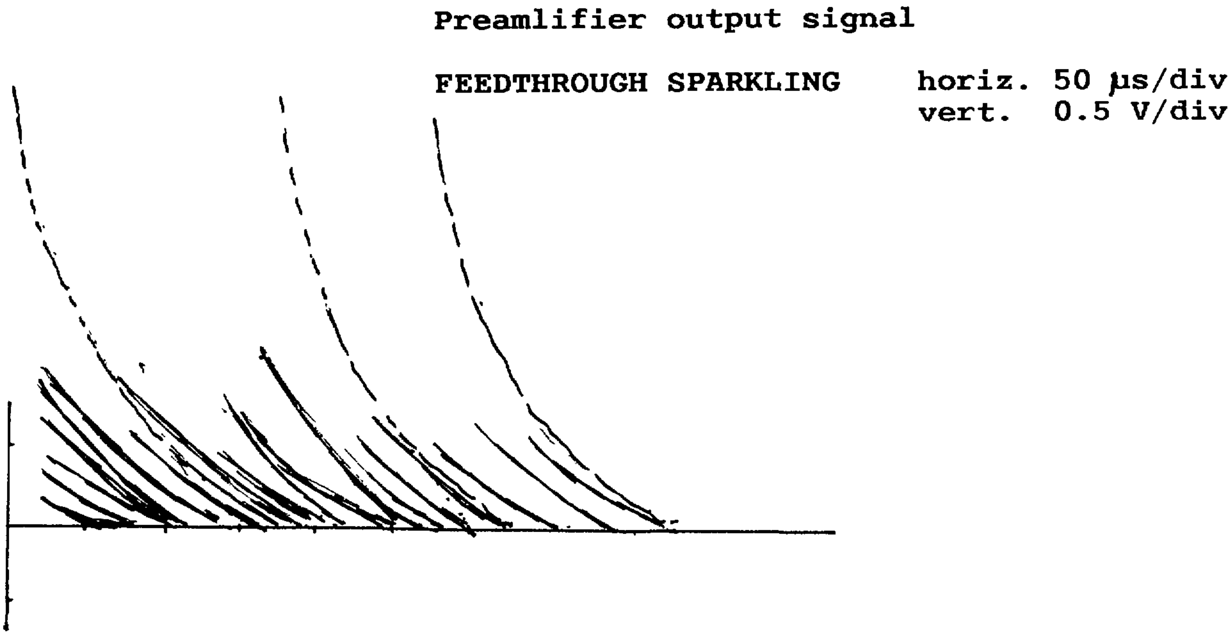


FIG. 5.11(e). Effect of HB-sparkling.

Ground Loops, Cross-Talks and Pick-Ups

Ground-loops, cross-talks between several parts of the spectrometer, or signal pick-up from high-frequency sources lead to increase of dead time, loss of weak pulses, and degradation of system resolution. These interferences can also be derived from monitoring with an oscilloscope the main amplifier output signal.

Ground-loop effects become visible as oscillations with frequencies related to AC frequency, e.g., 50, 60, 100 or 120 Hz. (Fig. 5.11b.) The effects can be reduced by using the same ground for all parts of the spectrometer. If possible, the AC power for the various units should be taken from a common wall socket.

Cross-talk may arise when signals are transferred from one piece of equipment either via power or earth connections to another part of the spectrometer. Often influence of HV supplies is observed. Such an interference shows up in the main amplifier output signal by 20 or 50 kHz oscillations (Fig. 5.11c), which originate from the converter frequency in the HV supply.

The cabling of a spectrometer also has a certain antenna behaviour for high frequency electromagnetic radiation, such as emitted by RF sources, accelerators, air conditioners, AC motors, etc. As a result high frequency oscillations may occur (Fig. 5.11d.). Display monitors and video terminals sometimes also turn out to be a source of RF radiation. A systematic investigation of the main source of this interference can be done by switching off suspected parts until the frequencies disappear. Cables should also be kept away from the vicinity of personal computers and monitors. Sometimes the use of 'super-screened' cable will reduce the pick-up problem.

Some simple measures can be taken against cross-talk and pick-up interferences. In the NIM bin, HV power supply and main amplifier should be inserted by preference at the opposite outermost positions, and also not directly next to the ADC. In stubborn cases, the HV cables may be wound through a ferrite ring. All cables should be in good condition; cables connecting preamplifier and NIM bin (HV, preamplifier power, output signal, event. pulser input) should be of equal length, and neatly tied together into one string (Fig 5.12.). Detector cryostats should not make electrical contact with grounded lead or steel shielding.

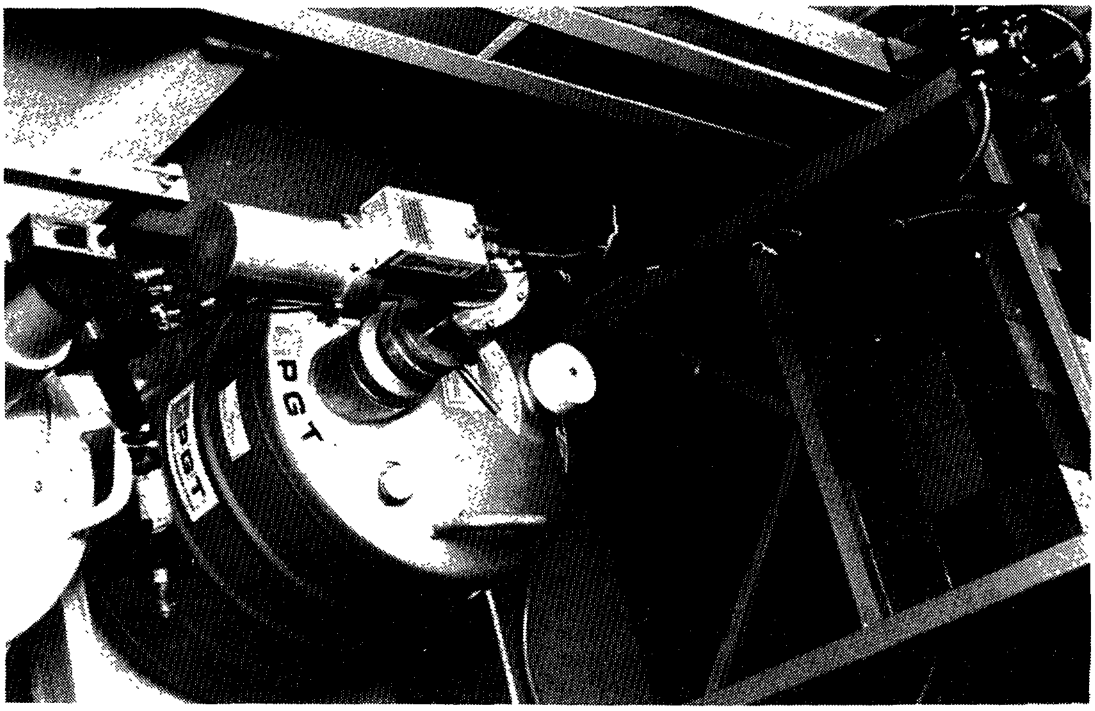


FIG. 5.12. Cabling between preamplifier and NIM bin, neatly tied together and of equal length.

Cables and Connectors

Impedance matching of cables and input-output connections is of importance to avoid reflections of signals and oscillations, resulting in peak-shape distortion and attenuation. In manufacurers' manuals of preamplifiers, main amplifiers and MCAs attention is paid to this subject and the type of cables to be used is specified. The connection between preamplifier and main amplifier requires much care and attention because of the weak signals. Interference from loose contacts or poor earthing results in noise and signal distortion. With respect to connectors, a serious source of interference may result from connectors not properly attached on home-made cables, in particular in the strain relief. If there is a suspected cable or connector, a drastic but probably the best solution is to remove the cable and to cut off at once the suspected part or connector. There are too many examples in which malfunctioning cables were put aside for a while, and used again by somebody else not knowing its uselessness.

Sending Signals Long Distances

When the detector system has to be placed at a remote distance from the other parts of the spectrometer, the preamplifier output signal is often chosen to be transferred over long distances, because of the lack of space for installing a NIM-bin near the detector. Several preamplifiers are able to transfer the weak signals over distances as long as 150 m without significant loss of resolution. Attention has to be paid to termination of the connections with shunt resistors, to avoid reflections. The use of 'super-screened' cable will reduce the problem of pick-up from outside interferences. Less difficulties may arise when transferring the main amplifier signal, but still termination of the connections might be necessary to avoid oscillations. At high counting rate the bipolar signal should be used to reduce peak drift. The digitized ADC signal can be transferred almost without any difficulty, although a booster module may be required for very long distances.

System Instability

Unstable electronics will result in either continuous or stepwise drifting peaks. Careful observation of spectrum analysis results will indicate the occurence of instability in time, before it becomes a big problem. Small day-to-day shifts, peak broadening and uninterpretable peaks closely spaced to prominent peaks are the first indications.

* Gain Instability. Corrosion and dust in the spectrometer parts (main amplifier, HV supply) cannot always be avoided. Sometimes it is sufficient to clean the contacts of switches, plugs and printed circuit boards. Cleaning can best be done using pressurized air and a soft brush. 'Contact-cleaner spray' is useful for cleaning the moving parts of switches, but should not be used to clean electronic boards as sometimes an oily residue which remains may cause its own problems; methanol is a better choice. A typical weak component in the main amplifier is the fine-gain potentiometer. When in use for a long time in the same setting, corrosion of the windings has been observed. Replacement by a new potentiometer or the use of a distinct different combination of coarse gain and fine gain setting can help to overcome this problem.

* Temperature and Humidity Effects. Many laboratories do not have well-conditioned counting rooms or suffer from variations of temperature. A shockwise change of a few degrees in ambient temperature may lead even for premium amplifiers to measurable gain variations. The specifications as quoted by manufacturers with respect to temperature stability are given in very small numbers, thus giving a wrong impression on the practical performance. Note that a typical theoretical temperature stability

specification of, e.g. <0.0075%/^{o}C still means that a one-degree change in temperature will shift a peak in channel number 4096 for 0.3 channel. If the temperature cannot be kept sufficiently constant (±1 degree), the only workable solution is to perform daily energy calibrations.

* Excessive humidity may cause difficulties at the detector side, in particular at the preamplifier signal feedthroughs of the cryostat. This can be checked by monitoring the main amplifier's output signal: HV sparking shows up as very large pulses on the baseline (Fig. 5.11e), which will decrease when the HV is lowered. Also the voltage level of the preamplifier's test jack will show an unstable behaviour. Sometimes it will be necessary to clean the cryostats vacuum feedthrough. This is a tedious operation, and the preamplifier's FET may easily be damaged. First switch off all power and wait for at least 5 minutes to discharge all capacitors completely. Disconnect all cables from the preamplifier and remove the hood. It should be remembered that even through contact with skin acids the megohm resistors and high voltage capacitors may be damaged. The feedthrough (glass or ceramic) can be cleaned with methanol and tissue. Dry the feedthrough thoroughly with a hot air gun at moderate temperature, and be sure that no tissue threads are left on the feedthrough. As mentioned before, covering of the preamplifier with a plastic bag with silica gel capsules may contribute to reducing condensation. Some manufacturers offer the possibility of extra treatment of the preamplifier at the factory when it is known beforehand that the detector will be used in an atmosphere of relative high humidity.

In cold climate the air can be very dry in central heated houses. The low humidity may cause problems through static electricity. Sparks are easily created when touching the analyzer. These sparks may stop the microprocessor in the analyzer. Therefore humidifiers should be used in counting rooms. In difficult cases electrically conducting carpets and tablecloths can be used to decrease the static electricity.

5.4 MULTICHANNEL PULSE HEIGHT ANALYZER (MCA)

5.4.1 PC-BASED SYSTEMS

For several years most of the functions required in a stand alone MCA have been realized through microprocessors incorporated into the MCA. It was soon realized that instead of building separate systems, commercial microcomputers, personal computers (PCs), could be used. This approach has several benefits:

- Low cost because of mass production.
- Reliability and good service almost everywhere because similar computers are used by many institutions in every country.
- The same computer can be used for advanced data handling and also other computations while measuring.
- Good availability of computer programs for gamma spectroscopy and other purposes. The reason for this is the standardization of PC operating systems.

The system thus comprises three parts: The ADC, a multichannel analyzer buffer (MCA buffer), and the computer. Depending on the manufacturer different combinations of these exist:

1. ADC+MCA buffer is one NIM-module;
2. ADC+MCA buffer is one card which can be inserted into the computer;
3. ADC is a NIM module and the MCA buffer a computer card;
4. ADC and MCA buffers are separate NIM modules.

Using a separate ADC has the advantage that the ADC can be chosen according to the count rate requirements while the buffer is a standard device. All the MCA buffers include a microprocessor and memory, enabling an independent functioning of the MCA during acquisition.

The data memory available varies from 4K to 32K channels. The count per channel capacity is always high, from 8.10^6 counts per channel upwards, usually more than what is needed in NAA. Both 100-450 MHz Wilkinson type and 5-25 µs fixed time ADCs are used. Some systems support high count rate acquisition through real-time dead time and pulse pile up correction. Multiscaling units are also available. Normally four MCAs can be connected to one computer and through a mixer-router, up to four detectors to one ADC.

Data transfer to the computer is no problem when the MCA buffer is a computer card. Some of the NIM modules have a RS232C interface as standard, rendering the data transfer unacceptably slow for many applications. In some analyzers an IEEE488 or similar interface is standard and in others optional. This enables a 8K spectrum to be transferred in 100 ms.

The MCA buffer microprocessor normally supports data acquisition and I/O functions including display, controlled via the host computer. During data acquisition the computer is free for control of other MCAs, analysis of spectra on disc or for running any other program like word processing.

The standard software includes the MCA emulation program enabling control of MCA and traditional operations like display, I/O, overlap, smooth, strip, transfer, energy calibration, ROI, and peak information, like centroid, FWHM, gross and net area within ROI. Optionally available are peak search, nuclide identification, peak integration often with multiplet deconvolution. A few NAA programs are available, but they are usually not very sophisticated.

Most of the MCAs are based on IBM XT, AT or System/2 compatible computers. Some manufacturers have also MCA:Buffers for DEC VAX computers.

When using a so-called IBM compatible computer it is important to assure that the degree of compatibility is high enough so that the combination really works. This can be best assured by buying the whole system from one supplier.

Systems based on standard computers have the additional benefit of enabling easy control of automated devices, like sample changers, and pneumatic transfer systems. Almost all standard software includes sample changer control. They also allow easy bookkeeping, data storage, reporting and connection to networks of different kinds.

It is to be noted that the above is valid in 1988 when this text was written but because of the fast technical development the information may be old in a few years.

5.4.2 MICROPROCESSOR-BASED MCAs

Conventional MCAs, where the counting functions are microprocessor-based, may take one of three general forms, depending on where the data handling is carried out: the 'stand-alone' analyser; the interfaceable system, where the MCA is connected to a separate computer for data processing; and the fully integrated system, where the MCA and computer are compatible in the analyser itself.

The stand-alone system, with its own central processor, can be a powerful analytical tool since it is designed specifically for spectroscopy. The display and acquitions system is tailor-made and the software is written to operate on the particular system. However, the operating systems are not always easily accessible so that it may be difficult to transfer information in and out of the analyser. This means that it may be cumbersome to transfer data, such as weights from an electronic balance, from outside, into the analyser. It also means that if NAA is to form part of a wider range of analytical facilities it may be difficult to integrate the stand-alone analyser into a laboratory processing system. On the other hand, these stand-alone systems are designed specifically with the job of gamma-ray spectrometry and/or neutron activation analysis in mind. They can have multi-user and multi-tasking facilities which support many ADCs and enable more than one person to use the system at the same time, running a number of jobs simultaneously. The result is a very powerful, self- contained analyser.

A computer-interfaceable system has the advantage that it can be used as an independent multichannel analyser but may be connected to a separate computer, if required. This means that it is suitable for running small simple tasks, such as the routine analysis of one or two elements, but data can be transferred to a large computer for complicated spectral analysis. In addition all the standard software programmes for chemical data management can be implemented and the NAA facility integrated into a wider analytical facility.

A compromise between the two types of MCAs described above is the integrated system, in which the data acquisition, storage, and computation are performed by a single hardware and software system which includes a standard minicomputer. The first generation of such systems, built around a single pool of general memory for ADCs and computer, worked well but compromises in performance and standardization have become less necessary as the price of memory and computers have decreased and as general-purpose operating systems have become more capable. In more recent systems the ADCs collect data in dedicated memory, which makes the MCA and computer functions independent. The integrated system is therefore as powerful as a stand-alone system in its ability to support multiple users simultaneously, with access to all the statistical, database, and communications software. The advantage over the interfaced system is that the spectral data can be viewed and manipulated like a stand-alone analyzer. An integrated system may be also the most suitable MCA for the automated control of external devices such as pneumatic irradiation systems and sample changers.

The choice of the MCA to use will depend on the nature of the NAA laboratory, how many people might wish to use it and what variety of analyses will be carried out. An important factor is how NAA is to be integrated into the work of NAA group and the reactor facility as a whole. Also important in the choice of system and manufacturer is the degree of support which is available from electronics engineers on site.

5.5 DATA PROCESSING

5.5.1. COMPUTERS AND INTERFACING

In NAA, gamma spectra are normally measured on 4096 or 8192 channels, although 16384 channels are needed on occasion. The amount of data varies normally between a few counts and hundreds of thousands of counts per channel. The amount of data makes manual interpretation time consuming. In addition several of the spectrum interpretation methods involve complicated mathematics. Therefore computers are commonly used for storage and interpretation of gamma spectrometric data.

There exists a multitude of computers of different size and performances and it is not within the scope of this book to give a comprehensive description of what is available. Only a short discussion will be made and more detailed information should be sought in the relevant literature. The development of computers has been extremely fast and today's microcomputer has the same or better performance than yesterday's minicomputers and last week's mainframe computer.

Less than ten years ago most NAA calculations were performed on central mainframe computers because computers, memory, and peripherals were expensive. With a few exceptions MCAs were not connected to mainframe computers but the data was transferred via magnetic tape. The use of a mainframe computer allows the use of large programmes and enough storage capacity. There may be a problem in that the control of the programme is located far from the measurement room. Some multichannel analyzers have been designed to work as terminals as well, enabling running the programmes from the analyzer itself.

In general, the use of a mainframe computer for spectrum analysis on large data sets may be quite expensive, depending on the policy of the computer centre. It may be more cost effective for the NAA group to have its own minicomputer. For most laboratories at present the economically attractive choice is the use of a personal computer, particularly if the PC is part of a local area network.

The kind of PC to choose is not very critical but some criteria should be kept in mind. The ultimate in performance is usually not needed, since real-time data handling is performed by the MCA. Only after data accumulation has ended is the spectrum transfered to the computer memory, and usually to the hard disc as a data file. The spectrum analysis and NAA calculations are performed separately from the data acquisition process.

The interfacing of old MCAs can be difficult and expensive. An expert has always to be consulted. All MCAs produced in the 1980s have commercial interfaces and mostly commercial communication programmes for interfacing to one or several computer types. These should be used to ensure problem-free communication. The most common one is the RS232 bus which is cheap and reliable also over long distances. However, the slow transfer rate, maximum 19,200 baud, corresponding to a transfer line of 30-80s per 4k spectrum, hampers its use in many instances. The IEEE 488 bus is very fast (350 kBytes/s corresponding to a transfer time of about 50 ms for a 4k spectrum), but cannot be used over long distances. Therefore some local area network system, like Ethernet, has to be used if fast transfer over long distances is needed. A drawback is high cost and complex software.

5.5.2 PROGRAMMES

Manufacturers of multichannel analyser systems usually provide fairly comprehensive software for the operation of the system and microprocessor-based systems will have control and emulation software depending on the type of MCA and the way it is integrated with the processor. The basic role of the MCA is to collect the counts into the appropriate channel addresses, record the live and dead times during the counting period, and present the data in a suitable form. All the additional software is designed for the calibration of the analyser and for the processing of the gamma ray spectra.

Calibration programmes include energy and efficiency calibrations. The energy calibration packages in commercial MCAs are based on counting reference sources and entering the data in the form of energy and corresponding channel number. The data, in the form of keV vs channel number, are stored as a linear or quadratic fit. Similarly the efficiency calibration is measured using reference sources of known activity. In many systems, the information that is required for calibration with a reference source, such as half-life and gamma-ray energies and intensities, are stored in a library provided by the manufacturer. The user simply counts the sources and enters the activity on the date when the source was originally certified, together with the measured count-rate. The system calculates the efficiency vs gamma-ray energy and stores the calibration constants, usually as a polynomial or spline fit.

The data is normally collected in the computer or MCA memory and transferred to storage disc at the end of the counting period for spectral analysis. However, simple print-out in the form of counts per channel or as regions of interest can be made from memory. Manipulation of the spectra can be quite sophisticated with options to expand regions and compare spectra, to smooth or add and subtract spectra, to identify energy lines and to evaluate peak areas. In fact it is possible to carry out a full analysis of a spectrum in the computer memory.

Any more complicated data handling, such as a peak search, is usually made on stored data. The peak search programme is one of the most important features of an analyser system and each manufacturer uses a different peak search programme for location and evaluation of gamma-ray lines. Recently some commercial peak search programmes have been modified for use on the PC-based systems; GeLiGam is now used in its new form of 'Minigam' on the EG & G Ortec system, Sampo has been converted by Aarnio [187] and is offered by Canberra as 'MicroSampo' and Nuclear Data has launched a micro-based system which operates with all their standard programmes from their large 'stand-alone' systems. A number of programs written for mainframes and minicomputers at universities and government laboratories are in use outside their original homes. Some examples are Gamanal [188], Hypermet [189], and Teabags [190]. Only the latter of these include NAA functions. All these programs provide adequate peak analysis for most NAA requirements and recent intercomparisons [191/192] of the programmes produced by the different manufacturers showed that they all gave very similar results.

Packages available in the commercial systems to compensate for losses in the electronics of the counting system include dead time and pulse pile-up corrections. In addition to these corrections there are interference corrections for the peak area evaluation similar to a spectrum stripping programme, where a clean peak is used to correct for an interference which cannot be separated, knowing the ratio of the clean and interfering peak.

This type of correction can only be applied to peaks which are not resolved by the peak search programme. If on occasions the programme is able to separate the peaks, then the additional application of an interference correction will give the wrong result. Neither can this correction be used where the interference is due to a nuclear reaction producing the same nuclide.

Nuclide identification libraries are used to confirm the identity of the peaks by energy and intensity and in many cases the manufacturers provide comprehensive lists of gamma-ray energies. However, since the commercial MCA systems are often designed with gamma-ray spectrometry, not NAA, in mind, some lists include fission products which are suited to the power station market. It is often more practical to build up one's own list of likely products. There are nuclide libraries available in the literature which are designed for neutron activation analysis, for example, the Tables included in the Appendix.

Most manufacturers now have a NAA package for quantitative analysis. Usually the NAA package uses the results of the peak search package, corrected for decay and for weight, to compare counts in the sample with counts in a standard. NAA packages may lack the sophistication of the nuclide identification programmes; for example, one commercial package averages the results from all the standards for a particular element, a procedure which may or may not be appropriate for a particular irradiation site. There are additional refinements which are not available commercially, for example, flux correction, a facility for flux monitor data, and for the use of comparators.

The manufacturers' software may require quite complex operations to give reliable data when analysis is carried out in an automated mode. Usually the software allows a sequence of the commands to be entered via an editor and run as a job. The 'jobstreams' are adequate for most operations, if a little inflexible when it comes to general applications.

5.6 AUTOMATION

5.6.1 NEED FOR AUTOMATION

If the NAA facility is to operate effectively it will almost certainly need to be automated in some aspects of the procedure. The main reasons for automation are speed, reliability, reproducibility, and saving in staff time. Aspects which are automated are most commonly the irradiation procedure and the counting stage, although there are other possibilities such as the sample preparation operations. Irradiations must be automated for the measurement of very short-lived radionuclides, where it is impossible for a worker to get the sample from the reactor to the detector quickly enough. In the case of counting, automation frees members of staff from the routine tasks of changing samples and to facilitate the 24-hour use of valuable counting equipment.

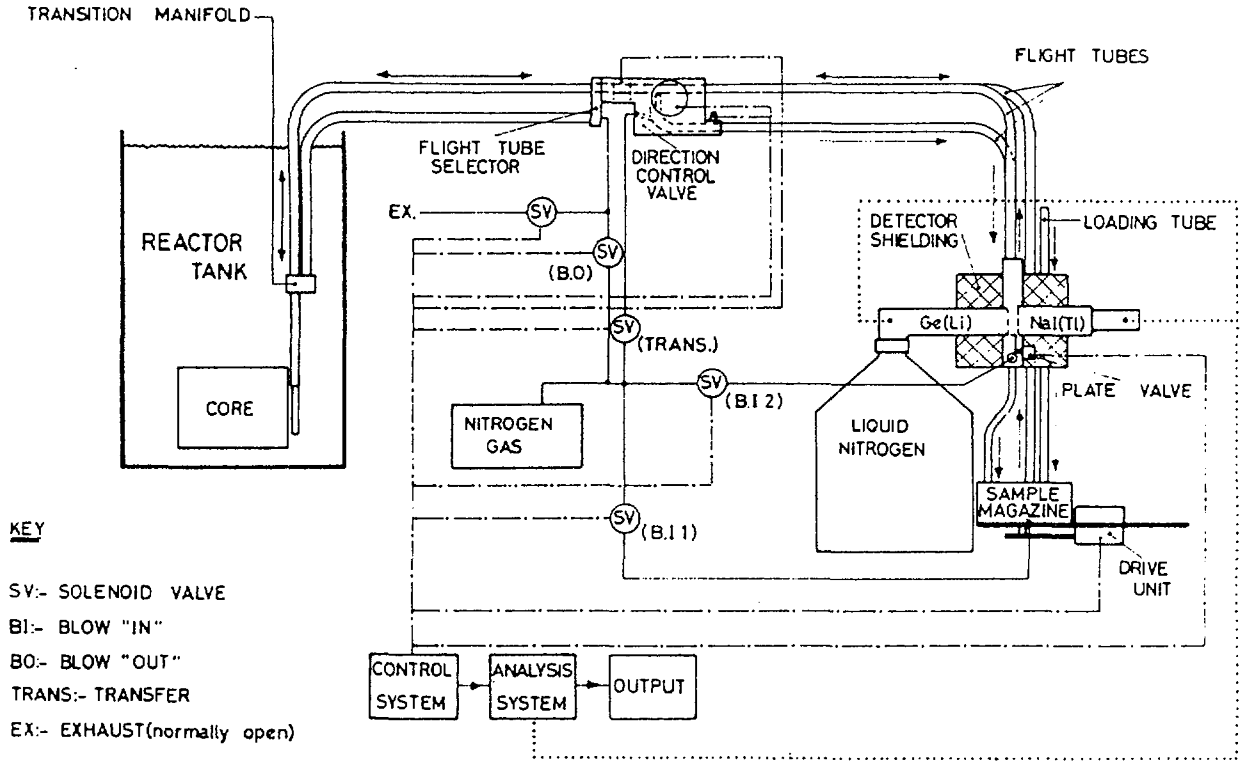


FIG. 5.13. Automatic activation analyzer.

5.6.2 IRRADIATION FACILITIES

To determine accurately trace elements by NAA, the irradiation and counting conditions must be reproducible. Pneumatic devices are commonly used to send the sample into the irradiation site, a timer being used to control the solenoid valves which operate the gas blowing the sample in and out of the reactor. A very simple device may be used to load the sample manually, start the timer which automatically blows the sample into the reactor and out at the end of the preset time, and to manually transfer the sample to the counting position. This simple system may be purchased commercially or built quite easily. The next step is a larger scale automated system where the process is repeated many times (Figs. 4.14, 6.1, 6.2.). It is only necessary to have some kind of loading device to allow many samples to be fed through the system. A programmable logic controller is a simple way to operate such a system since such a device has the facility for a number of input and output signals to operate relays to control the operation of solenoid valves, loaders, and diverters and sense microswitches. There are several advantages to building up an automatic pneumatic system slowly; with a programmable logic controller, input and output capacity can be added readily as required. For greater flexibility a PC-based system can be used to control the irradiation and counting sequences, with the control signals sent to the hardware of the system directly or indirectly via the controller.

Fully automated pneumatic systems are available commercially but they are manufactured for particular size 'rabbits' so they may not suit a specific requirement. In addition they are so expensive that it may be advisable to build one's own system if there are suitable workshop facilities available on site. There are many designs in routine use at the different reactor centres and examples of such pneumatic irradiation systems are described in the literature [193/194/155/156] and illustrated in the figures.

5.6.3 COUNTING AND DATA PROCESSING

Simple procedures for repeated counting and processing of data have been available even on hard-wired analysers for many years. A simple cycle of count, print, erase and count again, together with a signal from the ADC or the I/O system to tell the sample changer to operate, is all that is required.

It is possible to develop a fully automated irradiation and counting system for NAA incorporating a preset decay period. However, this is only suitable for relatively short-lived radionuclides and there is very often a requirement to unload the samples from their irradiation capsules before counting, if there is any contamination from the material of the capsule. However, once the samples are unloaded and ready for counting it saves a great deal of operator time if the routine counting and processing of the samples is automated. This requires that some means of changing the samples be available, and although occasionally it is useful for the analyser to count in a repetitive mode while samples are loaded manually onto the detector (e.g., for short-lived radionuclides where samples may be delivered and unpacked at regular intervals), an automatic sample changer is usually used for completely unattended counting.

The sample changers themselves can take a variety of forms. Recently the manufacturers of counting equipment have become more involved in marketing sample changers in particular to suit the environmental monitoring market but they are very expensive and it can be cheaper to build one to suit your particular needs. Examples of sample changers are given in the literature [155/195/196/197/198] and shown in the Figures 5.14, 5.15, 5.16, 5.17. One of the simplest forms is a wheel operating in a horizontal plane above a vertical dipstick detector. The samples can be separated sufficiently to avoid cross-talk provided that they are small and the detector can be surrounded with lead except on the top where the sample sits. The wheel can be rotated and located using a simple Geneva gear system. Pneumatic devices are useful if the detector has to be well shielded but it is necessary to provide a shielded store to locate the samples before counting (Fig. 5.17). For automatic counting care must be taken to ensure that sufficient time is allowed for the sample changer to have finished operating and for the next sample to be in position before the counting system starts the next analysis.

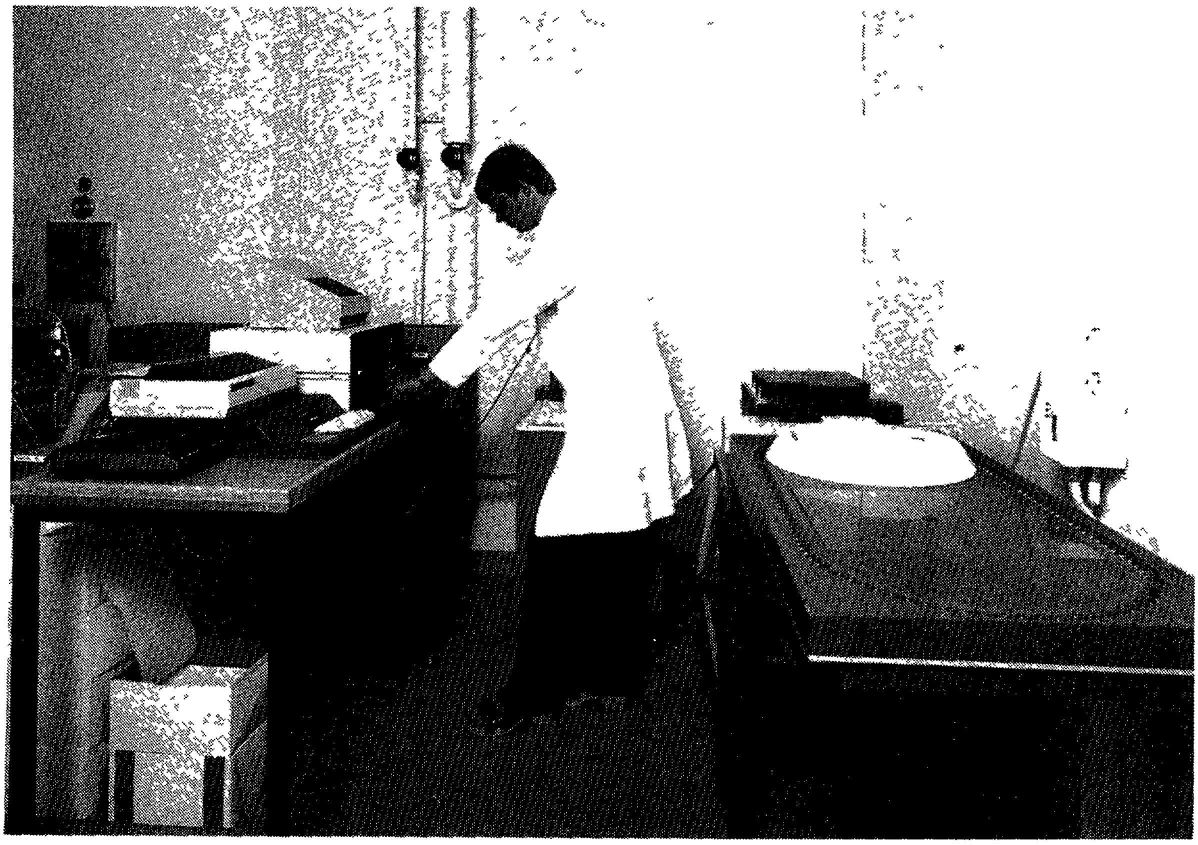
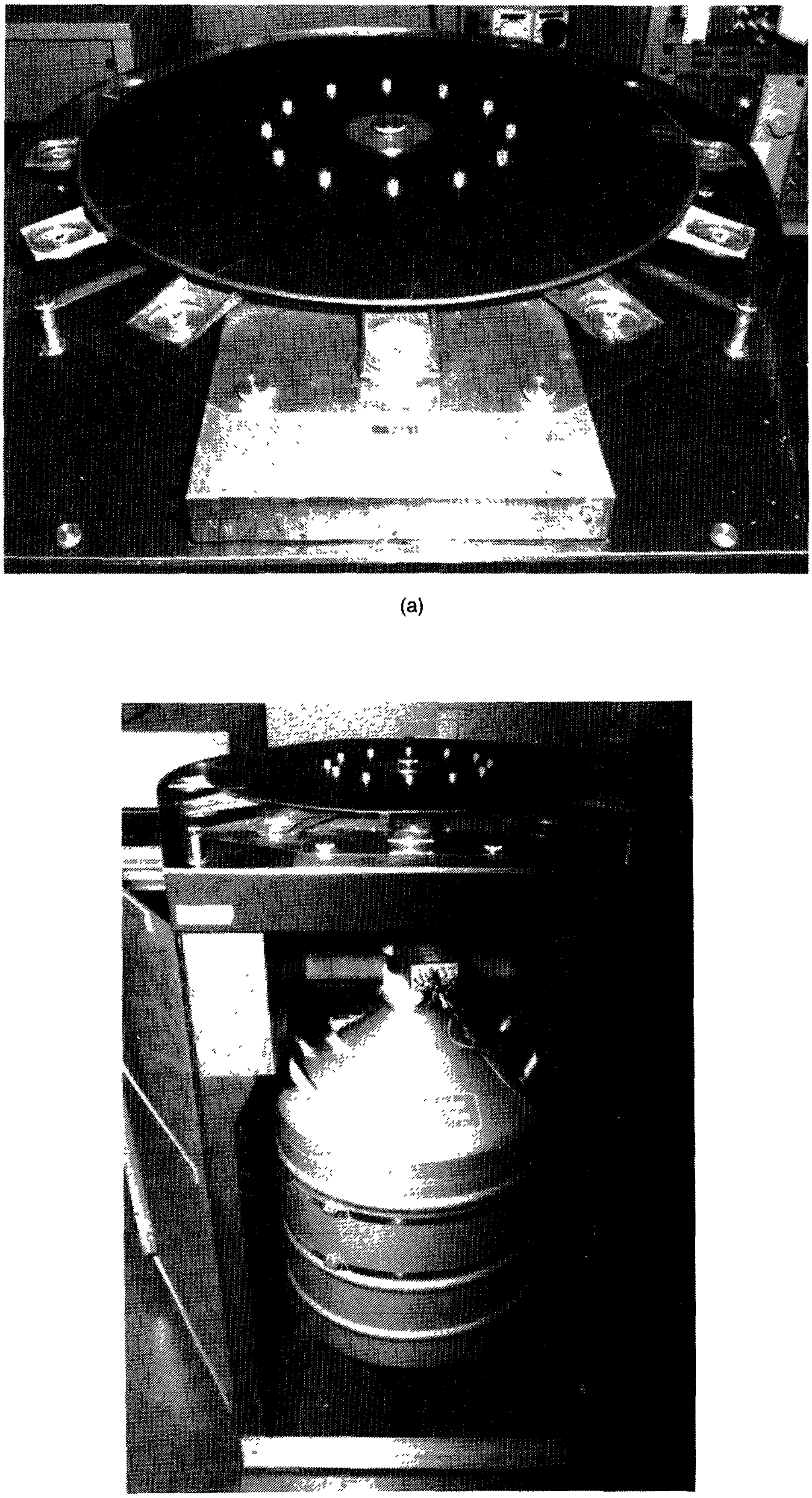


FIG. 5.14. A sample changer for a germanium detector (Imperial College of Science and Technology, UK).



(a)

(b)

FIG. 5.15. Sample changer.

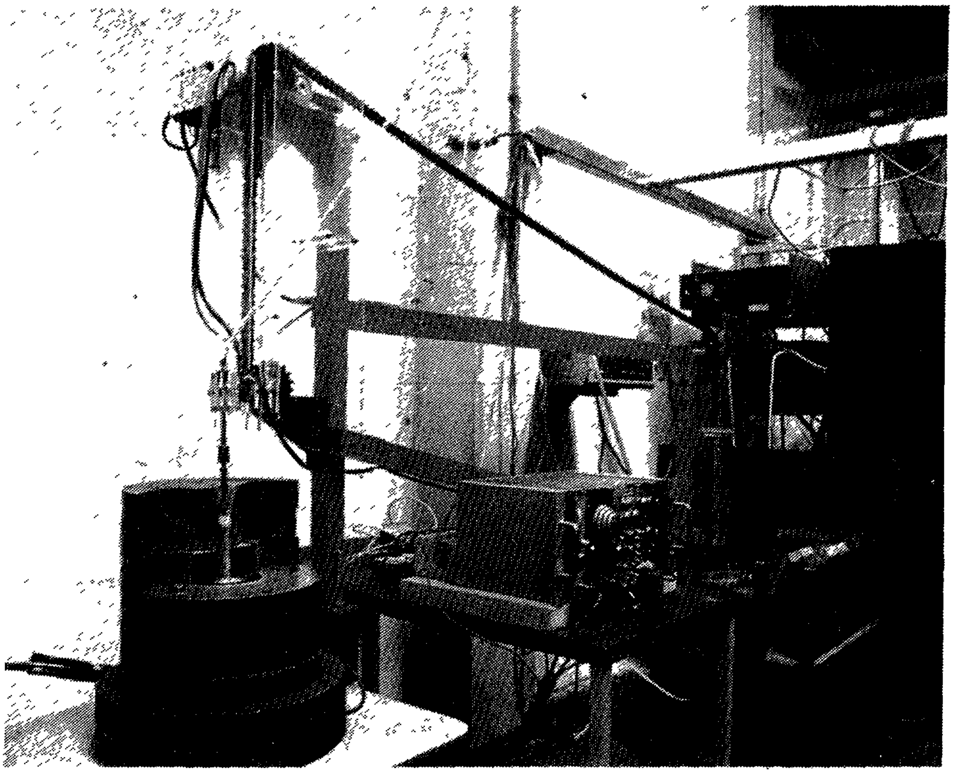
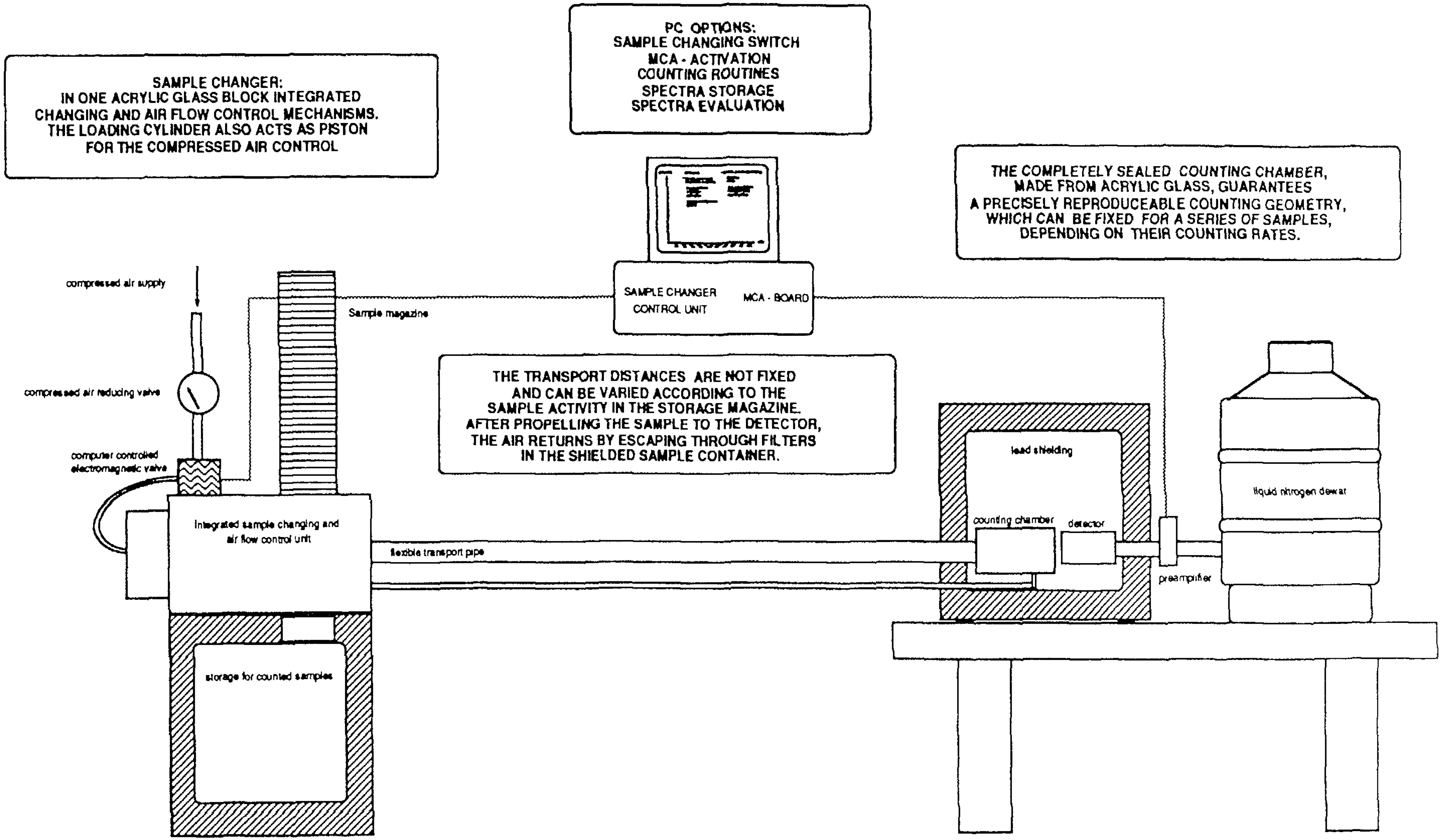


FIG. 5.16. A sample changer for a well-type detector (Interfaculty Reactor Institute, Netherlands).

5.7 CHOICE OF LOCATION

The position of the counting facilities will depend on the space available and the systems may not all be in one place. There are advantages in having certain types of counting separated to avoid cross-counting effects. It may be necessary to have a 'low-level' counting room if very low activity samples are to be measured, such as environmental monitoring samples. Also, there may be a detector located close to the reactor for counting short-lived radionuclides in order to keep the transit time to a minimum.

Apart from these special requirements it is usual to separate the counting equipment from the irradiation facilities to reduce the background activity, particularly from Ar-41. Care must be taken to avoid storing active samples in the vicinity of the detector. Background will be caused by a variety of sources including cosmic radiation; radioactivity in the material of the structure around the detector, such as building materials, metal, even lead bricks if they have been activated by storing them close to a neutron beam. Clean lead bricks are an important requirement for counting in low backgrounds. Counting rigs containing lead must be situated somewhere with



SAMPLE CHANGER:
IN ONE ACRYLIC GLASS BLOCK INTEGRATED
CHANGING AND AIR FLOW CONTROL MECHANISMS.
THE LOADING CYLINDER ALSO ACTS AS PISTON
FOR THE COMPRESSED AIR CONTROL

PC OPTIONS:
SAMPLE CHANGING SWITCH
MCA - ACTIVATION
COUNTING ROUTINES
SPECTRA STORAGE
SPECTRA EVALUATION

THE COMPLETELY SEALED COUNTING CHAMBER,
MADE FROM ACRYLIC GLASS, GUARANTEES
A PRECISELY REPRODUCEABLE COUNTING GEOMETRY,
WHICH CAN BE FIXED FOR A SERIES OF SAMPLES,
DEPENDING ON THEIR COUNTING RATES.

THE TRANSPORT DISTANCES ARE NOT FIXED
AND CAN BE VARIED ACCORDING TO THE
SAMPLE ACTIVITY IN THE STORAGE MAGAZINE.
AFTER PROPELLING THE SAMPLE TO THE DETECTOR,
THE AIR RETURNS BY ESCAPING THROUGH FILTERS
IN THE SHIELDED SAMPLE CONTAINER.

FIG. 5.17. A sample changer based on pneumatic transfer system.

strong floor supports and it is convenient to have the room on the ground floor to make it easier to move the heavy equipment about. Care must be taken to ensure that there is no danger of contamination of the counting system itself with the samples that are being counted. It is sensible to have some protecting material between the sample and the detector and usually this will be incorporated into a spacer device to ensure reproducible sample to detector distances. The sample holders should be manufactured from a material that is easily cleaned, such as Perspex, and checked for contamination on a regular basis.

Since liquid nitrogen is required for the operation of semiconductor detectors it is useful to avoid transporting Dewars too far. As discussed in section 5.3.7, it is often necessary to have air-conditioning to keep the equipment at a reasonable and constant temperature in an environment reasonably free of dust and chemical fumes.

6. RELATED TECHNIQUES

6.1. DELAYED NEUTRON ACTIVATION ANALYSIS

Delayed neutron activation analysis (DNAA), can be used for the analysis of oxygen and fissionable nuclides. The technique and the instrumentation needed has been thoroughly described elsewhere [199/200/201/209/156] and will be only briefly described here.

The method is based on a short irradiation followed by measurement of delayed neutrons, emitted with half-lives varying between 0.2 and 55's. Normally an irradiation time of 60's, decay time of 20's and measurement time of 60's are used. A pneumatic transfer system is used for irradiation and the delayed neutrons are counted in a device comprising several ^{3}He or $^{10}BF_3$ detectors in a moderator of paraffin or polyethylene. Because of its simplicity, the whole procedure is easy to automate and completely automatic analyzers with sample changer, pneumatic transfer system, measurement electronics and computer are described [156/203]. These analyzers both irradiate, measure and calculate the results automatically (Figs. 6.1, 6.2).

The method is most commonly used for the analysis of uranium in geological samples but also health physics applications are known. An example of a competitive application is the use of delayed neutron counting for uranium determination in urine. This can be favourably used as a routine monitoring technique because it is very rapid.

The method is specific to uranium when natural samples are irradiated with thermal neutrons. When a mixed reactor spectrum is used thorium interferes somewhat when in excess to uranium. Using a combination of thermal and epithermal activation both uranium and thorium can be analyzed, although the thorium analysis is not very sensitive or accurate [204/158]. For uranium, detection limits between a few ppb and 0.03 ppm have been reported.

The method is very much used because it is rapid and cheap. 300 samples per day can be easily analyzed.

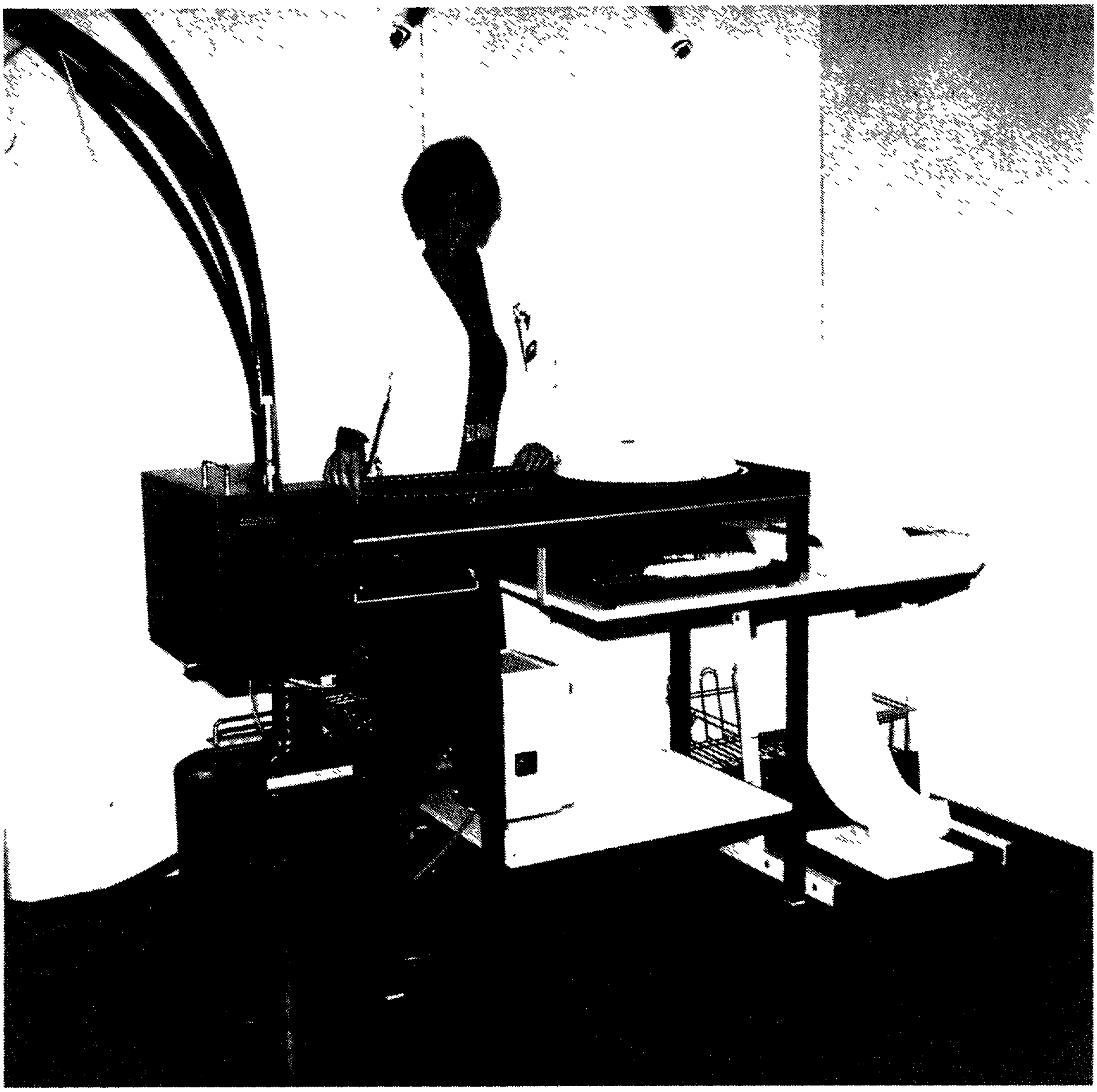


FIG. 6.1. Automatic uranium analyzer based on neutron activation and delayed neutron counting. The analyzer has a balance to weigh the samples (VTT/Reactor Laboratory, Finland).

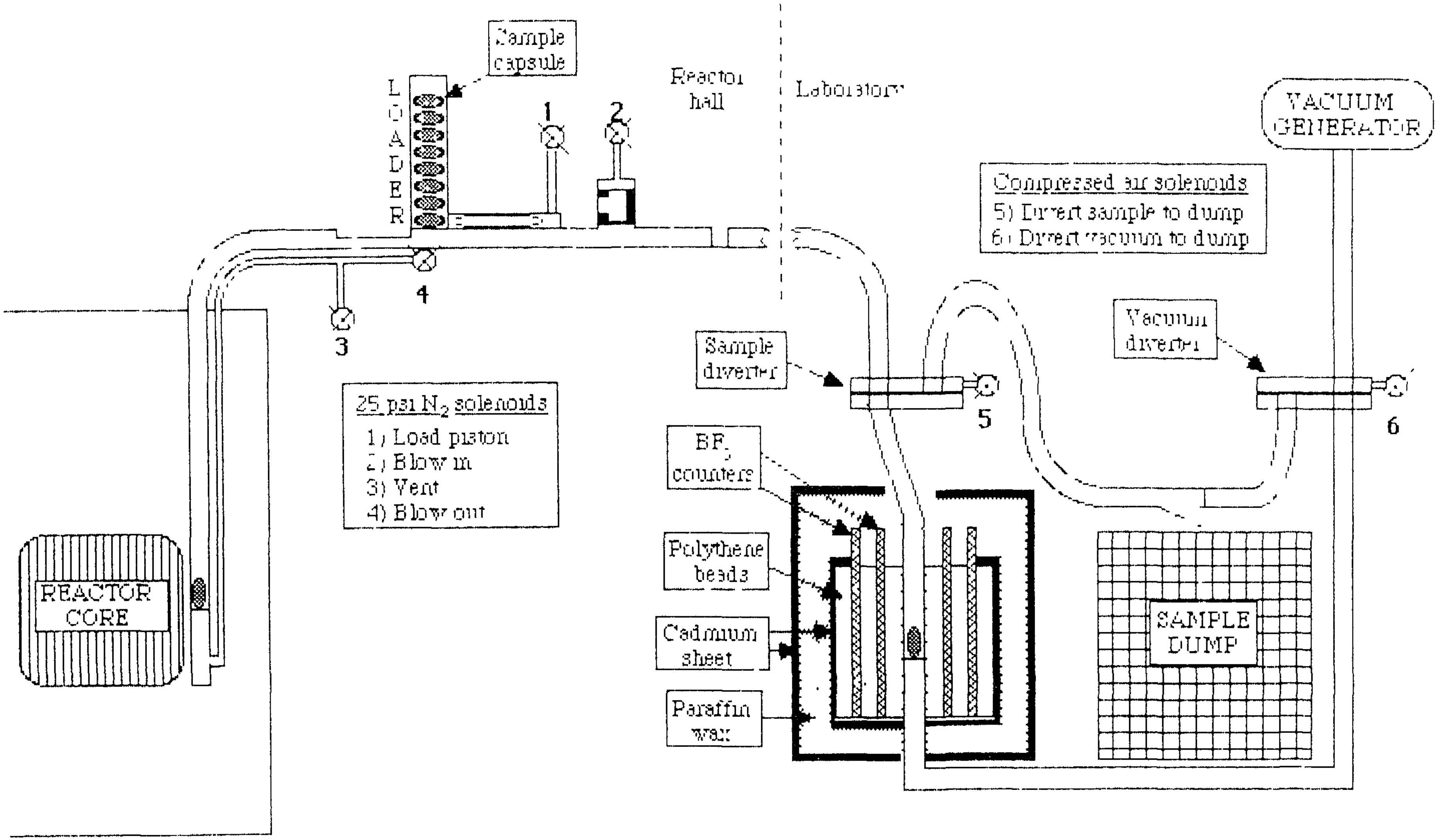


FIG 6 2 Delayed neutron activation analysis irradiation system

6.2. PROMPT-GAMMA NEUTRON ACTIVATION ANALYSIS

With the development of large high-resolution gamma-ray detectors with good efficiency and peak/Compton ratios at high energy, the use of prompt neutron-capture gamma rays as a method of elemental analysis has become practical as a complementary technique to INAA. Prompt gamma-ray neutron activation analysis (PGNAA) is particularly useful for determining elements which absorb neutrons but do not produce radioactive products in doing so. Nuclear parameters and the abundances of the elements in common matrices are such that PGNAA finds its greatest applicability in the determination of nonmetals that form the major and minor elements of common matrices (H, C, N, Si, P, S), or trace elements with high thermal capture cross-sections (B, Cd, Gd) that may be poorly determined by other techniques.

The application of PGNAA as a routine method of elemental analysis has been pursued todate at only a few laboratories on a full-time basis (for recent reviews see [205/206]), partly because of the need for continuing access to a reactor neutron beam. The sensitivity of the method (cps/mg) for most elements is not so good as conventional neutron activation, limiting most routine applications to the determination of the few elements just mentioned. Irradiation times of several hours are required for most samples in which many elements are to be measured, hence the throughput is low because only one sample can be irradiated and measured at a time. The low sensitivity of PGNAA is not due to a low neutron capture rate, but to a low detection efficiency for the analytical gamma rays due to the high energy of capture gammas, the complex spectra that result, the high counting rate from hydrogen in matrices containing this element, and the necessary bulk of active and passive shielding around the detector. Moving the detector closer to the sample increases the efficiency, but at the cost of higher background and nonlinearity due to high counting rate.

6.3. MEASUREMENT OF ENVIRONMENTAL RADIOACTIVITY

The availability of γ-ray spectrometers in an INAA laboratory, and the experience with interpretation of γ-ray spectra facilitates implementation into an environmental research program of monitoring programs on natural radioactivity (e.g., from coal-burning plants, or mining activities), or radioactivity from fall-out, nuclear reactor waste and accidental releases. Although actually not belonging to INAA applications, it might be considered when thinking of making a laboratory of more use for society. An example of this is the situation after the Chernobyl accident. The sudden need for measurement of radioisotopes in the environment and food saturated the available instruments of most environmental radioactivity groups in Europe. Therefore the NAA research groups took over a part, and in some countries the greatest part, of the responsibility to measure food and other products.

7. MAKING NAA AVAILABLE TO THE SCIENTIFIC AND TECHNICAL COMMUNITY

7.1 IDENTIFICATION OF POSSIBLE CONSUMERS

In attempting to identify potential consumers of activation analysis services a variety of factors must be taken into account. These will include the nature of the reactor being used and the irradiation facilities available, counting facilities available for use, industrial base and importance of that particular industry to the country as well as political considerations.

The irradiation facilities and reactor fluxes available may be important in influencing which potential consumers should be approached. If the reactor has the ability of irradiating large volumes of samples on a routine basis (i.e., the schedule of the reactor consistently provides irradiations at least several days every two or three weeks) it may be possible to operate on a service basis to industries like mineral exploration. If on the other hand, the reactor only has the capacity of irradiating small numbers of samples irregularly, it would probably be a better idea to approach consumers with small volume demand, more on a research or co-operative effort.

The industrial base of the country can determine who are the potential consumers. For example, if there is no advanced electronics material industrial base there will not be any local consumers in that particular field. If, however, agriculture is an important industry, this group is a potential consumer. Political considerations are also important. If the reactor is located at a university, it is obviously in the best interests of the university to support research at university departments. If funding comes from government departments, it would be advantageous to support government research as well. Generally it is useful to show that there are consumers in all aspects of government, university and industry.

It is important when beginning to provide analytical services that overselling of services or overstating the capabilities do not occur. This will tend to provide the analytical technique and the laboratory with a bad reputation, which once achieved is difficult to overcome. The activation laboratory is essentially now acting as a commercial facility inasmuch as it is going to serve the needs of its clients. To do this, it is important to find out about the competition. Competing analytical techniques like atomic absorption, X-ray fluorescence and inductively coupled plasma emission (ICP) spectrometry may be able to solve the customers' problem more easily or cheaply if they are readily available. It will usually be advantageous if the person selling the analytical service has a little knowledge of the advantages and disadvantages of the INAA technique versus the other analytical techniques.

Potential consumers of analytical services can be found in many places: universities, government establishments, research institutions, industry, and medical institutions. In many instances the consumer will have a problem and may make the approach to have INAA solve their problem if he knows this service is available. In most other instances the activation lab may have to go out and find the consumer. If the latter is the case, you must decide in what field or fields you are interested in approaching. This may be based on your interests, political considerations or national priorities. Regardless of how the market segment of interest is chosen, background information on the types of analyses this market segment is interested in should be done.

Generally, when an approach is made to the potential consumer it is useful to know what can be done on particular matrices. For an example, let us say that we have targeted the geochemical field for application of the INAA technique. Within this market segment there are three potential sources of consumer. These include government establishments like the geological survey, the geology department at university, mineral exploration companies or mineral exploration or processing research institutes.

A useful beginning is a literature survey on some past applications of the INAA technique to the field of interest. This information can be obtained from the bibliography section of the Journal of Radioanalytical Chemistry or the biennial compilation of Analytical Chemistry. We must note however that most papers listed are papers dealing with techniques rather than applications. In the field of geochemistry for example the use of INAA is now widespread and papers in most applied journals such as the Journal of Geochemical Exploration deal with interpretation of results and not analytical method. Once selected, suitable sample material should be located to try some irradiation and counting schemes to familiarize the analyst with what can be done on particular matrices of interest. Reference materials provide known composition to begin tests on. The National Institute of Standards and Technology Catalogue of Standard Reference Materials, or the IAEA catalogue of reference materials, also provides a good clue as to the various fields which activation analysis can support by providing a list of all the materials people are interested in. Generally reference material programs will only produce reference material where a demand is foreseen. In effect, they are doing some of the market research for you.

Consumers in our other major field of application - environmental control - can also be found in the above-described market segments. Examples of governmental consumers are the ministries of environmental health, of public health, of general welfare, of agriculture and their related research institutes, and comparable county and municipal authorities. Data on trace elements play an ever more important role in formulating legal pollution standards, to their enforcement, and in the prosecution of violators.

It is important to realize that governmental research institutes often may have access to one or more trace element analysis techniques. Their acceptance of INAA as an alternative technique will be stimulated by the specific advantages (non-destructive nature, sensitivity, multi-element capability, analysis cost). However this will be balanced against turnaround time and the inadequacy of determining the ever popular element lead. But often the generally known and accepted good accuracy of INAA and the quality assurance incorporated in the procedure might convince the potential consumer. Within the university market segment, environmental science oriented groups can be found in the chemistry and biology departments. But also in the physics and civil engineering departments there might be some interest in INAA service, e.g., for problems related to waste-water or sewage treatment studies. The mining department might be interested in the role of INAA in studies of environmental impact of residual waste of mining activities. University groups tend to select their analytical technique of choice generally by taking the most appropriate one. The missing of data on lead will often be solved by determination of this element by another technique. Nor is a short turnaround time of vital importance, although sometimes student projects are very tight. Multielement capability, large throughput and low cost are key elements; analysis costs may be reduced if the involved groups are actively participating in the analysis (e.g., weighing-in and preparing samples for analysis).

In the third market segment - industry and others - consumers' organizations are found, which may be interested in and consulted for use of INAA service to get an answer to their studies and problems on environmental pollution. Examples of industrial consumers are companies which specialize in waste management and treatment, industries with strongly polluting waste streams (coal-burning plants, waste incinerators, metallurgical industry). Demands for trace element analyses may be related not only because of eventual impact of the industrial activities, but also for environmental health control of the employees (e.g., by urine, hair and blood analysis). For these consumers, not always will the ultimate be asked of accuracy and sensitivity but multi-element capability and turnaround time are of importance. Industry will often experience INAA as an economical attractive technique.

7.2 COLLECTING BACKGROUND INFORMATION AND IDENTIFICATION OF APPLICATIONS

The previous section gave some indication of identification of possible consumers depending upon the application chosen. Market research into this application is important. The obvious place to start is the library where basic information can be found quickly. The next most useful sources of information are the universities or government departments. In setting up meetings with these people one should have a basic understanding of the potential applications to discuss as a starting point. Once discussions take place it may become apparent which specific applications may be most suitable. Through all of this, the person doing the market research and identification of applications should have a good understanding of the INAA technique and its potential.

7.3 CONSULTATION WITH POTENTIAL CONSUMERS

Once you have identified an application it is important to locate the consumer for that application. Let us again assume that geochemistry has been targeted as an application and some basic research has been done on why the geologist needs trace element data and what sort of analyses can be done on rocks by INAA. This, however, is only background information. It is going to be very difficult to approach a geologist and tell him he needs trace element data before you know his problem or field of interest in geology. For university or government departments employing geologists it would be useful to obtain a list of people and their specialties or current research programs to decide where the first approach will be made. An alternate method would be to offer to be a guest lecturer discussing the analytical technique in general and some of the potential applications, advantages and disadvantages of the technique. This latter approach will tend to be useful in having people discuss how the analytical technique can be useful to them.

Once interest is shown in the technique and its applications, it is usually a good idea to obtain some material to test the application. The quality of results obtained and speed of analysis are important to show what potential the technique has. Generally samples should be analyzed rapidly and the results discussed with the consumer to see if the accuracy and precision are sufficient. Frequently the consumer may not require the best precision or sensitivity possible to solve the problem at hand and compromises to support the consumers' needs could significantly reduce costs and perhaps turnaround time.

7.4 MODES OF PROVIDING NAA SERVICES

Operating an activation analysis laboratory requires personnel, equipment, and the funds to keep them in operation. There may be several alternative ways of obtaining these resources, depending on how the laboratory is operated. Some laboratories encourage access by anyone who has need for NAA facilities while some, for security or other reasons, permit work to be done only by permanent staff. Some require all funds for projects to come from outside the institution, while some at the other extreme forbid extramural work.

There may still exist laboratories in which direct funding of research is sufficient to support all the activities that the staff wish to pursue, but most need to justify their work and budget to government agencies, institute directors, university administrations, paying clients, or (most often) a combination of these. In all laboratories of which we are aware, a substantial and often dominant fraction of the work is "counting other people's atoms", in Lenihan's phrase [207]. Real costs must be covered, but the cost of NAA to the consumer of the data must be competitive. It is undesirable to provide unlimited analytical services free of charge to all comers, even from within the parent institution. If there is no price then a customer has no incentive to select his samples and think through his data interpretation before the measurements are made, and the analyst has no incentive to improve the quality of the data. The result will certainly be large quantities of bad data and a deservedly poor reputation for the laboratory.

7.4.1 SCIENTIFIC COLLABORATION

In institutions with a strong commitment to research, the workers in an NAA laboratory may function essentially as faculty members; that is, as independent scientists whose primary function is to pursue basic or applied research using NAA as a tool. Financial support may come from the general funds of a parent institution or from national or international granting foundations.

When the NAA laboratory has a certain amount of base funding from a parent institution, extramural support can take the form of cooperative scientific projects with outside groups which have problems that are readily solved by NAA. The "payment" from outside the institution takes the form of a division of labor and benefits, with no money changing hands. This mode of operation is a satisfying way to demonstrate to both analysts and users the usefulness of NAA in a project. Particularly in the beginning stages of a collaboration, the outside institution may select and prepare samples while the bulk of the analytical work is done by the NAA staff. As the project evolves, all the participants begin to learn each other's fields. An important part of the payment is coauthorship of publications, which is a sign to the participants and supervisors alike of the success of the work, and which may be expected to lead to further problem-solving projects in related fields of application. A later stage of this relationship is to apply for external financing of the project, divided between the participating institutions in relation to their expenses. This collaborative mode is unquestionably a drain on resources from an actuarial point of view, and can be followed to a large extent only if analysts are considered scientific professionals with responsibilities toward furthering the state of the art.

7.4.2 PAYMENT IN KIND

The guest may provide a more tangible contribution by supplying equipment or semi-permanent staff to the NAA laboratory for his program. Particularly productive relationships have been set up between analysts and manufacturers of counting and computer equipment. The laboratory may get the use of the best new equipment, while the manufacturer obtains in return the advice of skilled users of his products in real-life applications. Training of the guest's staff members in the host's standard procedures will be necessary in proportion as the laboratory work is taken over by the guest.

7.4.3 MULTI-USER CENTER

An approach to an efficient use of the potential of an NAA laboratory without expanding the size of the permanent staff can be found by encouraging and assisting scientists in other fields to apply NAA themselves in their research projects. The intent of a multi-user center is to make it easy for biologists or geologists to use NAA to solve their own problems without becoming an expert on all the details of the analytical process or setting up an off-site NAA laboratory of their own. Maintenance and calibration of the irradiation and counting equipment, and the solution of day-to-day problems, generally remains the responsibility of the permanent NAA staff. This concept has been proven to work well when the necessary investment in setting up standard procedures has been made [198].

Some training must be provided in any institution that relies on temporary or part-time workers, whether they are students or senior researchers from outside the field of NAA. For example, classroom training in the properties of ionizing radiation and the handling of radioactive materials is commonly required for safety reasons. In a center with a rapidly shifting population of researchers, the production of reliable results has to be assured with a reasonably short training period. If the analytical procedures established in the laboratory are well systematized, documented, and automated and simplified to the maximum possible extent, then the newcomers quickly become productive on their own with a minimum of time and effort required from the permanent staff.

Training of new users needs to cover the four phases of the analytical process:

a. Sample weighing, preparation and planning for irradiation and counting through scheduling of equipment, and setting up notebooks and procedures;

b. Data input procedures and the operation of MCAs, sample changers, and computer systems;

c. Handling of irradiated samples with regard to safety, avoiding contamination of equipment, and proper disposal;

d. Spectrum analysis, data interpretation, and quality control.

The last item on this list is of major concern. Despite highly developed computer procedures for qualitative and quantitative analyses, the interpretation of spectra and the generation of reports with realistic uncertainty statements requires some judgment. In the first contacts with potential users of NAA, the established precision and accuracy of routine analysis will be used to emphasize the possibilities of the technique, but it must be remembered that many years of experience by skilled specialists has been required to establish this quality. Planning the experimental measurements and the interpretation of results requires the involvement of an experienced staff member as well, particularly in the early stages of a project. Assuring that the center produces only reliable results is an essential function of the permanent staff. Careful attention must be paid to quality assurance procedures, since a reputation for quality carefully built up over many years can be quickly lost by a few bad measurements.

7.4.4 FEE FOR SERVICES

Some activation analysis laboratories are operated purely as a commercial venture, much like clinical service laboratories. Even a collaboration undertaken for purely scientific reasons may lead with time to so much routine NAA work that another form of relationship, less scientific and more commercial, may become more appropriate. As the relationship between analyst and customer becomes more businesslike, accurate accounting for costs becomes more important, and also more difficult. Assessing costs for analyses will be discussed in more detail in the following section.

7.5 COST ANALYSIS

There are many acceptable ways to calculate the cost of performing activation analysis. The following discussion is not likely to represent any institution's actuarial practice in detail, but may serve as a guide to which categories need to be considered.

Activation analysis can be performed in a manner competitive with other analytical techniques. The equipment is no more expensive than that used in some "chemical" techniques. A system with detector, sample changer, MCA, and PC can be assembled for under US$50,000 (1988 price level). Given several counting systems and a well-developed routine, experience has shown that one person can analyze 10,000 samples of similar material per year.

7.5.1. HOW TO CALCULATE THE COST OF ACTIVATION ANALYSIS

In calculating the cost of an analysis we may distinguish the following expenses :

- time for doing the analysis (labor), and supervising and maintenance;
- costs of consumables related to the analysis;
- costs related to the use of the reactor;
- costs related to measurement and data handling;
- miscellaneous costs.

a. The labor or working time for a specific analysis includes the time needed by personnel for a variety of tasks:

- sample preparation and handling (weighing, pelletization, crushing, preconcentration, freeze drying, packing for irradiation, preparation of standards, unpacking after irradiation, and transfer from reactor site to sample counting room);

- administrative tasks (bookkeeping, filling-in of forms, time needed for authorization of irradiation and writing reports);

- time needed during the measurement (changing samples or loading sample changers).

It is not always easy to make in advance an estimate of the time needed for an analysis. Factors affecting the working time are number of samples which can be analysed together in one batch, the availability of counting equipment and equipment for sample preparation, the skill of the person doing the work, and the other tasks of the personnel involved. A very straightforward but useful way to get an estimate of the time required to do an analysis is to time with a stopwatch all procedures during the course of a complete analysis.

In general it is better to overestimate a little. Not only corrections have to be applied for the time the personnel needs for leisure - lunch or refreshment breaks, vacations, etc. - but later, after some practical experience the cost can be adjusted, and customers accept a reduction in price more easily than an increase.

Time needed for supervising and maintenance has to be estimated on an annual basis, and then divided by the total number of samples that are being analyzed under this supervision. Supervising includes answering telephone enquiries, control of reports and control of quality-control samples, invoicing, assistance in spectrum and data interpretation, planning special analysis procedures, etc. If the NAA laboratory has to be fully self-supporting, this item also has to include the time spent on general research and development, necessary to keep the analytical performance up to date. Maintenance covers time required for daily, weekly or monthly calibrations, equipment checks, maintenance and repair.

All these time-items (labor, supervising, and maintenance) have to be multiplied by the appropriate direct and indirect costs. The direct costs include gross salaries and social security payments. It is obvious that the unit direct cost may be strongly different for labor carried out by a technician, supervising when an academic is in charge, and maintenance done by an electronic engineer. The indirect costs may include electricity, water, maintenance, capital cost of the laboratory building, workshops, health physics personnel, reactor operators, and adminstration. In some institutes the administration and cost calculation system is well developed giving monthly reports on working hours and expenses, separately for each task regardless in which section the involved persons belong in the line organization.

b. Costs of consumables directly related to the analysis can be easily calculated. It covers mainly the costs required for irradiation containers, and reference materials and standards. Usually, this item is nearly insignificant unless it is necessary to use ultra-pure quartz tubes for irradiation.

c. It is difficult to generalize about costs related to the use of the reactor. Different organizations have different actuarial practices. In many cases the cost of the irradiation is not included at all, because arguments like 'the reactor would be there anyway', 'it has so many users', etc. are used. None of these arguments is valid when a realistic estimate of analysis cost is required. Apart from this is the question whether this cost should be included in the charge for analysis service or not. That can be only decided separately in each laboratory.

An approach is to calculate the annual capital and running cost of the reactor and divide it with a number of produced neutrons. The obtained number, cost per neutron, can now be used for estimating the cost of irradiations. In this way the cost is directly related to irradiation time and flux. A more elegant and better way is to base the calculations on the total number of used neutrons. The total cost will then be covered by the various activities at the reactor. It is important to study closely the procedures followed in the different irradiation sites. The integrated number of used numbers for irradiations in a pneumatic transfer facility can be easy calculated, but in other manual-loaded sites, also the time required for cooling the irradiated sample still occupying the facility has to be incorporated.

A different approach is to include the capital and running costs in the general overhead already mentioned above, when indirect costs related to time was discussed. This system is easy but somewhat unfair because the cost is divided between activities in a relation which is not proportional to the actual use. However, it has to be remembered that, especially when low power reactors are used, the cost of keeping the reactor in running condition is a high proportion of the total cost, compared with the cost of actually running the reactor. This means that even if the isotope production group uses the reactor only one day per week, the cost of this service is much higher than 1/5 of the cost of running the reactor five days a week.

It is also important to realize that there is practically no difference in cost when one or ten irradiation positions are occupied. Therefore, it is not unfair to distribute the total costs per hour and use this as a basis for cost calculations. When the reactor is run for one group they pay 100 %; are there two groups involved, they each pay 50%, etc. It is too complicated to split up such an approach for each hour; an annual average should be estimated instead.

If the reactor personnel is used for actually performing the irradiations (preparing irradiation containers, loading and unloading in the reactor), these costs have to be included separately, e.g., in the labor time entry.

d. Costs related to measuring equipment and data handling. In this entry primarily the depreciation and maintenance costs of counting and computing equipment is involved. These costs can be easily calculated, and depreciation terms have to be chosen, which may be different for the different parts of a spectrometer, but also different in different laboratories. Computer costs are not always easy to estimate. When analyses are carried out on multi-user computer, the computer manager may be able to estimate to what extent the NAA-group has used the machine. This exercise ends up with a value representing the total depreciation cost of the laboratories' counting equipment. If expensive laboratory equipment is used (balances, freeze-drying equipment, etc.), also for these, a contribution to the depreciation cost has to be included. Maintenance can be a major cost of equipment, as much as 15% of the purchase price per year for a full service contract from the manufacturer. Other expenses are costs of printing paper, liquid nitrogen, disks, crucibles, filter paper, tissue, disposable gloves, etc.

e. Miscellaneous Costs. Expenses may be included for costs of advertising, telephone, shipping, stationery and postage, rent, taxes and insurance, accounting charges, radioactive waste disposal, etc. It should be noted that in many institutes several of these expenses are already buried under the term 'overhead'. Some universities may add a percentage of 40 - 60% of your cost as 'overhead' to be billed to your customer.

It is important to decide whether the commercial NAA service is part of a general NAA facility, in which the additional income will help to finance the facility, or whether the main justification for the facility is as a commercial operation. Such a decision defines to what extent each of the five different entries which contribute to the analysis cost will be used in the price to be charged and to what extent a profit margin will be added.

However, as mentioned in chapter 7.4, other factors may influence the final price to be charged. The charge has to be competitive with other analytical methods that can determine the elements of interest. The latter information can simply be obtained from competitors' price lists. It is too easy though to have prices that are competitive but do not cover the costs: the service is losing money then. It is better then to stop with this non-profitable work, and concentrate on other samples. Another outcome might be that it will be necessary to work with a minimum charge to ensure that very small batches are cost-effective. NAA is often used by the industry as a technique where all other methods have failed or as a referee analysis for an in-house standard. Consequently, samples are often received as batches of a few samples and it is easy to lose money on these analyses.

It may be feasible to charge less than the actual cost if the government or institute wants support research institutes in the country, or if the services otherwise have to be purchased in another country, causing foreign currency expenditure. It is important not to confuse these arguments with doing the work inefficiently.

7.5.2. EXAMPLES

The outcome of a cost analysis will of course be different for different laboratories. As an example, for a few strongly different laboratories a detailed specification of their cost analysis is given here, illustrating the difference and extent of the various items included.

laboratory 1.

analysis labor	58%
maintenance salaries	10%
supervisor salaries	9%
expendables	2%
depreciation equipment	21%

laboratory 2.

labor, benefits and overhead	66%
equipment depreciation and maintenance	7%
reactor charges	6%
small equipment, supplies, travel	21%

laboratory 3.

labor	25%
maintenance	4%
supervising	8%
expendables	10%
rent	20%
miscellaneous	15%
profit	15%

laboratory 4.

labor and benefits	37%
overhead including equipment, laboratory, reactor & administration	29%
expendables	3%
profit used for development of instruments and methods	31%

Table 7.1. shows examples of the cost of the analytical work charged by different laboratories. The figures are intended as order-of-magnitude examples of the real cost for analysis. The great variations are caused by

differences in sample type, required accuracy and the number of samples of one type analyzed in a series. The cost varies greatly when sets of tens or thousands of samples are analyzed in one series. Some of the prices contain a profit, some only the direct cost.

TABLE 7.1. EXAMPLES OF COMMERCIAL INAA PRICES COLLECTED FROM PRICE LISTS
(Cost based on January 1989 exchange ratios and 1988/1989 tariffs. Prices in US $)

	One irradiation/measurement (number of determined elements)	Total analysis with several irradiation/measurement sequences (number of elements)
Label 1	9-12[1] (28)	21[2] (34)
		58[3] (34)
Label 2	31 (24)	157 (35)
Label 3	53 (29)	137 (>40)
Label 4	90 (22)	252 (43)

[1] Depending on sample size.

[2] Exploration (higher detection limits).

[3] Research (lower detection limits).

8. ORGANIZATION OF WORK

8.1 STAFF

It is essential to have a full-time member of the staff with responsibility for the NAA facility - in particular to maintain and support the counting equipment. This person should be trained in a scientific discipline such as chemistry or physics, although experience in other disciplines such as geology, may be a real advantage. Essentially it is an analytical chemist that is required and as such the person must be able to understand not only the basic principles of the technique but also be able to anticipate problems and identify sources of error. He or she will also need to carry out some development to support new analytical work. The analyst must also be able to communicate with workers in other disciplines and collaborate in projects using the technique.

Although it is possible for one person with sufficient experience to fulfill all these requirements, the alternative is for a number of people to be available for consultation should the need arise. Technicians may be needed to prepare samples. At a reactor site it is likely that there will be physicists using gamma-ray equipment and health physicists who can assist the activation analyst with some aspects of the work. In addition there may be a radiochemist associated with the reactor operations who could assist with the chemistry of preparing standards and carrying out radiochemical separations. Such a multi-disciplinary team could cooperate to run the NAA system, but it is unlikely that the facility would be developed as a successful self-financing operation without one person with full-time responsibility for the day-to-day running of it.

Other support staff will be required in the case of a breakdown in the equipment or a desire to improve the existing facility. These include electronics and mechanical workshop staff. In the absence of such specialists, it may be necessary to 'buy in' expertise from manufacturers. It may also be desirable to have a computing expert on call, to support the computer-based counting equipment.

8.2 SAMPLE BOOKKEEPING AND CODING

From the first initiatives on analyses to be performed on certain samples, an administrative procedure has to be started - recording, for example:

- sample-origin description, or customer's name; information on people-in-charge
- order or contract number
- date and number of sample received; promised date of reporting results
- customer's identification code
- sample description
- your own identification number of the sample
- fresh and dry weight of the samples in the irradiation containers
- filling height of the irradiation container
- similar information on corresponding standards and fluxmonitors
- date, time, and duration of irradiation
- irradiation position

To keep samples identifiable, code numbers can be applied. Such a code may consist of several alphanumeric characters, and a sample sequence number. By implementing the same code into a spectrum filename, measured and stored spectra can be identified and linked to the samples. Alphanumerics can serve as:

- customer identifier, e.g., A,B,C,....Z . Different batches from one customer can be identified with a second alphanumeric.

- spectrometer identifier, to distinguish spectra of the same sample, measured at different spectrometers. When this label is added to the spectrum file-name, accidental overwriting of data is prevented.

- geometry or measurement identifier, in case spectra of the same sample are measured several times with the same spectrometer, but at different sample-detector distances.

As an example, a code may look like AB5F006; A and B being customer and batch identifier, respectively, 5 = spectrometer identifier, F = geometry identifier, and 006 = sample sequence number. Some spectrum storage systems allow for even more labels in the filename. Part of the code, like customer identifier(s) and sample sequence number (AB006) can be written or scratched on the irradiation container [208], and attached to the reminders of the original sample. After completion of the analysis, a copy of the reported analysis results is added to the relevant part of the bookkeeping system.

When analyzing a limited number of samples, bookkeeping is a simple manual administrative procedure. But for a large throughput laboratory, much time and manpower can be saved when this task is taken over by computer [209]. In brief, the principles of this computerized bookkeeping system are :

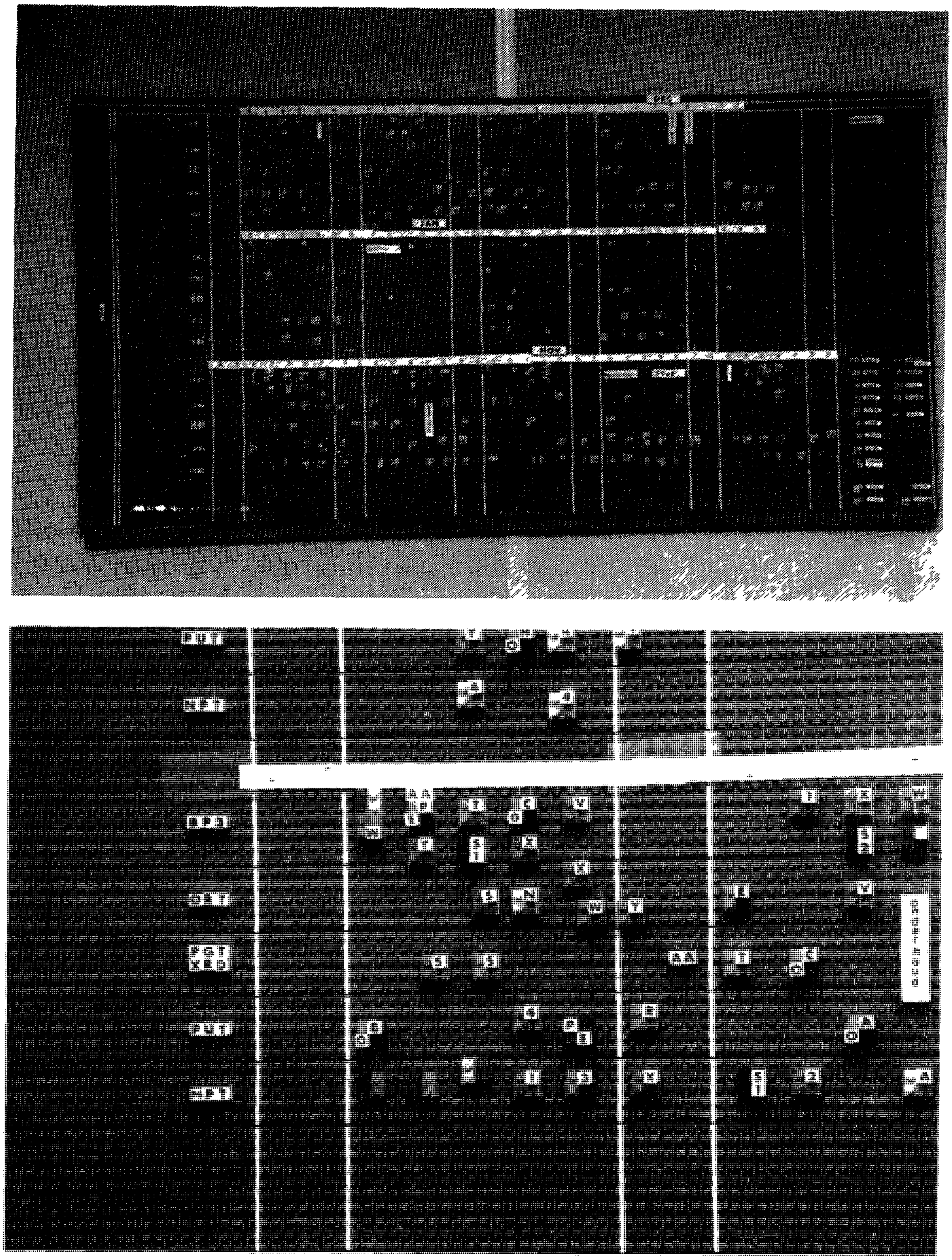
* For each 'customer' a file is made containing for every batch basic information on codes (both customer's own code and laboratory code), weights of samples, standards and flux monitors, capsule filling heights, irradiations, etc.

* This file can be called in every time the sample is analyzed, e.g., after different decay times, as the customer identifier label in the sample code links the recorded spectra and the information file.

* The analysis results of a specific sample spectrum can be stored in a separate file, still using the selected sample code. Every time a new analysis has been performed on the same sample, this new information is added to this result file; by also adding decay times all results remain recognizable.

* At completion, the result file can be updated and corrected, and incorporated in the report.

Different series of samples are sometimes processed simultaneously on different spectrometers, and irradiations and measurements of different series may overlap. A status scheme gives direct information on the degree of occupation of irradiation positions and spectrometers, and on available remaining time for rush orders without interfering with regular work. In such a scheme batches of samples can be denoted by their customer - and batch identifier labels. The laboratory can check quickly day by day whether all analyses proceed as scheduled. Answers can be given on queries from impatient customers. A schematic example of such a status scheme using 'LEGO'-type bricks is given in Figure 8.1.



Legend : 'BP3' : irradiation facility
'ORT','PGTXRD','PUT','NPT' : gamma-ray spectrometers
'onderhoud' : maintenance

A square block corresponds to a batch of samples to be irradiated or measured. Alphanumerics on the blocks serve as batch identifier. Each user has his own color identification.

As an example : on day 28 batches T and S1 are being irradiated; batch T is counted on day 02 on spectrometer PGTXRD, and batch S1 is counted on day 02/03 on spectrometer NPT. About 20 houres are required to count all samples and standards within a batch

FIG. 8.1. General view (top) and detail (bottom) of status information scheme.

8.3 SAMPLE PREPARATION

Depending on the type of samples to be analyzed sample preparation procedures and the preparation equipment required may be very different. Even within the field of geochemistry, the sample preparation required for rocks is not the same as for vegetation or soils.

Rocks will have to be crushed with an aliquot then ground into a fine powder. This is usually achieved using a combination of jaw crushers, cone crushers and ring or ball mill pulverisers to reduce the rocks to a powder usually finer than -150 mesh size. Soils on the other hand may only require screening to -80 mesh size. The aim of sample preparation is to reduce the sample size to allow a representative sample to be chosen for analysis. This aspect of preparing the sample for analysis is one which requires adequate space, equipment and know-how to prepare the sample properly. If the subsample is not representative or if contaminated there is no point in providing an accurate analysis (i.e., garbage in - garbage out). Various papers exist on sampling and sample size necessary for analysis [210/211/38].

In many circumstances the customer may have the ability of preparing the samples for irradiation. To maintain control of contamination the consumer may prefer this. To encourage this a discount may be provided if the customer does the preparation and encapsulation. In the event the necessary equipment is not available in the NAA laboratory, having the customer do the preparation may be the only alternative. Generally the activation facility should provide the irradiation vials as the reactor will probably need a certain size and type of vial to be acceptable for irradiation (Fig. 8.2). The activation analyst should know what contaminants are present in the vials to determine their suitability for a particular set of samples.

Before analysis, samples may require washing, drying (oven drying or freeze drying), homogenization (with or without cryogenic techniques), fractionating, or pelletization (Fig. 8.3). Liquid samples may require preconcentration or absorption. The primary concern of the activation analyst is to be acquainted with sources of contamination and losses of elements during these steps. One of the advantages of INAA compared to other analytical techniques is its relative freedom of contamination. In fact, the only steps where contamination may occur that influence the final result are sampling, sample handling and storage and sample preparation. Of these, often only sample preparation and storage are carried out under direct responsibility of the INAA laboratory.

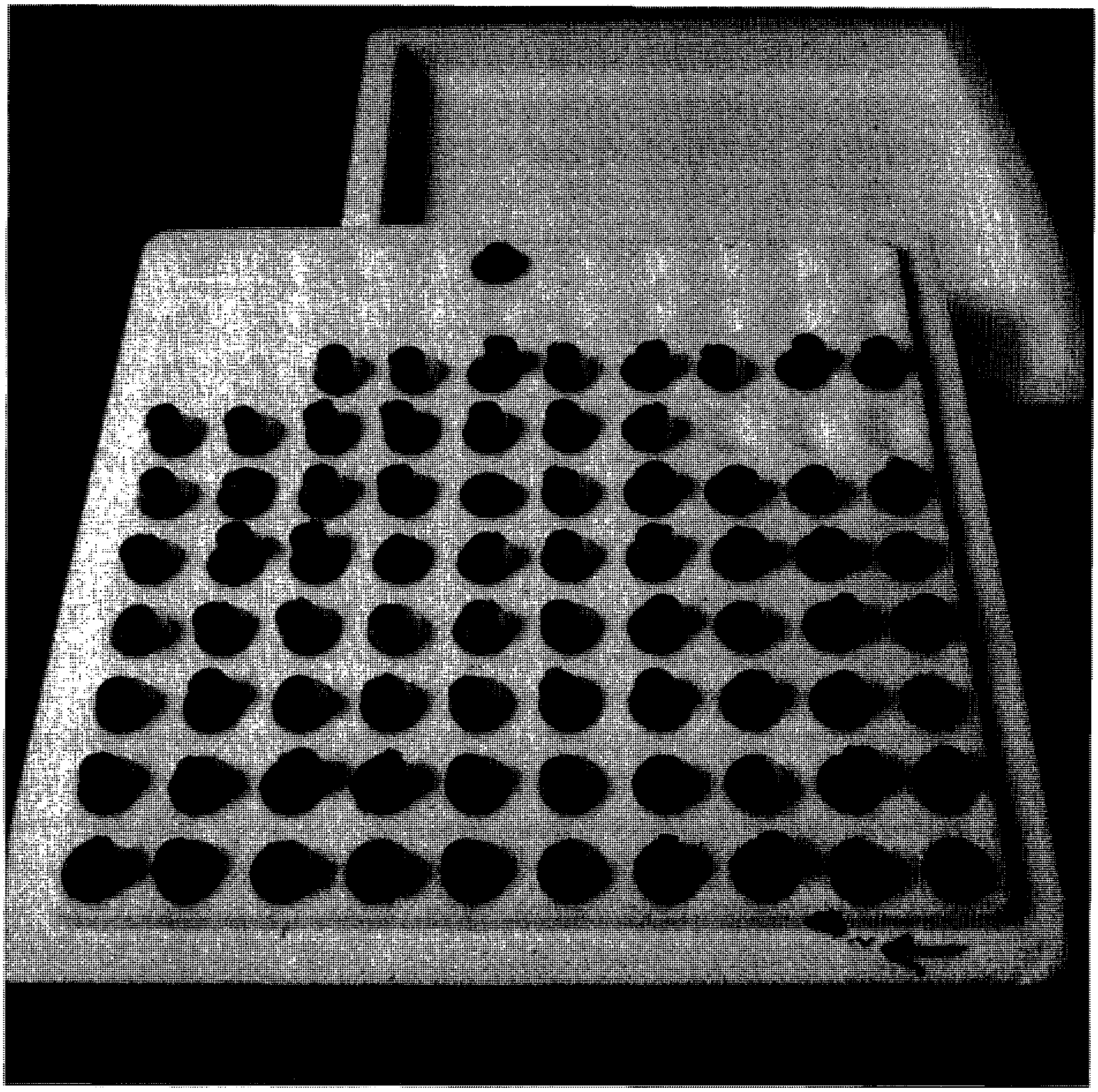


FIG. 8.2. Vials and transportation box for sending ready-weighed samples for activation analysis.

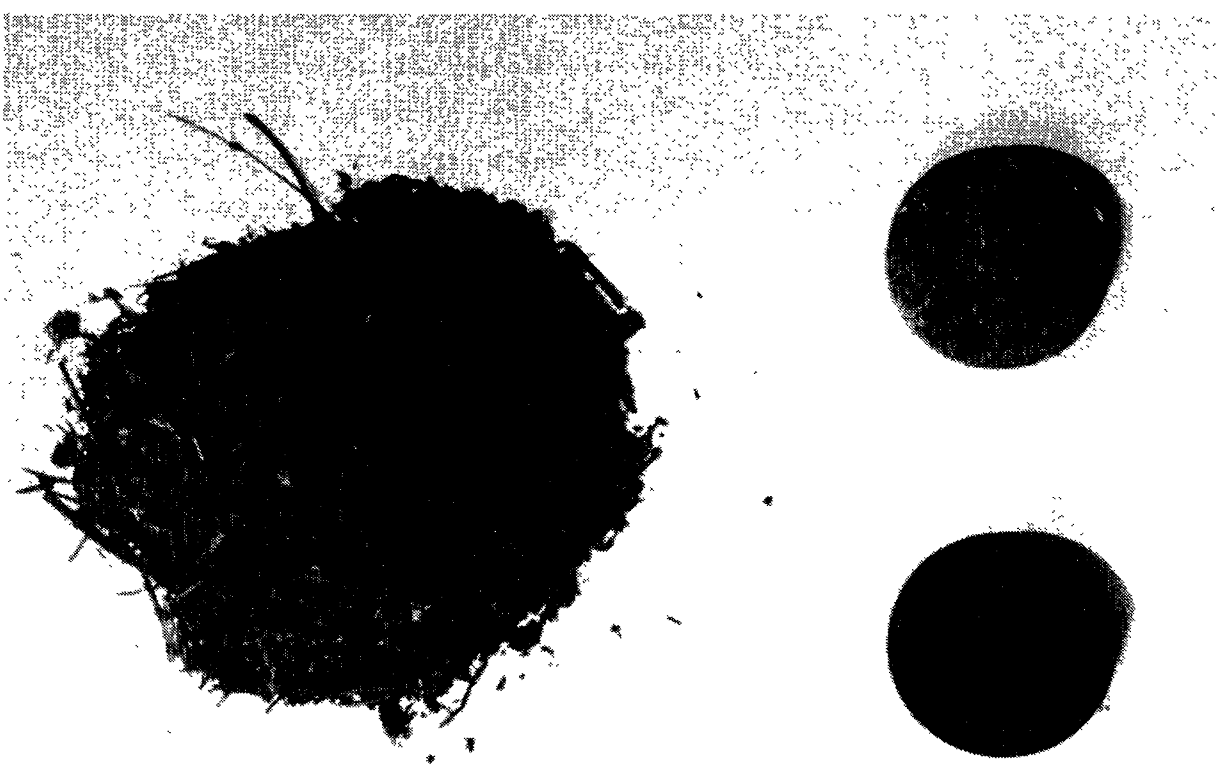


FIG. 8.3. Organic material can be pelletized to ensure constant geometry.

It is obvious that the lower the trace element content of the sample, the more will be asked of the analyst to avoid contamination. For certain sample types (human tissue, blood, or sea water), analysis should only be considered if the laboratory is very familiar with the problems encountered in such analysis, and equipped to handle them [212/213]. The results and recommendations on sample preparation from the IAEA Advisory Group Meeting on Quality Assurance in Biomedical Neutron Activation Analysis [179] were meant for biological samples; their applicability is certainly wider. However, as Iyengar states [214], "...it should be recognized that the purpose of the analysis (i.e., the elements analysed and the levels of contamination involved) is the deciding factor for the handling of the samples and the concept of controlled contamination suggested by Behne [215] can be advantageously used in this context." As an example, use of titanium scissors and knives does not present problems when Ti is not of interest; the contamination of samples with Si from agate ball mills seldom will give trouble in environmental analysis.

For most sample types in environmental analysis, trace element concentrations are not ultra low; even concentrations in biological materials such as plants and molluscs may be substantially higher. The advantage is that the extreme precautions do not have to be applied which are necessary when analyzing clinical samples; still one should be aware of some serious sources of contamination such as :

- airborne dust. There are no rules of thumb which elements are related to airborne dust, as the dust may originate from other activities in the laboratory, or from the outside, and the particulates may reflect soil composition. A clean hood strongly reduces this type of contamination. Even better is to have such a hood in a clean room.

- sample handling tools (see Table 8.1). Contamination of samples during homogenization was already described above. Trace element impurities in several laboratory materials are given by Sansoni [152]. An often overlooked source of contamination is the talc from plastic gloves; talc-free gloves are available.

TABLE 8.1. CONTAMINATION OF ORGANIC MATERIAL DURING SAMPLING WITH TOOLS OF VARIOUS MATERIALS

Material	Degree of contamination	Contaminating elements
Stainless steel	Large	Co,Cr,Fe,Mn,Mo, Nb,Ni,V,W,Ta
Aluminium	Medium	Al,Cu,Mg,Mn,Na, Sc
Pyrex glass	"	Al,B,K,Na,Si
Rubber	"	Mg,S,Sb,Zn
Quartz	Low	B,Na,Sb,Si
Polythene	"	Al,Cl,Ti,Zn
Teflon	Very low	F

By using a blank sample contamination during sample preparation may be detected. An empty container has to pass all sample treatment steps; however, when the containers with the real samples are packed with filter paper, or other inert filter, the blank container should hold these too. Such a contamination control method requires insight into trace element impurities in the container material (see Table 8.2.) and in the filter (Table 8.3, from [52] according to [216] (see also Table 4.1). The contamination caused by sampling and storage of samples are also discussed in references [7/148/149/150/217/218].

The other problem the analyst faces during sample storage and preparation is the loss of elements. For all materials of biological origin, it is recommended to store the samples after freeze-drying at low temperatures (e.g., -80°C or LN2 temperature). Sample containers should by preference be made of polyethylene or PTFE. Zeisler showed [219] that under these conditions there were no losses in elements over a longer period of time.

TABLE 8.2. TRACE ELEMENT IMPURITIES IN POLYETHYLENE CAPSULE MATERIAL

	RABBIT (polyethylene)
F	< 25
Na	0.1
Al	0.6
Cl	0.5
K	0.1
Sc	< 0.0005
Ti	0.1
V	0.002
Cr	5
Mn	0.06
Fe	< 5
Co	< 0.1
Ni	< 10
Cu	< 0.2
Zn	0.03
As	< 0.003
Br	0.005
Mo	< 0.1
Sb	< 0.002
Cs	< 0.05
La	< 0.002
Sm	< 0.0005
W	0.001
Au	0.00002

TABLE 8.3. TRACE ELEMENT IMPURITIES IN VARIOUS FILTER MATERIALS

							Applicability**** for:					
Material	Filter type	Por size (μm)	Electric charge*	Pressure loss**	Initial collecting efficiency***	Hygroscopicity****	Low volume air sampler	High voluem air sampler	Atomic absorption spectrometry	Activation analysis	Fluorescence X-ray analysis	Remarks
Glass fiber	Toyo GB-100R		o	o	o	o	o	o	o	X	Δ	
	Gelman type A		o	o	o	o	o	o	o	X	Δ	High Zn content
	Whatman type A		o	o	o	o	o	o	o	X	Δ	High Zn content
	Millipore AP-20		o	o	o	o	o	o	o	X	Δ	High Zn content
	MSA 1106 BH		o	o	o	o	o	o	o	X	Δ	
Quartz fiber	Tissue Quartz 2,500 QAST		o	o	o	o	o	o	o	Δ	Δ	SiO_2 99%
	Gelman Quartz Paper type I		o	o	o	o	o	o	o	Δ	Δ	SiO_2 98.5%
	Gelman Quartz Paper type II		o	o	o	o	o	o	o	Δ	Δ	SiO_2 99.5%
Polystyrene	Microsorban (sartorius)		o	Δ	o	Δ	o	Δ	o	Δ	X	
Polyvinyl cloride	Yumicron MF-100	1	o	Δ	o	o	o	Δ	o	X	o	High Cl and Ti content
Nitro-cellulose	Millipore-RA	1-3	Δ	X	o	Δ	o	X	o	o	o	
	Sartorius SM		Δ	X	o	Δ	o	X	o	o	o	
	Toyo TM-100		Δ	X	o	Δ	o	X	o	o	o	
Cellulose acetate	Gelman GA-3		Δ	X	o	Δ	o	X	o	o	o	
Fluorine resin	Polyfuron PF-3 (Toyo)		o	Δ	o	o	o	X	Δ	o	-	Fibrous
	Millipore Mitex LS		o	Δ	o	o	o	X	Δ	o	-	Fibrous
	Fluoropore AF-07P (Sumitomo Denko)	10	X	X	o	o	o	Δ	o	o	-	Membrane type
	Millipore Florinert FA	1	Δ	Δ	o	o	o	Δ	o	o	-	Membrane type

* o, Trace; Δ, moderate; X, too high for use.

** o, Very small; Δ, moderate; X, large.

*** o, Not less than 99%.

**** Moisture content: o, 0.1-0.5%; Δ, 1-2%.

There is some controversy on storage of other materials, such as soils, sludges, sediments and air filters. With respect to trace element stability, there is no specific preference for room temperature storage, low-temperature storage, dried or moist. But when other characteristics of the material have to be studied, e.g., by chemical speciation, the best way to avoid changes in chemical behaviour is by storage at low temperatures. For all materials clean containers are essential.

Losses also may occur during drying of the sample. For nearly all sample types, drying appears to be essential to remove water and to decrease the risk of pressure build-up during irradiation, which eventually may lead to exploding of the sample container. Except for air drying at room temperature, which is sometimes preferred to decrease losses of volatile elements, the most straightforward way is oven drying. The method is very well suited for sediments, soils, sludges and ashes. Temperatures have to be maintained well below 100°C, by preference 50 - 70°C, to avoid matrix decomposition and losses of volatile elements such as As, Se, Sn and Hg. The laboratory has to be well informed about possible ways of losses of such volatile elements, which are often of importance in environmental studies.

Certain types of samples like biological materials, coals, or potash may absorb water from the air on standing. Generally analyses are done on a dry-weight basis and the samples should be dried prior to weighing by a procedure appropriate for the material. The samples should be weighed immediately on coming out of the oven so that moisture content does not get reabsorbed.

For samples of biological origin (plants, fish, mollusc, mosses, lichens, etc.) freeze drying, also known as lyophilization, is certainly the most appropriate method. It is generally accepted that this process does not cause losses of any but the most volatile elements. The samples have to be prefrozen (e.g., at -30°C or lower) prior to placement in the freeze drier, and that vacuum pump must be able to obtain in short time an adequate vacuum. Generally any form of drying may invalidate the sample for other experiments in which the chemical state is of interest, such as organic extractable contents, nitrification rate, loss of enzymes, or change in membranes.

It is hardly possible to give rules for the amount of sample to be weighed for analysis. Too many variables play a role: total available amount of material, neutron flux, counting efficiency, size of the sample container, etc. These variables are all related to the amount of radioactivity to be induced and to be measured. Very small samples (e.g., <10 mg) may suffer from loss of representativity and homogeneity; for this reason, a minimum amount of 200 mg is recommended for many reference materials. Such a weight may then also be chosen for the corresponding samples. A large sample (e.g., >500mg) may give difficulties in making accurate corrections for neutron self-shielding and gamma-ray self attenuation. A similar problem arises from the presence of strongly neutron absorbing elements such as boron. High amounts of B (e.g., as in some borosilicate glass filters) may cause unacceptably high increases in temperature during irradiation, eventually leading to melting of the sample container.

Contamination during sample preparation may be a major problem for geological samples [220]. Airborne dust during rock crushing and milling can create a serious problem without proper dust control. Contamination from elements like gold, which are very malleable and can plate out on grinding mills, is also possible. Samples may be contaminated during screening (from solder joints) even when using nylon screens. Contamination during weighing from unclean spatulas or in some instances from rings worn by the person handling the vials or weighing the sample is possible. The grinding equipment or homogenizing equipment used is also important. Tungsten carbide drill bits used frequently for archaeometry samples can add a high tungsten and cobalt content to the samples and greatly increase the overall activity of the sample. Trace amounts of Hf and Ta are also added. Alumina grinding equipment can add large amounts of Al contamination. Hardened steel will add Fe, Ni, and Co contamination. Agate mills will add Si. From our experience agate for geological matrices or plexiglass for biological samples is usually best. The cheapest alternative is usually hardened steel. The list of possible contamination is endless. It is usually a good idea to include blanks (in the case of rocks, put a silica sand sample through the whole sample preparation process) to detect contamination. In addition to the above, the reader is referred to the survey on sampling and sample handling of environmental samples by Maienthal and Becker [221].

8.4 STANDARDS

Good standardization is the basis for the accuracy of the analytical facility. The approach to standardization varies from facility to facility and it often depends on the background of the analyst involved. Physicists may prefer to irradiate flux monitors along with their samples and make calculations based on nuclear data to determine the concentration of the element present. A chemist may use standards prepared from chemical elements or compounds. On the other hand a geologist may adopt geological reference materials as standards in the analysis.

In-house comparator standards are in regular use in most laboratories for calibration of the measurement process. For the ultimate accuracy there is no substitute for making one's own standards. Given an analytical balance and pure elements or pure compounds with well-known composition, standard laboratory methods of gravimetric and volumetric analysis can produce standards whose concentration is known to 1% or better.

Careful attention to all possible errors in preparing standards, especially multielement standards, is important if accurate results are desired. Potential sources of error in preparing single element standards include evaporative losses of solvent; pipette calibration and imprecision; contamination of the standard from reagents, equipment, the laboratory environment, or final matrix; purity and stoichiometry and moisture content of starting material used to prepare the standard; instability of solutions (i.e., precipitation), and loss of volatile elements during dissolution and irradiation. Additional sources of error in preparing multielement standards include the stability of mixed multielement solutions, and cross-contamination of one element by the addition of a second element. The latter is especially important for NAA where standards are often prepared with greatly differing amounts of the various elements. For example, if Fe and Sc are included in the same standard, an Fe concentration ten thousand times greater than that of Sc might be desired to produce comparable peak areas. If the Fe used contained 0.01% Sc, the Sc content of the standard would be twice as great as expected, unless this additional source of Sc is recognized.

In view of the many potential sources of error in preparing multielemental standards for NAA, is it reasonable to expect that such standards can be produced with an error of 1 per cent or less? In 1976- 1977 [222] a set of four synthetic multielement standards were produced for INAA. A great deal of care was taken in preparing these standards but heroic efforts to achieve the ultimate accuracy were not made. For example, these standards were prepared by volumetric dilutions; significantly smaller errors could have been achieved if gravimetric methods had been used. All sources of error in preparing these standards, except for residual moisture content and non-stoichiometry of compounds, were evaluated, and the total error in each pipetted standard was calculated to be slightly less than 1 per cent at the 95% confidence level. These standards have been used at NIST for the past nine years in the analysis of Standard Reference Materials. The results from numerous intercomparisons with other NAA standards and with other techniques have indicated that the 1 per cent error originally calculated is indeed reasonable [223].

Few reliable primary standards are available [227/225]. Unless it is accompanied by an explicit report of analysis, a material labeled "99.99% pure" may not truly be so pure. Rarely is a pure substance assayed for the number of moles of the desired component per gram. Stoichiometry is not always as labeled; metal oxides may contain carbonate. Water of crystallization might be unknown. Usually only the most plausible impurities are searched for by the supplier: surface oxides and gases in metals are generally ignored. Commercial chemical zirconium invariably includes hafnium and vice versa. Labels may simply be wrong; we have found 3% Sb in "99.9%" lead and 1.4% Cs in RbCl specified to contain less than 10 ppm [222]. The literature on thermogravimetry is a useful guide to procedures for producing hydrates and oxides with well-defined composition [226], and comparing multiple standards prepared from several sources will reveal the most serious problems of poor assay.

A number of publications have addressed the need for a working multielement calibrant material which is homogeneous, similar in matrix composition to the samples to be analyzed, and of well-known composition. If a liquid or colloid is uniformly doped and then solidified into storable form, a standard can be prepared whose homogeneity is guaranteed merely by the mode of preparation. Many laboratories have used fine silica slurried with solution standards. An improvement on this is homogeneously precipitated doped silica gel [227/228]. Photographic grade gelatin [229], urea-formaldehyde polymer [230], and polyacrylamide gel [231] have been used as analogs of plant and animal tissue, while clay [232] and mineral glasses [233] have been made as geological materials. Pure aluminum has also been used [234]. Gelatin based standards are commercially available [235]. Other synthetic multielement standards are under active development in several laboratories.

'Natural' standards may be preferred on the basis that they represent, as closely as possible, the sample that is to be analysed. It is a matter of personal choice as to whether it is better to work with a clean, well-known chemical standard with a simpler spectrum than the real sample or to use a similar matrix with the same interference problems as the sample. Unless the matrices are identical the interference effects will be different. If a natural standard is used, it is important that it be well characterised - for the elements of interest. Since it is expensive to use international reference materials as standards on a daily basis, it is necessary to have an 'in-house' standard for each of the sample types to be analysed. These must be well analysed for the elements of interest and be homogeneous, and there must be sufficient material available for the requirements of the work. The in-house standard must be checked against a suitable primary standard (chapter 9).

8.5 IRRADIATION PROCEDURES

The purpose of the irradiation is to produce sufficient activity in the sample, taking into account the decay time, to measure the gamma-spectrum in ideal circumstances. However, this principle may be partly overruled by the principle that the worker's exposure to radiation must be minimized (chapter 10). The benefits of high activity are that the measurement can be made at a large distance to the detector, minimizing the error caused by counting geometry variations, and that short measurement times can be used. The drawback with high activity samples is radiation exposure during handling and heavy shielding during storage and sample changer operation. It has also to be taken into account that high count rates cause pulse pile up problems. The relative statistical error is inversely proportional to the square root of the number of counts in the photopeak. Thus a significant increase in the number of counts is required for a moderate improvement in accuracy.

When short-lived isotopes are measured high count rates usually cannot be avoided.

The general principle is that the use of short-lived nuclides require short irradiations and long-lived require long irradiations. What is really sought is a certain total number of net counts. This can be varied according to local conditions. One can either use large samples with correspondingly shorter irradiation times, or smaller samples with longer irradiation times. When limited irradition space is available short irradiations of large samples can be preferable. This allows the use of automatic irradiation facilities. In some cases large samples have to be used because of homogeneity problems. This again may cause problems with neutron and gamma-ray absorption.

Another decision to make is the neutron spectrum. Most commonly the mixed reactor neutron flux is used but other applications are possible. A highly thermal flux or a fast flux can be used. The benefits of these are few and therefore they are not discussed more in this context. Epithermal NAA, however, is commonly used and the benefits obtained are considerable for some elements through improved detection limits because of increased photopeak/ background ratio. The reason is that the epithermal/thermal cross-section ratio of the nuclides of interest is higher than the corresponding ratio for the nuclides causing most of the background activity. The most important benefits of using epithermal irradiation for analysis of rock samples are up to 3 times lower detection limit for gold, decreased disturbance from fission products and improved precision through decreased background for most elements. The benefit of using epithermal neutrons for irradiation have been discussed by several authors. The most comprehensive investigation was made by Steinnes [236]. He tabulated theoretical advantage factors for most nuclides of interest in reactor neutron activation analysis. Parry tabulated experimental advantage factors for short-lived NAA of geological samples [237]. The largest improvements in detection limit were found to be a factor of 6. The cross sections are listed in Appendix A, Table I. From these the improvement by using epithermal irradiation can be estimated directly when pairs of elements are compared. The true improvement depends on the sample analyzed. Table 8.4 shows some improvement factors for rock samples. Another advantage of epithermal irradiation is the decrease of interference caused by fission of uranium. This is especially significant for molybdenum and zirconium.

TABLE 8.4. IMPROVEMENT FACTORS IN SHORT LIVED ACTIVATION ANALYSIS OF ROCK SAMPLES. IMPROVEMENT IN DETECTION LIMIT OBTAINED WITH EPITHERMAL IRRADIATION COMPARED TO THERMAL IRRADIATION WHEN THE BACKGROUND NUCLIDE IS ^{18}Al [238]

Element	Nuclear Reaction	Improvement Factor
F	$^{19}\mathrm{F}(n,\gamma)^{20}\mathrm{F}$	0.17
Mg	$^{26}\mathrm{Mg}(n,\gamma)^{27}\mathrm{Mg}$	0.23
Al	$^{27}\mathrm{Al}(n,\gamma)^{28}\mathrm{Al}$	-
Cl	$^{37}\mathrm{Cl}(n,\gamma)^{38}\mathrm{Cl}$	0.17
Ca	$^{48}\mathrm{Ca}(n,\gamma)^{49}\mathrm{Ca}$	0.20
Sc	$^{45}\mathrm{Sc}(n,\gamma)^{46m}\mathrm{Sc}$	0.15
Ti	$^{50}\mathrm{Ti}(n,\gamma)^{51}\mathrm{Ti}$	0.19
V	$^{51}\mathrm{V}(n,\gamma)^{52}\mathrm{V}$	0.15
Mn	$^{55}\mathrm{Mn}(n,\gamma)^{56}\mathrm{Mn}$	0.27
Co	$^{59}\mathrm{Co}(n,\gamma)^{60m}\mathrm{Co}$	0.47
Cu	$^{65}\mathrm{Cu}(n,\gamma)^{66}\mathrm{Cu}$	0.27
Ga	$^{69}\mathrm{Ga}(n,\gamma)^{70}\mathrm{Ga}$	2.6
Ge	$^{74}\mathrm{Ge}(n,\gamma)^{75m}\mathrm{Ge}$	0.62
Se	$^{76}\mathrm{Se}(n,\gamma)^{77m}\mathrm{Se}$	0.20
Br	$^{79}\mathrm{Br}(n,n')^{79m}\mathrm{Br}$	4.4
	$^{79}\mathrm{Br}(n,\gamma)^{80}\mathrm{Br}$	1.6
Rb	$^{85}\mathrm{Rb}(n,\gamma)^{86m}\mathrm{Rb}$	2.0
Y	$^{89}\mathrm{Y}(n,n')^{89m}\mathrm{Y}$	6.7
Mo	$^{100}\mathrm{Mo}(n,\gamma)^{101}\mathrm{Mo}$	2.4
Rh	$^{103}\mathrm{Rh}(n,\gamma)^{104}\mathrm{Rh}$	1.2
	$^{103}\mathrm{Rh}(n,\gamma)^{104m}\mathrm{Rh}$	1.3
Pd	$^{106}\mathrm{Pd}(n,\gamma)^{107m}\mathrm{Pd}$	2.7
	$^{108}\mathrm{Pd}(n,\gamma)^{109m}\mathrm{Pd}$	2.7
Ag	$^{109}\mathrm{Ag}(n,\gamma)^{110m}\mathrm{Ag}$	2.0
In	$^{115}\mathrm{In}(n,\gamma)^{116m}\mathrm{In}$	2.4
Sn	$^{122}\mathrm{Sn}(n,\gamma)^{123m}\mathrm{Sn}$	1.8
	$^{124}\mathrm{Sn}(n,\gamma)^{125m}\mathrm{Sn}$	3.8
Sb	$^{121}\mathrm{Sb}(n,\gamma)^{122m}\mathrm{Sb}$	3.2
	$^{123}\mathrm{Sb}(n,\gamma)^{124m}\mathrm{Sb}$	2.7
I	$^{127}\mathrm{I}(n,\gamma)^{128}\mathrm{I}$	2.2
Ba	$^{136}\mathrm{Ba}(n,\gamma)^{137m}\mathrm{Ba}$	4.1
	$^{138}\mathrm{Ba}(n,\gamma)^{139}\mathrm{Ba}$	0.23
Nd	$^{148}\mathrm{Nd}(n,\gamma)^{149}\mathrm{Nd}$	1.1
	$^{150}\mathrm{Nd}(n,\gamma)^{151}\mathrm{Nd}$	2.0
Sm	$^{154}\mathrm{Sm}(n,\gamma)^{155}\mathrm{Sm}$	1.1
Eu	$^{151}\mathrm{Eu}(n,\gamma)^{152m}\mathrm{Eu}$	0.22
Gd	$^{160}\mathrm{Gd}(n,\gamma)^{161}\mathrm{Gd}$	1.6
Dy	$^{164}\mathrm{Dy}(n,\gamma)^{165m}\mathrm{Dy}$	1.0
Er	$^{166}\mathrm{Er}(n,\gamma)^{167m}\mathrm{Er}$	5.7
	$^{170}\mathrm{Er}(n,\gamma)^{171}\mathrm{Er}$	1.0
Yb	$^{176}\mathrm{Yb}(n,\gamma)^{177m}\mathrm{Yb}$	2.0
Hf	$^{178}\mathrm{Hf}(n,\gamma)^{179m}\mathrm{Hf}$	2.3
W	$^{182}\mathrm{W}(n,\gamma)^{183m}\mathrm{W}$	3.0
	$^{184}\mathrm{W}(n,\gamma)^{185m}\mathrm{W}$	1.4
Re	$^{187}\mathrm{Re}(n,\gamma)^{188}\mathrm{Re}$	0.78
	$^{187}\mathrm{Re}(n,\gamma)^{188m}\mathrm{Re}$	0.78
Ir	$^{191}\mathrm{Ir}(n,\gamma)^{192m}\mathrm{Ir}$	0.62
Pt	$^{198}\mathrm{Pt}(n,\gamma)^{199}\mathrm{Pt}$	2.2
	$^{198}\mathrm{Pt}(n,\gamma)^{199m}\mathrm{Pt}$	1.9
Au	$^{197}\mathrm{Au}(n,n')^{197m}\mathrm{Au}$	4.1
Th	$^{232}\mathrm{Th}(n,\gamma)^{233}\mathrm{Th}$	1.7
U	$^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U}$	3.8

Tables 8.5, 8.6, 8.7 show some typical irradiation schemes used for instrumental NAA in different laboratories. Most of these are compromises between reaching maximum sensitivity and being able to analyze as many elements as possible using fewer irradiations. Two principally different procedures can be distinguished: sequential and simultaneous.

TABLE 8.5. SCHEME FOR THE DETERMINATION OF 32 ELEMENTS IN ROCKS [21]
(The thermal neutron flux is 1.2 × 10^{12} $cm^{-2}\cdot s^{-1}$ for all but the 7–30 h irradiation for which it is 10^{13} $cm^{-2}\cdot s^{-1}$)

Irradiation time	Decay time	Detector	Measurement time	Elements determined
0.5 min	2 min	Large	2 min	Al, V
0.5 min	5 min	Large	5 min	Ti, Al, Ca, V
5 min	0.5–4 h	Large	5 min	Mn
5 min	0.5–4 h	Small	10–20 min	Dy
20–60 min	c. 24 h	Large	5–60 min	Na, K
7–30 h	4–7 d	Large	0.5–2 h	La, Sm, Lu
7–30 h	4–7 h	Small	10–60 min	Sm, U
7–30 h	3–4 weeks	Large	1–3 h	Sc, Cr, Fe, Ni, Co, Rb Zr, Sb, Cs, Ba, Hf, Th
7–30 h	c. 6 weeks	Small	2–4 h	Ce, Nd, Eu, Gd, Tb, Tm, Yb, Ta

TABLE 8.6. ANALYSIS SEQUENCE FOR THE COMPLETE ANALYSIS OF A GEOLOGICAL SAMPLE (T: thermal neutron; E: epithermal neutron; C: coaxial detector; L: low energy photon detector)

Irradiation	Decay	Measurement	Elements
T 1 min	2 min	C 5 min	Al, Ti, Mn, Mg, Ca, V
T 5 min	30 min	L 20 min	Dy
T 1 h	24 h	C 20 min	Na, K
E 35 h	5 d	C 20 min	As, Sb, Zn, Sn, Ag, W, Mo, Au, La, Sm, Ni, Fe, Co, Na, Sc, Ba, Cs, Rb, Ta, U, Th, Br
T 35 h	7 d	C 1 h	La, Sm, Yb, Lu
	30 d	L 3 h	Ce, Nd, Eu, Gd, Tb, Tm, Yb
		C 1 h	Zr, Hf

TABLE 8.7. ANALYSIS SCHEME USED AT THE INTERFACULTY REACTOR INSTITUTE IN DELFT

Irradiation time	Decay time	Counting time	Elements determined
30 s[1]	600-900 s	300 s[2]	Na, Al, Mg, Cl, K, Ca, Ti, V, Mn, Br, Sr, In, I, Ba, Dy, Si, S
4 h[3]	3-5 d	2 h[4]	Na, K, Ca, As, Br, Mo, Sb, La, Sm, Yb, W, Au, K, Ga, Cd, Re, Sc, Fe, Cr, Ba, Ce, Lu
	20-28 d	1-2 h[5]	Sc, Cr, Fe, Co, Ni, Zn, Se, Rb, Sr, Zr, Sb, Cs, Ba, Ce, Nd, Eu, Tb, Yb, Lu, Hf, Ta, Ir, Hg, Th, Ca, Ag, Sn, Te, Os

[1] Thermal flux: 1.0×10^{13} n·s^{-1}·cm^{-2}.

[2] Detector 10% coaxial, source to end cap distance 4 cm.

[3] Thermal flux: 5×10^{12} n·s^{-1}·cm^{-2}.

[4] Detector 17% coaxial, source to end cap distance 4 cm.

[5] Well-type detector.

Sequential irradiations are performed using a pneumatic transfer system and usually for short-lived isotopes. However, when a high flux is available or a considerable sample size is used, the technique can be used for long-lived isotopes also. This is usually the case when completely automatic activation analyzers are used [238]. When only restricted space is available for irradiation, this is also the choice. To avoid complicated corrections when short-lived isotopes are used, it is important that all samples and standards in a series have the same irradiation times. When these corrections are made different irradiation times can be employed.

For irradiating samples for measurement of medium or long-lived isotopes, simultaneous irradiation is commonly used. Using some reactors, it is possible to irradiate several hundreds of samples simultaneously.

Care must be exercised when choosing irradiation conditions. Samples causing danger for explosion cannot be irradiated. Volatile and fissionable materials have to be irradiated in proper containers, usually quartz, to avoid spreading of radioactive gases. The irradiation time has to be adjusted to the expected activity. The samples coming from the reactor have always to be monitored. A sample may be more active than expected because of unknown composition. The facilities have to be such that samples with unexpectedly high activities can be safely transferred to storage.

The quantitative calibration is normally based on the assumption that the standard or flux monitor and the sample receive an equal neutron dose. This, however, is not always the case. As a matter of fact it more commonly is not.

If a pneumatic device is used to irradiate the samples singly, then the standard and sample should be irradiated for exactly the same length of time while the reactor flux is kept constant. Sudden changes in flux can be caused by changes in the vicinity of the irradiation position. The presence of neutron absorbing objects in close vicinity to the irradiation position should be avoided when running a series of samples.

For a longer irradiation it may be necessary to irradiate the standard and the sample at the same time. In this case it is unlikely that they will see an identical neutron flux, except where a flux equalisation system is used. Figures 8.4, 8.5, 8.6, 8.7 show typical variations in neutron flux. If the neutron flux does vary then there must be some means of monitoring the difference, which will depend on the reason for the variation. There are several possible reasons for variation of the neutron flux along an irradiation site. The obvious one is the fall-off in flux with distance from the centre line of the reactor core. The effect is very significant, and can only be overcome using a sample rotating device.

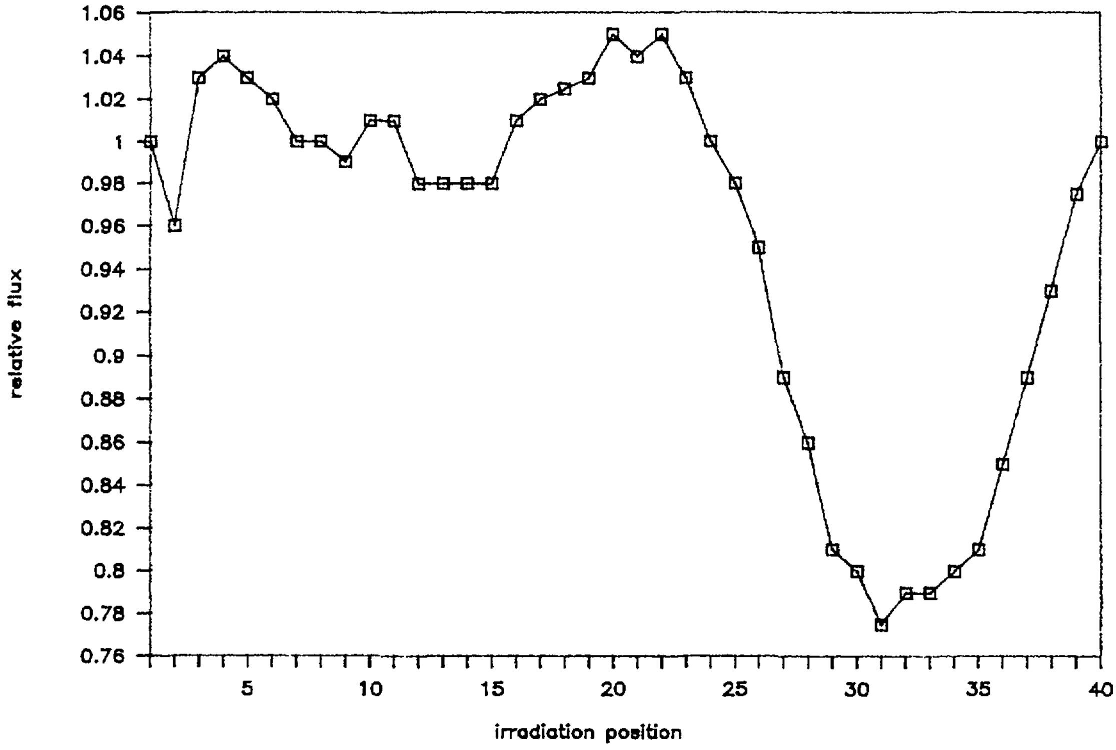


FIG. 8.4. Relative thermal neutron flux in the bottom of the 40 irradiation positions of the Lazy Susan of a Triga Mk II reactor. Typical radial flux variation is 1.4%/cm.

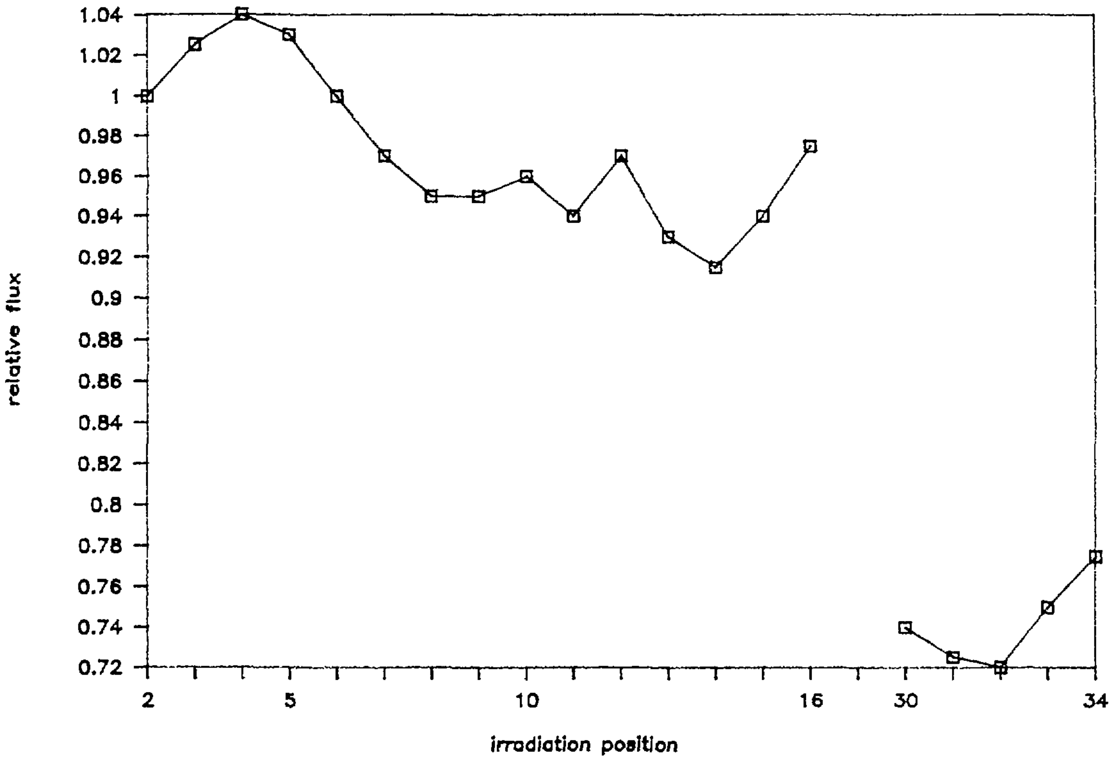


FIG. 8.5. Epithermal flux variation in the bottom of 20 cadmium containers in the Lazy Susan of a Triga Mk II reactor. Maximum difference between four samples in the bottom of one container is 3%.

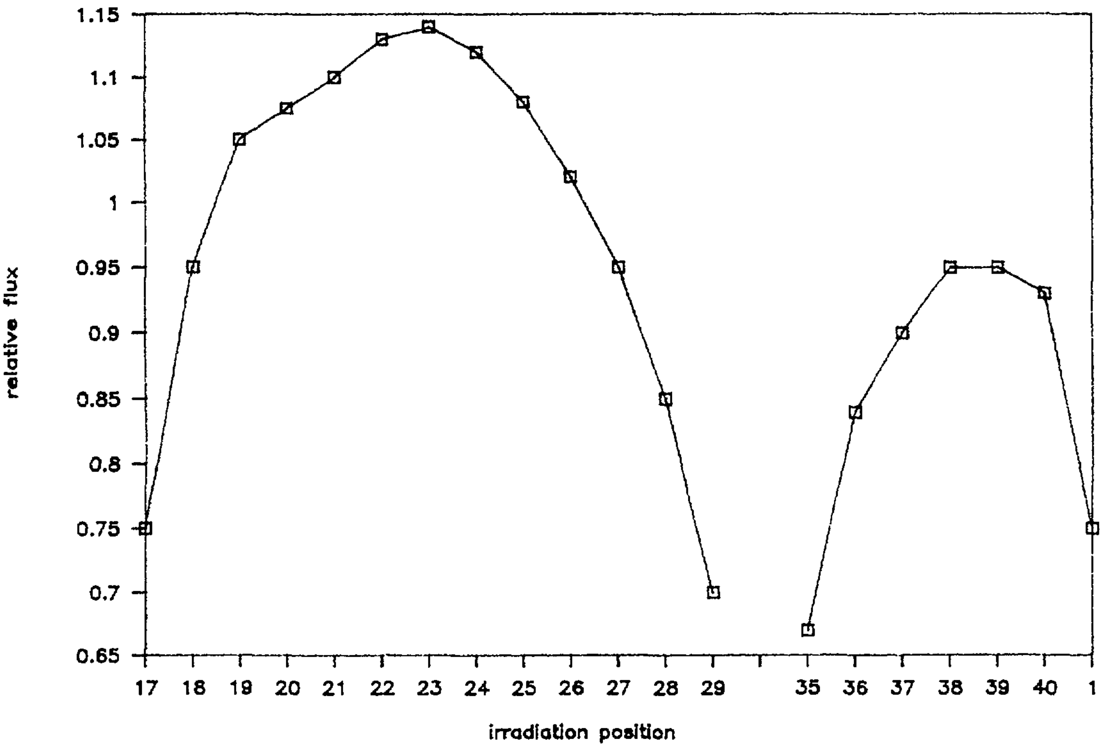
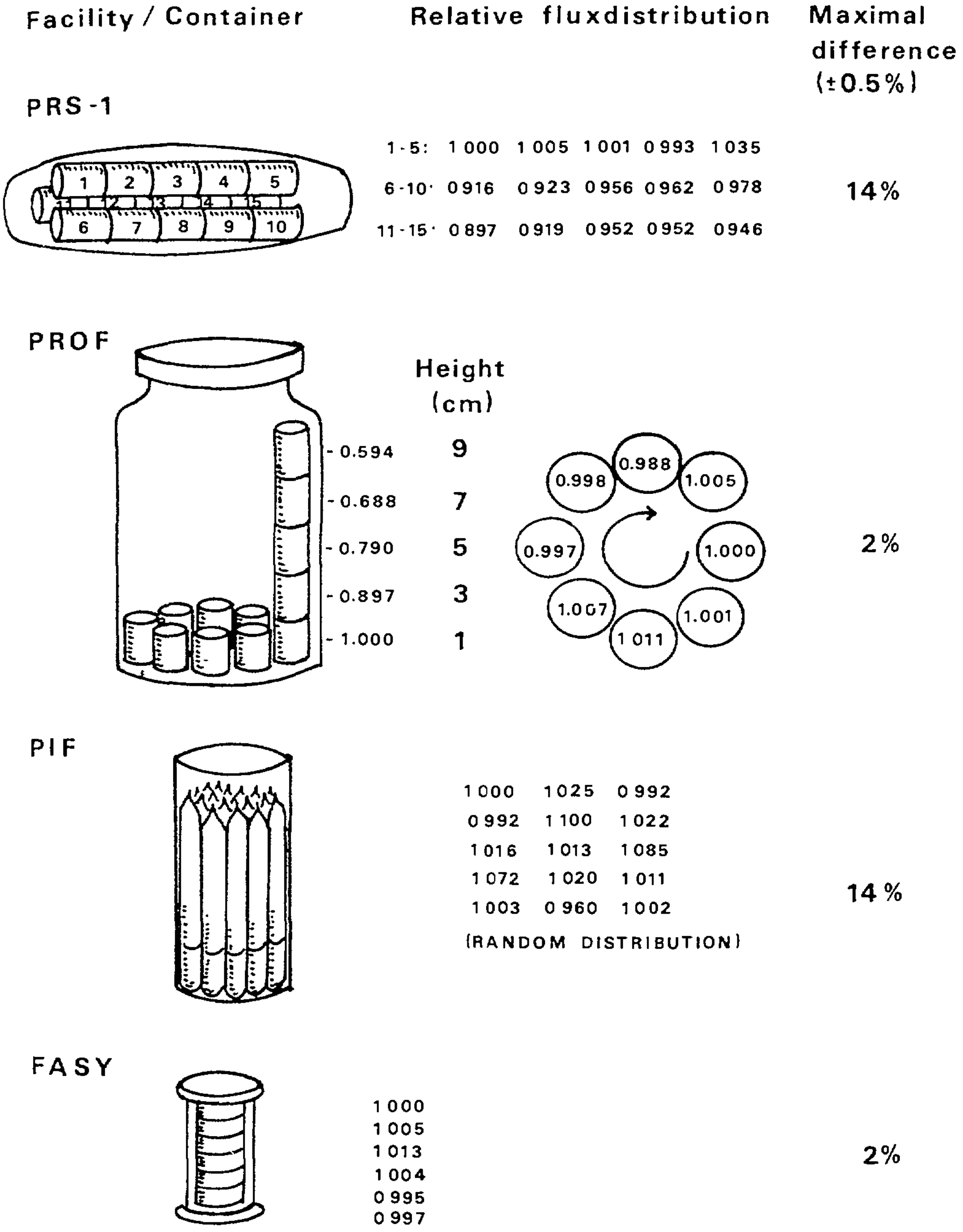


FIG. 8.6. Effect of strong neutron absorbers on the relative thermal neutron flux in the Lazy Susan of a Triga Mk II reactor. All the 20 positions not indicated contain cadmium containers ϕ 3 cm x 25 cm in size.



PRS-1 = Slow pneumatic rabbit ϕ_{th} ~ 5.10^{13}cm^{-2}s^{-1}

PROF = Poolside rotating facility ~ 5.10^{12}

PIF = Poolside isotope faciltiy ~ 8.10^{13}

FASY = Fast rabbit system ~ 5.10^{13}

FIG. 8.7. Relative flux distribution over some irradiation facilities at ECN.

If maximum accuracy is required the flux is measured for each sample. When some error is allowed fewer measurement points can be used, depending on the required accuracy and the magnitude of the flux gradient. Work can be saved by first mapping the irradiation positions and only inserting some control samples in routine irradiations.

When a single comparator is used another problem is introduced if the reactor starts up and shuts down during the course of the irradiation, since the length of the decay period will affect the elements of interest quite differently to the flux monitor.

8.6 DECAY

The optimum decay time to be applied for the measurement of a certain nuclide depends on the half-life of that nuclide and on half-lives of the major spectral interferences. In the case of longer lived interferences, waiting times should be as short as possible. If the half-life of the nuclide of interest is much longer than that of the interferences, waiting times can be thus long that measurements can be performed almost interference-free. There is an optimum decay time where the interferences have sufficiently decayed and the activity of the relevant nuclide is still adequate. Figures 8.8 and 8.9 show the calculated activities produced in a USGS BCR-1 sample [6] and in an NBS SRM-1648 sample (Urban Particulate) at the end of irradiation, and their decay with time. When only Al has to be determined, a measurement can be carried out as soon as possible after irradiation. But when one is also interested in other elements, the ^{28}Al with its high activity and high γ-ray energy will produce a high Compton background, thus decreasing considerably the sensitivities for other radionuclides. After a decay of 10 - 20 minutes the ratio of the ^{28}Al activity and the activity of other nuclides is much reduced, and now ^{52}V, ^{51}Ti, ^{27}Mg, ^{56}Mn or ^{165}Dy can be determined much better. After a long irradiation of 1 - 2 hours, the major activity is that of ^{56}Mn and ^{24}Na, and decay times of 3 - 5 days are often applied. The optimum decay time can be determined experimentally; when the elemental composition is approximately known, the optimum decay time can be calculated [239]. In multielement INAA the optimum decay time will of course be a compromise.

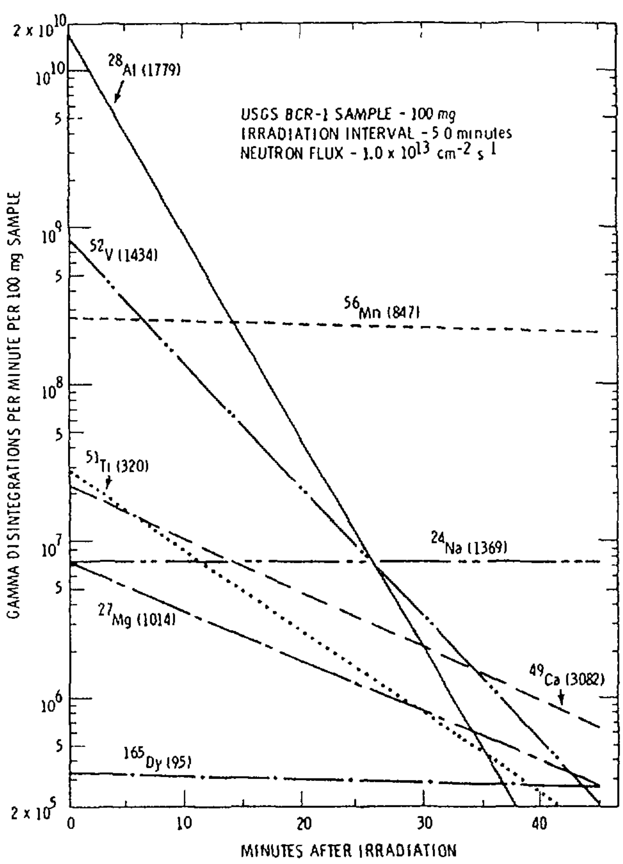


FIG. 8.8. Produced gamma activities of short-lived radionuclides and their decays with time in a USGS BCR-1 sample [6].

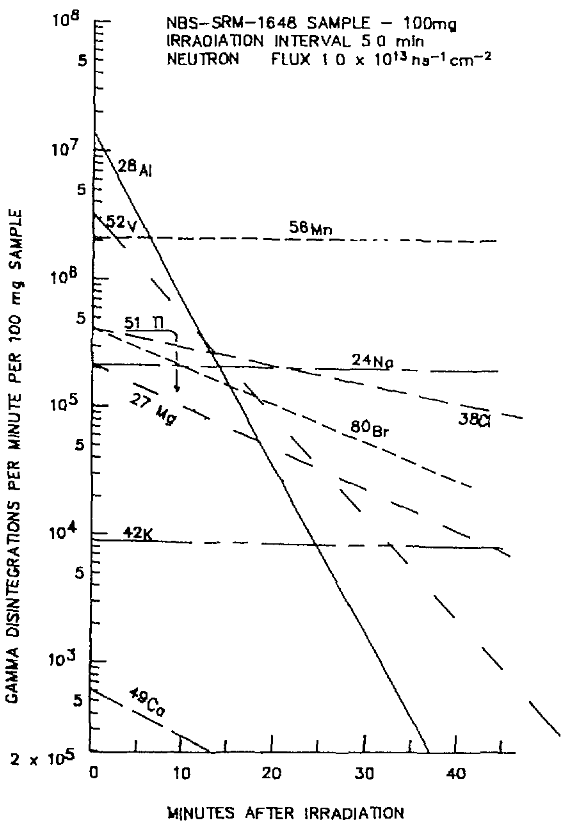


FIG. 8.9. Produced gamma activities of short-lived radionuclides and their decays with time in an NBS-SRM-1648 sample (urban dust).

8.7 MEASUREMENTS

Although measurement of the γ-spectrum in itself is rather straightforward, several parts of this procedure deserve attention or have to be checked out beforehand

a. Energy Range. For the procedure in which short half-life nuclides are involved, it might be found necessary to measure the energy range up to 3.2 MeV, in order to determine ^{49}Ca and ^{37}S. A 4096 or 8192-channel spectrum has to be preferred above 2048 channels for such measurements. For the low-energy range to be measured with a planar detector, gain settings of 100 eV/channel are a necessity to obtain analyzable peaks, and 4096 channels will cover the range from, e.g., 20 keV up to 400 keV.

For measurements of spectra with peaks in the range 75 keV - 2000 keV typical useful gain settings are 250 eV - 1 keV/channel, depending on detector resolution and on the behaviour of the software. More channels are usually better.

b. Sample-Detector Distance. The closer the sample is measured to the detector, the larger the effect of summation and the errors introduced by irreproducible dimension and position of sample and standard. Summation may take place when a radionuclide decays through coincident emission of multiple γ-rays. Such coincidence events are counted in the sum peak with apparent energy equal to the sum of the energies of the individual γ-ray photons. Summation results in alteration of spectral distribution [240] and attention therefore has to be paid when interpreting such spectra, or comparing measured intensities with tabulated values. This effect increases with detector efficiency [241], and is most prominent with well-type detectors [242]. No special precautions have to be taken when comparing sample spectra with spectra of standard materials measured under exactly the same geometrical conditions.

Counting geometry errors can easily become the most important source of error when samples are counted close to the detector. A 1-mm difference in thickness between sample and standard will produce an error of approximately 10% when samples and standards are counted directly on the detector can (Figure 8.10).

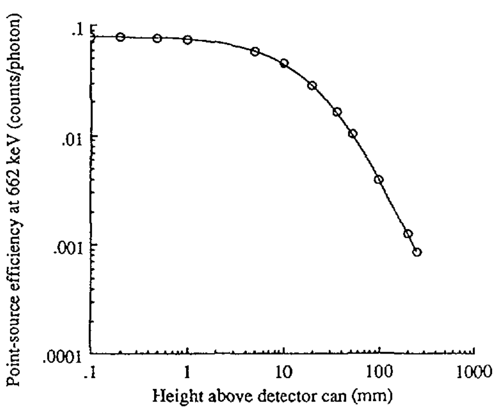


FIG. 8.10. Counting efficiency of a large Ge detector as a function of source height above the detector can.

For this reason, measurements with samples close to the detector are only allowed when both sample position and dimensions are precisely reproducible and identical for sample and standard. In view of the difficulty of producing samples and standards with exactly the same thickness, source-to-detector distance should be 10 cm or more whenever possible to reduce counting geometry errors. Even at 10 cm, a 1-mm thickness difference will produce an error of almost 1%.

The effect of the thickness difference (filling height of capsules) between samples and standards effect can simply be derived experimentally with, e.g., dissolved ^{60}Co source; equal quantities are pipetted in two or more capsules, one to be evaporated to dryness, and to the others water is added to the desired filling height (Figure 8.11). The formula for applying the

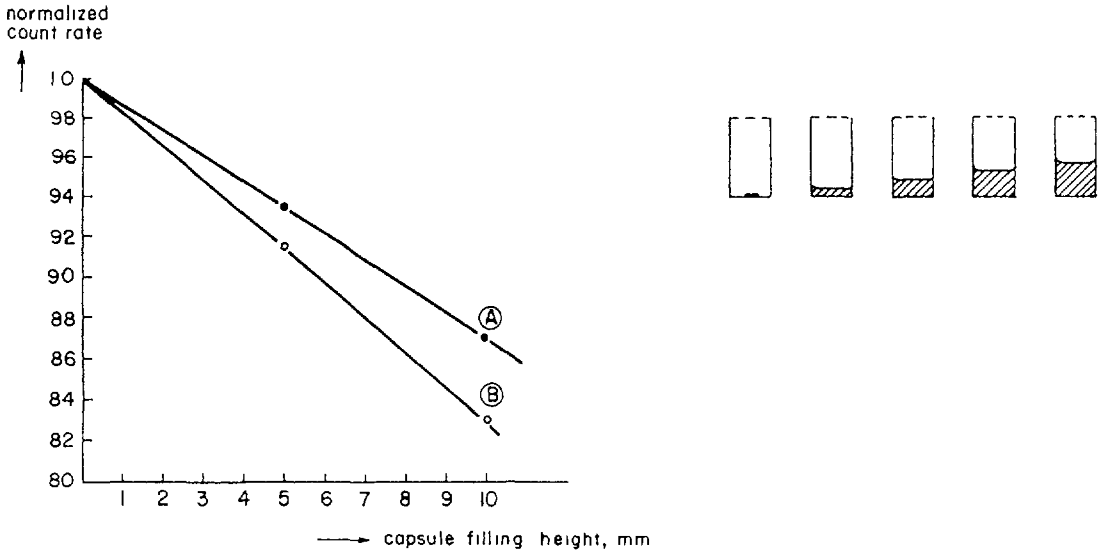


FIG. 8.11. Effect of capsule filling height to detector counting efficiency, and experimental set-up to determine such an effect.

correction for γ-ray self-absorption is well known [244]. When γ-rays <400 keV are of prime interest, such an experiment can better be carried out with a more appropriate source. Moreover, differences between sample and standard in γ-ray self attenuation may be more prominent than differences in counting geometry (see also section 8.7.h).

It should be noted that the use of well-type detectors limits the extent of geometrical errors; this detector type allows for measurement with high detector efficiency, which is within certain limits independent of sample height and position (Figure 8.12 a and b) [174].

c. Sample holders should be thus designed that distance to the end-cap and centering of the sample are reproducible. Surrounding the sample with 1 g cm^{-2} absorber of a low-Z material (plastic) reduces bremsstrahlung resulting from high energy β-radiation [245]. The sample holder may also contain a replaceable plastic cover to prevent contamination of the detector end-cap.

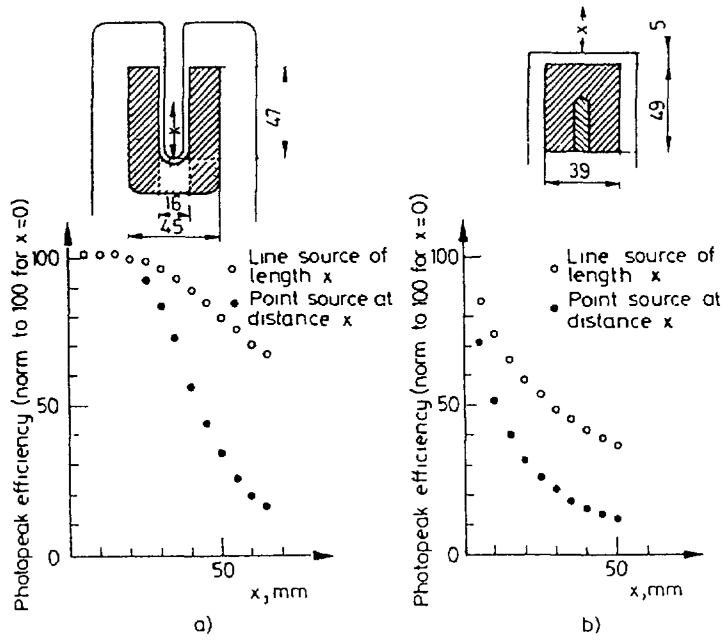


FIG. 8.12. Photopeak efficiency of a well-type (a) and a solid (b) Ge(Li) detector for 1330 keV gamma rays from a point source at varying distances from the detector and from a line source of varying length.

d. Energy and efficiency calibration [246]. Drift and instability in electronics make it necessary to carry out regular energy calibrations, i.e., the relationship between peak position and photon energy has to be checked with high precision. For many applications a two-point calibration will turn out to be enough. Sometimes the linearity of the spectrometer is insufficient for the peak assignment routine. The overall linearity of a spectrometer comprises the individual linearities of preamplifier, main amplifier and ADC. Even for premium equipment this may lead to an overall non-linearity of 0.075 %, effectively meaning a 1.5 channel uncertainty at 4096 channels. A higher (e.g., 3rd) order calibration curve might then be required to obtain a sufficiently precise calibration. This implies the measurement of 10 - 15 calibration lines equally spread over the energy interval of interest. Data are available on a wide range of nuclides suitable for calibration, including many that can be produced in a nuclear reactor [247/248/249].

Gamma-ray spectrum analysis programs are used which derive from the energy calibration step not only the position-energy relationship, but also important fitting parameters, like low and high-energy tail parameters, FWHM as function of energy, etc. To get a good estimate of these parameters, peaks in the spectrum should be well defined, i.e., precision has to be 1 - 2 %. The shape of the 511 keV annihilation peak is distinctly different (broadened) from the shape of the γ-ray lines, and fitting this peak in spectra using the γ-ray fitting parameters will give erroneous results. If any analytical use of this peak is considered (e.g., for the determination of ^{64}Cu) it is necessary to determine also in the energy calibration step the specific fitting parameters of this peak. A ^{22}Na-source can then be included in the calibration source set. If a pulser peak is used for live-time correction, the fitting parameters of this peak should also be separately determined in the energy calibration step, as the pulser peak is more narrow than the γ-ray lines.

Sometimes the precision of the energy determinations is limited by short-term gain shifts due to count rate variations. This problem can be overcome for a good deal by applying a recalibration procedure on the basis of two or more well-defined peaks present in the actual spectrum.

Although detector efficiency cancels out of the NAA equations in the direct comparator method, knowledge of the relative or absolute photopeak efficiency of a detector at the applied geometry is a necessity when quantitative spectrum interpretation is done using computerized γ-ray catalogues. The peak areas are then corrected for the detector's response function resulting in directly comparable peak intensities. The determination of a relative efficiency curve is based on measurements of nuclides emitting multiple gamma-rays with well-known intensity ratios [250/251/252]. This method is very attractive as no information is required on the absolute activity of the sources. But in high efficiency situations (total efficiency > 10%) special corrections have to be applied to correct for summation [253/254].

The shape of the relative efficiency curve as a function of energy is less dependent of the source-detector geometry, but has to be established for each individual sample position closer than 10 cm to the detector. For larger distances, the shape of the curve is almost independent of this distance. Absolute efficiency calibrations require a set of calibrated sources of either multiple or single gamma-ray emitting nuclides, with the same restrictions as mentioned for the relative efficiency calibration. When only a few calibrated sources are available, it is possible to measure first a relative curve, which can be made absolute on the basis of a few absolute calibration points.

Measurement of the absolute efficiency curve of a well-type detector [254] has to be carried out with calibrated sources decaying by preference by emitting a single gamma-ray. Usable nuclides are ^{109}Cd, ^{57}Co, ^{137}Cs, ^{54}Mn, ^{65}Zn. For sources emitting multiple gamma-rays, corrections for summation effects have to be applied. Commercially available mixed nuclide sources are very well suited for measuring efficiency curves, provided the necessary corrections for summation can be made [241].

So far it has been assumed that the real sample will be small (e.g., up to 250 mg), and sample-detector distances are such that point-source geometry, eventually in combination with filling height corrections may yield adequate accuracy. But when large samples are encountered, or measurements close to the end-cap are inevitable (e.g., because of low-induced activities), efficiency curves have to be determined in a different way. The most relevant efficiency curve is of course obtained by using calibration sources reproducing exactly sample geometry and composition, however, this is not always feasible. There are companies which provide mixtures of calibration radionuclides in a variety of special configurations, such as plastic sample bottles with volumes varying from 250 up to 1000 ml, filter papers of various diameters, cartridges and Marinelli beakers with volumes from 500 ml up to 4000 ml. Still, attention has to be paid to possible differences in gamma-ray self attenuation between calibration source and actual sample.

When accurate data can be obtained from the manufacturer on crystal dimensions, on source-to-crystal distance and some other parameters, photopeak efficiency curves can be calculated with adequate accuracy, even for sources of extended geometry (see Figure 8.13) [255/256].

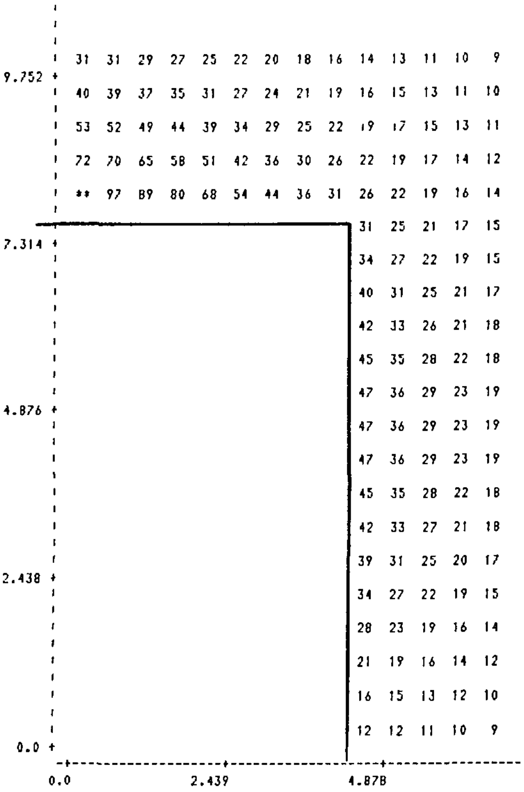


FIG. 8.13. Relative Ge(Li) detector efficiency curve for surrounding point source geometries [256].

e. Choice of measurement time. Precision and sensitivity of an analysis of long-lived nuclides increase with the length of the counting time, but only as the square root of the time. In practice, the equipment availability and number of samples to be analyzed daily set limits to the maximum counting time. For measurements with short half-life nuclides an optimum is sometimes found in measurement times as long as one half-life for half-lives in the seconds range. Practical examples are 0.5 - 5 min for short half-life nuclide measurements, and 15 min - 4 hours for 'normal' INAA. Very short measurements may affect precision and sensitivity, which can partly be overcome by cyclic activation. These procedures have been extensively reviewed [257/258].

f. The γ-ray spectrum background in the counting room at the location of the spectrometer has to be known. Background radiation includes contributions from cosmic rays, natural activities present in constructing materials of counting room and equipment, samples present in the counting room, and radioactive contamination of the detector. A distinction has to be made between the height of the constant part of the background due to the first two sources, and the variable part of the background. The following measurements are suggested to be carried out :

- a long measurement during 24 or 48 hours, with all sample sources removed. This gives information on the constant part of the background.

- a similar measurement during the maximum counting time to be applied, but under realistic conditions, i.e., with sources in the counting room and sample changers fully loaded gives an idea on the quality of applied shielding. This measurement has to be carried out regularly as the contributions may vary strongly.

g. Of equal importance is to know the spectral distribution of a 'blank' irradiated sample capsule. Such measurements can be made during each batch of samples to be analyzed .

h. When measuring samples of finite size, part of the radiation will be absorbed in the sample itself, and thus be prevented from reaching the detector. When analyzing a 100-mg sample of low Z material such as biological specimen or silicates, the effect of self-absorption can be neglected above 100 keV. But for larger samples, high-Z matrices or when measuring low energy photons, certain measures must be taken in order to avoid inaccuracies in the results :

- use of sample and standards with identical dimensions, density and matrix composition [36], or

- calculation of sample self-absorption from the known sample dimensions, density, and composition [259], or

- experimental determination of sample self-absorption from transmission or backscatter measurements [260], or

- calculation of self-absorption from changes in actual sample spectra [244].

The first two methods require a priori knowledge of the sample composition. Application of the last two methods implies a complication of either measurement or spectrum analysis procedure. If no such special measures are taken, the sample size has to be so small [261/262] that errors due to self-absorption stay within the limits set by the required analytical precision.

i. Corrections have to be applied for dead time due to finite time (10 - 100 µs) required for the ADC to digitize a detector pulse, and for random coincidence (pile-up) losses due to the finite resolving time of the amplifier [179/180/263]. Depending on the speed of the ADC and the shaping time of the amplifier, each of these effects may cause errors of 10% or more at counting rates less than 10000 c.p.s. The IAEA has conducted an intercomparison of the various methods of correcting rate-related counting losses; several methods have shown to work well when correctly used [264]. The most commonly used methods are:

- use of the dead-time correction circuit in a multichannel analyzer. This corrects very well for ADC dead time but not at all for pile-up.

- a pile-up inspection circuit in the amplifier which generates an output logic pulse whenever two input pulses overlap in time too closely for the amplifier to shape them properly. The logic pulse is used to reject the analog pulse at the linear gate of the ADC. This removes summed events from the high-energy end of the spectrum and improves the resolution of all peaks at moderately high counting rates. To obtain the correct counting rate the live time must also be corrected for the time required for this logic to be performed; not all combinations of amplifier and ADC do this properly.

- correcting the live time for pile-up losses (with or without a pile-up rejection circuit) by calculation, using a factor of the form exp (- P*DT/LT), where DT is the dead time, LT is the live time and P, a constant related to the resolving time of the amplifier [265/180].

- use of a reference peak in the spectrum, originating from a pulse generator connected to the spectrometer or from a fixed radioactive source with very long half life. This method can give very accurate results, but there may be a deterioration in the resolution from the presence of a pulser and an increase in the Compton baseline if a source is used.

- use of advanced electronics to correct the counting rate in real time by actively restoring lost pulses [186].

Problems occur when measuring a mixture of radionuclides with strongly different half-lives, which decay considerably during measurement. This situation normally occurs in INAA with short half-life radionuclides. Even when the overall correction for dead-time or pulse pile-up is correct, overcompensation may occur for nuclides with long half-life, and undercompensation for nuclides with short half-life. Proper correction requires the use of a dedicated electronic unit [266/267] or additional computer processing of the measured spectra [268/269]. Also loss-free counting circuits using compensating pulse storage and a virtual pulser [186] have been developed to solve this problem.

j. In applications of INAA where only one or a limited number of nuclides is of interest, it can be considered not to read out and analyze the entire measured spectrum, but to use regions of interest (ROI) set on the peaks of interest; most modern multichannel analyzers have this option. The advantage lies in speed and reduced storage space for data; the disadvantage is the risk of disregarding other valuable data.

8.7.1. MANUAL OPERATIONS

Manual procedures have some distinct advantages above automatic procedures. It is probably the most sensible way to understand procedure and spectrometer, in particular when new materials have to be analyzed or when trouble is encountered. By doing all steps in an analysis by hand, the user meets the majority of possible difficulties and sources of errors. Moreover, it is a better opportunity to observe the recorded γ-ray spectrum. Spectrum distortion is often more rapidly noticed in a manual procedure than in an automatic one, in which direct observation of every individual recorded spectrum seldom occurs. The semi-logarithmic display of the γ-ray spectrum is a valuable aid to the analyst to observe the occurence of count rate effects, instability, drifts, peak shape alteration or high noise levels. Regular observation of spectra contributes to a better insight in the different types of spectra that may occur, and to a better understanding of the results of spectrum analysis. Manual procedures are therefore ideal for training, and for test procedures, for determining sensitivity versus sample-detector distance.

8.7.2. AUTOMATIC OPERATIONS

In automatic procedures the emphasis will often lie on throughput of samples. As a result, there is a realistic risk of getting sloppy. Processing many samples a day implies that little opportunity remains to check whether in each individual measurement all conditions were fullfilled so that results reflect realistic situations. Measurements in which something has gone wrong may be discovered' sometimes many days later, when results are being interpreted. Several precautions should therefore be taken :

a. The position in the sample changer of the sample being measured should be read-out, e.g., by printing on hard copy or by storage with spectrum data. The most effective measure would of course be to read out the code number on the sample container itself. Other feedbacks to hard copy may include the confirmation that a sample has indeed been near the detector, the time of the day and the day of the year the measurement was started and stopped, sample-detector distance, and dead-time.

b. Measurement of an unirradiated capsule gives information on both contamination of sample changer or sample holder, and on the effectiveness of the shielding. Results of measurements between several batches of samples can be used to locate a leaking capsule. It will be obvious that such a precaution is only effective, when results are checked as quickly as possible after measurements have been completed.

c. Usually sample-detector distances are set on the basis of experience for certain types of activated material. Still sometimes a too active sample may occur in a batch; in automatic procedures seldom will this be noticed in time. To some extent it is a waste of time to carry out measurements of these samples as spectra may be strongly distorted. Measurement systems have been developed in which the total sample count rate is quickly monitored, in a few seconds, using a G.M. counter before measurement starts. At a too high count rate, either the sample is skipped, and the procedure proceeds with the next sample, or sample-detector distance is automatically enlarged [270]. In the latter solution a feedback signal to control has to be fired too.

d. Another nuisance of an unexpected too-active sample occurs when the measurement is carried out with the analyzer in live-time mode. A high dead-time will then involve a longer real or clock-time than was foreseen, and the entire measuring schedule may be disturbed. Real or clock-time setting of the analyzer has therefore always to be preferred. When the automatic procedure is computer controlled, some of these precautions and checks can be included in the procedure. As an example, a file can be stored on disk with 'normal' background data or 'blank' spectral data. At completion of the analysis of the spectra of the blank and/or unirradiated vial of a batch, the computer may quickly compare the new results with the stored data, and, if necessary, fire an alarm signal.

On entering the field of automated INAA procedures, it is important to evaluate the capabilities of the technical staff with respect to immediate assistance when a sample changer or spectrometer malfunctions. Measuring schedules should not be so tight that there is little time for maintenance.

8.8. DATA PROCESSING

Only a brief outline of data processing in activation analysis can be given here; textbooks and conference proceedings [271] should be consulted for details. The calculations of activation analysis have been discussed in section 2.2.3, and in the reference works listed in chapter 11.

Spectral data from the MCA are usually transferred to computer disk for archiving and for complete qualitative and quantitative analysis. A number of hardware manufacturers' programs do an adequate job of finding net peak areas [272/273]. Only a few programs are commercially available which perform the calculations specific to NAA: correcting for interferences, comparing samples with standards or with monitors, and averaging multiple gamma rays or multiple spectra. Mini and superminicomputer programs exist, but as yet there are no well-tested program packages readily available for personal computers. Many university groups and other users have written programs for spectral analysis and NAA; some (for example, varieties of SAMPO [274/187], GAMANAL [188/275], and TEABAGS [190]) are fairly widely distributed and are in use in several laboratories. Most of these are written for larger computers, though some are being transported to personal computers.

Most activation analysts use the comparator method of analysis, using the ratio of the counting rate of samples to that of one or more standards irradiated and counted at the same time. A great advantage of this approach is that most sources of systematic error - flux gradients, detector efficiency variations, and count-rate related nonlinearities - can usually be made to cancel in the design of the measurement procedure. A disadvantage is that the preparation, irradiation, and counting of standards for all elements to be measured requires time and labor that could be used for sample analysis. Another disadvantage sometimes cited is that the experimental uncertainties in the preparation and assay of the standards add to the uncertainty of the sample analysis, although it is preferable to consider that this additional information is desirable in assessing the true uncertainty in the total measurement process.

An attractive alternative to the comparator method is the so-called "absolute" method of activation analysis, in which the concentration of the elements sought for is computed from the observed activity (counting rate divided by detector efficiency) of the sample, the activity of a flux monitor such as a cobalt wire irradiated with the sample, and the cross sections for production of the radionuclides observed. Experience (sometimes bitter) has shown that tabulated cross sections and gamma-ray yields are not sufficiently accurate for reliable analysis, so that in practice it is necessary to measure experimentally the ratios of the production rates of each element to that of the flux monitor for a particular irradiation facility. Particularly when a suite of many similar samples are to be analyzed, this modified method has given reliable results.

A compromise between comparator and absolute activation analysis has been shown to give reliable results once a modest amount of calibration work has been carried out for a particular irradiation and detection system [276]. This method employs dimensionless parameters k(0) and Q(0) to characterize thermal and epithermal reaction reaction rates so that many of the inaccuracies in the purely absolute method are made to cancel in the calculation of elemental concentrations.

It is important to note that the method takes into account nuclear reactions by thermal and epithermal neutrons - which are of the (n,γ)-type, and for this the data collected by the Ghent-group is very valuable (though for some important half-life nuclides still k0-values have to be acquired). For not fully thermalized facilities, where also (n,p), (n,α), etc. reactions with fast neutrons may occur, the user has to make his own additional calibrations.

A number of corrections must be taken into account in processing gamma-ray spectra into elemental concentrations. Spectral interferences may often be taken into account by correcting an interfered-with peak by measuring an accompanying clean peak of the interfering nuclide. Most of the troublesome interferences are well characterized, and are tabulated in the Appendix (Tables VII and VIII). Samples containing uranium produce fission products which are also produced by neutron capture in La, Ce, Nd, Sm, Mo, Ba, and other elements. These fission corrections have been tabulated [277]. Blanks (from sampling implements or irradiation containers) and background (from radioactivity in the counting room) are usually unimportant in NAA, but must be evaluated individually.

8.9 REPORTING

8.9.1 WHAT INFORMATION SHOULD BE GIVEN

The most common situation is that the customer sends samples for analysis expecting to get in return a report containing the sample codes and corresponding elemental concentrations. However, a report containing only this information cannot be always considered complete. Commonly additional data is given to increase the information content of the report.

In general the customer should be made aware of the analytical procedure used, in the report, in oral discussions, or as a part of the price list distributed to all customers. The report itself contains sample and work identification and the results of the analysis with errors indicated (see chapter 9.3). The error should be defined indicating if it is one or two sigma. The number of digits given should reflect the accuracy of the results. Thus, as a rule of thumb, the last digit will have an error, the previous ones none. Sometimes it is not sensible to report results with errors greater than 30%. When the elements have not been detected, the detection limits, or upper values have to be indicated. It is not enough to say "not detected", because the information value of such a statement is very low. The report may also contain the results of the control samples incorporated in the series containing the analyzed samples. Some customers insist on these and some others find them only disturbing. It is better to err by providing too much information rather than too litle.

8.9.2 FORMAT

There are several different formats in which the results can be given. Good service includes customer tailored reporting. The sample coding sometimes causes problems because the code of the customer may include much sample information. Then its format is usually not logical and suitable for frequent repeating or for sample changer operation. In such situations the samples can be given a temporary code and in the final report the original code is again joined to the elemental concentrations.

The results are usually presented in the form of a table of the elemental concentrations and errors. The results should be given in units requested by the customer. Figure 8.14 gives an example of such a table. If computer treatment is used there can be two different formats, one which is easily understandable by people and another to be read by a computer. Figure 8.15 shows a typical computer readable table.

The results can be further treated when required, for example, to present tables containing concentrations of one specific element for all samples. Different kinds of graphic representations may be called for, such as chondritic ratio plots of rare earth elements or platinum metals (Figure 8.16). Different kinds of frequency distributions or even geochemical maps may be included (Figure 8.17). In most cases the customers are prepared to do these data presentations themselves, but in some cases the availability of advanced forms of presentations is requested. Again, results presented to the customer in his own terms are most useful to him and are the most likely to bring repeat business.

Activation Laboratories Ltd   Work Order: 464   Report: 448

Sample description	AU PPB	AG PPM	AS PPM	BA PPM	BR PPM	CA %	CO PPM	CR PPM	CS PPM	FE %	HF PPM	HG PPM	IR PPB	K %	MO PPM	NA PPM	NI PPM	RB PPM	SB PPM	SC PPM	SE PPM	SR PPM	TA PPM	TH PPM	U PPM	W PPM	ZN PPM
88/NS1	15	<2	34	2800	8	22 6	27	<1	1 2	0 06	<0 5	<1	<2	13 2	<2	1710	<50	300	0 4	0 1	<2	1700	<0 5	<0 1	<0 1	<1	4300
88/NS2	7	<2	33	2900	8	21 1	28	<1	1 2	<0 05	<0 5	<1	<2	13 6	<2	1950	89	260	0 5	0 1	<2	1900	<0 5	<0 1	<0 1	<1	4400
88/NS3	48	<2	7 9	2100	35	12 6	6	10	2 6	0 45	1 0	<1	<4	19 4	5	8240	<50	260	2 0	0 8	<2	<190	<0 6	<0 1	<0 1	<1	1700
88/NS4	22	<2	4 4	2400	38	17 4	6	10	2 4	0 51	<0 5	<1	<3	14 8	3	4160	<50	79	2 5	1 1	<2	<130	<0 5	<0 1	<0 1	<1	2100
88/NS5	27	<2	9 8	1400	63	11 8	7	34	5 9	1 67	3 0	<1	<6	10 1	9	15900	<50	160	6 0	5 7	<2	<220	<0 8	2 9	1 3	<1	1400
88/NS6	30	<2	2 8	3200	38	18 2	4	11	3 1	0 36	<0 5	<1	<4	15 4	<2	3420	<50	180	3 5	0 9	<2	<180	<0 5	<0 1	<0 1	<1	2200
88/NS7	36	<2	4 2	3800	30	16 8	5	8	<0 5	0 30	<0 5	<1	<4	15 2	<2	4240	<50	<8	4 4	0 8	<2	<160	<0 5	0 2	<0 1	<1	1800
88/NS8	13	<2	4 5	4000	35	15 2	3	6	1 5	0 42	1 9	<1	<3	16 3	2	3400	<50	79	1 4	1 1	<2	2000	<0 5	<0 1	0 5	<1	2900
88/NS9	27	<2	3 8	2700	26	18 1	4	9	1 6	0 37	1 2	<1	<3	18 4	<2	3390	<50	58	1 2	1 0	<2	<140	<0 5	0 2	0 6	<1	2400
88/NS10	13	13	1 6	2600	14	25 5	4	28	2 6	1 17	1 0	<1	<2	7 23	5	6000	<50	190	1 2	1 1	<2	1600	<0 5	1 0	0 5	<1	2500
88/NS11	9	<2	2 6	1200	35	17 9	3	8	<0 5	0 49	1 0	<1	<3	9 76	<2	2390	<50	63	1 2	1 3	4	<100	<0 5	0 3	<0 1	<1	1700
88/NS12	26	<2	4 2	2900	25	16 9	3	<1	<0 5	0 51	<0 5	<1	<4	12 4	<2	3070	<50	86	1 2	1 1	<2	<200	<0 5	<0 1	<0 1	<1	2000
88/NS13	83	<2	6 3	1700	22	11 1	13	<1	6 8	0 52	<0 5	<1	<3	16 0	<2	3050	<50	440	0 6	0 5	<2	<140	<0 5	0 6	<0 1	<1	1100
88/NS14	70	<2	2 1	3200	19	12 4	10	6	7 3	0 14	<0 5	<1	<3	13 9	<2	2630	<50	490	0 5	0 4	<2	<150	<0 5	<0 1	0 5	<1	1000
88/NS15	85	<2	3 0	3100	30	13 6	3	<1	13	0 27	<0 5	<1	<3	16 8	<2	3130	<50	560	0 6	0 5	<2	<140	<0 5	<0 1	0 6	<1	1300
88/NS16	24	<2	2 3	1600	63	16 9	5	<1	7 0	0 23	<0 5	<1	<3	16 8	<2	1570	<50	310	0 4	0 3	<2	<120	<0 5	<0 1	<0 1	<1	940
88/NS17	55	<2	5 5	3500	21	14 6	7	8	12	0 42	<0 5	<1	<3	9 51	<2	3170	<50	430	0 7	0 6	<2	<110	<0 5	<0 1	<0 1	<1	1300
88/NS18	6	<2	<0 5	3500	13	21 6	2	<1	4 2	0 05	<0 5	<1	<3	11 6	<2	8350	<50	350	0 1	0 2	<2	6600	<0 5	<0 1	<0 1	<1	1000
88/NS19	<5	<2	<0 5	350	20	6 0	2	<1	6 8	0 12	<0 5	<1	<2	25 5	<2	994	<50	990	0 1	0 2	<2	1100	<0 5	0 3	<0 1	<1	350
88/NS20	24	<2	1 4	1900	20	17 4	9	<1	6 0	0 19	<0 5	<1	<3	13 0	<2	5400	<50	340	0 4	0 3	<2	3700	<0 5	<0 1	<0 1	<1	8200
88/NS21	<5	<2	5 4	2500	10	16 9	2	5	<0 5	0 08	<0 5	<1	<2	17 5	<2	10000	<50	390	0 2	0 1	<2	2900	<0 5	<0 1	<0 1	<1	1200
88/NS22	<5	<2	4 7	2600	10	19 1	<1	<1	1 5	<0 05	<0 5	<1	<2	16 8	<2	10500	<50	390	0 1	0 2	<2	3100	<0 5	<0 1	<0 1	<1	1200
88/NS23	6	<2	3 7	240	11	8 0	2	3	1 4	0 11	<0 5	<1	<2	30 0	<2	947	<50	870	<0 1	0 1	<2	910	<0 5	<0 1	<0 1	<1	370
88/NS24	11	11	1 2	2200	11	21 8	4	22	2 6	1 16	<0 5	<1	<2	6 62	4	5100	<50	160	1 0	0 9	<2	1400	<0 5	0 8	0 5	<1	2200
88/NS25	13	<2	0 5	1300	8	20 0	7	3	3 3	0 13	<0 5	<1	<2	17 5	6	410	<50	750	0 2	0 2	<2	1800	<0 5	<0 1	<0 1	<1	520
88/NS26	23	<2	1 2	310	18	11 0	21	8	2 6	0 14	<0 5	<1	<2	24 9	<2	698	76	820	0 5	0 4	<2	800	<0 5	<0 1	<0 1	<1	230
88/NS27	20	<2	1 3	1200	12	19 3	27	6	8 6	0 19	<0 5	<1	<2	20 4	31	560	96	700	0 8	0 3	<2	1600	<0 5	<0 1	<0 1	<1	1500
88/NS28	48	<2	1 3	180	18	10 8	61	7	8 1	0 22	<0 5	<1	<2	25 4	4	927	72	760	2 0	0 4	<2	830	<0 5	<0 1	<0 1	<1	430
88/NS29	200	<8	20	<100	46	3 8	80	22	<2 0	0 44	<2 0	<4	<10	35 6	20	23200	<200	140	1300	1 2	<8	<500	<2 0	2 4	2 2	<4	700
88/NS30	72	<8	7 6	<100	68	3 2	88	16	<2 0	0 28	<2 0	<4	<10	34 0	12	20000	<200	100	960	0 8	<8	<500	<2 0	1 6	3 2	<4	170

FIG 8.14. Elemental concentrations

```
VTT/REACTOR LABORATORY          FINLAND

DATE 86 - 11 - 11    TIME 15 : 23 : 9


GTK   81/86/1


CODE=S-7 2
AS      13        1.6          SB      1.6       1.2          ZN      51.5      MAX
SN      66.9      MAX          AG      2.97      MAX          W       1.31      14.6
MO      .783      21.7         AU      .0025     MAX          LA      26.2      1.9
SM      4.77      .2           LU      .7        10.9         CR      88.4      7.5
NI      22.3      MAX          FE      27100     2.9          CO      8.95      6
NA      2880      2.9          SC      11.9      4.3          BA      176       5.5
CS      7.01      3.7          RB      50        5            TA      .763      10.1
U       2.35      1.8          TH      7.82      1.2          BR      8.45      2.3




CODE=-SOILP3
AS      3.19      2.6          SB      .396      1.9          ZN      26.7      MAX
SN      31        MAX          AG      1.56      MAX          W       .707      15.7
MO      .328      MAX          AU      .00118    MAX          LA      19.7      1.6
SM      3.37      .2           LU      .713      6.2          CR      49.9      7.3
NI      10.9      MAX          FE      10400     3.3          CO      3.06      8.9
NA      4510      1.4          SC      5.8       4.1          BA      302       2.4
CS      1.8       5.4          RB      46.3      2.9          TA      .784      7.5
U       1.85      1.3          TH      6.62      .8           BR      1.79      4.1



CODE=-XVIII17
AS      82.9      1.1          SB      9.81      .9           ZN      12600     1.3
SN      10700     1.4          AG      807       1.7          W       189       1.2
MO      143       .6           AU      .459      1.3          LA      79.9      1.8
SM      17.3      .2           LU      26.2      1.8          CR      1040      2.9
NI      75.3      MAX          FE      4360      MAX          CO      5.52      MAX
NA      354       MAX          SC      1.2       MAX          BA      152       MAX
CS      108       2.4          RB      16.8      MAX          TA      .622      MAX
U       .439      MAX          TH      .726      MAX          BR      2.33      21.2
```

FIG. 8.15. Computer readable output of an automatic gamma spectrometer. The first column is the elemental concentration in ppm and the second column is the relative error in %. 'MAX' indicates that the result is an upper value.

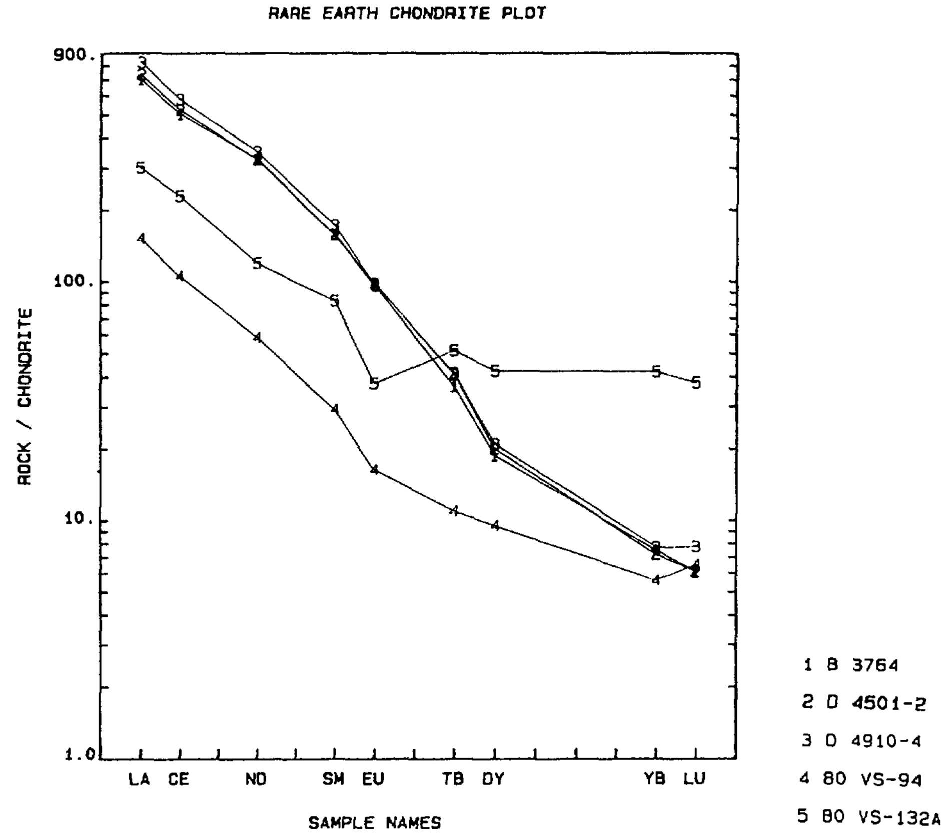


FIG. 8.16. Chondritic ratio plot of REE elements in rock samples.

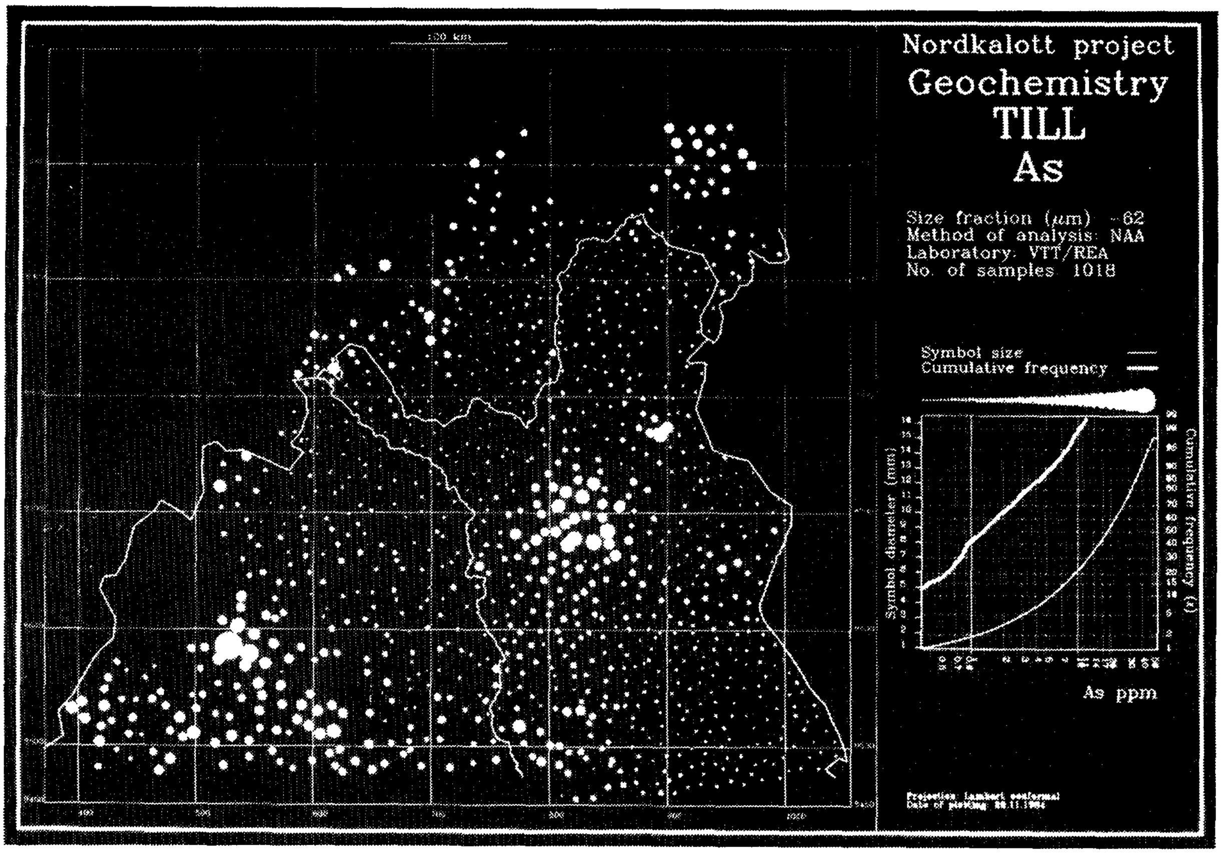


FIG. 8.17. A geochemical map of arsenic prepared by the Geological Survey of Finland and based on neutron activation analysis results of the Technical Research Centre of Finland.

8.9.3 DEVICE

When urgent, the results can be initially given by telephone. This shows good service. The method of reporting almost always used is by a hard copy. When manually made, it may be convenient to have a special form prepared and reproduced by photocopying or printing. This way the standard information need not be repeated and the report has a standard form, easily readable by everybody. It is increasingly common to produce the report by computer. If a separate off-line word processor is used, compatibility should be ensured so that the data can be transferred through a floppy disc or magnetic tape.

The hard copy can be sent to the customers by mail, telex or facsimile. It is also possible to send the reports directly by telephone line to the customer's computer. Compatible magnetic tape, digital cassettes, and floppy discs are convenient for transferring data. All the above devices can be sent by mail. Special boxes should be used.

9. QUALITY ASSURANCE

Quality assurance comprises a set of experimental and statistical procedures designed to test, systematically and continually, whether a measurement process is in a state of statistical control, and consequently whether it is capable of producing data that can be used with confidence. If a process is demonstrably well behaved, then statistical statements can be made, and supported in a court of law if necessary, about the likelihood of errors of various kinds in a particular reported value. Only measurement data obtained in conjunction with a good quality assessment discipline can meet the criterion of transparent and self-evident reliability [278].

9.1. NEED FOR QUALITY ASSURANCE

A quality assessment program necessarily occupies time and effort that could otherwise be used in analyzing samples for pay. There are compensating benefits, notably a reduction in the need to repeat measurements whenever questions are raised. The need for quality assurance depends on the value of the measurement data. Where lives or very large sums of money are at stake, it is obviously important that analytical measurements be of provably high quality, and consequently it is worth the time and money required to demonstrate that quality. Professional reputations are also of great value, and worthy of being supported by provably reliable measurements.

9.2. METHODS FOR QUALITY ASSURANCE

Perhaps the simplest quality control procedure is to include one or more samples of an appropriate standard material in each batch of unknown samples to be analyzed. If the result obtained for the standard material agrees with the known composition within the expected uncertainty, the corresponding results for the unknown sample acquire considerable (but not absolute) confidence that the procedure was performed correctly. If aliquant portions of the same material are analyzed repeatedly, a laboratory history is built up on both the mean value and the precision that can be attained. Plotting repeated measurements of the same quantity against time on a control chart [279] is an old fashioned but invaluable graphic way of showing the reproducibility of a measurement (Figure 9.1).

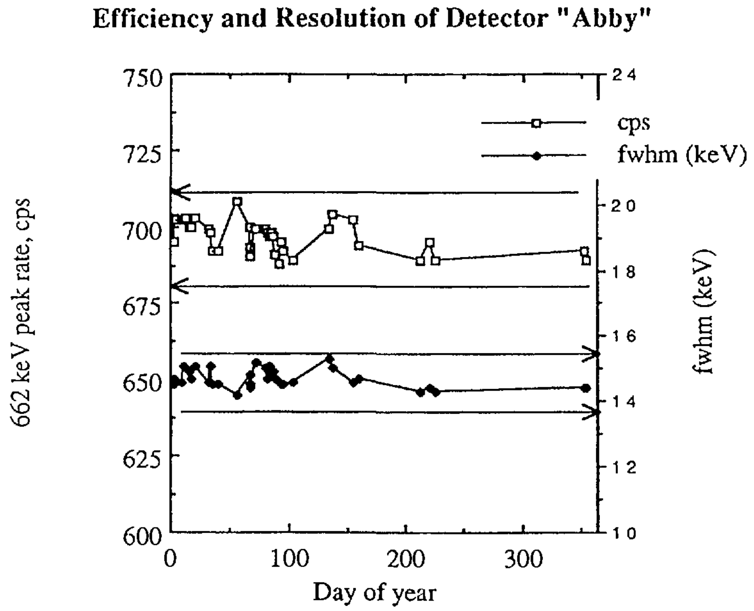


FIG. 9.1 Control chart for detector efficiency and resolution. The same Cs-137 source was counted repeatedly over a period of a year and the count rate and resolution plotted as a function of time. The control levels at which action is taken to correct a malfunction are drawn as lines three standard deviations above and below the means. Decay of the Cs source is just measurable in this data set (r = 0.5), so that for a longer series of measurements the count rate would need to be corrected for decay.

A large number of possible problems in the measurement process can be detected and thereby prevented by a systematic quality assurance program. Others cannot, because the standard test material cannot be identical to real samples even if exactly the same experimental conditions are used.

The analyst must be aware of unrepresentative sampling, the result of which may be that the samples are not worth analyzing [280/281]. While this problem is ultimately the responsibility of the client, the analyst can save misunderstanding and disappointment by discussing the sampling scheme with the client before the samples are collected.

Human errors can never be entirely avoided, but it should be possible to detect most of them by cross-checking where possible so that suspect analyses can be rejected. Unit operations in the laboratory can often be systematized so as to make blunders less likely [282]. For example, in packaging for irradiation the sample storage containers can be racked in order on one side of the workbench with the prelabelled irradiation containers in order on the other side. If only one storage container is opened at a time, mislabelling and cross-contamination are much less likely. In forensic or regulatory work with legal implications, rigorous recording and specimen handling procedures are designed to ensure a verifiable, continuous chain of custody from sampling to reporting.

Transposition errors and other mistakes in recording data can be made less likely to occur by automating much of the data input through direct computer reading of balances and clocks and by manual data entry only once into preset forms on a computer screen. Fortunately, automation is most worthwhile in routine high-volume work where occasional errors are least likely to be detected by the eye of the analyst. Automatic sample changers may malfunction, for instance by counting the same sample twice. This occurence may be difficult to find after the fact, but checking the identifications of the sample containers against the counting log at the time the changer is unloaded is a simple test for trouble.

Computer software cannot always be trusted to produce correct results without supervision, especially when a new material is being analyzed. Commercial program packages for gamma-ray spectroscopy and nuclide identification include some of the functions of expert systems, but even authorities need to be questioned. Since many of the programs in use in activation analysis laboratories have been written by analysts with little skill in computer programming, by numerical analysts with minimal knowledge of gamma-ray spectroscopy and analytical chemistry, or by students who are learning both sets of skills for the first time, a data processing procedure in successful use in one laboratory cannot always be transferred to another laboratory with equal success. In an intercomparison of spectrum analysis software conducted by the IAEA [191], the differences among the algorithms used in the programs were smaller than the differences in the manner in which they were used. Skilled users obtain more reproducible and accurate results, partly because better values for the input parameters are supplied to the programs (energy, peak shape, and pile-up coefficients, and half-lives and other physical constants), and partly because of their ability to recognize when the results are likely to be unreliable. With time, if and when these skills are translated into algorithms and incorporated into computer procedures, the likelihood of error will be decreased.

9.2.1 COMPARISONS

The precision of an analysis can often be improved by combining multiple gamma-rays, radionuclides, counts, and subsamples, provided that they agree with each other within the expected uncertainties. If they do agree, then the weighting factor to be used for each individual measurement is the reciprocal of its variance (the square of the standard deviation). Since in general the precision of a mean improves proportionally to the square root of the number of determinations, replicate measurements or multiple gamma rays cannot improve random error more than a factor of two or three over the best single peak. However, analytical multiplicity can assure the analyst and the client with qualitative confidence that interfering gamma rays, sample inhomogeneity, or other errors are absent.

Analysis of duplicate samples of the same material is commonly used as a test of analytical precision within a sample set. The statistics of counting and other measurement errors are discussed in standard texts [283/284/154]. As a rule of thumb, duplicate analyses should agree within two standard deviations as estimated from counting statistics (two-sigma error bounds should overlap) more than 99% of the time; if they do not, then the measurement system contains non-Poisson sources of variation such as weighing error, neutron flux gradient, counting efficiency differences, or material inhomogeneity. If one material in each sample set is measured in duplicate over a series of runs, a estimate of the excess variability can be obtained, although obtaining a good numerical value is surprisingly difficult [285].

If one of a series of related samples is anomalous, it should be remeasured. If the anomaly is due to an error in the measurement process, repetition may reveal the difficulty; if the anomaly is verified then stronger conclusions about the sample can be drawn.

Since radioactive decay follows Poisson statistics, the properties of this distribution are a powerful tool in quality assessment. If the observed variation among replicate measurements (as judged by the T-test) is in excess of the Poisson precision, then other sources of random error are present [286/254]. On the other hand, if over the long term replicates agree better than expected, then the counting uncertainty is surely overestimated; some peak integration programs have had this problem.

Once precision (reproducibility) has been demonstrated, accuracy (nearness to the true value) can be assessed. Intra-laboratory comparisons between analysts can help show independence of particular personal procedures, but a surer way of demonstrating accuracy is to repeat the analysis by a totally different method with a different set of possible errors. If the first measurement is made by instrumental neutron activation, it might be checked by plasma emission spectrometry (ICP-AES), an atomic technique which requires that the sample be dissolved. If the measurements agree, then confidence in both is strengthened. This is one method used by the U.S. National Institute of Standards and Technology (formerly National Bureau of Standards) in certifying its Standard Reference Materials.

Interlaboratory comparisons are often done on a one-to-one basis by exchanging samples, but in order for the analyses of rocks and pottery or clinical tissue specimens to be truly intercomparable from one laboratory to another, each contributing laboratory must regularly analyze samples of a widely available homogeneous material. A common interlaboratory comparison reported in the literature, particularly for the validation of new methods of analysis, is the analysis of national and international reference materials.

9.2.2. STANDARDS AND REFERENCE MATERIALS

Two distinct uses are made of standards in the laboratory. In analytical terms, they may be treated as knowns or unknowns; that is, they may be used either to calibrate the measurement procedure or to test the procedure after its completion. These two uses carry corresponding requirements on the accuracy with which the composition of the standard needs to be known. Because of error propagation, the composition of a calibrator must be known to better accuracy than the desired accuracy with which the unknown samples are to be determined. Available multielement reference materials are not so well characterized as one might desire. These considerations have been discussed in section 8.4.

Definitions: A chemical "primary standard" has been defined as a commercially available substance of better than 99.98% purity [287]. A laboratory "working" standard, prepared from or referenced to a primary standard if possible, is used for regular instrument calibration. This may be prepared by the analyst, purchased from a chemical supplier, or obtained from national or international standardizing organizations. A "reference material" (RM) is defined as a widely distributed material intended to be used for calibrating apparatus or testing an analytical procedure [288]. A "certified reference material" (CRM) is a reference material issued by a national or international organization which certifies that its composition is known within stated limits. Finally, a Standard Reference Material (SRM) is a CRM issued by the U.S. National Institute of Standards and Technology.

A quality assurance material is usually chosen to be a reasonably close match to real everyday samples with regard to major elements (to equalize the total activity and thus self-shielding and rate-related effects) and important minor elements (particularly those that may have spectral interferences). Within these constraints, homogeneity and well-known composition are the most desirable characteristics for such a material.

Several national and international agencies produce reference materials of use to analysts. In some cases these organizations lend their authority to certifying the composition of the RMs, and sometimes merely prepare and distribute them and allow a consensus on the "best" composition to develop among the analytical community. The geological surveys and related organizations in a number of countries distribute reference samples of many rock types, the analyses of which are regularly reported [289]; recent compilations of analyses have been published [290/291]. The U.S. National Institute of Standards and Technology issues a wide variety of materials [292/293]. The Bureau of Reference (BCR) of the European Community, the International Standards Organisation [288], the International Atomic Energy Agency, and other international agencies provide reference materials in their particular fields of responsibility. A compilation of 100 available biological and environmental reference materials from 11 suppliers has been prepared [294].

9.3 ASSIGNMENT OF UNCERTAINTY

Statements of uncertainty in reported numbers must be defined. Some readers, perhaps a majority, interpret a "±" statement as one standard deviation, and some as a 95% confidence interval; there are also precedents for interpreting an error statement as the probable error (the range within which repeated measurements should fall half the time), or even as the maximum possible error. When the reported value is the result of replicate measurements, either the uncertainty of a single measurement or of the mean may be stated and clearly identified; the latter is smaller by a factor of the square root of the number of degrees of freedom.

As mentioned in section 7.2.1, one strength of activation analysis is that the analytical precision may be estimated from a single measurement by applying Poisson statistics. The overall uncertainty contains other sources of random and systematic measurement error, which may be separately listed in the overall error analysis or combined according to some defensible algorithm. A variety of approaches of differing degrees of conservatism has been suggested [295/296]. Even if statisticians always agreed on an algorithm, the use to be made of the uncertainty statement must be considered, with the definition clearly stated on the report of analysis.

One possible approach is to add the random error to the linear sum (taken without regard to sign) of the all-possible systematic errors, but this makes no allowance for high errors cancelling low. One procedure that is being used is the following: the 95% confidence level of the mean is computed to be the observed value of s/sqrt(n) for replicate samples plus the (1's) uncertainties in standards counting, standards preparation, and counting geometry, added in quadrature, the square root of the sum of squares being multiplied by the value of Student's t for the appropriate number of degrees of freedom. For a single determination, the uncertainty is estimated by combining counting statistics with the observed reproducibility for check standards that have been analyzed repeatedly.

An example may help to illustrate some of these points. The data obtained for six replicate determinations of zinc in NIST Coal SRM 2685 and the results of an analysis of precision are as follows:

Sample	ppm Zn +/- s.d.	Normalized residual	Relative weight
1	17.1 ± 1.1 (6.4%)	-0.04	0.17
2	16.3 ± 1.3 (8.0%)	-0.65	0.13
3	18.8 ± 1.1 (5.9%)	1.51	0.17
4	17.1 ± 1.1 (6.4%)	-0.04	0.17
5	15.8 ± 1.1 (7.0%)	-1.22	0.17
6	17.5 ± 1.1 (6.3%)	0.33	0.17

Weighted mean = 17.14, unweighted 17.10
s about wtd mean = 1.038 (6.1%)
s about unwtd mean = 1.037 (6.1%)
ts/sqrt(n) [at P=0.05; t=2.571] = 1.090 (6.4%)
Observed s.d. of mean [s/sqrt(n)] = 0.423 (2.5%)
A priori s.d. of mean = 0.460 (2.7%)
Reduced chi squared = 0.86 for 5 degrees of freedom
Prob of exceeding = 50.9% in a normal population

The agreement between the observed and expected standard deviations is good; the value of chi-squared is near unity, as it should be. In this measurement the additional uncertainty due to standard preparation and counting geometry combined as the square root of the sum of squares is 0.7% (which is small in this case, as the value of chi-squared confirms for the counting geometry component). The total uncertainty is then calculated by adding an additional 0.7% in quadrature to the a priori standard deviation of the mean and multiplying by t(5) = 2.447. The final result reported is 17.1 ± 1.2 ppm Zn, where the uncertainty is the 95% confidence level of the mean (n = 6).

9.4 LOCATION OF SOURCES OF ERRORS

The results of control sample analysis have to be checked by preference as quickly as possible. Systematic errors may have been introduced which affect not only the analysis of the entire batch of samples but sometimes also all following batches of samples. Sometimes immediate action to control and to restore such a source of errors can be undertaken without loss of too much valuable time.

Sources of errors can be located from the way and the extent the results of analysis of the control deviate from expected values, i.e., outside limits of precision. As an example, the following checks can be performed.

1. All significant gamma-ray lines should be identified qualitatively;
2. Identification should be reasonable for the decay time;
3. Corrections for dead time (and pulse pile-up) should be small;
4. Element concentrations should be consistent on all peaks emitted by the radionuclide of interest;
5. Element concentrations also should be consistent when more than one radionuclide is used for determination.

These types of deviating results can be distinguished.

1. Only one, or a few element concentrations differ in a consistent way from expected values;

2. All element concentrations differ in a consistent way from expected values;

3. All element concentrations differ randomly from expected values.

[In the search for sources of errors, it is assumed that the analysis procedure already has been calibrated]

* Checks.

1. All significant gamma-ray lines in the spectrum should be identified. If prominent peaks are not assigned to nuclides, various sources of error may occur:

- the peak-position vs. gamma-ray energy relationship may be different in the measurement of the sample from what was determined in the energy calibration step. This may be due to gain shifts. Also, especially when high order calibration curves are used, erroneous data points may have been introduced.

- decay time may be fully wrong. Several analysis programs have options to exclude peak assignment to nuclides when the decay time exceeds e.g., 12 half-lives of that nuclide. If an error of an order of magnitude has been made in decay time, it may certainly affect all peak assignments.

- instability of the spectrometer, in particular of the amplifiers, may cause peaks to become doublets. This can be observed from peak-widths and reported goodness-of-fit. Sometimes only one of the peaks of such a doublet or multiplet still can be assigned to a nuclide, while the other(s), closely spaced one(s) cannot.

- a too high count rate or temperature changes may have caused a gain drift so that peaks cannot be assigned anymore under the used energy calibration function.

2. Identification should be reasonable for the decay time. As previously mentioned, most computer programs have options to exclude peak assignment when the decay correction exceeds a certain value. Still nuclide assignments after

decay times as long as 10 - 12 half lives should be interpreted with some skepticism. Especially in the case of measurements of short half-life nuclides, this source of error should not be overlooked.

3. Corrections for dead time (and pulse pile-up) should be small. Again this is of special importance when measuring short half-life nuclides, in particular when measuring times are applied which are larger than the half-life of the nuclide of interest.

4. Element concentration is different when determined on different γ-ray lines from one nuclide.

In the quantitative step of the spectrum analysis, final element concentrations may be determined either by using the most usable or most intense line, or, even better, after weighting the contributions of the various peaks of one nuclide (only a few elements are determined on a single gamma-ray emitting nuclide). It is important to compare not only this final element concentration but also to check, for nuclides emitting multiple gamma-rays, the individual results on the basis of the different peaks. Such a check is valuable even when the final element concentration is correct.

Deviations may result from:

- the use of an incorrect efficiency curve in the chosen geometry;

- Sample self-absorption. A systematic gradual increase in element concentration will be observed at increasing gamma-ray energies. In such a case, either a self-absorption correction has to be applied, or a different type of control sample or a smaller amount has to be taken;

- Other sources of errors may be of instrumental origin and/or originate from computer analysis. Due to drift and instability or a too-high count rate the spectum may thus be distorted that peaks have become doublets and become difficult to fit or are only partially assigned to specific nuclides (see above). Also summation effects or interferences from other nuclides by closely spaced γ-ray lines have to be checked.

5. Element concentrations determined on multiple nuclides are different. When half-lives of the different radionuclides of a certain element are strongly different, inconsistent results indicate erroneous decay corrections. Errors

may also been introduced by sample self-absorption or neutron shielding. Finally, the chemical compound in the calibration step should be altered, in order to check if deviations occur from natural abundances. Such effects are known to occur with sulphur [297], but also attention has to be paid in particular to uranium; many chemical compounds tend to be depleted on ^{235}U without any notice on the labels. Such a depletion has a neglible effect on the determination of U on the basis of ^{239}Np, but may lead to erroneous results when determining U through fission products or by delayed neutron counting.

Recount and reanalysis of the sample, or analysis of the selected material with samples of increasing size may help to determine the nature of the inconsistent results. Also analysis of reference or control materials has to be done to verify results.

* Deviating results.

6. One or a few element concentrations differ consistantly. Check:

- results on different gamma-ray lines or different nuclides, also of those elements which showed a correct value. The latter is particularly important when the corresponding nuclides of the elements for which a deviating result is found emit only low-energy gammas, or single gamma-rays;

- blank and background values. Even with heavily shielded detectors, contributions from samples present in the same counting room may be observable when many of the samples have the same radionuclide as major component. This often applies to nuclides used as comparator or for flux monitor purposes;

- decay time of both sample and standard.

It is important to be familiar with the way your spectrum analysis program calculates the decay time correction. Some programs use for the decay time the time elapsed between the end of the irradiation and the beginning of the measurement, with - or even without - corrections for decay during irradiation and measurement; others calculate the time between the end of the irradiation and the midpoint of the measurement, but also, programs exist in which the beginning of irradiation has to be entered as $t = 0$ for decay correction.

Especially when measuring nuclides with half-lives in the order of several seconds (^{77m}Se, ^{20}F), every second counts, in particular, as often the precision of all timing sequences is in the order of 1 second.

- half-life of the relevant nuclides;

- spectral interferences. Sources of error in gamma-ray spectroscopy related to the spectrum analysis and spectrum interpretation step, such as impure peaks, additional peaks (annihilation and escape peaks etc.), and summation effects [179].

If most of the element concentrations determined are correct, and only a few differ either consistently or in a random way, it is most likely not sufficient to check only these sources of error. A new measurement of the same sample may be considered, e.g., at a different geometry or on a different spectrometer.

7. All element concentrations differ consistently. Check :

- results from individual peaks;

- weight of sample and standard (don't rely on so-called consistent weights of sample capsules by not weighing them individually);

- measurement time of sample and standard, and applied dead-time corrections (sometimes a loose contact may result in a temporary loss of pulse transfer to MCA, while time is still running-on);

- measurement and irradiation geometry of sample and standard, and applied corrections for dimensions (filling height) and self-absorption;

- possibility of difference in flux between sample and standard due to differences in neutron absorption or neutron self-shielding.

8. All element concentrations differ randomly.

One of the most common causes of randomly varying results is confusion of samples and/or standards. A series of samples may have been inserted in the sample changer in reverse order. Check therefore first the code numbers on the vials as they are found in the sample changer or in the sample storage room. If mix-up of samples can be excluded, some of the checks mentioned above (peak assignment, dead-time aspect, results from multiple gamma-ray lines from one nuclide and results from multiple nuclides from one element) have to be performed. It may also be valuable to make sure there are no errors in decay times, weights of sample and standard, whilst also the possibility of contamination should not be overlooked. Sometimes a malfunctioning sample changer is capable of 'forgetting' to remove a sample from the detector side, and all new samples are measured on top of it. In large throughput laboratories the effect of shielding is also sometimes underestimated or temporarily a very active sample is transported through the counting room.

Another possibility is that sample and standard have experienced a different neutron spectrum during irradiation. A thermalisation of the epithermal and fast components of the spectrum in sample or standard may have taken place but also a 'hardening' of the neutron spectrum (relative loss of thermal neutrons) may have occurred. Such effects may be due to extremely high concentrations of hydrogen, boron, cadmium or gadolinium. Use of different sample weights, in particular smaller amounts, may help to detect such a problem if the elemental composition is completely unknown (e.g., with respect to boron). It is important to check also what may have happened in other irradiation channels in the vicinity of the one used for activation analysis work.

If all these do not give an indication for a source of error, a recount and reanalysis of the sample has to be done, if possible, also on a different spectrometer and/or in a different geometry. Alternatively, other reference materials should be tried. Sometimes typical results are caused by unstable or inhomogeneous materials, or even contaminated materials.

For more information on the topic of this chapter, the reader is referred especially to the extended treatments in [298] (for general chemical and management issues) and [179/154/299] (for activation analysis in particular). These publications contain extensive bibliographies.

10. RADIATION PROTECTION

All possible measures have to be taken to keep the radiation dose of the workers within the permissible limits, and in fact much lower. Practice has shown that with appropriate procedures instrumental activation analysis can be performed with very low radiation doses to the workers. An example of this is the laboratory of one of the authors where a person annually analyzing 13000 geological samples receives a whole body dose from this work of about 1mSv per annum. The basis of radiation protection measures is a clear understanding about radiation, radioisotopes and basic principles of radiation protection.

That means that only well trained personnel can be used for radiation work. This understanding will automatically result in good working procedures which minimize the received doses but at the same time enables an efficient performance of the tasks. There must always be a logical compromise between received radiation dose and the effectiveness of the work. Unnecessary doses should be avoided but if the work becomes too cumbersome there is often no meaning in doing it at all.

It is outside the scope of this book to go into detail about radiation protection and the reader is strongly recommended to read carefully the following Agency publications before starting work with radioactive sources: IAEA Safety Series 1, "Safe Handling of Radionuclides". In addition, the IAEA Safety Series no. 9, "Basic Safety Standards for Radiation Protection", No. 84, "Basic Principles for Occupational Radiation Monitoring", No. 14, "Basic Requirements for Personnel Monitoring", No. 48, "Manual on "Decontamination of Surfaces" and the Technical Reports Series No. 120, "Monitoring of Radioactive Contamination of Surfaces", are recommended readings.

The following measures are obligatory. The detailed procedures are described in the above-referred books.

- Continuous monitoring of whole body dose.

- Monitoring of hand dose periodically for routine tasks in order to get an understanding of the normal dose, and always when handling abnormally active sources with the hands, which should be avoided when possible.

- The activity of the samples should be monitored from the moment they leave the reactor.

- The radiation level of all rooms where radioactive sources are handled must be monitored regularly and at least always when new samples are taken into the room. When several people work in the same room it is not always known what samples are brought to the room and therefore a regular check is necessary.

- The possible contamination of all surfaces have to be measured regularly, and always when work with unsealed sources or sealed sources which may have surface contamination has been done. It is important to remember that containers and vials which have been in the reactor usually have surface contamination.

- Protective clothing has to be used. Laboratory coats are always necessary. Rubber or plastic gloves should be used when handling radioactive sources. Protective glasses are used when opening vials which may have built in pressure.

- Whenever possible sources should be handled with forceps. Even one of a few cm of length decreases the dose to hands considerably. Containers coming from the reactor are handled with long forceps. However, it is important to understand the influence of both distance and time on the received dose. Thus it may be better to use hands (with gloves) in situations where the use of forceps would prolong the handling too much.

- The sources should be shielded when possible. Here again it is important to note that if shielding during operation prolongs the operation too much, the received dose might be smaller when not shielding at all. This has to be separately decided for each procedure.

- Sources, like irradiated vials, which may emit radioactive gases or dust must be handled in a fume hood or in some cases in a glove box.

- Clothes, hands and feet have to be monitored regularly for contamination and always when leaving the active area.

- Active sources have to be properly marked in order to allow easy identification. All persons working in an area or using a storage for sources have to the aware of the activity level in that area or storage.

- All sources have to be stored in a shielded place, like a lead castle or room with walls of concrete thick enough to absorb the radiation. If a storage room is used, individual shielding should be used in order to avoid excessive doses to persons using the room.

- Irradiated containers should not be opened before the samples are needed. They are preferably stored in the reactor hall to avoid unnecessary transport and spread of the activity in the container itself.

- All transport of irradiated samples should be made in a tray, bucket or wagon, depending on the activity, and avoiding to spend too much time on the transport.

- In the laboratories and measurement rooms samples have to be handled and stored in a way to minimize radiation dose to the handler and other persons working in the area. It is especially important to avoid background irradiation in a measurement room with several gamma spectrometers, or from adjacent rooms.

- All laboratories and measurement rooms including laboratory furniture have to be appropriate and specially designed for work with radioactivity.

- When samples are not needed anymore they have to be stored away from measurement rooms and areas where people work regularly.

11. SUGGESTED READING

ANALYTICAL CHEMISTRY: KEY TO PROGRESS ON NATIONAL PROBLEMS, N.B.S. Special Publication No. 351, WAYNE MEINKI, W., TAYLOR,J.K. (Eds) NBS, Washington D.C. (1972).

BAUMGARTNER, F., "Tabelle zur Neutronenaktivierung", Kerntechnik 3 (1961) 356-369.

CLEANING OUR ENVIRONMENT: A CHEMICAL PERSPECTIVE. Report Committee on Environmental Improvement, American Chemical Society, Washington D.C. (1978).

ERDTMANN, G., "Neutron Activation Tables", Verlag Chemie Weinheim 1976.

HEYDORN, K., "Aspects of Precision and Accuracy in Neutron Activation Analysis", Thesis, Riso, Report RISO-R-419 (1980).

IAEA SUMMARY REPORT - CONSULTANTS MEETING ON TRAINING REQUIREMENTS IN MODERN ASPECTS OF RADIOCHEMISTRY, Munich, FRG 1987, IAEA Vienna (1987).

KRATOCHVIL, B., TAYLOR, J.K., "Sampling for Chemical Analysis", Anal. Chem. 53 (1981) 924A-938A.

KUHN, W., "New Radiometric and Radioanalytical Methods in Agricultural Research", At.Energ.Rev. 16 (1978) 619-655.

NON DESTRUCTIVE ACTIVATION ANALYSIS, AMIEL S. (Ed), Elsevier Series 'Studies in Analytical Chemistry 3', Amsterdam (1981).

SAYRE E.V., "Activation Analysis in Art and Archaelogy, in: Advances in Activation Analysis", vol. 2 (LENIHAN, J.M.A., THOMSON, S.J., GUINN, V.P. (Eds), Academic Press, London (1972) 155-184.

TABLE OF ISOTOPES (LEDERER MICHAEL C., SHIRLEY, V.S. (Eds), Wiley, New York (1978).

VEILLON, C., Trace Element Analysis of Biological Samples - Problems and Precautions, Anal. Chem. 58 (1986) 851A-866A.

DE SOETE, D., GIJBELS, R., HOSTE, J., Neutron Activation Analysis, John Wiley, New York (1972).

FRIEDLANDER, G., KENNEDY, J.W., MACIAS, E.S., MILLER, J.M., Nuclear and Radiochemistry, John Wiley, New York (1981).

KRUGER, P., Principles of Activation Analysis, John Wiley, New York (1971).

HEYDORN, K., Neutron Activation Analysis for Clinical Trace Element Research, Vol. I, CRC Press, Boca Raton, Fla. (1984).

KNOLL, G.F., Radiation Detection and Measurement, John Wiley, New York (1979).

DAMS, R., Environmental Samples, KOLTHOFF, I.M., ELVING, P.J., KRIVAN, V. (Eds), "Treatise on Analytical Chemistry", 2nd ed., part I, vol. 14, pp 665-684.

HILLEBRAND' W.F., LUNDELL, G.E.F., BRIGHT, H.A., HOFFMAN, J.I., "Applied Inorganic Analysis", 2nd ed., Wiley, New York (1953).

ELVING, P.J., KRIVAN V. (Eds), "Treatise on Analytical Chemistry, Part I: Theory and Practice", 2nd ed., vol. 14, Wiley-Interscience, New York (1986).

REFERENCES

[1] Comparison of Nuclear Analytical Methods with Competitive Methods. IAEA TECDOC 435, Vienna (1987).

[2] HEVESY,G. & LEVI,H., The Action of Neutrons on the Rare Earth Elements. Det. Kgl. Danske videnska- pernes selskab. Matematisk-fysiske meddelelser 14 (1936) 5, p.3...34.

[3] GLADNEY,E.S., O'MALLEY,B.T., ROELANDTS,I., GILLS,T.E., Standard Reference Materials: Compilation of Elemental Concentration Data for NBS Clinical, Biological, Geological, and Environmental Standard Reference Materials," U.S. Nat. Bur. Stds. Spec. Publ. 260-111 (1987).

[4] LIPSCHUTZ,M.E., Anal. Chem. 58 969A (1986).

[5] BRUNFELT,A.O. & STEINNES (eds), Activation Analysis in Geochemistry and Cosmochemistry (1971) published by Universitetforlaget, 339pp.

[6] LAUL,J.C., Neutron Activation Analysis of Geological Materials, At. Energ. Rev. 17 no.3, (1979) 603-695.

[7] VERSIECK,J.M.J., SPEECKE,A.B.H., Contaminations Induced by Collection of Liver Biopsies and Human Blood, in Nuclear Activation Techniques in the Life Sciences, IAEA, Vienna (1972), 39.

[8] LUX, F, BEREZNAI,T., HAEBERLIN,S.T., Minimization of the Blank Values in the Neutron Activation Analysis of Biological Samples Considering the Whole Procedure, J. Radioanal. Nucl. Chem. 112 (1987), 11.

[9] SIMONITS,A., MOENS,L., DE CORTE,F., DE WISPELAERE,A., ELEK,A., HOSTE,J., J. Radioanal. Chem. 60 (1980) 461.

[10] RAGAINI,R., RALSTON,R., GARVIS,D., Trace Element Analysis at the Livermore Pool Type Reactor, Using Neutron Activation Analysis Techniques, Lawrence Livermore Laboratory, UCRL 51855 (June 1975) p.11.

[11] LYON,W.L., ROSS,H.H, Nucleonics, Anal. Chem. 50 (1978) 80R-86R.

[12] LYON,W.L., ROSS,H.H, Nucleonics, Anal. Chem. 52 (1980) 69R-75R.

[13] LYON,W.L., ROSS,H.H, Nucleonics, Anal. Chem. 54 (1982) 227R-232R.

[14] LYON,W.L., ROSS,H.H, Nucleonics, Anal. Chem. 56 (1984) 83R.

[15] EHMANN,W.D., YATES,S.W., Nuclear and Radiochemical Analysis, Anal. Chem. 58 (1986) 49R-65R.

[16] EHMANN,W.D., YATES,S.W., Nuclear and Radiochemical Analysis, Anal.Chem. 60 (1988) 42R-62R.

[17] CORTE,F.,HOSTE,J., Activation analysis in Europe : Present and Future Perspectives, Nuclear Methods in Environmental and Energy Research, (Proc. 5th. Intern. Conf. Mayaguez, Puerto Rico, 1984) 1 vol., (VOGT,J.R., Ed.), U.S. Dept.of Energy, Columbia, Mo., (1984) 2-22.

[18] GUINN,V.P., Activation analysis in the Americas: Present and Future Perspectives, Nuclear Methods in Environmental and Energy Research, (Proc. 5th Intern. Conf., Mayaguez, Puerto Rico, 1984) 1 vol., (VOGT,J.R.,Ed), U.S. Dept.of Energy, Columbia, Mo., (1984) 23-42.

[19] MUECKE,G.K. (ed), Short Course in Neutron Activation in the Geosciences, Halifax (May 1980) published by the Mineralogical Association of Canada, 279pp.

[20] GIJBELS,R.H., HERTOGEN,J., Activation Analysis of Ores and Minerals, Pure & Appl. Chem. 49 (1977) 1555.

[21] ROSENBERG,R.J., Instrumental Neutron Activation Analysis as a Routine Method for Rock Analysis. Technical Research Centre of Finland, Electrical and Nuclear Technology, Publication 19, Espoo (1977).

[22] COBB,J.C., Determination of Lanthanide Distribution in Rocks by Neutron Activation and Direct Gamma Counting. Anal. Chem.39, (1967) 127-131.

[23] GORDON,G.C., RANDLE,K., GOLES,G.G., CORLISS,J.B., BEESON,M.H. and OXLEY,S.S., Instrumental Activation Analysis of Standard Rocks with High-Resolution Gamma-Ray Detectors. Geochim. Cosmochim. Acta 32 (1968) 369-396.

[24] ROSENBERG,R.J., WIIK,H.B., Instrumental Activation Analysis of 11 Lanthanide Elements in Apollo 12 Lunar Samples. Radiochem. Radioanal. Letters 6, (1971) 45.

[25] HASKIN,L.A., HELMKE,P.A., POSTER T.P., & ALLEN,R.O., Rare-Earths in Meteoritic, Terrestial and Lunar Matter, Activation Analysis in Geochemistry and Cosmochemistry, Denmark, Universitetsförlaget (1971) 201.

[26] HANSON,G.N., Rare Earth Elements in Petrogenetic Studies of Igneous Systems, Ann. Rev. Earth Plant. Sci. 8 (1980) 371.

[27] HOFFMAN,E.L. unpublished results.

[28] HOFFMAN,E.L., NALDRETT,A.J., VAN LOON,J.C., HANCOCK, R.G.V. & MANSON,A. The Determination of all the Platinum Group Elements and Gold in Rocks and Ore by Neutron Activation Analysis after Preconcentration by a Nickel Sulphide Fire-assay Technique on Large Samples, Analytica Chemica Acta, 102 (1978) 157.

[29] PARRY,S.J., Simultaneous Determination of the Noble Metals in Geological Materials by Radio- chemical Neutron Activation Analysis, L. Radioanal. Chem. 105 (1980) 1157.

[30] BRUGMANN,G.E., GORTON,M.P. and HANCOCK,R.G.V., Simultaneous Determination of Noble Metals, Re, Se, As, and Sb by Means of Radiochemical Neutron Activation Analysis, J. Geochem. EXPL (submitted 1988).

[31] FILEY,M.P., ANDERSON,D.L., ZOLLER,W.H., GORDON,G.E. and LINDSTROM, R.M., Neutron Capture Prompt X-ray Activation Analysis for Multielement Determination in Complex Samples, Anal. Chem. 51 (1979) 2209.

[32] LAMB,J.F., PRUSSIN,S.G., HARRIS,J.A. & HOLLANDER,J.M., Applications of Lithium Drifted Germanium Gamma-Ray Detectors to Neutron Activation Analysis. Nondestructive analysis of a Sulfide Ore. Anal. Chem. 38 (1966), p.813...818.

[33] PLANT,J., GOODE,G.C. and HERRINGTON J., J. Geochem. Exploration 6 (1976) 299.

[34] BAEDECKER,P.A., ROWE,J.J., STEINNES,E., Application of Epithermal Neutron Activation in Multi- element Analysis of Silicate Rocks Employing both Coaxial Ge(Li) and Low Energy Photon Detector Systems, J. Radioanal. Chem. 40 (1977) 115-146.

[35] ROSENBERG,R.J., KAISTILA,M. & ZILLIACUS,R., Instrumental Epithermal Neutron Activation Analysis of Solid Geochemical Samples. J. Radioanal. Chem 71 (1982), 419-428.

[36] HERTOGEN,J., GIJBELS, R., Instrumental Neutron Activation Analysis of Rocks with a Low-Energy Photon Detector, Anal. Chim. Acta, 56 (1971) 61-82.

[37] ROSENBERG,R.J., Instrumental Activation Analysis of Lunar Samples. Suomen Kemistilehti 45B, (1972) 399.

[38] CLIFTON,H.E., HUNTER,R.E., SWANSON,F.J. & PHILLIPS,R.L., Sample Size and Meaningful Gold Analysis. U.S.G.S. Professional Paper 625-C (1969).

[39] PLANT,J. and COLEMAN,R.F., Application of Neutron Activation Analysis to the Evaluation of Placer Gold Concentrations, Does Susan Know Journal, pp.373-381.

[40] BUGBY,E.E., A Textbook on Fire Assaying, 2nd edition, New York, Wiley (1933).

[41] BEAMISH,F.E. The Analytical Chemistry of Noble Metals, 1st edition , Toronto, Permagon (1966).

[42] HOFFMAN,E.L. & BROOKER,E.J., Biogeochemical Prospecting for Gold Using Instrumental Neutron Activation Analysis with reference to Some Canadian Gold Deposits, Chapter 9 in "Mineral Exploration: Biological Systems and Organic Matter", Carlisle,D., Berry,W.L., Kaplan, I.R. & Watterson,J.R (eds) Rubey Volume V, Prentice-Hall, New Jersey (1986).

[43] COHEN,D.R., HOFFMAN,E.L. & NICHOL,I., Biogeochemistry: A Geochemical Method for Gold Exploration in the Canadian Shield, Journal of Geochemical Exploration, 29 (1987) 49.

[44] SAUERBRIE,J.A., PATTISON,E.F. & AVERILL,S.A., Till Sampling in the Casa Berardi Gold Area, Quebec: A Case History in Orientation and Discovery, Journal of Geochemical Exploration 28 (1987) 297.

[45] SHELP,G.S. and NICHOL,I., Distribution and Dispersion of Gold in Glacial Till Associated with Gold Mineralization in the Canadian Shield, Journal of Geochemical Exploration, 28, (1987) 315.

[46] BERGSTROM,J., BJORKLUND,A., BOLVIKEN,B., KONTI,M., LEHMUSPELTO,P., LINDHOLM,T., MAGNUSSON,J., OTTESEN,R.T., STEENFELT,A. & VOLDEN,T., Regional Geochemical Mapping in Northern Finland, Norway and Sweden, Journal of Geochemical Exploration 29 (1987) 383.

[47] GREENBERG,R.R., FLEMING,R.F., ZEISLER,R, Envir.Intern. 10 (1984) 129-136.

[48] KEITH,L.H., CRUMMETT,W., DEEGAN,J., LIBBY,R.A., TAYLOR,J.H., WENTLER,G., Principles of Environ- mental Analysis, Anal. Chem. 55 (1983) 2210-2218.

[49] ROBERTSON,D.E., CARPENTER,R., Nuclear Activation Techniques for the Measurement of Trace Metals in Environmental Samples, Rep. NAS-ns-2114 (1974).

[50] COLEMAN,R.F., Comparison of Analytical Techniques for Inorganic Pollutants, Anal. Chem. 46 (1974) 989A-996A.

[51] BUJDOSO,E., Environmental Radiochemistry and Radioactivity, A Current Bibliography, J. Radioanal. Chem. 111 (1987) 487-502.

[52] DAS,H.A., FAANHOF,A., VAN DER SLOOT,H.A., Environmental Radioanalysis, Studies in Environmental Science, vol.22 , Elsevier, Amsterdam (1983).

[53] Measurement, Detection and Control of Environmental Contamination (Proceed. Symp. Vienna 1976), 1 vol. IAEA, Vienna (1976 a).

[54] STEINNES,E. The Present Status of Neutron Activation Analysis in Environmental Research, in: Nuclear Methods in Environmental and Energy Research, (Proc. 5th Intern. Conf. Mayaguez, Puerto Rico (1984) 1 vol., (VOGT, J.R. Ed.)U.S. Dept. of Energy, Columbia, Mo. (1984) 135-140.

[55] Guidelines for Data Acquisition and Data Quality Evaluation in Environmental Chemistry, ANAL. CHEM. 52 (1980) 2242-2249.

[56] RAHN,K.A., WINCHESTER,J.W., Sources of Trace Elements - An Approach to Clean Air. Techn. Rep. 089030-9-T, Univ. of Michigan, Ann Arbor (1971).

[57] MILLER,M.S., FRIEDLANDER,S.K., HIDDY,G.M., A Chemical Element Balance for the Pasadena Aerosol, J. Colloid Interface Sc. 39 (1972) 165-176.

[58] KOWALCZYK,G.S., CHOQUETTE,C.E., GORDON,G.E., Chemical Element Balances and Identification of Air Pollution Sources in Washington, D.C., Atmosph. Environm. 12 (1978) 1143-1153.

[59] GASTRELL,G., FRIEDLANDER,S.K., Atmosph. Environm. 9 (1975) 279.

[60] STEVENS,R.K., PACE,T.G., Atmospheric Environment 18 (1984) 1499-1506.

[61] HOPKE,Ph.K., MARLIN,R.C., EVINS,M.A., The Interpretation of Multielement INAA-Data Using Pattern Recognition Methods, J. Radioanal. Chem. 112 1 (1987) 215-222.

[62] ALPERT,D.J., HOPKE,Ph.K., A Quantitative Determination of the Sources in the Boston Urban Aerosol Atmosph. Environm. 14 (1980) 1137.

[63] DE BRUIN,M., WOLTERBEEK,H.Th., Identification of Sources of Heavy Metals in the Dutch Atmosphere Using Air Filter and Lichens Analysis, Nuclear Methods in Environmental and Energy Research, (Proc. 5th. Intern. Conf., Mayaguez, 1984), 1 vol., (VOGT,J.R. Ed.), US. Dept.of Energy, Columbia, Mo. (1984) 266-276.

[64] HOPKE,Ph.K., The Application of Factor Analysis to Urban Aereosol, Atmospheric Aereosol, (MACIAS,E.S., HOPKE,Ph.K., Eds), ACS Monograph 167 (1981).

[65] VAN ESPEN,P., ADAMS,F., The Application of Principal Component and Factor Analysis in Procedures to Data for Element Concentrations in Aerosols of a Remote Region, Anal. Chim. Acta. 150 (1983) 153-161.

[66] Chapter I, Comprehensive Investigation on the Comparison of Air Pollutants, and Chapter II, Activation Analysis of Air Particulate Matter, in Measurement, Detection and Control of Environmental Contamination (Proceed. Symp. Vienna 1976), 1 vol. IAEA, Vienna (1976 b).

[67] ZOLLER,W.H., GLADNEY,E.S., DUCE,R.A., Science 183 (1974) 198.

[68] DAMS,R., DE JONGE, J., Atmosph.Environm. 10 (1976) 1079.

[69] AMUNDSEN,C.E., HANSSEN,J.E., RANBAEK,J.P., SEMB,A., STEINNES,E., Long Range Transport of Trace Elements to Southern Norway by INAA of Air Filters, J. Radioanal. Chem. 114 (1987) 5-12.

[70] PRINGLE, T.C., JERVIS, R.E., Multielement Correlation for Airborne Particulate Source Attribution, J. Radioanal. Chem. 110 (1987) 321-333.

[71] TOMRA,U., MAENHAUT,W., CAFMEYER,J., Trace Subst. Environm. Health, 16 (1982) 105.

[72] WINCHESTER,J.W., DESAEDELEER,G.S., Application of Trace Element Analysis to Studies of the Atmospheric Environment, Ch. 3 in Non-Destructive Activation Analysis, (AMIEL,S., Ed.) Elsevier, Amsterdam 1981.

[73] ZOLLER,W.H., GORDON, G.E., Instrumental Neutron Activation Analysis of Atmospheric Pollutants with Ge(Li) Q-Ray Detectors, Anal. Chem. 42 (1970) 257-265.

[74] JIN,Y.S., FANG,Q.Q., NAN,Y.Y., RU,C.B., Determination of Composition versus Size of Airborne Particulate Matter by INAA, J. Radioanal. Chem. 112 (1987).

[75] JERVIS,R.E., PACIGA,J.J, CHATTODAHYAY,A.,Characterization of Urban Aereosols and their Hazard Assessment by Size Sampling combined with Inter-Element Relationships, in Measurement, Detection and Control of Environmental Contamination, (Proceed. Symp. Vienna 1976), 1 vol. Vienna (1976), 125-148.

[76] HAMILTON,E.P., CHATT,A., Determination of Trace Elements in Atmospheric Wet Precipitation by Instrumental Neutron Activation Analysis, J. Radioanal. Chem. 71 (1982) 29-45.

[77] STEINNES,E., Atmospheric Deposition of Heavy Metals in Norway Studied by the Analysis of Moss Samples Using Neutron Activation Analysis and Atomic Absorption Spectroscopy, J. Radioanal. Chem. 58 (1980) 387-391.

[78] RAMBAEK,J.P., STEINNES,E., Atmospheric Deposition of Heavy Metals Studied by Analysis of Moss Samples Using INAA and AAS, Nuclear Methods in Environmental and Energy Research, (Proc. 4th. Intern. Conf. Col., Mo. 1980), (VOGT,J.R. Ed.), U.S. Dept. of Energy, Columbia (1980) 175-180).

[79] PUCKETT,K.J., FINEGAN,E.J., Can. J. Botany, 58 (1980) 2073-2089.

[80] GREENBERG,R.R., GORDON,G.E., ZOLLER,W.H., Composition of Particles from the Nicosia Municipal Incinerator, Environm. Sci.Techn. 12 (1978) 1329 -1332.

[81] RAGAINI,R.C., ONDOV,J.M., Trace Element Emission from Western US Coal-Fired Power Plants, J. Radioanal. Chem. 37 (1977) 679-692.

[82] FILBY,R.H., SHAH,K.R., SAUTTER,C.A., A study of Trace Element Distribution in the Solvent Refined Coal (SRC) Process Using Neutron Activation Analysis, J. Radioanal. Chem. 37 (1977) 693-704.

[83] ADRIANO,D.C., PAGE,A.C., ELSEEWI,A.A., CHAMG,A.C., STRAUGHAN,I., Utilization and disposal of Fly- Ash and Other Coal Residues in Terrestial Eco-Systems : A Review, J. Environ. Quality 9 (1980) 333-34.

[84] ROWE,J.J., STEINNES,E., Determination of 30 Elements in Coal and Fly-Ash by Thermal and Epithermal Neutron Activation Analysis, Talanta 24 (1979) 433-439.

[85] BLOCK,C., DAMS,R., HOSTE, J., Chemical Composition of Coal and Fly-Ash in Measurement, Detection and Control of Environmental Contamination, (Proceed. Symp. Vienna 1976), 1 vol. IAEA, Vienna (1976) 101-109.

[86] ZHANG,J., BILLIET,J., DAMS,R., Elemental Composition and Source Investigation of Particulates Suspended in the Air of an Iron Fouldry, The Science of the Total Environment, 41 (1985) 13-28.

[87] VUCINA,J., SCEPANOVIC,V., DRASKOVIC,R., Determination of Some Trace Elements in the Industrial Process of Al-Production, J. Radioanal. Chem. 44 (1978) 371-378.

[88] HUTCHINSON,T.C., AUFREITER,S., HANCOCK,R.G.V., Arsenic pollution at the Yellowknife Area from Gold Smelter Activities, J. Radioanal. Chem. 71 (1982) 59-74.

[89] DAMS,R., BUYSSE,A.M., HELSEN,M., Instrumental Neutron Activation Analysis of Sewage Sludge and Compost, J. Radioanal. Chem. 68 (1982) 219-231.

[90] NADKARNI,R.A., MORRISON, N.G.H., Environm. Lett. 64 (1974) 273.

[91] WISEMAN,B.F.H., BEDRI,G.M., A Neutron Activation Scheme for the Detection and Determination of Pollutant Heavy Metals in Sewage Based Fertilizer, J. Radioanal. Chem., 24 (1975) 313-320.

[92] SIKORA,L.P., CHASMY,R.L., FRANKA,N.H., MURRAY,C.M., Metal Uptake by Crops Grown Over Entrenched Sewage Sludge, J. Agrig. Food Chem. (1980) 1281-1285.

[93] CAPAR,S.G.,TANNER,J.T., FREIDMAN,M.H., BORGER,K.W., Multielement Analysis of Animal Feed, Animal Waste and Sewage Sludge, Environm. Sci. Techn. 12 (1978) 785-790.

[94] EGAN,A., SPYROU,N.M., Determination of Heavy Metals in Sewage-Based Fertilizer Using Short-Lived Isotopes, J. Radioanal. Chem. 37 (1977) 775-784.

[95] EDELMAN,Th., DE BRUIN,M., Background Values of 32 Elements in Dutch Top-Soils, Determined with Non-Destructive Neutron Activation Analysis, Contaminated Soil (ASSINK,J.W., VAN DE BRINK,W.J., Eds.), M.Nijhoff Publ., Dordrecht 89-99.

[96] SCHUETZ,L., RAHN,K.A., Trace Element Concentration in Erodible Soils, Atmosph. Environm. (1981).

[97] CAPLAN,J., LOBERSLI,E., NAEMANN,R., STEINNES,E., A nNutron Activation Study of Race Contents in Plants Growing on Soils of Different Acidity, J. Radioanal. Chem. 114 (1987) 13-19.

[98] KAMIAS,G.D., PHILIANOS,S.M., Neutron Activation Analysis Study of Distribution of Certain Elements between Plant and Soil. J. Radioanal. Chem. 52 (1979) 389-397.

[99] WOLTERBEEK,H.Th, VAN DIE, J., The Contents of Some Hitherto Not Reported Trace Elements in Phloem Exudate from Yucca Fuccida Ham Determined by Non-Destructive Neutron Activation Analysis, Acta. Bot. Neerl. 29 (1980) 307-309.

[100] TOUT,R.E., GILBOY,W.B.,SPYROU,N.M., Neutron Activation Studies of Trace Elements in Tree Rings, J. Radioanal. Chem. 37 (1977) 705-717.

[101] EVANS,G.J.,J ERVIS,R.E., Hair as a Bio-Indicator: Limitations and Complications in the Interpret- ation of Results, J. Radioanal. Chem. 110 (1987) 613-627.

[102] TAKEUCHI,T., NAKANO,Y., AOKI,A., OHMORI,S., TSUKATANI,T., Comparison of Elemental Concentrations in Hair of the Inhabitants of Heavy Metal Polluted Areas with those of Normal Japanese, J. Radio- anal. Chem. 112 (1987) 259-272.

[103] BHAT,K.R., ARUNACHALAN,J., YEGNASUBRAMANIAN,S., GAGADHARAN,S., Trace Elements in Hair and Envi- ronmental Exposure, The Science of the Total Environment, 22 (1982) 169-178.

[104] BOWEN,H.J.M., Determination of Trace Elements in Hair Samples from Normal and Protein-Deficient Children by Activation Analysis, The Science of the Total Environment, 1 (1972) 75-79.

[105] WARD,N.E., STEPHENS,R.,RYAN,D.E., Comparison of Three Analytical Methods for the Determination of Trace Elements in Whole Blood, Anal. Chim. Acta. 110 (1979) 9-19.

[106] MAENHAUT,W., DE REU,L., TOMRA,U., DE ROOSE, J., Application of PIXE and INAA to Biological Material: Analysis of Serum and Serum Albumin, Nuclear Methods in Environmental and Energy Research, (Proc. 4th Intern. Conf., Columbia, Mo. 1980) (VOGT,J.R. Ed.) U.S. Dept.of Energy, Columbia, 1980, 378-388.

[107] MORRIS,J.S., STAMPFER,M.J., WILLETT,W., Dietary Selenium in Humans: Toe-nails as an Indicator, Biol. Trace Elem. Research, 5 (1983) 529-533.

[108] CORNELIS,R., SPEECKE,A., HOSTE,J., NAA for Bulk and Trace Elements in Urine, Anal. Chim. Acta, 78 (1975) 317-327.

[109] BLOTCHKY,A.J.,SULLIVAN,J.F.,SHERMAN,M.S.,WOODWARD,G.P., VOORS,A.W., JOHNSON,W.P., Selenium Levels in Liver and Kidney, Trace Subst. Environm. Health, 10 (1976) 97-103.

[110] LINEKIN,D.M., Multielement INAA of Biological Tissue Using a Single Comparator Standard and Data Processing by Computer, Int. J. Appl. Rad. Isot. 24 (1973) 343-351.

[111] HOFFMANN,P., LIESER,K.H., Determination of Metals in Biological and Environmental Samples, The Science of the Total Environment, 64 (1987) 1-12.

[112] IYENGAR,G.V., Concentrations of 15 Trace Elements in Some Selected Adult Human Tissues and Body Fluids of Clinical Interest from Several Countries: Results from a Pilot Study for the Establishment of Reference Values, Report KFA-Juelich Jul-1974 (1985).

[113] GOODMAN, G.T., ROBERTS,T.M., Nature 231(1971) 287-292.

[114] KARBE,L., SCHNIER,Ch., SIEWER,H.O., Trace Elements in Mussel (mytilus eduli) from Coastal Areas of the North Sea and the Baltic. Multielement Analyses Using INAA, J. Radioanal. Chem. 37 (1977) 927-945.

[115] LEBLANC,F., RAO,D.N., Soc. Bot. Fr., Coll. Bryologe, (1974) 237-255.

[116] DRABAEK,I., EICHNER,P., RASMUSSEN,L., Concentrations of Rare Earth Elements in Sediments, Mussels and Fish from a Danish Marine Environment, Lillebaelt, J. Radioanal. Chem. 112 (1987).

[117] ELLIS,K.M., CHATTAPADHYAY,A., Multielement Determinations in Estuarine Suspended Particulate Matter by INAA, Anal. Chem. 57 (1979) 942-947.

[118] DE GROOT,A.J., ZSCHUPPE,K.M., DE BRUIN,M., HOUTMAN,J.P.W., AMIN SINGGIH,P., Activation Analysis Applied to Sediments from Various River Deltas, Proceed. 2nd. Intern. Vonf. Modern Trends in Activation Analysis, Gaithersburg (1968) 62-71.

[119] GRIMANIS,A.P., VASSILAKIS-GRIMANI,M., GRIGG,G.B., Pollution Studies of Trace Elements in Sediments from Upper Saronikos Gulf, Greece, J. Radioanal. Chem., 37 (1977) 761-774.

[120] KAHMARAN,N.I., OLMEZ,I., PAMUK,F., Identification of Inorganic Pollutants in Stream Water, Measurement, Detection and Control of Environmental Contamination, (Proceed. Symp. Vienna 1976), 1 vol. Vienna (1976) 427-433.

[121] MERRITT, W.F., Trace Element Composition of Ground Water by INAA, in Nuclear Techniques in Ground Water Research, Proceed. IAEA Adv. Group, Krakow 1976, IAEA Vienna (1980) 153-158.

[122] SALBU,B., STEINNES,E., PAPPAS,A.C., Multielement NAA of Fresh Water Using Ge(Li) Gamma-Ray Spectrometry, Anal. Chem. 47 (1975) 1011-1016.

[123] Nuclear Techniques in Ground Water Research, (Proc. IAEA Adv. Group, Krakow 1976), IAEA Vienna (1980).

[124] SMITS,J., NELISSEN,J., VAN GRIEKEN,R., Comparison of Preconcentration Procedures for Trace Elements in Natural Water, Anal. Chim. Acta., 111 (1979) 215-226.

[125] VAN DER SLOOT,H.A., LUTEN,J.B., Two Applications of Neutron Activation for Trace Analysis of Water Samples, in Measurement, Detection and Control in Environmental Contamination (Proc. Symp. Vienna, 1976), 1 vol. Vienna (1976), 435-448.

[126] GREENBERG,R.R, KINGSTON,H.M., Trace Element Analysis of Natural Water Samples by Neutron Activation Analysis with Chelating Resins, Anal. Chem. 55 (1983) 1160-1165.

[127] LIESER,K.H., NEITZERT,V., Determination of Trace Elements in Water by Non-Destructive NAA., J. Radioanal. Chem. 31 (1976) 397-405.

[128] NYARKU,S., CHATT,A., Removal of Sodium and Chlorine from Sea-Water prior to NAA for Trace Elements, J. Radioanal. Chem. 71 (1982) 129-146.

[129] MILLEY,J.E., CHATT,A., Preconcentration and INAA of Acid Rain for Trace Elements, J. Radioanal. Chem. 110 (1987) 345-365.

[130] DAMS,R., BILLIET,J., BLOCK,C., DEMUYNCK,M., JANSSEN,M., Atmosph. Environm. 9 (1975) 1099.

[131] GUINN,V.P., HOSTE,J., Neutron Activation Analysis, in "Elemental Analysis of Biological Materials," (Tech. Report 197), IAEA, Vienna (1980).

[132] HEYDORN,K., Neutron Activation Analysis for Clinical Trace Element Research (2 vols), CRC Press, Boca Raton, FL (1984).

[133] CORNELIS,R., VERSIECK, J., Biological Materials, in Kolthoff,I.M., Elving,P.J., Krivan,V. (Eds.), "Treatise on Analytical Chemistry," 2nd Ed., Part 1, Vol. 14, pp.665-684.

[134] Nuclear Activation Techniques in the Life Sciences, Proc. Symp. Amsterdam, IAEA, Vienna (1967).

[135] Nuclear Activation Techniques in the Life Sciences, Proc. Symp. Bled, IAEA, Vienna (1972).

[136] Nuclear Activation Techniques in the Life Sciences, Proc. Symp. Vienna, IAEA, Vienna (1979).

[137] ZEISLER,R., HARRISON,S.H., WISE,S.A., Trace elements in Human Livers Using Quality Control in the Complete Analytical Process, Biol. Trace Element Res. 6 (1984) 31.

[138] SHAFFNER,T.J., Techniques for the Characterization of Trace Impurities in Silicon, Analytical Chemistry in Semiconductor Manufacturing; Techniques, Role of Nuclear Methods and Need for Quality Control, IAEA TECDOC (1989).

[139] HAOS, E.W., HOFFMAN,R., The Application of Radioanalytical Methods in Semiconductor Technology, Solid-State Electronic 30 (1987) 329-337.

[140] LINDSTROM,R.M., Activation Analysis of Electronic Materials, ACS Symposium Series 295, p.294-307.

[141] Diagnostic Techniques for Semiconductor Materials and Devices, Proceedings of the Electro-Chemical Society, vol.88-20.

[142] GUINN,V.P., Application of Nuclear Science in Crime Investigation, Ann. Rev. Nucl. Sci. 24 (1974) 561-591.

[143] YELLIN,E., Forensic Applications in Non-Destructive Activation Analysis (S.Amiel, ed.), Elsevier Series Studies in Analytical Chemistry 3, Amsterdam 1981, 281-302.

[144] GUINN,V.P., FIER,S.R., HEYE,C.L., JOURDAN,T.H., New Studies in Forensic Neutron Activation Analysis, J. Radioanal. Nucl. Chem., 114 (2), (1987), 265-273.

[145] CARTER,G.F. (ed), Archaeological Chemistry - II, Adv. in Chem. Ser. 171, Am. Chem. Soc., Washington (1978).

[146] ROSENBERG,R.J., The Determination of the Silver Content of Ancient Silver Coins. J. Radioanal. Chem. 92 (1985) 171-176.

[147] HOLTTA,P. & ROSENBERG,R.J., Determination of the Elemental Composition of Copper and Bronze Objects by Neutron Activation Analysis, J. Radioanal. Nucl. Chem. 114 (1987) 403.

[148] GILATH,Ch., Industrial Applications of Nondestructive Activation Analysis, Nondestructive Activation Analysis, S.Amiel ed., Elsevier, Amsterdam (1981), 303.

[149] NUCLEAR RESEARCH REACTORS IN THE WORLD, May 1988 Ed., IAEA, Vienna (May 1988).

[150] KOSTA,C.L., Contamination as a Limiting Parameter in Trace Analysis, Talanta 29 (1982) 985-992.

[151] MOODY,J.R., LINDSTROM,R.M., Selection and Cleaning of Containers for Storage of Trace Element Samples, Anal. Chem. 49 (1977), 2264.

[152] SANSONI,B., IYENGAR,G.V., Sampling of Biological Material for Trace Element Analysis, in: Elemental Analysis of Biological Materials: Current Problems and Techniques with Special Reference to Trace Elements, IAEA Technical Report 197 Vienna (1980).

[153] LAKOMAA,E.L., unpublished results.

[154] HEYDORN,K., Neutron Activation Analysis for Clinical Trace Element Research (2 vols), CRC Press, Boca Raton, FL, (1984).

[155] BICHLER,H., BöCK,H., BUCHTELA,K. & HAMMER,J. Pneumatic Transfer Systems, AIAU 88308 (1988), Atomic Institut der Osterr. Universitâten Internal Report.

[156] ROSENBERG,R.J., PITKäNEN,V., SORSA,A., An Automatic Uranium Analyser Based on Delayed Neutron Counting. J. Radioanal. Chem. 37 (1977), 169-179.

[157] ROSENBERG,R.J., ZILLIACUS,R., Improving Accuracy in Routine Instrumental Activation Analysis. J. Radioanal. Chem. 39 (1977), 189-200.

[158] ROSENBERG,R.J., A Simple Method for the Determination of Uranium and Thorium by Delayed Neutron Counting. J. Radioanal. Chem. 62 (1981), 145-149.

[159] GLADNEY,E.S., PERRIN,D.R., BALOGNA,J.P. & WARNER,C.L., Anal. Chem. 52 (1980) 2128.

[160] NAPIER,B.A. et al., Nuclear Instruments and Methods 138 (1976) 463.

[161] PAPANICOLOPOULOS,C. & FINK,R.W., Ibid 151 (1978) 63.

[162] DE BRUIN,M., KORTHOVEN,P.J.M., Camac-Based Instrumentation for a Non-Destructive Neutron Activation Analysis System, J. Radioanal. Chem. 22 (1974) 131-138.

[163] COOPER,J.A., PERKINS,R.W., A Versatile Ge(Li)-NaI(Tl) Coincidence-Anticoincidence Q-Ray Spectro- meter for Environmental and Biological Problems, Nucl. Instr. Meth. 99 (1972) 125-146.

[164] CAMP,D.C., GASTROUSIS,G., MAYNARD,L.A., Low Background Ge(Li) Detector System for Radioenviron- mental Studies, Nucl. Instr. Meth. 117 (1974) 189-211.

[165] GOULDING,F.S., PEHL,R.E., Semiconductor Radiation Detectors.

[166] GOULDING,F.S., LANDIS,D.A., Semiconductor Spectrometer Electronics, in Nuclear Spectroscopy and Reactions (LERNY,J., Ed.) Part A, Acad. Press, York (1974).

[167] TAIT,W.H., Radiation Detection, Buttersworth, London (1980).

[168] KNOLL,G.F.; Radiation Detection and Measurement, J. Wiley and Sons (1979) New York.

[169] PAULUS,T.J., RAUDORF,T.W., COYNE,B., TRAMMELL,R., Comparative Timing Performance of Large Volume HPGe Germanium Detectors, IEEE Transact. Nucl. Sci. NS-28 (1981) 544-548.

[170] NAKANISHI,T, SANSONI,B., Low Energy Photon Spectrometry in Non-Destructive Neutron Activation Analysis of Environmental Samples, J. Radioanal. Chem. 37 (1977) 945-955.

[171] SCHMITT,B.F., SEGEBADE,C., Multielement Analysis of Soil of a Sewage Farm by Photon and Neutron Activation Analysis Using Waste Incineration Ash as Reference Material, Proceed. 4th. Intern. Conf. on Nuclear Methods in Energy and Environmental Research, Columbia, Mo. 1980 (VOGT, J.R. Ed.),U.S. Dept. of Energy, Columbia (1980) 159-168.

[172] MANTEL M., AMIEL,S., Simultaneous Determination of Uranium and Thorium by INAA and High Resolution X-Ray Spectrometry, Anal. Chem. 45 (1975) 2393-2399.

[173] HNATOWICZ,V., Dependence of Efficiency Curve for Ge(Li) Detectors on Detector Shape, Nucl. Instr. Meth. 142 (1977) 403-407.

[174] DE BRUIN,M., KORTHOVENP.J.M., The Well-Type Ge(Li) Detector as a Tool in Radiochemistry, Radio- chem. Radioanal. Lett. 44 (1980) 139-150.

[175] LANDIS,D.A., MADDEN,N.W., GOULDING,F.S., Energy Dependent Losses in Pulsed-Feedback Preamplifiers, IEEE Transact. Nucl. Science, NS-26 No.1 (1979) 428-432.

[176] PESSARA,W., Amplitude Dependent Count Rate Losses in Pulsed Optical Feedback Preamplifiers, Nucl. Instr. Meth., 173 (1980) 307-309.

[177] BODE,P., DE BRUIN,M., Preamplifiers with Pulsed Optical Feedback as a Source of Errors in Instrumental Activation Analysis, Nucl. Instr. Meth. 216 (1983) 529-530.

[178] FUNCK,E., Counting Losses from Pulsed Optical Feedback Preamplifiers Used with Semi-Conductor Detectors, Int. J. Appl. Radiat. Isot. 34 (1983) 1123-1131.

[179] Quality Assurance in Biomedical Neutron Activation Analysis, IAEA TECDOC 323, Vienna (1984).

[180] LINDSTROM,R.M., FLEMING,R.F., Accuracy in Activation Analysis: Count Rate Effects, Nuclear Methods in Environmental and Energy Research, (Proc. 4th. Intern. Conf., Columbia, Mo. 1980, VOGT.J.R., Ed.) U.S. Dept. of Energy, Columbia (1980) 25-35.

[181] ANDERS,O.U., Experiences with the Ge(Li) Detector for High Resolution Gamma-Ray Spectroscopy and a Practical Approach to the Pulse Pile-Up Problem, Nucl. Instr. Meth., 68 (1968) 205.

[182] STRAUSS,M.G., SIFTER,L.L., LENKIZUS,F.R., BREMER,R., Ultra Stable Reference Pulser for High Resolution Spectrometers, IEEE Transact. Nucl. Science, NS-15, (1968) 518-530.

[183] HARMS, J.P., Automatic Dead-Time Correction for Multichannel Pulse-Height Analyzers at Variable Count Rates, Nucl. Instr. Meth. 53 (1967) 192-196.

[184] WESTPHAL,G.P., Loss-Free Counting - A Concept for Real-Time Compensation of Dead-Time and Pile-Up Losses in Nuclear Pulse Spectroscopy, Nucl. Instr. Meth. 146 (1977) 605-606.

[185] WESTPHAL,G.P., On the Performance of Loss-Free Counting - A Method for Real-Time Compensation of Dead Time and Pile-Up Losses in Nuclear Pulse Spectroscopy, Nucl. Instr. Meth. 163 (1979) 189-196.

[186] WESTPHAL,G.P., Real-Time Correction of Counting Losses in Nuclear Pulse Spectroscopy, J. Radio- anal. Chem. 70 (1982) 387-410.

[187] AARNIO,P.A., ROUTTI,J.T., SANDBERG,J.V., MicroSAMPO - Personal Computer-Based Advanced Gamma Spectrum Analysis System, J. Radioanal. Nucl. Chem. 124 (1988), 457.

[188] GUNNINK,R. & NIDAY,J.B., Computerized Qauntitative Analysis by Gamma-Ray Spectrometry. Vol. I. Description of the Gamanal Program, UCRL-51061, vol, 1 (1972).

[189] PHILLIPS,G, MARLOW,K.W., Nucl. Instr. Methods, 137 (1976) 525.

[190] LINDSTROM,D.J. & KOROTOV,R.L., Teabags: Computer Programs for Instrumental Neutron Activation Analysis 6th Modern Trends in Activation Analysis, (1981) Toronto, 197.

[191] PARR,R.M., HOUTERMANS,H., SCHAERF,K., The IAEA Intercomparison of Methods for Processing Ge(Li) Gamma-Ray Spectra: A Preliminary Report in Computers in Activation Analysis (Proc. Conf. Mayaguez, 1978), Carpenter,B.S., D'Agostino,M.D., Yule,H.P., eds. (CONF-780421) USDOE (1979), 544.

[192] BODE,P., DE BRUIN,M., KORTHOVEN,P.J.M., Increased utilization of Research Reactor Facilities without Staff Personnel Expansion by a User-Friendly System for Routine Instrumental Neutron Activation Analysis, IAEA TECDOC 409 Research Reactor Activities in Support of National Nuclear Programmes ,Vienna (1987).

[193] BURHOLT,G.D., CAESAR,E.A.Y., JONES,T.C., A Description of the Cyclic Activation System (CAS) on the University of London Reactor, Nucl. Instr. Methods, 204 (1982) 231.

[194] BODE,P., DE BRUIN,M., An Automated System for Activation Analysis with Short Half-Life Radionuclides Using a Carbonfiber Irradiation Facility, J. Radioanl. Nucl. Chem., 123(2) (1988) 365-376.

[195] GARFINKEL,S.B., MANN,W.B. & YOUDEN,W.J., Design and Statistical Procedures for the Evaluation of an Automatic Gamma-Ray Point-Source Calibrator, J. of Research of NBS - C Engineering & Instrumentation, 70C (1966) 92-53 - 102-63.

[196] BERTOZZI,G., GIRARDI,F., GUZZI, G. & COLA, DI., Comparative Analysis of Different Computer Handling Systems for Gamma-Spectrometric Data Developed at C.C.R. ISPRA. J. Radioanal. Chem. 15 (1973), p.637...646.

[197] VâNSKâ,L., ROSENBERG,R.J., & PITKâNEN,V., An Automatic Gamma Spectrometer for Activation Analysis. Nuclear Instruments and Methods 213 (1983), pp.343-347.

[198] DE BRUIN.M, KORTHOVEN,P.J.M., BODE,P., Evaluation of a System for Routine Instrumental Neutron Activation Analysis, J. Radioanal. Chem. 70 (1982) 497-512.

[199] ECHO,M.W. & TURK,E.H., Quantitative Determination of ^{235} U by delayed neutron counting. PTR-143 (Jan. 28, 1957).

[200] AMIEL, S., Analytical Applications of Delayed Neutron Emission in Fissionable Elements. IA-621 (May 1961).

[201] DYER,F.F., EMERY,J.F. & LEDDICOTE,G.W., A Comprehensive Study of the Neutron Activation Analysis of Uranium by Delayed Neutron Counting. ORNL-3342 (Oct. 1962).

[202] OSTLE,D., COLEMAN,R.F. & BALL,T.K., Uranium Prospecting Handbook, Proceedings of a NATO-Sponsored Advanced Study Institute on Methods of Prospecting for Uranium Minerals, London, 21 Sept. - 2 Oct. 1972, p.95.

[203] MINOR,M.M., HENSLEY,W.K., DENTON,M.M., GARCIA,J.R., J. Radioanal. Chem. 70 (1982) 459.

[204] MILLARD,Jr.,H.T., Geol. Surv. Prof. Paper 840, p.61, unpublished reports.

[205] CHRIEN,R.E., Practical Uses of Neutron Capture Gamma-Ray Spectroscopy, in B.J. Allen, I. Berggvist, R.E. Chrien, and D. Gardner (eds) "Neutron Radiative Capture" Oxford: Pergamon (1984), 187.

[206] LINDSTROM,R.M. & ANDERSON,D.L., Analytical Neutron-Capture Gamma-Ray Spectroscopy: Status and Prospects, in S. Raman (ed) "Capture Gamma-Ray Spectroscopy and Related Topics - 1984" New York: Am. Inst. Physics, (1985), 810.

[207] LENIHAN,J.M.A., Talk Presented at 4th Internat. Conf. Nucl Methods in Envir. and Energy Res., Columbia, Mo. (1980).

[208] KELLER,H., Present Sample Identification Systems, J. Autom. Chem. 3 (1981) 196-198.

[209] KORTHOVEN,P.J.M., DE BRUIN,M., Computer Aspects of Large-Scale Routine Instrumental Neutron Activation Analysis, Computers in Activation Analysis and q-ray Spectroscopy, (Proceed. Intern. Conf. Mayaguez (1978) 639-651.

[210] INGAMELLS,C.O., SWITZER,P., A Proposed Sampling Constant for Use in Geochemical Analysis, Talanta 20 (1973), 547.

[211] HILLEBRAND,W.F., LUNDELL,G.E.F., BRIGHT,H.A., HOFFMAN,J.I., Applied Inorganic Analysis (2nd Ed.), Wiley, New York (1953).

[212] VERSIECK,J., BARBIER,F., CORNELIS,R., HOSTE,J., Sample Contamination as a Source of Error in Trace-Element Analysis of Biological Samples, Talanta 29 (1982) 973-984.

[213] CORNELIS.R., Sample Handling of Clinical Specimens for Ultra-Trace Element Analysis, J. Radioanal. Chem. 112 (1987) 141-150.

[214] IYENGAR,G.V., Preservation and Preparation of Biological Materials for Trace Element Analysis: Quality Assurance Considerations in: Quality Assurance in Biomedical Neutron Activation Analysis, Rep. Advis. Group Meeting Vienna, 1982, IAEA-TECDOC 323 Vienna (1984) 83-05.

[215] BEHNE,D., Problems of Sampling and Sample Preparation for Trace Element Analysis in the health Sciences, Trace Element Analytical Chemistry in Medicine and Biology, Bratter,P., Schramel P. (eds.), de Gruyter (1980) 769-782.

[216] DIKAWA,K., Trace Analysis of Atmospheric Samples, Kodanska Ltd., Tokyo and J. Wiley and Sons, New York (1977); chapter 2, pp.5-59.

[217] LAKOMAA,E.L., Element Analysis of Small-Size Biological Samples, Kemia-Kemi, 8 (1981) 378-380.

[218] LAKOMAA,E.L., MUSSALO-RAUHAMAA,H., SALMELA,S., Avoidance of Contamination in Elemental Analysis of Serum Samples, submitted to J. of Trace Elements and Electrolytes in Health and Disease.

[219] ZEISLER,R., GREENBERG,R.R., STONE,S.F., SULLIVAN,T.M., Selenium Determination in the Assessment of Sample Stability in Specimen Banking, Trans. American Nuclear Society Meeting, San Diego (1988) 153-154.

[220] BENEDETTI-PICHLER,A.A., Theory and Principles of Sampling for Chemical Analysis, 1956, in W.G. Bert (ed.) Physical Methods in Chemical Analysis VIII (1956) Academic Press, New York.

[221] MAIENTHAL,E.J., BECKER,D.A., A Survey of Current Literature on Sampling, Sample Handling and Long Term Storage for Environmental Materials, NBS Technical Note 929 (1976).

[222] GREENBERG, R.R., Trace Element Characterization of the NBS Urban Particulate Matter Standard Reference Material by Instrumental Neutron Activation Analysis, Anal. Chem. 51 (1979) 2004.

[223] GREENBERG, R.R., The Role of Neutron Activation Analysis in the Certification of NBS Standard Reference Materials, J. Radioanal. Nucl. Chem. 113 (1987), 233.

[224] MOODY,J.R., GREENBERG,R.R., PRATT,K.W., RAINS,T.C., Recommended Inorganic Chemicals for Calibration, Anal. Chem. 60 (1988) 1203A-1218A.

[225] BECKER,D.A., Primary Standards in Activation Analysis, J. Radioanal. Chem. 113 (1987), 5.

[226] DUVAL, C., Inorganic Thermogravimetric Analysis, Elsevier, New York (1953).

[227] DATE,A.R., Preparation of Trace Element Reference Materials by a Co-precipitated Gel Technique, Report No. 101, Institute of Geological Sciences, London (March 1977).

[228] MITCHELL,J.W., BLITZER,L.D., KOMETANI,T.Y., GILLS,T., CLARK,Jr.,L., Homogenuously Doped Silica Matrices for Trace Element Standards in Neutron Activation Analysis, J. Radioanal. Chem. 39 (1977) 335-342.

[229] ANDERSON,D.H., MURPHY,J.J., WHITE,W.W., Gelatin Multicomponent Trace Element Reference Material, Anal. Chem. 48 (1976) 116.

[230] MOSULISHVILI,L.M., DUNDUA,V.Y., KHARABADZE,N.E., EFREMOVA,E.Y., CHIKHLADZE,N.V., Synthetic Multielement Standard Samples for Serial Neutron Activation Analysis of Biological Materials, J. Radioanal. Nucl. Chem. 83 (1984) 13.

[231] MATSUMOTO,K., SUZUKI,N., A New Trace Element Standard Reference Materials with Polyacrylamide Gel Matrix for Radioactivation Analysis, Radiochem. Radioanal. Letters 42 (1980) 99.

[232] PERLMAN,I., ASARO,F., Pottery Analysis by Neutron Activation, in "Science and Archaeology," (BRILL,R.H., Ed), MIT Press, Cambridge (1971), 182.

[233] MARINENKO,R.B., Preparation and Characterization of K-411 and K-412 Mineral Glasses for Micro- analysis: SRM 470 (NBS Spec. Pub. 260-74), National Bureau of Standards, Washington, DC (1982).

[234] ROUCHAUD,J.C., DEBOVE,L., FEDOROFF,M., MOSULISHVILI,L.M., DUNDUA,V.Y., KHARABADZE,N.E., SHONIA, N.I., EFREMOVA,E.Y., CHIKHLADZE,N.V., A Comparison of Synthetic Irradiation-Resistant Multi- Element Standards for Activation Analysis, J. Radioanal. Nucl. Chem. 113 (1987) 209.

[235] Eastman Kodak Company, Rochester, NY 14650, USA.

[236] STEINNES,E. Epithermal Neutron Activation Analysis of Geological Material. Activation Analysis in Geochemistry and Cosmochemistry. Denmark, Universetetsförlaget (1971), 113-128.

[237] PARRY,S.J., Epithermal Neutron Activation Analysis of Short-Lived Neuclides in Geological Material, J. Radioanal. Chem. 72 (1982) 195-207.

[238] MINOR,M.M., HENSLEY,W.K., DENTON,M.M., GARCIA,J.R., J. Radioanal. Chem. 70 (1982) 459.

[239] GUINN, V.P., LESLIE,J., NAKAZAWA,L., Performance of the Updated INAA Advance Prediction Computer Program, J. Radioanal. Chem. 70 (1982) 513-525.

[240] DE BRUIN,M., KORTHOVEN,P.J.M., The Influence of Summation on the Determination of Relative Counting Efficiencies, Radiochem. Radioanal. Lett. 19 (1975) 153-156.

[241] ERTEN,H.N., AKSOYOGLU,S., GOKTURK,H., Efficiency Calibration and Summation Effects in Gamma-Ray Spectrometry, J. Radioanal. Chem.125, no.1 (1988) 3-10.

[242] DE BRUIN,M., KORTHOVEN,P.J.M., BODE,P., Spectrum Interpretation Problems with Well-Type Ge(Li) Detectors due to Self-Absorption Variations, Nucl. Instr. Meth. 159 (1979) 301-303.

[244] BODE,P., DE BRUIN,M., KORTHOVEN,P.J.M., A method for the Correction of Self-Absorption of Low- Energy Photons for Use in Routine INAA, J. Radioanal. Chem. 64 (1981) 153-166.

[245] AMIEL,S., MANTEL,M., ALFASSI,Z.B., Development of a New Approach to Trace Element Analysis Using Neutron Activation Followed by High Resolution X-Ray Spectrometry, J. Radioanal. Chem. 37 (1977) 189-193.

[246] MANN,W.B., LOWENTHAL,G.C., TAYLOR,J.C.V. (Eds), Applied Radionuclide Metrology, (Proceed Seminar Geel 1983), Int. J. Appl. Radiat. Isot. 34 (1983).

[247] ADAMS,F., DAMS,R., A Compilation of Precisely Determined Gamma-Ray Transition Energies of Radio_ nuclides Produced by Reactor Irradiation, J. Radioanal. Chem. 3 (1969) 99-125.

[248] HELMER,R.G., GREENWOOD, R.C., GEHRKE,R.J., Reevaluation of Precise Q-Ray Energies for Calibration of Ge(Li)-Spectrometers, Nucl. Instr. Meth. 155 (1978) 189-201.

[249] HELMER,R.G., VAN DE ASSCHE,P.M.W., VAN DER LEUN,C., Atomic Data and Nuclear Data Tables, 24 (1979) 39-48.

[250] HELMER,R.G., Efficiency Calibration of a Ge-Detector for 30-2800 keV q-rays, Nucl. Instr. Meth. 199 (1982) 521-529.

[251] HELMER,R.G., Variation of Ge-Detector Efficiency with Source Diameter and Radial Source Position, Int. Journ. Appl. Radiat. Isotop. 34 (1983) 1105-1108.

[252] GEHRKE,R.J., HELMER,R.G., GREENWOOD,R.C., Precise Relative Q-Ray Intensities for Calibration of Ge-Semiconductor Detectors, Nucl. Instr. Meth. 147 (1977) 405-413.

[253] MICHAELIS, W., Experimental Gamma-Ray Response Characteristics of Lithium Drifted Germanium Detectors, Nucl. Instr. Meth. 70 (1969) 253-261.

[254] VERPLANCKE,J.C., Full Energy Peak Efficiency of a Well-Type Ge(Li) Gamma-Ray Detector, Nucl. Instr. Meth. 96 (1971) 557-560.

[255] MOENS,L., HOSTE,J., Calculation of the Peak Efficiency of High-Purity Germanium Detectors, Int. J. Appl. Rad. Isotop., 34 no.8 (1983) 1085-1096.

[256] LIPPERT,J., Detector-Efficiency Calculation based on Point-Source Measurement, Int. J. Appl. Rad. Isotop. 34 no.8 (1983) 1097-1104.

[257] SPYROU,N.M., Cyclic Activation Analysis: A Review, J. Radioanal. Chem. 61 (1981) 211-242.

[258] SPYROU,N.M., OZEK,F., INGLE,K., Cyclic Activation in Trace Element Analysis of Environmental Samples, Nuclear Methods in Environmental and Energy Research, (Proc. 2nd Intern. Conf. Nucl. Methods in Energy and Environmental Research, Columbia, Mo. (1974) 106.

[259] SEGEBADE,C., WEISE,H.P., Comparison of Sensitivity Estimates for Low Energy Photon and Classical Gamma-Ray Spectroscopy Applied to Photon Activation Analysis, J. Radioanal. Chem. 45 (1978) 209-220.

[260] ROWSON,J.W., HONTZEAS,S.A., Radioisotopic X-ray Analysis of Uranium Ores by K-shell Fluorescence, Nucl. Instr. Meth. 163 (1978) 555-568.

[261] HOZBECKER,J., RYAN,D.E., Determination of Trace Metals by Neutron Activation Analysis after Coprecipitation with Lead Phosphate, J. Radioanal. Chem. 74 (1982) 25-30.

[262] SHENBERG,C.; GILAT,J., FINST,H.L., Use of X-Ray Spectrocmetry in Activation Analysis, Determination of Bromine, Anal. Chem. 39 (1967) 780-785.

[263] WIERNIK,M., Comparison of Several Methods Proposed for Correction of Dead-Time losses in the Q-Ray Spectrometry of Very Short-Lived Isotopes, Nucl. Instr. Meth. 95 (1974) 13-18.

[264] HOUTERMANS,H., SCHAERF,K., REICHEL,R., DEBERTIN,K., International Comparison of Methods to Test the Validity of Dead-Time and Pile-Up Corrections for High Precision Q-Ray Spectroscopy, Int. J. Appl. Rad. Isotop. 34 (1983) 487-489.

[265] WYTTENBACH,A., Coincidence Losses in Activation Analysis, J. Radioanal. Chem. 8 (1971) 335-343.

[266] BARTOSEK,J., ADAMS,F., HOSTE,J., A Dead-Time Correction System for Gamma-Ray Spectrometry of Short-Lived Isotopes, Nucl. Instr. Meth. 103 (1972) 45-47.

[267] DE BRUIN,M., THEN, S.S., BODE,P., KORTHOVEN, P.J.M., A simple Deadtime Stabilizer for Gamma-Ray Spectrometers, Nucl. Instr. Meth. 121 (1974) 611-613.

[268] STERLINSKI,S., HAMMER,W., Simple Methods for Dead-Time and Pile-Up Corrections in Analytical Gamma-Ray Spectroscopy, J. Radioanal. Chem. 31 (1976) 235-237.

[269] STERLINSKI,S., HAMMER,W., WASEK,M., The Nature of Dead-Time in Multichannel Pulse Height Analyzers at High Counting Rate and Related Problems, J. Radioanal. Chem. 114 (1987) 243-255.

[270] ANDEWEG,A.H., Automatic Setting of the Distance Between Sample and Detector in Gamma-Ray Spectro- metry, National Institute of Mining (Randsburg, South Africa) Report NIM-Report 2069 (1980).

[271] CARPENTER, B.S., D'AGOSTINO,M.D., YULE,H.P. (Eds.), Computers in Activation Analysis and Gamma-Ray Spectroscopy (CONF-780421), U.S. Dept. of Energy, Springfield, Va. (1978).

[272] HEYDORN,K., CHRISTENSEN,L.H., Verification Testing of Commercially Available Computer Programs for Photopeak Area Evaluation, J. Radioanal. Nucl. Chem. 124 (1988), 467.

[273] SANDERSON,C.G., An Evaluation of Commercial IBM PC Software for the Analysis of Low-Level Environmental Gamma-ray Spectra, Proc. Conf. Low-Level Techniques Group, Internat. Comm. Radionucl. Metrol., Wurlingen (1987).

[274] ROUTTI,J.R., PRUSSIN,S.G., Photopeak Method for the Computer Analysis of Gamma-Ray Spectra from Semiconductor Detectors, Nucl. Instr. Meth. 72 (1969) 125.

[275] HENSLEY,W.K., LEPEL,E.A., YULY,M.E., ABEL,K.H., Adaptation and Implementation of the RAYGUN Gamma-Ray Analysis Code on the IBM PC, J. Radioanal. Nucl. Chem. 124 (1988) 481.

[276] DE CORTE,F.,SIMONITS,A. DE WISPELAERE,A., HOSTE,J., Accuracy and Applicability of the k_0 Standardization Method, J. Radioanal. Chem. 113 (1987) 145-161.

[277] LANDSBERGER,S. Spectral Interferences from Uranium Fission in Neutron Activation Analysis., Chem. Geol. 57 (1986) 415.

[278] DE BIEVRE,P., Transferring Accuracy to the Trace Level and Then to the Field, J. Res. Nat. Bur. Stds. (U.S.) 93 (1988), 520.

[279] WILSON,E.B., Jr., An Introduction to Scientific Research, McGraw-Hill, New York (1952).

[280] KRATOCHVIL,B., TAYLOR,J.K., Sampling for Chemical Analysis, Anal. Chem. 53 (1981), 924A.

[281] INGAMELLS,C.O., SWITZER,P., A Proposed Sampling Constant for Use in Geochemical Analysis, Talanta 20 (1973), 547.

[282] LIPPONEN,M. & ROSENBERG,R.J., Quality control in Routine Instrumental Epithermal Neutron Activation Analysis of Geological Materials, J. Res. Nat. Bur. Stds. 93 (1988) 224.

[283] DE SOETE,D., GIJBELS,R., HOSTE,J., Neutron Activation Analysis, Wiley-Interscience, London (1972).

[284] FRIEDLANDER,G., KENNEDY,J.W., MACIAS,E.S., MILLER,J.M., Nuclear and Radiochemistry, 3rd ed., Wiley-Interscience, New York (1981).

[285] CURRIE,L.A., The Limit of Precision in Nuclear and Analytical Chemistry, Nucl. Inst. Methods 100 (1972), 387.

[286] HEYDORN,K., Detection of Systematic Errors by the Analysis of Precision, in "Accuracy in Trace Analysis: Sampling, Sample Handling, Analysis", LAFLEUR, P.D., ed., Nat. Bur. Stds. (U.S.) Spec. Pub. 422 (1976).

[287] Analytical Methods Committee, IUPAC, Sodium Carbonate as a Primary Standard in Acid-Base Titri- metry, Analyst 90 (1965), 251.

[288] Terms and Definitions Used in Connection with Reference Materials, ISO Guide 30-1981 (E).

[289] Geostandards Newsletter (Paris), published semiannually.

[290] FLANAGAN,F.J., Reference Samples in Geology and Geochemistry, U.S. Geological Survey Bulletin 1582 (1986) 70.

[291] ABBEY,S., Studies in "Standard Samples" for Use in the General Analysis of Silicate Rocks and Minerals, Geostandards Newsletter (1980) 4, 163.

[292] ISO Catalog and Compilation of Standard Materials.

[292] SEWARD,R.W. (ed.), NBS Standard Reference Materials Catalog 1988-89, Nat. Bur. Stds. (U.S.) Spec. Pub. 260 (1988).

[293] TAYLOR,J.K., Handbook for SRM Users, Nat. Bur. Stds. (U.S.) Spec. Pub. 260-100 (1985).

[294] MURAMATSU,Y., PARR,R.M., Survey of Currently Available Reference Materials for Use in Connection with the Determination of Trace Elements in Biological and Environmental Materials, Report IAEA/ RL/128 (1985).

[295] EISENHART,C.E., Expression of the Uncertainties of Final Results, Science 160 (1968), 1201.

[296] KU,H.H., Notes on the Use of Propagation of Error Formulas, J. Res. Nat. Bur. Stds. (U.S.) 70C (1966), 263.

[297] FLEMING,R.F., LINDSTROM,R.M., Limitations on the Accuracy of Sulphur Determination by NAA, Transact. Amer. Nucl. Soc. 41 (1982) 223.

[298] GARFIELD,F.M., Quality Assurance Principles for Analytical Laboratories, AOAC, Arlington, Va. (1984).

[299] HEYDORN,K., Quality Assurance in Neutron Activation Analysis, in Proc. 5th Internat. Conf. Nucl. Methods Envir. Energy Res. (Mayaguez, 1984), VOGT, J.R., ed., (CONF-840408) USDOE (1984) 620.

Appendix A

TABLES FOR NEUTRON ACTIVATION ANALYSIS

INTRODUCTION

Activation analysts and their collaborators from other disciplines frequently find themselves searching the literature for nuclear data to be used when analyzing materials by NAA, making activity calculations, etc. In recognition of the desirability of placing the most reliable information into a single source, the following tables were compiled. The data in these tables represent a compilation of all literature reviewed by the author through November 1987.

Presentation of data in Table I

A compilation of thermal neutron cross sections and resonance integrals is presented in tabular form for (n,γ) reactions with stable isotopes.

Column 1 (Target Isotope): The relevant target nucleus is presented in a standard manner.

Column 2 (Isotope Abundance): Fractional isotopic abundances for elements with isotopes in their natural abundance are given. These data were taken from a recent compilation by De Bievre and Barnes [1].

Column 3 (σ_{th}, Thermal Neutron Cross Section): The neutron capture (n,γ) reaction cross sections for thermal neutrons with an average velocity of 2200 m/s (0.0253 eV) are given.

Column 4 (RI, Resonance Integral): Neutrons above the cadmium cutoff energy, 0.5 eV, which induce (n,γ) reactions are usually called the epithermal or resonance neutrons. The resonance integral cross sections as defined by the expression

$$RI = \int_{0.5\text{ eV}}^{\infty} \sigma(E)dE/E$$

are listed. The data in columns 3 and 4 were taken from compilations by Gryntakis and Kim [2] and De Corte et al. [3].

Columns 5 and 6 (Product Isotope and Halflife): The product radionuclide and its halflife from the (n,γ) reaction is listed. For many reactions both stable and metastable products are produced and the nuclear data for both are given. Product halflives were taken from the references cited in Table III.

Presentation of data in Table II

A compilation of recommended cross sections for reactions induced by U-235 fission spectrum neutrons is given in Table II.

Column 1 (Target Isotope) and Column 2 (Isotope Abundance): The data for target nuclides are presented in the same manner as they were presented in Table I.

Column 3 ($\bar{\sigma}$, Average Cross Sections for Fast Reactor Neutrons): At neutron energies of 100 keV and above the (n,p), (n,α), (n,2n), (n,n′) and (n,F) reactions must be considered. Below a particular threshold energy, E_T, all of these reactions have a cross section of zero. Above the threshold the cross section exhibits an energy dependence. The average cross section for reactions induced by neutrons in a U-235 fission neutron spectrum is defined by

$$\bar{\sigma} = \frac{\int_{E_T}^{\infty} \sigma(E)\phi(E)dE}{\int_{E_T}^{\infty} \phi(E)dE}$$

Column 4 (Product Isotope) and Column 5 (Product Halflife): These data are presented in the same way as they were given in Table I.

Presentation of data in Table III

The production modes, halflives and most common gamma-ray energies and their abundances for radioisotopes observed in neutron activation analysis are compiled. Table III also includes other isotopes which activation analysts may encounter: those naturally occurring isotopes observed in background spectra; fission product isotopes sometimes found in gamma-ray spectra collected at nuclear reactors; and several accelerator product isotopes which are frequently used for detector calibration, etc.

Column 1 (Isotope) and Column 2 (Halflife): The isotopes and their halflives are listed according to atomic number.

Column 3 (Energy) and Column 4 (Abundance): The main gamma rays and their percent abundances (absolute intensities) are given for each isotope. Energies are given in units of keV. For each isotope the gamma ray recommended for use in activity calculations is identified with an asterisk (*).

Column 5 (Production Modes): The reactions by which the radioisotope can be produced are listed. For a number of daughter isotopes the precursor isotope and its halflife are given.

Column 6 (Ref.): The listed reference is the source from which the nuclear data on halflife, gamma-ray energies and abundances were adopted.

Presentation of data in Tables IV and V

The gamma rays from Table III are arranged according to increasing energy with their associated gamma rays. Table IV lists those isotopes with halflives under 1 day and Table V lists those isotopes with halflives greater than 1 day.

Column 1 (Energy1): Energies are given in increasing order in units of keV.

Column 2 (Isotope) and Column 3 (Halflife): The isotope in whose radioactive decay the gamma ray is observed and isotope halflife are reported.

Columns 4, 5 and 6 (Energy2, Energy3 and Energy4): Energies of the three most intense gamma rays associated with the gamma ray of column 1 are listed.

Presentation of data in Tables VI, VII and VIII

Gamma rays recommended for analysis of elements and common interferences observed in NAA are compiled in these tables. The data are separated into three groups according to halflives for the identifying isotopes. Table VI lists isotopes with halflives less than 5 hours, Table VII includes isotopes with halflives between 5 hours and 7 days and Table VIII includes isotopes with halflives greater than 7 days.

Column 1 (Element): The elements are listed alphabetically in each table where an isotope useful for analysis exists.

Column 2 (Isotope), Column 3 (Halflife) and Column 4 (Energy): The isotope, halflife and energies of most useful gamma rays are listed.

Column 5 (Interfering Isotope), Column 6 (Halflife) and Column 7 (Interference Energy): The interfering isotope, halflife and energy are listed. In general, the interference is considered serious when the energies are less than 2 keV apart.

Column 8 (Reference): The energy of a reference gamma ray in the interfering isotope is given.

Column 9 (Abund. Ratio): The abundance ratio of interfering gamma ray to reference gamma ray is computed.

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REFERENCES TO INTRODUCTION

[1] De Bievre, P., Barnes, I.L., Intern. J. Mass Spectrom. and Ion Processes **65** (1985) 211.

[2] Gryntakis, E.M., Kim, J.I., J. Radioanal. Chem. **76** (1983) 341.

[3] De Corte, F., Simonits, A., De Wispelaere, A., Hoste, J., Moens, L., DeMeter, A., INW/KFKI Interim Report (Gent, June 1986).

[4] Calamand, A., in Handbook on Nuclear Activation Cross-Sections, IAEA Techn. Repts. Ser. No. 156 (IAEA, Vienna 1974)

TABLE I. THERMAL NEUTRON CROSS-SECTIONS AND RESONANCE INTEGRALS

Target Isotope	Isotope Abundance	σ_{th} (barns)	RI (barns)	Product Isotope	Product Halflife
B-10	0.1990	3837.	1722.	FRAGMENTATION	
O-18	0.0020	0.00016	0.00081	O-19	26.91 s
F-19	1.0000	0.0095	0.039	F-20	11.03 s
Na-23	1.0000	0.513	0.303	Na-24	14.96 h
Mg-26	0.1101	0.0372	0.024	Mg-27	9.46 m
Al-27	1.0000	0.226	0.16	Al-28	2.24 m
Si-30	0.0310	0.108	0.106	Si-31	2.62 h
P-31	1.0000	0.180	0.08	P-32	14.28 d
S-34	0.0421	0.024	0.554	S-35	87.51 d
S-36	0.0002	0.16	0.18	S-37	5.05 m
Cl-37	0.2423	0.423	0.29	Cl-38	37.24 m
Ar-40	0.9960	0.66	0.41	Ar-41	1.83 h
K-41	0.0673	1.45	1.41	K-42	12.36 h
Ca-46	0.00004	0.62	0.81	Ca-47	4.54 d
Ca-48	0.00187	1.12	0.50	Ca-49	8.72 m
Sc-45	1.0000	26.3	11.3	Sc-46	83.81 d
Sc-45	1.0000	9.6	—	Sc-46m	18.75 s
Ti-50	0.0540	0.171	0.115	Ti-51	5.76 m
V-51	0.9975	4.79	2.63	V-52	3.75 m
Cr-50	0.0435	15.2	8.1	Cr-51	27.7 d
Mn-55	1.0000	13.2	13.9	Mn-56	2.58 h
Fe-58	0.0028	1.31	1.28	Fe-59	44.5 d
Co-59	1.0000	37.13	74.	Co-60	5.27 y
Co-59	1.0000	20.0	39.7	Co-60m	10.47 m
Ni-64	0.0091	1.69	1.13	Ni-65	2.52 h
Cu-63	0.6917	4.28	4.88	Cu-64	12.7 h
Cu-65	0.3083	2.48	2.63	Cu-66	5.10 m
Zn-64	0.4860	0.726	1.42	Zn-65	243.9 d
Zn-68	0.1880	0.0699	0.223	Zn-69m	13.76 h
Zn-70	0.0060	0.009	0.04	Zn-71m	3.94 h
Ga-69	0.6010	1.68	15.6	Ga-70	21.15 m
Ga-71	0.3990	4.61	30.6	Ga-72	14.1 h
Ge-74	0.3650	0.383	0.43	Ge-75	82.78 m
Ge-74	0.3650	0.143	0.35	Ge-75m	47.7 s
Ge-76	0.0780	0.05	2.0	Ge-77	11.3 h
Ge-76	0.0780	0.092	1.0	Ge-77m	52.90 s
As-75	1.0000	3.86	52.5	As-76	26.32 h
Se-74	0.0090	51.2	507.	Se-75	119.77 d
Se-76	0.0900	21.	16.	Se-77m	17.45 s
Se-78	0.2360	0.33	3.7	Se-79m	3.91 m

TABLE I. (cont.)

Target Isotope	Isotope Abundance	σ_{th} (barns)	RI (barns)	Product Isotope	Product Halflife
Se-80	0.4970	0.61	1.7	Se-81	18.45 m
Se-80	0.4970	0.080	0.50	Se-81m	57.25 m
Se-82	0.0920	0.045	0.09	Se-83	22.3 m
Se-82	0.0920	0.0058	---	Se-83m	70.4 s
Br-79	0.5069	11.1	132.5	Br-80	17.68 m
Br-79	0.5069	2.4	32.0	Br-80m	4.42 h
Br-81	0.4931	2.58	49.8	Br-82	35.3 h
Br-81	0.4931	2.43	34.	Br-82m	6.13 m
Kr-84	0.5696	0.90	6.03	Kr-85m	4.48 h
Kr-86	0.1730	0.60	0.14	Kr-87	76.31 m
Rb-85	0.7217	0.494	7.31	Rb-86	18.66 d
Rb-85	0.7217	0.050	1.16	Rb-86m	1.02 m
Rb-87	0.2783	0.102	2.38	Rb-88	17.8 m
Sr-84	0.0056	0.690	9.14	Sr-85	64.84 d
Sr-84	0.0056	0.61	8.8	Sr-85m	67.66 m
Sr-86	0.0986	0.770	3.17	Sr-87m	2.81 h
Sr-88	0.8258	0.0058	0.06	Sr-89	50.55 d
Y-89	1.0000	0.001	0.006	Y-90m	3.19 h
Zr-94	0.1738	0.0530	0.268	Zr-95	64.02 d
Zr-96	0.0280	0.0213	5.28	Zr-97	16.74 h
Nb-93	1.0000	0.863	6.34	Nb-94m	6.26 m
Mo-92	0.1484	0.006	---	Mo-93m	6.85 h
Mo-98	0.2413	0.131	6.96	Mo-99	65.94 h
Mo-100	0.0963	0.200	3.77	Mo-101	14.6 m
Ru-96	0.0552	0.229	6.12	Ru-97	69.12 h
Ru-102	0.3160	1.16	4.21	Ru-103	39.26 d
Ru-104	0.1870	0.491	6.28	Ru-105	4.44 h
Rh-103	1.0000	134.	1275.	Rh-104	42.3 s
Rh-103	1.0000	11.	82.	Rh-104m	4.34 m
Pd-102	0.0102	4.8	---	Pd-103	16.99 d
Pd-106	0.2733	0.013	0.2	Pd-107m	21.3 s
Pd-108	0.2646	8.77	253.	Pd-109	13.7 h
Pd-108	0.2646	0.20	2.26	Pd-109m	4.69 m
Pd-110	0.1172	0.36	7.0	Pd-111	23.4 m
Pd-110	0.1172	0.12	0.24	Pd-111m	5.5 h
Ag-107	0.5184	33.1	96.0	Ag-108	2.37 m
Ag-109	0.4816	89.	1112.	Ag-110	24.6 s
Ag-109	0.4816	3.90	69.0	Ag-110m	249.76 d
Cd-106	0.0125	1.00	---	Cd-107	6.5 h
Cd-108	0.0089	1.10	4.29	Cd-109	462.6 d

TABLE I. (cont.)

Target Isotope	Isotope Abundance	σ_{th} (barns)	RI (barns)	Product Isotope	Product Halflife
Cd-110	0.1249	0.10	2.0	Cd-111m	48.6 m
Cd-114	0.2873	0.22	8.7	Cd-115	53.46 h
Cd-114	0.2873	0.036	3.16	Cd-115m	44.6 d
Cd-116	0.0749	0.05	—	Cd-117	2.49 h
Cd-116	0.0749	0.027	0.422	Cd-117m	3.36 h
In-113	0.0430	8.2	224.	In-114m	49.51 d
In-115	0.9570	157.	2638.	In-116m	54.15 m
Sn-112	0.0097	0.541	26.2	Sn-113	115.09 d
Sn-112	0.0097	0.35	—	Sn-113m	21.4 m
Sn-116	0.1453	0.00596	0.336	Sn-117m	13.6 d
Sn-118	0.2422	0.016	2.00	Sn-119m	293. d
Sn-122	0.0463	0.18	0.83	Sn-123	129. d
Sn-122	0.0463	0.146	0.788	Sn-123m	40.08 m
Sn-124	0.0579	0.0042	0.25	Sn-125	9.64 d
Sn-124	0.0579	0.116	6.97	Sn-125m	9.52 m
Sb-121	0.5730	6.33	209.	Sb-122	2.70 d
Sb-121	0.5730	0.055	1.80	Sb-122m	4.21 m
Sb-123	0.4270	4.08	118.	Sb-124	60.2 d
Sb-123	0.4270	0.035	0.93	Sb-124m	93.0 s
Te-120	0.00096	2.00	—	Te-121	16.78 d
Te-120	0.00096	0.34	—	Te-121m	154. d
Te-122	0.26000	2.80	—	Te-123m	119.7 d
Te-124	0.04816	0.040	7.	Te-125m	58.0 d
Te-126	0.1895	0.90	8.00	Te-127	9.35 h
Te-126	0.1895	0.135	1.04	Te-127m	109. d
Te-128	0.3169	0.20	1.60	Te-129	69.6 m
Te-128	0.3169	0.015	0.086	Te-129m	33.60 d
Te-130	0.3380	0.27	0.446	Te-131	25.0 m
Te-130	0.3380	0.02	0.0485	Te-131m	30.0 h
I-127	1.0000	4.04	100.	I-128	24.99 m
Xe-124	0.00096	106.	3600.	Xe-125	16.9 h
Xe-128	0.01919	0.36	10.17	Xe-129m	8.0 d
Xe-130	0.0408	0.42	1.17	Xe-131m	11.77 d
Xe-132	0.2689	0.385	0.8	Xe-133	5.24 d
Xe-132	0.2689	0.025	0.217	Xe-133m	2.19 d
Xe-134	0.1044	0.253	0.57	Xe-135	9.14 h
Xe-134	0.1044	0.003	0.101	Xe-135m	15.29 m
Xe-136	0.0887	0.16	0.12	Xe-137	3.82 m
Cs-133	1.0000	30.7	390.	Cs-134	2.06 y
Cs-133	1.0000	2.74	32.3	Cs-134m	2.91 h

TABLE I. (cont.)

Target Isotope	Isotope Abundance	σ_{th} (barns)	RI (barns)	Product Isotope	Product Halflife
Ba-130	0.00106	9.04	224.	Ba-131	11.8 d
Ba-130	0.00106	2.50	——	Ba-131m	14.6 m
Ba-132	0.00101	8.50	100.	Ba-133	10.52 y
Ba-132	0.00101	0.82	4.6	Ba-133m	38.9 h
Ba-134	0.02417	0.158	24.2	Ba-135m	28.7 h
Ba-136	0.07854	0.010	0.75	Ba-137m	2.55 m
Ba-138	0.71700	0.405	0.36	Ba-139	84.63 m
La-139	0.9991	9.34	11.6	La-140	40.27 h
Ce-136	0.0019	6.30	70.	Ce-137	9.0 h
Ce-136	0.0019	0.95	70.	Ce-137m	34.4 h
Ce-138	0.0025	1.10	1.20	Ce-139	137.66 d
Ce-140	0.8848	0.575	0.48	Ce-141	32.5 d
Ce-142	0.1108	0.975	1.17	Ce-143	33.0 h
Pr-141	1.0000	11.2	16.9	Pr-142	19.12 h
Nd-146	0.1719	1.45	2.90	Nd-147	10.98 d
Nd-148	0.0576	2.36	12.1	Nd-149	1.72 h
Nd-150	0.0564	0.91	11.2	Nd-151	12.44 m
Sm-144	0.0310	0.70	——	Sm-145	340. d
Sm-152	0.2670	220.	3168.	Sm-153	46.27 h
Sm-154	0.2270	7.74	33.3	Sm-155	22.3 m
Eu-151	0.4780	5900.	5564.	Eu-152	13.33 y
Eu-151	0.4780	3300.	2764.	Eu-152m	9.32 h
Eu-153	0.5220	307.	1738.	Eu-154	8.59 y
Gd-152	0.0020	1100.	3000.	Gd-153	241.6 d
Gd-158	0.2484	3.1	96.	Gd-159	18.56 h
Gd-160	0.2186	1.51	5.78	Gd-161	3.66 m
Tb-159	1.0000	23.8	426.	Tb-160	72.3 d
Dy-156	0.0006	33.	960.	Dy-157	8.1 h
Dy-158	0.0010	43.	120.	Dy-159	144.4 d
Dy-164	0.2820	2723.	517.	Dy-165	2.33 h
Dy-164	0.2820	1698.	425.	Dy-165m	1.26 m
Ho-165	1.0000	58.1	636.	Ho-166	26.8 h
Ho-165	1.0000	3.5	——	Ho-166m	1200. y
Er-170	0.1490	8.85	39.1	Er-171	7.52 h
Tm-169	1.0000	107.	1552.	Tm-170	128.6 d
Yb-168	0.0013	3470.	31000.	Yb-169	32.02 d
Yb-174	0.3180	128.	58.9	Yb-175	4.19 d
Yb-176	0.1270	3.11	7.8	Yb-177	1.88 h
Lu-175	0.9741	16.7	581.	Lu-176m	3.68 h
Lu-176	0.0260	2100.	1160.	Lu-177	6.71 d

TABLE I. (cont.)

Target Isotope	Isotope Abundance	σ_{th} (barns)	RI (barns)	Product Isotope	Product Halflife
Lu-176	0.0260	7.	3.8	Lu-177m	160.9 d
Hf-174	0.00162	549.	428.	Hf-175	70.0 d
Hf-176	0.05206	38.	700.	Hf-177m2	51.4 m
Hf-178	0.27297	53.	1039.	Hf-179m	18.68 s
Hf-179	0.13629	0.450	6.4	Hf-180m	5.52 h
Hf-180	0.35100	13.5	34.0	Hf-181	42.39 d
Ta-181	0.99988	20.4	679.	Ta-182	114.5 d
Ta-181	0.99988	0.0103	0.415	Ta-182m	15.84 m
W-180	0.0013	3.5	200.	W-181	121.2 d
W-184	0.3067	1.8	14.	W-185	75.1 d
W-186	0.2860	38.7	530.	W-187	23.9 h
Re-185	0.3740	106.	1632.	Re-186	90.64 h
Re-187	0.6260	73.2	318.	Re-188	16.98 h
Re-187	0.6260	2.05	9.4	Re-188m	18.6 m
Os-184	0.0002	3613.	1554.	Os-185	93.6 d
Os-189	0.1610	0.00026	0.013	Os-190m	9.9 m
Os-190	0.2640	3.90	7.9	Os-191	15.4 d
Os-190	0.2640	9.1	29.	Os-191m	13.1 h
Os-192	0.4100	3.12	7.30	Os-193	30.5 h
Ir-191	0.3730	924.	3750.	Ir-192	73.83 d
Ir-191	0.3730	300.	1060.	Ir-192m	1.45 m
Ir-193	0.6270	115.	1380.	Ir-194	19.15 h
Pt-190	0.0001	150.	67.	Pt-191	2.96 d
Pt-192	0.0079	2.2	—	Pt-193m	4.33 d
Pt-194	0.3290	0.09	—	Pt-195m	4.02 d
Pt-196	0.2530	0.74	8.0	Pt-197	18.3 h
Pt-196	0.2530	0.050	—	Pt-197m	94.4 m
Pt-198	0.0720	3.58	60.9	Pt-199	30.8 m
Au-197	1.0000	98.65	1550.	Au-198	2.70 d
Hg-196	0.0014	3080.	413.	Hg-197	64.1 h
Hg-196	0.0015	101.	46.	Hg-197m	23.8 h
Hg-198	0.1002	0.018	1.8	Hg-199m	42.6 m
Hg-202	0.2980	4.35	3.8	Hg-203	46.61 d
Hg-204	0.0680	0.43	0.8	Hg-205	5.20 m
Th-232	1.0000	7.26	83.7	Th-233	22.3 m
U-235	0.0072	584.	280.	FISSION PRODUCTS	
U-238	0.9927	2.75	284.	U-239	23.47 m

TABLE II. CROSS-SECTIONS AVERAGED IN A ^{235}U FISSION NEUTRON SPECTRUM

Target Isotope	Isotope Abundance	$\bar{\sigma}$ (mb)	Product Isotope	Product Halflife
		(n,p) reactions:		
Mg-24	0.7899	1.53	Na-24	14.96 h
Al-27	1.0000	4.0	Mg-27	9.46 m
Si-28	0.9223	6.4	Al-28	2.24 m
Si-29	0.0467	3.01	Al-29	6.56 m
S-32	0.9502	69.	P-32	14.28 d
Cl-37	0.2423	0.218	S-37	5.05 m
Ti-46	0.0800	12.5	Sc-46	83.81 d
Ti-47	0.0730	21.4	Sc-47	3.35 d
Ti-48	0.7380	0.303	Sc-48	43.7 h
V-51	0.9975	0.87	Ti-51	5.76 m
Cr-52	0.8379	1.09	V-52	3.75 m
Fe-54	0.0580	82.5	Mn-54	312.12 d
Fe-56	0.9172	1.07	Mn-56	2.58 h
Co-59	1.0000	1.42	Fe-59	44.5 d
Ni-58	0.6827	113.	Co-58	70.82 d
Ni-60	0.2610	2.1	Co-60	5.27 y
Cu-65	0.3083	0.48	Ni-65	2.52 h
Zn-64	0.4860	0.62	Cu-64	12.7 h
Zn-66	0.2790	0.96	Cu-66	5.10 m
		(n,α) reactions:		
Al-27	1.0000	0.725	Na-24	14.96 h
Si-30	0.0310	0.155	Mg-27	9.46 m
P-31	1.0000	1.9	Al-28	2.24 m
Mn-55	1.0000	0.11	V-52	3.75 m
Fe-54	0.0580	0.6	Cr-51	27.7 d
Co-59	1.0000	0.156	Mn-56	2.58 h
Ni-62	0.0359	0.09	Fe-59	44.5 d
Cu-63	0.6917	0.50	Co-60	5.27 y
		(n,2n) reactions:		
Mn-55	1.0000	0.258	Mn-54	312.12 d
Co-59	1.0000	0.40	Co-58	70.82 d
As-75	1.0000	0.33	As-74	17.77 d
Au-197	1.0000	2.97	Au-196	6.18 d
		(n,F) reactions:		
U-235	0.0072	1250.	FISSION PRODUCTS	
U-238	0.9927	69.	FISSION PRODUCTS	

TABLE III. RADIOACTIVE ISOTOPES ARRANGED BY ATOMIC NUMBER

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Be-7	53.29 d	477.61 *	10.39	Accelerator produced	1
O-19	26.91 s	197.14 * 1356.84	95.90 50.40	O-18(n,γ)	2
F-20	11.03 s	1633.60 *	100.00	F-19(n,γ)	3
Ne-23	37.24 s	439.85 *	32.90	Ne-22(n,γ)	5
Na-22	2.60 y	511.00 1274.53 *	179.80 99.94	Accelerator produced	4
Na-24	14.96 h	1368.60 * 2754.00	100.00 99.94	Na-23(n,γ); Mg-24(n,p); Al-27(n,α)	6
Mg-27	9.46 m	843.76 1014.43 *	71.40 28.60	Mg-26(n,γ); Al-27(n,p); Si-30(n,α)	7
Al-28	2.24 m	1778.99 *	100.00	Al-27(n,γ); Si-28(n,p); P-31(n,α)	8
Al-29	6.56 m	511.00 1273.36 *	200.00 91.30	Si-29(n,p)	9
Si-31	2.62 h	1266.20 *	0.07	Si-30(n,γ); P-31(n,p)	10
S-37	5.05 m	3103.98 *	94.00	S-36(n,γ); Cl-37(n,p)	11
Cl-38	37.24 m	1642.69 * 2167.68	31.00 42.00	Cl-37(n,γ)	12
Ar-41	1.83 h	1293.64 *	99.16	Ar-40(n,γ)	14
K-40	1.28E+09 y	1460.83 *	10.67	Natural product	13
K-42	12.36 h	1524.58 *	18.80	K-41(n,γ)	15
Ca-47	4.54 d	489.23 807.86 1297.09 *	6.51 6.51 74.00	Ca-46(n,γ)	17
Ca-49	8.72 m	3084.54 * 4072.00	92.10 7.00	Ca-48(n,γ)	19
Sc-46	83.81 d	889.28 * 1120.55	99.98 99.99	Sc-45(n,γ); Ti-46(n,p)	16
Sc-46m	18.75 s	142.53 *	62.00	Sc-45(n,γ); Ti-46(n,p)	16
Sc-47	3.35 d	159.38 *	67.90	Ti-47(n,p); Ca-46(n,γ) Precursor: Ca-47 (halflife = 4.54 d)	17

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Sc-48	43.7 h	983.52 *	100.00	Ti-48(n,p)	18
		1037.52	97.50		
		1312.10	100.00		
Ti-51	5.76 m	320.08 *	93.10	Ti-50(n,γ)	20
		928.64	6.90		
V-52	3.75 m	1434.08 *	100.00	V-51(n,γ)	21
Cr-51	27.7 d	320.08 *	10.08	Cr-50(n,γ)	20
Mn-54	312.12 d	834.84 *	99.98	Fe-54(n,p)	22
Mn-56	2.58 h	846.76	98.87	Mn-55(n,γ); Fe-56(n,p)	23
		1810.72 *	27.19		
		2113.05	14.34		
Fe-59	44.5 d	142.65	1.02	Fe-58(n,γ)	26
		192.35	3.08		
		1099.25 *	56.50		
		1291.60	43.20		
Co-56	77.7 d	846.76	99.94	Accelerator produced	23
		1037.84	14.10		
		1238.29 *	68.42		
		1771.35	15.50		
		2034.76	8.14		
		2598.46	17.39		
		3253.42	7.60		
Co-57	271.8 d	14.41	9.67	Accelerator produced	24
		122.06 *	85.94		
		136.47	10.33		
Co-58	70.82 d	810.77 *	99.45	Ni-58(n,p)	25
Co-60	5.27 y	1173.24 *	99.90	Co-59(n,γ)	27
		1332.50	99.98		
Co-60m	10.47 m	58.60 *	2.04	Co-59(n,γ)	27
		1332.50	0.24		
Ni-65	2.52 h	366.27	4.61	Ni-64(n,γ)	29
		1115.55	14.83		
		1481.84 *	23.50		
Cu-64	12.7 h	511.00	35.80	Cu-63(n,γ)	28
		1345.77 *	0.48		
Cu-66	5.10 m	833.00	0.17	Cu-65(n,γ)	30
		1039.20 *	7.40		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Cu-67	61.92 h	91.27	7.00	Zn-67(n,p); Cu-65(2n,γ)	31
		93.31	16.10		
		184.58 *	48.70		
Zn-65	243.9 d	1115.55 *	50.70	Zn-64(n,γ)	29
Zn-69m	13.76 h	438.63 *	94.80	Zn-68(n,γ)	32
Zn-71m	3.94 h	386.28 *	93.00	Zn-70(n,γ)	33
		487.34	62.00		
		511.55	28.50		
		596.07	27.90		
		620.19	57.00		
Ga-72	14.1 h	601.02	5.56	Ga-71(n,γ)	34
		630.02 *	24.90		
		834.09	95.63		
		894.34	9.88		
		1050.88	6.96		
		1861.12	5.25		
		2201.60	25.90		
		2491.12	7.67		
		2507.86	12.78		
Ge-75	82.78 m	264.66 *	11.30	Ge-74(n,γ)	36
Ge-77	11.3 h	211.02	29.20	Ge-76(n,γ)	38
		215.48	27.10		
		264.42 *	51.00		
		367.38	13.30		
		416.31	20.60		
		557.98	15.20		
		631.79	6.59		
		714.33	6.77		
Ge-77m	52.9 s	159.71	11.30	Ge-76(n,γ)	38
		215.48 *	20.90		
As-74	17.77 d	511.00	59.00	As-75(n,2n)	35
		595.83 *	59.40		
		634.78	15.48		
As-76	26.32 h	559.10 *	44.60	As-75(n,γ)	37
		563.23	1.20		
		657.05	6.17		
		1212.92	1.44		
		1216.08	3.42		
		1228.52	1.22		
As-77	38.83 h	238.97 *	1.60	Ge-76(n,γ); As-75(2n,γ) Precursor: Ge-77 (halflife = 11.3 h)	38

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Se-75	119.77 d	121.12	17.30	Se-74(n,γ)	36
		136.01	59.00		
		264.66 *	59.20		
		279.54	25.20		
		400.66	11.56		
Se-77m	17.45 s	161.93 *	52.40	Se-76(n,γ)	38
Se-79m	3.91 m	95.73 *	9.50	Se-78(n,γ)	39
Se-81	18.45 m	275.93 *	0.51	Se-80(n,γ)	41
		290.04	0.38		
Se-81m	57.25 m	102.99 *	9.80	Se-80(n,γ)	41
Se-83	22.3 m	225.18	32.64	Se-82(n,γ)	43
		356.70 *	69.90		
		510.06	42.64		
		718.03	14.96		
		799.04	14.82		
		836.52	13.28		
Br-80	17.68 m	511.00	5.00	Br-79(n,γ)	40
		616.30 *	6.70		
Br-80m	4.42 h	37.05 *	39.10	Br-79(n,γ)	40
Br-82	35.3 h	554.35	70.76	Br-81(n,γ)	42
		619.11	43.44		
		698.37	28.49		
		776.52 *	83.54		
		827.83	24.03		
		1044.08	27.23		
		1317.47	26.48		
		1474.88	16.32		
Br-82m	6.13 m	776.50 *	0.60	Br-81(n,γ)	42
Kr-85m	4.48 h	151.18 *	75.10	Kr-84(n,γ); Fission	44
		304.86	13.70		
Kr-87	76.31 m	402.58 *	49.60	Kr-86(n,γ); Fission	46
		845.44	7.34		
		2554.80	9.20		
		2558.10	3.92		
Kr-88	2.84 h	196.34 *	26.00	Fission	47
		834.86	13.00		
		1529.77	10.93		
		2195.80	13.20		
		2392.14	34.60		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Rb-86	18.66 d	1076.60 *	8.78	Rb-85(n,γ)	45
Rb-86m	1.02 m	556.07 *	98.19	Rb-85(n,γ)	45
Rb-88	17.8 m	898.07 *	14.10	Rb-87(n,γ); Fission Precursor: Kr-88 (halflife = 2.84 h)	47
		1836.08	21.40		
Sr-85	64.84 d	514.00 *	99.27	Sr-84(n,γ)	44
Sr-87m	2.81 h	388.40 *	82.26	Sr-86(n,γ)	46
Sr-89	50.55 d	909.15 *	0.10	Sr-88(n,γ); Fission	48
Y-88	106.61 d	898.07	92.70	Accelerator produced	47
		1836.08 *	99.35		
Y-90m	3.19 h	202.47 *	96.60	Y-89(n,γ)	49
		479.49	91.00		
Zr-95	64.02 d	724.20	44.15	Zr-94(n,γ); Fission	51
		756.73 *	54.50		
Zr-97	16.74 h	743.33 *	97.90	Zr-96(n,γ); Fission	52
Nb-94m	6.26 m	871.10 *	0.50	Nb-93(n,γ)	50
Nb-95	34.97 d	765.79 *	99.79	Zr-94(n,γ); Fission Precursor: Zr-95 (halflife = 64.02 d)	51
Nb-97	72.1 m	657.92 *	98.39	Zr-96(n,γ); Fission Precursor: Zr-97 (halflife = 16.74 h)	52
Mo-99	65.94 h	140.51	90.70	Mo-98(n,γ); Fission	53
		181.06	6.08		
		739.58 *	12.13		
		778.00	4.34		
Mo-101	14.6 m	191.92	18.80	Mo-100(n,γ); Fission	54
		505.94	11.84		
		590.90 *	22.00		
		1012.48	12.78		
Tc-99m	6.01 h	140.51 *	89.06	Mo-98(n,γ); Fission Precursor: Mo-99 (halflife = 65.94 h)	53
Tc-101	14.2 m	306.83 *	88.00	Mo-100(n,γ); Fission Precursor: Mo-101 (halflife = 14.6 m)	54
		545.05	5.99		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Ru-97	69.12 h	215.68 *	86.17	Ru-96(n,γ)	52
		324.53	10.24		
Ru-103	39.26 d	497.08 *	90.90	Ru-102(n,γ); Fission	55
		610.33	5.73		
Ru-105	4.44 h	316.44	11.12	Ru-104(n,γ); Fission	57
		469.37	17.55		
		676.36	15.66		
		724.30 *	47.30		
Rh-104m	4.34 m	51.42 *	48.20	Rh-103(n,γ)	56
		77.53	2.08		
		97.11	2.99		
		555.81 *	2.00		
Rh-105	35.36 h	306.10	5.10	Ru-104(n,γ); Fission	57
		318.90 *	19.10	Precursor: Ru-105	
				(halflife = 4.44 h)	
Pd-109	13.7 h	88.03 *	3.61	Pd-108(n,γ)	59
Pd-109m	4.69 m	188.90 *	55.30	Pd-108(n,γ)	59
Ag-108	2.37 m	433.94	0.50	Ag-107(n,γ)	58
		618.86	0.26		
		632.98 *	1.76		
Ag-110	24.6 s	657.76 *	4.50	Ag-109(n,γ)	60
Ag-110m	249.76 d	657.76 *	94.64	Ag-109(n,γ)	60
		677.62	10.35		
		706.68	16.44		
		763.94	22.29		
		884.69	72.68		
		937.49	34.36		
		1384.30	24.28		
		1505.04	13.04		
Cd-109	462.6 d	88.03 *	3.61	Cd-108(n,γ)	59
Cd-111m	48.6 m	150.82 *	29.10	Cd-110(n,γ)	61
		245.38	94.00		
Cd-115	53.46 h	336.26	50.10	Cd-114(n,γ)	64
		492.36	8.03		
		527.91 *	27.50		
Cd-115m	44.6 d	484.41	0.29	Cd-114(n,γ)	64
		933.85 *	2.00		
		1290.60	0.89		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
In-114m	49.51 d	190.27 *	15.40	In-113(n,γ)	63
		558.43	4.39		
		725.24	4.33		
In-115m	4.49 h	336.26 *	45.80	Cd-114(n,γ) Precursor: Cd-115m (halflife = 53.46 h)	64
In-116m	54.15 m	416.86	29.20	In-115(n,γ)	65
		818.74	11.48		
		1097.29 *	56.21		
		1293.54	84.40		
		1507.40	10.00		
		2112.32	15.53		
Sn-113	115.09 d	255.07	1.82	Sn-112(n,γ)	62
		391.69 *	64.00		
Sn-117m	13.6 d	156.02	2.11	Sn-116(n,γ)	66
		158.56 *	86.40		
Sn-119m	293. d	23.87 *	16.10	Sn-118(n,γ)	67
Sn-123m	40.08 m	160.32 *	85.60	Sn-122(n,γ)	70
Sn-125	9.64 d	822.48	3.99	Sn-124(n,γ)	72
		915.55	3.85		
		1067.10 *	9.04		
		1089.19	4.28		
Sn-125m	9.52 m	332.10 *	99.57	Sn-124(n,γ)	72
Sb-122	2.70 d	564.24 *	69.30	Sb-121(n,γ)	69
		692.65	3.78		
Sb-122m	4.21 m	61.41 *	53.65	Sb-121(n,γ)	69
		76.06	18.50		
Sb-124	60.2 d	602.73	97.80	Sb-123(n,γ)	71
		645.86	7.38		
		722.79	10.76		
		1368.16	2.62		
		1690.98 *	47.34		
		2090.94	5.58		
Sb-124m	93. s	498.40	24.50	Sb-123(n,γ)	71
		602.73	25.00		
		645.86 *	25.00		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Sb-125	2.73 y	176.33	6.79	Sn-124(n,γ); Sb-123(2n,γ);	72
		427.89 *	29.44	Fission	
		463.38	10.45	Precursor: Sn-125	
		600.56	17.78	(halflife = 9.64 d)	
		606.64	5.02		
		635.90	11.32		
Te-121	16.78 d	507.59	17.67	Te-120(n,γ)	68
		573.14 *	80.30		
Te-123m	119.70 d	158.99 *	84.00	Te-122(n,γ)	70
Te-129	69.6 m	459.60 *	7.70	Te-128(n,γ); Fission	74
		487.39	1.42		
Te-131	25.0 m	149.72 *	68.90	Te-130(n,γ); Fission	75
		452.33	18.20	Precursor: Te-131m	
				(halflife = 30.0 h)	
Te-131m	30.0 h	773.68 *	38.10	Te-130(n,γ); Fission	75
		793.77	13.80		
		852.24	20.60		
		1125.48	11.41		
Te-132	78.2 h	49.82	14.40	Fission	76
		228.26 *	88.20		
I-125	60.14 d	35.49 *	6.66	Xe-124(n,γ)	72
				Precursor: Xe-125	
				(halflife = 16.9 h)	
I-128	24.99 m	442.90 *	16.90	I-127(n,γ)	73
		526.56	1.59		
I-131	8.04 d	80.19	2.62	Fission	75
		284.30	6.06	Precursor: Te-131	
		364.48 *	81.20	(halflife = 24.99 m)	
		636.98	7.27		
I-132	2.28 h	522.68	16.10	Fission	76
		630.27	13.80	Precursor: Te-132	
		667.73 *	98.70	(halflife = 78.2 h)	
		772.68	76.20		
		954.62	18.10		
I-133	20.8 h	529.87 *	87.00	Fission	77
I-134	52.6 m	847.03	95.40	Fission	78
		884.09 *	64.87		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
I-135	6.57 h	526.56	13.30	Fission	79
		546.56	7.20		
		836.80	6.73		
		1038.76	8.01		
		1131.51	22.74		
		1260.42 *	28.90		
		1457.56	8.73		
		1678.08	9.62		
		1791.22	7.77		
Xe-125	16.9 h	188.43 *	54.90	Xe-124(n,γ)	72
		243.40	28.82		
Xe-131m	11.77 d	163.94 *	1.96	Xe-130(n,γ); Fission	75
Xe-133	5.24 d	81.00 *	38.00	Xe-132(n,γ); Fission	77
Xe-133m	2.19 d	233.22 *	10.00	Xe-132(n,γ); Fission	77
Xe-135	9.14 h	249.79 *	90.20	Xe-134(n,γ); Fission	79
Xe-135m	15.29 m	526.56 *	92.00	Xe-134(n,γ); Fission Precursor: I-135 (halflife = 6.57 h)	79
Xe-137	3.82 m	455.49 *	31.20	Xe-136(n,γ); Fission	81
Xe-138	14.08 m	258.41 *	31.50	Fission	82
		434.56	20.32		
		1768.26	16.73		
		2015.82	12.25		
Cs-134	2.06 y	563.23	8.38	Cs-133(n,γ)	78
		569.32	15.43		
		604.70	97.56		
		795.85 *	85.44		
		801.93	8.73		
		1365.15	3.04		
Cs-134m	2.91 h	127.50 *	12.70	Cs-133(n,γ)	78
Cs-136	13.16 d	66.91	12.49	Fission	80
		176.55	13.59		
		273.65	12.69		
		340.55	42.17		
		818.52	99.70		
		1048.07 *	79.76		
		1235.36	20.04		
Cs-137	30.17 y	661.66 *	85.21	Fission	81

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Cs-138	32.2 m	462.80	30.75	Fission	82
		547.00	10.76	Precursor: Xe-138	
		1009.78	29.83	(halflife = 14.17 m)	
		1435.86 *	76.30		
		2218.00	15.18		
Ba-131	11.8 d	123.77	29.10	Ba-130(n,γ)	75
		216.05	20.00		
		373.19	13.30		
		496.26 *	44.00		
Ba-131m	14.6 m	108.12 *	55.00	Ba-130(n,γ)	75
Ba-133	10.52 y	53.16	2.20	Ba-132(n,γ)	77
		79.62	2.62		
		81.00	34.06		
		276.40	7.16		
		302.85	18.33		
		356.02 *	62.05		
		383.85	8.94		
Ba-133m	38.9 h	275.93 *	17.50	Ba-132(n,γ)	77
Ba-135m	28.7 h	268.22 *	15.60	Ba-134(n,γ)	79
Ba-137m	2.55 m	661.66 *	90.10	Ba-136(n,γ); Fission	81
Ba-139	84.63 m	165.85 *	22.05	Ba-138(n,γ); Fission	83
Ba-140	12.75 d	162.67	6.21	Fission	85
		304.87	4.30		
		423.73	3.12		
		437.59	1.90		
		537.31 *	24.39		
La-140	40.27 h	328.76	20.61	La-139(n,γ); Fission	85
		432.49	2.91	Precursor: Ba-140	
		487.02	44.27	(halflife = 12.75 d)	
		751.64	4.24		
		815.77	22.90		
		867.85	5.59		
		919.55	2.70		
		925.19	6.93		
		1596.21 *	95.40		
Ce-137	9.0 h	436.59	0.33	Ce-136(n,γ)	81
		447.15 *	2.24		
Ce-137m	34.4 h	254.29 *	11.04	Ce-136(n,γ)	81
Ce-139	137.66 d	165.85 *	79.90	Ce-138(n,γ)	83

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Ce-141	32.5 d	145.44 *	48.20	Ce-140(n,γ); Fission	85
Ce-143	33.0 h	57.36	11.56	Ce-142(n,γ); Fission	87
		293.27 *	42.80		
Ce-144	284.9 d	133.54 *	11.09	Fission	88
Pr-142	19.12 h	1575.60 *	3.70	Pr-141(n,γ)	86
Nd-147	10.98 d	91.10	28.00	Nd-146(n,γ); Fission	90
		319.41	1.95		
		531.01 *	13.10		
Nd-149	1.72 h	114.31	19.04	Nd-148(n,γ); Fission	91
		211.31 *	25.90		
		270.17	10.72		
Nd-151	12.44 m	116.84	46.21	Nd-150(n,γ); Fission	137
		255.72	17.50		
		1180.86 *	15.77		
Pm-149	53.08 h	285.95 *	3.10	Nd-148(n,γ); Fission Precursor: Nd-149 (halflife = 1.72 h)	91
Pm-151	28.4 h	340.06 *	22.00	Nd-150(n,γ); Fission Precursor: Nd-151 (halflife = 12.44 m)	92
Sm-145	340. d	61.22 *	12.70	Sm-144(n,γ)	89
Sm-153	46.27 h	69.67 *	4.85	Sm-152(n,γ); Fission	138
		103.18	28.82		
Sm-155	22.3 m	104.35 *	74.60	Sm-154(n,γ); Fission	96
		141.44	2.01		
		245.79	3.73		
Eu-152	13.33 y	121.78	28.37	Eu-151(n,γ)	93
		244.69	7.51		
		344.29	26.58		
		411.12	2.23		
		443.89	3.12		
		778.92	12.96		
		867.38	4.16		
		964.11	14.62		
		1085.89	10.16		
		1112.08	13.50		
		1408.00 *	20.85		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Eu-152m	9.32 h	121.78	7.20	Eu-151(n,γ)	93
		344.29	2.44		
		841.59 *	14.60		
		963.36	12.00		
Eu-154	8.59 y	123.07	40.42	Eu-153(n,γ)	95
		247.93	6.84		
		591.76	4.92		
		723.30	19.98		
		756.86	4.50		
		873.20	12.09		
		996.30	10.34		
		1004.76	17.90		
		1274.51 *	34.40		
Eu-155	4.68 y	86.54	32.80	Eu-153(2n,γ)	96
		105.31 *	21.84		
Gd-153	241.6 d	69.67	2.32	Gd-152(n,γ)	94
		97.43 *	27.60		
		103.18	19.60		
Gd-159	18.56 h	58.00	2.27	Gd-158(n,γ)	97
		363.56 *	10.80		
Gd-161	3.66 m	102.32	13.87	Gd-160(n,γ)	99
		314.92	22.69		
		360.94 *	60.05		
Tb-160	72.3 d	86.79	12.76	Tb-159(n,γ)	98
		197.04	5.61		
		215.65	4.41		
		298.58	28.89		
		879.38 *	32.90		
		962.32	10.53		
		966.17	27.18		
		1177.96	16.22		
		1271.88	8.13		
Tb-161	6.90 d	48.92	16.69	Tb-159(2n,γ); Gd-160(n,γ)	99
		74.58 *	10.70	Precursor: Gd-161	
				(halflife = 3.66 m)	
Dy-159	144.4 d	58.00 *	2.22	Dy-158(n,γ)	97
Dy-165	2.33 h	94.70 *	3.58	Dy-164(n,γ)	100
		279.76	0.50		
		361.67	0.84		
		633.43	0.57		
		715.33	0.53		
Dy-166	81.6 h	82.47 *	13.80	Dy-164(2n,γ)	101

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Ho-166	26.8 h	80.57 *	6.33	Ho-165(n,γ)	101
		1379.32	0.93		
Ho-166m	1200. y	80.57	12.50	Ho-165(n,γ)	101
		184.10	73.90		
		280.45	29.70		
		410.93	11.30		
		529.80	9.80		
		711.68 *	55.90		
		752.27	12.50		
		810.28	59.70		
		830.57	10.00		
Er-171	7.52 h	111.65	20.50	Er-170(n,γ)	104
		295.90	28.90		
		308.29 *	64.40		
Er-172	49.3 h	407.34 *	43.00	Er-170(2n,γ)	105
		610.06	45.20		
Tm-170	128.6 d	84.30 *	3.26	Tm-169(n,γ)	103
Tm-171	1.92 y	66.73 *	0.14	Tm-169(2n,γ); Er-170(n,γ)	104
				Precursor: Er-171	
				(halflife = 7.52 h)	
Tm-172	63.6 h	78.79	6.50	Er-170(2n,γ)	105
		1093.67 *	6.00	Precursor: Er-172	
		1387.22	5.47	(halflife = 49.3 h)	
		1466.01	4.47		
		1529.82	5.10		
		1608.61	4.05		
Yb-169	32.02 d	63.12	43.74	Yb-168(n,γ)	102
		109.78	17.36		
		130.52	11.11		
		177.21 *	21.45		
		197.96	34.94		
		307.74	10.80		
Yb-175	4.19 d	113.81	1.91	Yb-174(n,γ)	106
		282.52	3.05		
		396.33 *	6.50		
Yb-177	1.88 h	121.62	3.40	Yb-176(n,γ)	107
		138.61	1.33		
		150.40 *	20.00		
		1080.25	5.50		
		1241.31	3.35		
Lu-177	6.71 d	112.95	6.40	Lu-176(n,γ)	107
		208.36 *	11.00		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Lu-177m	160.9 d	105.35	11.50	Lu-176(n,γ)	107
		112.95	21.50	Most gamma rays are	
		128.50	15.20	from daughter Hf-177m1	
		153.29	17.80		
		174.40	12.70		
		204.10	14.40		
		208.36 *	60.90		
		228.47	37.20		
		281.79	14.10		
		319.03	11.00		
		327.69	17.40		
		378.50	27.70		
		413.66	17.50		
		418.53	20.10		
Hf-175	70.0 d	343.40 *	87.00	Hf-174(n,γ)	106
Hf-180m	5.52 h	57.54	48.52	Hf-179(n,γ)	108
		215.26	81.66		
		332.30 *	94.40		
		443.19	83.26		
Hf-181	42.39 d	133.03	35.87	Hf-180(n,γ)	109
		136.28	5.80		
		345.94	15.07		
		482.18 *	80.60		
Ta-182	114.5 d	67.75	42.30	Ta-181(n,γ)	110
		84.68	2.74		
		100.11	14.10		
		113.67	1.90		
		116.42	0.44		
		152.43	7.17		
		156.39	2.72		
		179.39	3.18		
		198.35	1.51		
		222.11	7.60		
		229.32	3.64		
		264.08	3.64		
		1121.30	35.00		
		1189.05	16.30		
		1221.41 *	27.10		
		1231.02	11.50		
		1257.42	1.49		
		1289.16	1.35		
Ta-182m	15.84 m	146.80	33.00	Ta-181(n,γ)	110
		171.60 *	43.30		
		184.90	21.70		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Ta-183	5.10 d	99.10	11.50	Ta-181(2n,γ)	111
		107.90	10.50		
		161.30	10.20		
		162.30	5.50		
		209.90	4.30		
		244.30	8.70		
		246.10 *	25.90		
		354.00	11.20		
W-181	121.2 d	136.28	0.03	W-180(n,γ)	109
		152.32 *	0.08		
W-185	75.1 d	125.36 *	0.02	W-184(n,γ)	112
W-187	23.9 h	72.00	10.77	W-186(n,γ)	114
		134.25	8.56		
		479.57 *	21.13		
		551.52	4.92		
		618.28	6.07		
		685.74	26.39		
		772.91	3.98		
W-188	69.4 d	227.09	0.22	W-186(2n,γ)	115
		290.67 *	0.40		
Re-186	90.64 h	122.43	0.66	Re-185(n,γ)	113
		137.14 *	8.50		
Re-188	16.98 h	155.06 *	14.90	Re-187(n,γ); W-186(2n,γ) Precursor: W-188 (halflife = 69.4 d)	115
Re-188m	18.6 m	63.58	21.60	Re-187(n,γ); W-186(2n,γ) Precursor: W-188 (halflife = 69.4 d)	115
		92.40	5.20		
		105.90 *	10.80		
Os-185	93.6 d	646.12 *	81.00	Os-184(n,γ)	112
Os-190m	9.9 m	186.71	70.20	Os-189(n,γ)	116
		361.13 *	94.90		
		502.54	97.80		
		616.09	98.60		
Os-191	15.4 d	129.43 *	25.70	Os-190(n,γ)	117
Os-193	30.5 h	73.01	3.24	Os-192(n,γ)	119
		138.89	4.27		
		280.43	1.24		
		321.56	1.28		
		387.46	1.26		
		460.49 *	3.95		
		557.36	1.30		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Ir-192	73.83 d	295.96	28.73	Ir-191(n,γ)	118
		308.46	29.75		
		316.51 *	83.00		
		468.07	47.72		
Ir-192m	1.45 m	58.00 *	0.04	Ir-191(n,γ)	118
Ir-194	19.15 h	293.54	2.52	Ir-193(n,γ)	120
		328.46 *	13.00		
Ir-194m	171. d	328.46	92.80	Ir-193(n,γ)	120
		338.80 *	55.10		
		390.80	35.10		
		482.66	96.90		
		562.40	69.90		
		600.50	62.30		
		687.80	59.10		
Pt-191	2.96 d	82.43	4.90	Pt-190(n,γ)	117
		359.93	6.00		
		409.48	8.00		
		538.91 *	13.70		
Pt-195m	4.02 d	30.88	2.28	Pt-194(n,γ)	121
		98.88 *	11.40		
		129.77	2.80		
Pt-197	18.3 h	77.34 *	17.10	Pt-196(n,γ)	123
		191.36	3.70		
Pt-197m	94.4 m	279.11	2.30	Pt-196(n,γ)	123
		346.81 *	11.10		
Pt-199	30.8 m	185.78	3.26	Pt-198(n,γ)	125
		191.69	2.38		
		246.44	2.16		
		317.06	4.87		
		493.74	5.70		
		542.96 *	14.80		
Au-196	6.18 d	332.87	22.85	Au-197(n,2n)	122
		355.58 *	86.90		
		425.64	7.20		
Au-198	2.70 d	411.80 *	95.50	Au-197(n,γ)	124
		675.89	0.80		
Au-199	3.14 d	158.38 *	36.90	Au-197(2n,γ); Pt-198(n,γ)	125
		208.20	8.37	Precursor: Pt-199	
				(halflife = 30.8 m)	
Hg-197	64.1 h	77.34 *	18.00	Hg-196(n,γ)	123

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Hg-197m	23.8 h	133.96 *	34.10	Hg-196(n,γ)	123
		279.11	4.90		
Hg-199m	42.6 m	158.38 *	53.00	Hg-198(n,γ)	125
		374.10	13.90		
Hg-203	46.61 d	279.20 *	81.46	Hg-202(n,γ)	126
Hg-205	5.20 m	203.75 *	2.20	Hg-204(n,γ)	127
Tl-208	3.05 m	277.36	6.31	Precursor: Nat. Th-232	128
		510.77	22.61	(halflife = 1.4E10 y)	
		583.19	84.48		
		860.56	12.42		
		2614.53 *	99.16		
Pb-212	10.64 h	238.63 *	53.65	Precursor: Nat. Th-232	129
		300.09	3.34	(halflife = 1.4E10 y)	
Pb-214	26.8 m	241.92	7.46	Precursor: Nat. U-238	130
		295.09	19.20	(halflife = 4.5E09 y)	
		351.87 *	37.10		
Bi-212	60.55 m	727.25 *	11.80	Precursor: Nat. Th-232	129
		785.51	2.00	(halflife = 1.4E10 y)	
		1620.66	2.80		
Bi-214	19.9 m	609.31 *	46.10	Precursor: Nat. U-238	130
		768.35	4.88	(halflife = 4.5E09 y)	
		934.04	3.16		
		1120.27	15.00		
		1238.11	5.92		
		1377.66	4.02		
		1729.58	3.05		
		1764.49	15.90		
		2204.09	4.99		
Ra-226	1600. y	186.10 *	3.50	Precursor: Nat. U-238	131
				(halflife = 4.5E09 y)	
Ac-228	6.13 h	129.07	2.45	Precursor: Nat. Th-232	132
		209.25	3.88	(halflife = 1.4E10 y)	
		270.24	3.43		
		328.00	3.06		
		338.32	11.25		
		409.46	1.94		
		463.01	4.44		
		794.95	4.34		
		911.21 *	26.60		
		964.77	5.11		
		968.97	16.17		
		1588.21	3.27		

TABLE III. (cont.)

Isotope	Halflife	Energy (keV)	Abundance (%)	Production Modes	Ref.
Th-233	22.3 m	29.38	2.60	Th-232(n,γ)	133
		86.53	2.60		
		94.72	0.90		
		459.31 *	1.40		
		669.78	0.68		
Pa-233	27.0 d	75.34	1.17	Th-232(n,γ)	133
		86.65	1.76	Precursor: Th-233	
		300.18	6.20	(halflife = 22.3 m)	
		312.01 *	36.00		
		340.59	4.20		
		398.66	1.19		
		415.93	1.51		
U-235	7.10E+08 y	109.14	1.50	Natural product	134
		143.76	10.50		
		163.35	4.70		
		185.72 *	54.00		
		205.31	4.70		
U-239	23.47 m	45.53	4.45	U-238(n,γ)	135
		74.66 *	50.00		
Np-239	2.36 d	106.12	22.86	U-238(n,γ)	135
		209.75	3.27	Precursor: U-239	
		228.18	10.79	(halflife = 23.47 m)	
		277.60 *	14.20		
		334.31	2.05		
Am-241	432.2 y	59.54 *	35.70	Reactor produced	136

TABLE IV. GAMMA RAYS ARRANGED BY ENERGY ($t_{1/2}$ < 1 day)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
29.4	Th-233	22.3 m	459.3	94.7	86.5
37.1	Br-80m	4.42 h	—	—	—
45.5	U-239	23.47 m	74.7	—	—
51.4	Rh-104m	4.34 m	97.1	77.5	555.8
57.5	Hf-180m	5.52 h	332.3	443.2	215.3
58.0	Gd-159	18.56 h	363.6	—	—
58.0	Ir-192m	1.45 m	—	—	—
58.6	Co-60m	10.47 m	1332.5	—	—
61.4	Sb-122m	4.21 m	76.1	—	—
63.6	Re-188m	18.6 m	105.9	92.4	—
72.0	W-187	23.9 h	685.7	479.6	134.2
74.7	U-239	23.47 m	45.5	—	—
76.1	Sb-122m	4.21 m	61.4	—	—
77.3	Pt-197	18.3 h	191.4	—	—
77.5	Rh-104m	4.34 m	51.4	97.1	555.8
86.5	Th-233	22.3 m	459.3	94.7	669.8
88.0	Pd-109	13.7 h	—	—	—
92.4	Re-188m	18.6 m	105.9	63.6	—
94.7	Dy-165	2.33 h	361.7	279.8	633.4
94.7	Th-233	22.3 m	459.3	86.5	669.8
95.7	Se-79m	3.91 m	—	—	—
97.1	Rh-104m	4.34 m	51.4	77.5	555.8
102.3	Gd-161	3.66 m	360.9	314.9	—
103.0	Se-81m	57.25 m	—	—	—
104.4	Sm-155	22.3 m	245.8	141.4	—
105.9	Re-188m	18.6 m	63.6	92.4	—
108.1	Ba-131m	14.6 m	—	—	—
111.7	Er-171	7.52 h	308.3	295.9	—
114.3	Nd-149	1.72 h	211.3	270.2	—
116.8	Nd-151	12.44 m	1180.9	255.7	—
121.6	Yb-177	1.88 h	150.4	1080.3	1241.3
121.8	Eu-152m	9.32 h	841.6	963.4	344.3
127.5	Cs-134m	2.91 h	—	—	—
134.0	Hg-197m	23.8 h	279.1	—	—
134.2	W-187	23.9 h	685.7	479.6	772.9
138.6	Yb-177	1.88 h	150.4	1080.3	1241.3
140.5	Tc-99m	6.01 h	—	—	—
141.4	Sm-155	22.3 m	104.4	245.8	—
142.5	Sc-46m	18.75 s	—	—	—
146.8	Ta-182m	15.84 m	171.6	184.9	—

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
149.7	Te-131	25.0 m	452.3	-----	-----
150.4	Yb-177	1.88 h	1080.3	1241.3	138.6
150.8	Cd-111m	48.6 m	245.4	-----	-----
151.2	Kr-85m	4.48 h	304.9	-----	-----
155.1	Re-188	16.98 h	-----	-----	-----
158.4	Hg-199m	42.6 m	374.1	-----	-----
159.7	Ge-77m	52.9 s	215.5	-----	-----
160.3	Sn-123m	40.08 m	-----	-----	-----
161.9	Se-77m	17.45 s	-----	-----	-----
165.9	Ba-139	84.63 m	-----	-----	-----
165.9	Kr-88	2.84 h	196.3	2392.1	1529.8
171.6	Ta-182m	15.84 m	146.8	184.9	-----
184.9	Ta-182m	15.84 m	171.6	146.8	-----
185.8	Pt-199	30.8 m	543.0	493.7	317.1
186.7	Os-190m	9.9 m	361.1	502.5	616.1
188.4	Xe-125	16.9 h	243.4	-----	-----
188.9	Pd-109m	4.69 m	-----	-----	-----
191.4	Pt-197	18.3 h	77.3	-----	-----
191.7	Pt-199	30.8 m	543.0	493.7	317.1
191.9	Mo-101	14.6 m	590.9	505.9	1012.5
196.3	Kr-88	2.84 h	2392.1	1529.8	2195.8
197.1	O-19	26.91 s	1356.8	-----	-----
202.5	Y-90m	3.19 h	479.5	-----	-----
203.8	Hg-205	5.20 m	-----	-----	-----
211.0	Ge-77	11.3 h	264.4	215.5	416.3
211.3	Nd-149	1.72 h	270.2	114.3	-----
215.3	Hf-180m	5.52 h	332.3	443.2	57.5
215.5	Ge-77	11.3 h	264.4	211.0	416.3
215.5	Ge-77m	52.9 s	159.7	-----	-----
225.2	Se-83	22.3 m	356.7	718.0	799.0
243.4	Xe-125	16.9 h	188.4	-----	-----
245.4	Cd-111m	48.6 m	150.8	-----	-----
245.8	Sm-155	22.3 m	104.3	141.4	-----
246.4	Pt-199	30.8 m	543.0	493.7	317.1
249.8	Xe-135	9.14 h	-----	-----	-----
255.7	Nd-151	12.44 m	1180.9	116.8	-----
258.4	Xe-138	14.08 m	434.6	1768.3	2015.8
264.4	Ge-77	11.3 h	211.0	215.5	416.3
264.7	Ge-75	82.78 m	-----	-----	-----
270.2	Nd-149	1.72 h	211.3	114.3	-----

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
275.9	Se-81	18.45 m	290.0	-----	-----
279.1	Hg-197m	23.8 h	134.0	-----	-----
279.1	Pt-197m	94.4 m	346.8	-----	-----
279.8	Dy-165	2.33 h	94.7	361.7	633.4
290.0	Se-81	18.45 m	275.9	-----	-----
293.5	Ir-194	19.15 h	328.5	-----	-----
295.9	Er-171	7.52 h	308.3	111.7	-----
304.9	Kr-85m	4.48 h	151.2	-----	-----
306.8	Tc-101	14.2 m	545.0	-----	-----
308.3	Er-171	7.52 h	295.9	111.7	-----
314.9	Gd-161	3.66 m	360.9	102.3	-----
316.4	Ru-105	4.44 h	724.3	469.4	676.4
317.1	Pt-199	30.8 m	543.0	493.7	246.4
320.1	Ti-51	5.76 m	928.6	-----	-----
328.5	Ir-194	19.15 h	293.5	-----	-----
332.1	Sn-125m	9.52 m	-----	-----	-----
332.3	Hf-180m	5.52 h	443.2	215.3	57.5
336.3	In-115m	4.49 h	-----	-----	-----
344.3	Eu-152m	9.32 h	841.6	963.4	121.8
346.8	Pt-197m	94.4 m	279.1	-----	-----
356.7	Se-83	22.3 m	225.2	718.0	799.0
360.9	Gd-161	3.66 m	314.9	102.3	-----
361.1	Os-190m	9.9 m	502.5	616.1	186.7
361.7	Dy-165	2.33 h	94.7	279.8	633.4
363.6	Gd-159	18.56 h	58.0	-----	-----
366.3	Ni-65	2.52 h	1481.8	1115.6	-----
367.4	Ge-77	11.3 h	264.4	211.0	215.5
374.1	Hg-199m	42.6 m	158.4	-----	-----
386.3	Zn-71m	3.94 h	487.3	620.2	596.1
388.4	Sr-87m	2.81 h	-----	-----	-----
402.6	Kr-87	76.31 m	845.4	2554.8	2558.1
416.3	Ge-77	11.3 h	264.4	211.0	215.5
416.9	In-116m	54.15 m	1097.3	1293.5	818.7
433.9	Ag-108	2.37 m	633.0	618.9	-----
434.6	Xe-138	14.08 m	258.4	1768.3	2015.8
436.6	Ce-137	9.0 h	447.2	-----	-----
438.6	Zn-69m	13.76 h	-----	-----	-----
439.9	Ne-23	37.24 s	-----	-----	-----
442.9	I-128	24.99 m	526.6	-----	-----
443.2	Hf-180m	5.52 h	332.3	215.3	57.5

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
447.2	Ce-137	9.0 h	436.6	——	——
452.3	Te-131	25.0 m	149.7	——	——
455.5	Xe-137	3.82 m	——	——	——
459.3	Th-233	22.3 m	94.7	86.5	669.8
459.6	Te-129	69.6 m	487.4	——	——
462.8	Cs-138	32.2 m	1435.9	1009.8	547.0
469.4	Ru-105	4.44 h	724.3	316.4	676.4
479.5	Y-90m	3.19 h	202.5	——	——
479.6	W-187	23.9 h	685.7	134.2	772.9
487.3	Zn-71m	3.94 h	386.3	620.2	596.1
487.4	Te-129	69.6 m	459.6	——	——
493.7	Pt-199	30.8 m	543.0	317.1	246.4
498.4	Sb-124m	93.0 s	645.9	602.7	——
502.5	Os-190m	9.9 m	361.1	616.1	186.7
505.9	Mo-101	14.6 m	590.9	191.9	1012.5
510.1	Se-83	22.3 m	356.7	225.2	718.0
511.6	Zn-71m	3.94 h	386.3	487.3	620.2
522.7	I-132	2.28 h	667.7	772.7	954.6
526.6	I-128	24.99 m	442.9	——	——
526.6	I-135	6.57 h	1260.4	1131.5	1457.6
526.6	Xe-135m	15.29 m	——	——	——
529.9	I-133	20.8 h	——	——	——
543.0	Pt-199	30.8 m	493.7	317.1	246.4
545.0	Tc-101	14.2 m	306.8	——	——
546.6	I-135	6.57 h	1260.4	1131.5	526.6
547.0	Cs-138	32.2 m	1435.9	462.8	1009.8
551.5	W-187	23.9 h	685.7	479.6	134.2
555.8	Rh-104m	4.34 m	51.4	97.1	77.5
556.1	Rb-86m	1.02 m	——	——	——
558.0	Ge-77	11.3 h	264.4	211.0	215.5
590.9	Mo-101	14.6 m	191.9	505.9	1012.5
596.1	Zn-71m	3.94 h	386.3	487.3	620.2
601.0	Ga-72	14.1 h	834.1	630.0	2201.6
602.7	Sb-124m	93.0 s	645.9	498.4	——
616.1	Os-190m	9.9 m	361.1	502.5	186.7
616.3	Br-80	17.68 m	——	——	——
618.3	W-187	23.9 h	685.7	479.6	134.2
618.9	Ag-108	2.37 m	633.0	433.9	——
620.2	Zn-71m	3.94 h	386.3	487.3	596.1
630.0	Ga-72	14.1 h	834.1	2201.6	2507.9

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
630.3	I-132	2.28 h	667.7	772.7	954.6
631.8	Ge-77	11.3 h	264.4	211.0	215.5
633.0	Ag-108	2.37 m	433.9	618.9	-----
633.4	Dy-165	2.33 h	94.7	361.7	279.8
645.9	Sb-124m	93.0 s	498.4	602.7	-----
657.8	Ag-110	24.6 s	-----	-----	-----
657.9	Nb-97	72.1 m	-----	-----	-----
661.7	Ba-137m	2.55 m	-----	-----	-----
667.7	I-132	2.28 h	772.7	954.6	630.3
669.8	Th-233	22.3 m	459.3	94.7	86.5
676.4	Ru-105	4.44 h	724.3	469.4	316.4
685.7	W-187	23.9 h	479.6	134.2	772.9
714.3	Ge-77	11.3 h	264.4	211.0	215.5
715.3	Dy-165	2.33 h	94.7	361.7	279.8
718.0	Se-83	22.3 m	356.7	225.2	799.0
724.3	Ru-105	4.44 h	469.4	316.4	676.4
743.3	Zr-97	16.74 h	-----	-----	-----
772.7	I-132	2.28 h	667.7	954.6	630.3
772.9	W-187	23.9 h	685.7	479.6	134.2
776.5	Br-82m	6.13 m	-----	-----	-----
799.0	Se-83	22.3 m	356.7	225.2	718.0
818.7	In-116m	54.15 m	1097.3	1293.5	416.9
833.0	Cu-66	5.10 m	1039.2	-----	-----
834.1	Ga-72	14.1 h	630.0	2201.6	2507.9
834.9	Kr-88	2.84 h	196.3	2392.1	1529.8
836.5	Se-83	22.3 m	356.7	225.2	718.0
836.8	I-135	6.57 h	1260.4	1131.5	526.6
841.6	Eu-152m	9.32 h	963.4	121.8	344.3
843.8	Mg-27	9.46 m	1014.4	-----	-----
845.4	Kr-87	76.31 m	402.6	2554.8	2558.1
846.8	Mn-56	2.58 h	1810.7	2113.1	-----
847.0	I-134	52.6 m	884.1	-----	-----
871.1	Nb-94m	6.26 m	-----	-----	-----
884.1	I-134	52.6 m	847.0	-----	-----
894.3	Ga-72	14.1 h	834.1	630.0	2201.6
898.1	Rb-88	17.8 m	1836.1	-----	-----
928.6	Ti-51	5.76 m	320.1	-----	-----
954.6	I-132	2.28 h	667.7	772.7	630.3
963.4	Eu-152m	9.32 h	841.6	121.8	344.3
1009.8	Cs-138	32.2 m	1435.9	462.8	547.0

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
1012.5	Mo-101	14.6 m	590.9	191.9	505.9
1014.4	Mg-27	9.46 m	843.8	———	———
1038.8	I-135	6.57 h	1260.4	1131.5	526.6
1039.2	Cu-66	5.10 m	833.0	———	———
1050.9	Ga-72	14.1 h	834.1	630.0	2201.6
1080.3	Yb-177	1.88 h	150.4	1241.3	138.6
1097.3	In-116m	54.15 m	1293.5	416.9	818.7
1115.6	Ni-65	2.52 h	1481.8	366.3	———
1131.5	I-135	6.57 h	1260.4	526.6	1457.6
1180.9	Nd-151	12.44 m	255.7	116.8	———
1241.3	Yb-177	1.88 h	150.4	1080.3	138.6
1260.4	I-135	6.57 h	1131.5	526.6	1457.6
1266.2	Si-31	2.62 h	———	———	———
1273.4	Al-29	6.56 m	———	———	———
1293.5	In-116m	54.15 m	1097.3	416.9	818.7
1293.6	Ar-41	1.83 h	———	———	———
1332.5	Co-60m	10.47 m	58.6	———	———
1345.8	Cu-64	12.7 h	———	———	———
1356.8	O-19	26.91 s	197.1	———	———
1368.6	Na-24	14.96 h	2754.0	———	———
1434.1	V-52	3.75 m	———	———	———
1435.9	Cs-138	32.2 m	462.8	1009.8	547.0
1457.6	I-135	6.57 h	1260.4	1131.5	526.6
1481.8	Ni-65	2.52 h	1115.6	366.3	———
1507.4	In-116m	54.15 m	1097.3	1293.5	416.9
1524.6	K-42	12.36 h	———	———	———
1529.8	Kr-88	2.84 h	196.3	2392.1	2195.8
1575.6	Pr-142	19.12 h	———	———	———
1633.6	F-20	11.03 s	———	———	———
1642.7	Cl-38	37.24 m	2167.7	———	———
1678.1	I-135	6.57 h	1260.4	1131.5	526.6
1768.3	Xe-138	14.08 m	258.4	434.6	2015.8
1779.0	Al-28	2.24 m	———	———	———
1791.2	I-135	6.57 h	1260.4	1131.5	526.6
1810.7	Mn-56	2.58 h	846.8	2113.1	———
1836.1	Rb-88	17.8 m	898.1	———	———
1861.1	Ga-72	14.1 h	834.1	630.0	2201.6
2015.8	Xe-138	14.08 m	258.4	434.6	1768.3
2029.9	Kr-88	2.84 h	196.3	2392.1	1529.8
2035.5	Kr-88	2.84 h	196.3	2392.1	1529.8

TABLE IV. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
2112.3	In-116m	54.15 m	1097.3	1293.5	416.9
2113.1	Mn-56	2.58 h	846.8	1810.7	-----
2167.7	Cl-38	37.24 m	1642.7	-----	-----
2195.8	Kr-88	2.84 h	196.3	2392.1	1529.8
2201.6	Ga-72	14.1 h	834.1	630.0	2507.9
2218.0	Cs-138	32.2 m	1435.9	462.8	1009.8
2231.8	Kr-88	2.84 h	196.3	2392.1	1529.8
2392.1	Kr-88	2.84 h	196.3	1529.8	2195.8
2491.1	Ga-72	14.1 h	834.1	630.0	2201.6
2507.9	Ga-72	14.1 h	834.1	630.0	2201.6
2554.8	Kr-87	76.31 m	402.6	845.4	2558.1
2558.1	Kr-87	76.31 m	402.6	845.4	2554.8
2754.0	Na-24	14.96 h	1368.6	-----	-----
3084.5	Ca-49	8.72 m	4072.0	-----	-----
3104.0	S-37	5.05 m	-----	-----	-----
4072.0	Ca-49	8.72 m	3084.5	-----	-----

TABLE V. GAMMA RAYS ARRANGED BY ENERGY ($t_{1/2}$ > 1 day)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
14.4	Co-57	271.8 d	122.1	136.5	-----
23.9	Sn-119m	293. d	-----	-----	-----
30.9	Pt-195m	4.02 d	98.9	129.8	-----
35.5	I-125	60.14 d	-----	-----	-----
48.9	Tb-161	6.90 d	74.6	-----	-----
49.8	Te-132	78.2 h	228.3	-----	-----
53.2	Ba-133	10.52 y	356.0	302.9	383.9
57.4	Ce-143	33.0 h	293.3	-----	-----
58.0	Dy-159	144.4 d	-----	-----	-----
59.5	Am-241	432.2 y	-----	-----	-----
61.2	Sm-145	340. d	-----	-----	-----
63.1	Yb-169	32.02 d	177.2	198.0	307.7
66.7	Tm-171	1.92 y	-----	-----	-----
66.9	Cs-136	13.16 d	1048.1	818.5	340.6
67.8	Ta-182	114.5 d	1221.4	1189.1	100.1
69.7	Gd-153	241.6 d	97.4	103.2	-----
69.7	Sm-153	46.27 h	103.2	-----	-----
73.0	Os-193	30.5 h	460.5	138.9	280.4
74.6	Tb-161	6.90 d	48.9	-----	-----
75.3	Pa-233	27.0 d	312.0	340.6	300.2
77.3	Hg-197	64.1 h	-----	-----	-----
78.8	Tm-172	63.6 h	1093.7	1387.2	1466.0
79.6	Ba-133	10.52 y	356.0	302.9	383.9
80.2	I-131	8.04 d	364.5	284.3	637.0
80.6	Ho-166m	1200. y	711.7	184.1	810.3
80.6	Ho-166	26.8 h	1379.3	-----	-----
81.0	Ba-133	10.52 y	356.0	302.9	383.9
81.0	Xe-133	5.24 d	-----	-----	-----
82.4	Pt-191	2.96 d	538.9	409.5	359.9
82.5	Dy-166	81.6 h	-----	-----	-----
84.3	Tm-170	128.6 d	-----	-----	-----
84.7	Ta-182	114.5 d	1221.4	1189.1	100.1
86.5	Eu-155	4.68 y	105.3	-----	-----
86.7	Pa-233	27.0 d	312.0	340.6	300.2
86.8	Tb-160	72.3 d	879.4	298.6	966.2
88.0	Cd-109	462.6 d	-----	-----	-----
91.1	Nd-147	10.98 d	531.0	319.4	-----
91.3	Cu-67	61.92 h	184.6	93.3	-----
93.3	Cu-67	61.92 h	184.6	91.3	-----
97.4	Gd-153	241.6 d	103.2	69.7	-----

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
98.9	Pt-195m	4.02 d	129.8	30.9	———
99.1	Ta-183	5.10 d	246.1	354.0	161.3
100.1	Ta-182	114.5 d	1221.4	1189.1	67.8
103.2	Sm-153	46.27 h	69.7	———	———
103.2	Gd-153	241.6 d	97.4	69.7	———
105.3	Eu-155	4.96 y	86.5	———	———
105.3	Lu-177m	160.9 d	208.4	378.5	228.5
106.1	Np-239	2.36 d	277.6	228.2	209.8
107.9	Ta-183	5.10 d	246.1	354.0	161.3
109.1	U-235	7.1E+08 y	185.7	143.8	163.4
109.8	Yb-169	32.02 d	177.2	198.0	307.7
112.9	Lu-177m	160.9 d	208.4	378.5	228.5
112.9	Lu-177	6.71 d	208.4	———	———
113.7	Ta-182	114.5 d	1221.4	1189.1	100.1
113.8	Yb-175	4.19 d	396.3	282.5	———
116.4	Ta-182	114.5 d	1221.4	1189.1	100.1
121.1	Se-75	119.77 d	264.7	136.0	279.5
121.8	Eu-152	13.33 y	1408.0	344.3	778.9
122.1	Co-57	271.8 d	136.5	14.4	———
122.4	Re-186	90.64 h	137.1	———	———
123.1	Eu-154	8.59 y	1274.5	1004.8	723.3
123.8	Ba-131	11.8 d	496.3	373.2	216.0
125.4	W-185	75.1 d	———	———	———
128.5	Lu-177m	160.9 d	208.4	378.5	228.5
129.1	Th-232	1.4E+10 y	2614.5	583.2	238.6
129.4	Os-191	15.4 d	———	———	———
129.8	Pt-195m	4.02 d	98.9	30.9	———
130.5	Yb-169	32.02 d	177.2	198.0	307.7
133.0	Hf-181	42.39 d	482.2	345.9	136.3
133.5	Ce-144	284.9 d	———	———	———
136.0	Se-75	119.77 d	264.7	279.5	400.7
136.3	W-181	121.2 d	152.3	———	———
136.3	Hf-181	42.39 d	482.2	133.0	345.9
136.5	Co-57	271.8 d	122.1	14.4	———
137.1	Re-186	90.64 h	122.4	———	———
138.9	Os-193	30.5 h	460.5	73.0	280.4
140.5	Mo-99	65.94 h	181.1	739.6	778.0
142.7	Fe-59	44.5 d	1099.3	1291.6	192.4
143.8	U-235	7.1E+08 y	185.7	163.4	205.3
145.4	Ce-141	32.5 d	———	———	———

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
152.3	W-181	121.2 d	136.3	——	——
152.4	Ta-182	114.5 d	1221.4	1189.1	100.1
153.3	Lu-177m	160.9 d	208.4	378.5	228.5
156.0	Sn-117m	13.6 d	158.6	——	——
156.4	Ta-182	114.5 d	1221.4	1189.1	100.1
158.4	Au-199	3.14 d	208.2	——	——
158.6	Sn-117m	13.6 d	156.0	——	——
159.0	Te-123m	119.7 d	——	——	——
159.4	Sc-47	3.35 d	——	——	——
161.3	Ta-183	5.10 d	246.1	354.0	244.3
162.3	Ta-183	5.10 d	246.1	354.0	161.3
162.7	Ba-140	12.75 d	537.3	304.9	423.7
163.4	U-235	7.1E+08 y	185.7	143.8	205.3
163.9	Xe-131m	11.77 d	——	——	——
165.9	Ce-139	137.66 d	——	——	——
174.4	Lu-177m	160.9 d	208.4	378.5	228.5
176.3	Sb-125	2.73 y	427.9	600.6	463.4
176.6	Cs-136	13.16 d	1048.1	818.5	340.6
177.2	Yb-169	32.02 d	198.0	307.7	63.1
179.4	Ta-182	114.5 d	1221.4	1189.1	100.1
181.1	Mo-99	65.94 h	140.5	739.6	778.0
184.1	Ho-166m	1200. y	711.7	810.3	280.5
184.6	Cu-67	61.92 h	93.3	91.3	——
185.7	U-235	7.1E+08 y	143.8	163.4	205.3
186.1	U-238	4.5E+09 y	351.9	295.1	609.3
190.3	In-114m	49.51 d	558.4	725.2	——
192.4	Fe-59	44.5 d	1099.3	1291.6	142.7
197.0	Tb-160	72.3 d	879.4	298.6	966.2
198.0	Yb-169	32.02 d	177.2	307.7	63.1
198.4	Ta-182	114.5 d	1221.4	1189.1	100.1
204.1	Lu-177m	160.9 d	208.4	378.5	228.5
205.3	U-235	7.1E+08 y	185.7	143.8	163.4
208.2	Au-199	3.14 d	158.4	——	——
208.4	Lu-177m	160.9 d	378.5	228.5	112.9
208.4	Lu-177	6.71 d	112.9	——	——
209.3	Th-232	1.4E+10 y	2614.5	583.2	238.6
209.8	Np-239	2.36 d	106.1	277.6	228.2
209.9	Ta-183	5.10 d	246.1	354.0	161.3
215.6	Tb-160	72.3 d	879.4	298.6	966.2
215.7	Ru-97	69.12 h	324.5	——	——

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
216.0	Ba-131	11.8 d	496.3	373.2	123.8
222.1	Ta-182	114.5 d	1221.4	1189.1	100.1
227.1	W-188	69.4 d	290.7	-----	-----
228.2	Np-239	2.36 d	106.1	277.6	209.8
228.3	Te-132	78.2 h	49.8	-----	-----
228.5	Lu-177m	160.9 d	208.4	378.5	112.9
229.3	Ta-182	114.5 d	1221.4	1189.1	100.1
233.2	Xe-133m	2.19 d	-----	-----	-----
238.6	Th-232	1.4E+10 y	2614.5	583.2	300.1
239.0	As-77	38.83 h	-----	-----	-----
241.9	U-238	4.5E+09 y	351.9	295.1	186.1
244.3	Ta-183	5.10 d	246.1	354.0	161.3
244.7	Eu-152	13.33 y	1408.0	344.3	778.9
246.1	Ta-183	5.10 d	354.0	161.3	244.3
247.9	Eu-154	8.59 y	1274.1	1004.8	723.3
254.3	Ce-137m	34.4 h	-----	-----	-----
255.1	Sn-113	115.09 d	391.7	-----	-----
264.1	Ta-182	114.5 d	1221.4	1189.1	100.1
264.7	Se-75	119.77 d	136.0	279.5	400.7
268.2	Ba-135m	28.7 h	-----	-----	-----
270.2	Th-232	1.4E+10 y	2614.5	583.2	238.6
273.7	Cs-136	13.16 d	1048.1	818.5	340.6
275.9	Ba-133m	38.9 h	-----	-----	-----
276.4	Ba-133	10.52 y	356.0	302.9	383.9
277.4	Th-232	1.4E+10 y	2614.5	583.2	860.6
277.6	Np-239	2.36 d	106.1	228.2	209.8
279.2	Hg-203	46.61 d	-----	-----	-----
279.5	Se-75	119.77 d	264.7	136.0	400.7
280.4	Os-193	30.5 h	460.5	138.9	73.0
280.5	Ho-166m	1200. y	711.7	184.1	810.3
281.8	Lu-177m	160.9 d	208.4	378.5	228.5
282.5	Yb-175	4.19 d	396.3	113.8	-----
284.3	I-131	8.04 d	364.5	637.0	80.2
286.0	Pm-149	53.08 h	-----	-----	-----
290.7	W-188	69.4 d	227.1	-----	-----
293.3	Ce-143	33.0 h	57.4	-----	-----
295.1	U-238	4.5E+09 y	351.9	186.1	609.3
296.0	Ir-192	73.83 d	316.5	468.1	308.5
298.6	Tb-160	72.3 d	879.4	966.2	1178.0
300.1	Th-232	1.4E+10 y	2614.5	583.2	238.6

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
300.2	Pa-233	27.0 d	312.0	340.6	398.7
302.9	Ba-133	10.52 y	356.0	383.9	276.4
304.9	Ba-140	12.75 d	537.3	162.7	423.7
306.1	Rh-105	35.36 h	318.9	———	———
307.7	Yb-169	32.02 d	177.2	198.0	63.1
308.5	Ir-192	73.83 d	316.5	468.1	296.0
312.0	Pa-233	27.0 d	340.6	300.2	398.7
316.5	Ir-192	73.83 d	468.1	308.5	296.0
318.9	Rh-105	35.36 h	306.1	———	———
319.0	Lu-177m	160.9 d	208.4	378.5	228.5
319.4	Nd-147	10.98 d	91.1	531.0	———
320.1	Cr-51	27.7 d	———	———	———
321.6	Os-193	30.5 h	460.5	138.9	73.0
324.5	Ru-97	69.12 h	215.7	———	———
327.7	Lu-177m	160.9 d	208.4	378.5	228.5
328.0	Th-232	1.4E+10 y	2614.5	583.2	238.6
328.5	Ir-194m	171. d	338.8	482.7	687.8
328.8	La-140	40.27 h	1596.2	487.0	815.8
332.9	Au-196	6.18 d	355.6	425.6	———
334.3	Np-239	2.36 d	106.1	277.6	228.2
336.3	Cd-115	53.46 h	527.9	492.4	———
338.3	Th-232	1.4E+10 y	2614.5	583.2	238.6
338.8	Ir-194m	171. d	482.7	328.5	687.8
340.1	Pm-151	28.4 h	———	———	———
340.6	Cs-136	13.16 d	1048.1	818.5	1235.4
340.6	Pa-233	27.0 d	312.0	300.2	398.7
343.4	Hf-175	70.0 d	———	———	———
344.3	Eu-152	13.33 y	1408.0	778.9	964.1
345.9	Hf-181	42.39 d	482.2	133.0	136.3
351.9	U-238	4.5E+09 y	295.1	186.1	609.3
354.0	Ta-183	5.10 d	246.1	161.3	244.3
355.6	Au-196	6.18 d	332.9	425.6	———
356.0	Ba-133	10.52 y	302.9	383.9	276.4
359.9	Pt-191	2.96 d	538.9	409.5	82.4
364.5	I-131	8.04 d	284.3	637.0	80.2
373.2	Ba-131	11.8 d	496.3	216.0	123.8
378.5	Lu-177m	160.9 d	208.4	228.5	112.9
383.9	Ba-133	10.52 y	356.0	302.9	276.4
387.5	Os-193	30.5 h	460.5	138.9	73.0
390.8	Ir-194m	171. d	338.8	482.7	328.5

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
391.7	Sn-113	115.09 d	255.1	———	———
396.3	Yb-175	4.19 d	282.5	113.8	———
398.7	Pa-233	27.0 d	312.0	340.6	300.2
400.7	Se-75	119.77 d	264.7	136.0	279.5
407.3	Er-172	49.3 h	610.1	———	———
409.5	Th-232	1.4E+10 y	2614.5	583.2	238.6
409.5	Pt-191	2.96 d	538.9	359.9	82.4
410.9	Ho-166m	1200. y	711.7	184.1	810.3
411.1	Eu-152	13.33 y	1408.0	344.3	778.9
411.8	Au-198	2.70 d	675.9	———	———
413.7	Lu-177m	160.9 d	208.4	378.5	228.5
415.9	Pa-233	27.0 d	312.0	340.6	300.2
418.5	Lu-177m	160.9 d	208.4	378.5	228.5
423.7	Ba-140	12.75 d	537.3	162.7	304.9
425.6	Au-196	6.18 d	355.6	332.9	———
427.9	Sb-125	2.73 y	600.6	463.4	635.9
432.5	La-140	40.27 h	1596.2	487.0	328.8
437.6	Ba-140	12.75 d	537.3	162.7	304.9
443.9	Eu-152	13.33 y	1408.0	344.3	778.9
460.5	Os-193	30.5 h	138.9	73.0	280.4
463.0	Th-232	1.4E+10 y	2614.5	583.2	238.6
463.4	Sb-125	2.73 y	427.9	600.6	635.9
468.1	Ir-192	73.83 d	316.5	308.5	296.0
477.6	Be-7	53.29 d	———	———	———
482.2	Hf-181	42.39 d	133.0	345.9	136.3
482.7	Ir-194m	171. d	338.8	328.5	687.8
484.4	Cd-115m	44.6 d	933.8	1290.6	———
487.0	La-140	40.27 h	1596.2	328.8	815.8
489.2	Ca-47	4.54 d	1297.1	807.9	———
492.4	Cd-115	53.46 h	336.3	527.9	———
496.3	Ba-131	11.8 d	373.2	216.0	123.8
497.1	Ru-103	39.26 d	610.3	———	———
507.6	Te-121	16.78 d	573.1	———	———
510.8	Th-232	1.4E+10 y	2614.5	583.2	860.6
514.0	Sr-85	64.84 d	———	———	———
527.9	Cd-115	53.46 h	336.3	492.4	———
529.8	Ho-166m	1200. y	711.7	184.1	810.3
531.0	Nd-147	10.98 d	91.1	319.4	———
537.3	Ba-140	12.75 d	162.7	304.9	423.7
538.9	Pt-191	2.96 d	409.5	359.9	82.4

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
554.4	Br-82	35.3 h	776.5	619.1	698.4
557.4	Os-193	30.5 h	460.5	138.9	73.0
558.4	In-114m	49.51 d	190.3	725.2	——
559.1	As-76	26.32 h	657.1	1216.1	563.2
562.4	Ir-194m	171. d	338.8	482.7	328.5
563.2	Cs-134	2.06 y	795.8	604.7	569.3
563.2	As-76	26.32 h	559.1	657.1	1216.1
564.2	Sb-122	2.70 d	692.7	——	——
569.3	Cs-134	2.06 y	795.8	604.7	563.2
573.1	Te-121	16.78 d	507.6	——	——
583.2	Th-232	1.4E+10 y	2614.5	860.6	238.6
591.8	Eu-154	8.59 y	1274.5	1004.8	723.3
595.8	As-74	17.77 d	634.8	——	——
600.5	Ir-194m	171. d	338.8	482.7	328.5
600.6	Sb-125	2.73 y	427.9	463.4	635.9
602.7	Sb-124	60.2 d	1691.0	722.8	645.9
604.7	Cs-134	2.06 y	795.8	569.3	563.2
606.6	Sb-125	2.73 y	427.9	600.6	463.4
609.3	U-238	4.5E+09 y	351.9	295.1	186.1
610.1	Er-172	49.3 h	407.3	——	——
610.3	Ru-103	39.26 d	497.1	——	——
619.1	Br-82	35.3 h	776.5	554.4	698.4
634.8	As-74	17.77 d	595.8	——	——
635.9	Sb-125	2.73 y	427.9	600.6	463.4
637.0	I-131	8.04 d	364.5	284.3	80.2
645.9	Sb-124	60.2 d	1691.0	602.7	722.8
646.1	Os-185	93.6 d	——	——	——
657.1	As-76	26.32 h	559.1	1216.1	563.2
657.8	Ag-110m	249.76 d	884.7	937.5	1384.3
661.7	Cs-137	30.17 y	——	——	——
675.9	Au-198	2.70 d	411.8	——	——
677.6	Ag-110m	249.76 d	657.8	884.7	937.5
687.8	Ir-194m	171. d	338.8	482.7	328.5
692.7	Sb-122	2.70 d	564.2	——	——
698.4	Br-82	35.3 h	776.5	554.4	619.1
706.7	Ag-110m	249.76 d	657.8	884.7	937.5
711.7	Ho-166m	1200. y	184.1	810.3	280.5
722.8	Sb-124	60.2 d	1691.0	602.7	645.9
723.3	Eu-154	8.59 y	1274.5	1004.8	123.1
724.2	Zr-95	64.02 d	756.7	——	——

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
725.2	In-114m	49.51 d	190.3	558.4	——
727.3	Th-232	1.4E+10 y	2614.5	583.2	238.6
739.6	Mo-99	65.94 h	140.5	181.1	778.0
751.6	La-140	40.27 h	1596.2	487.0	328.8
752.3	Ho-166m	1200. y	711.7	184.1	810.3
756.7	Zr-95	64.02 d	724.2	——	——
756.9	Eu-154	8.59 y	1274.8	1004.8	723.3
763.9	Ag-110m	249.76 d	657.8	884.7	937.5
765.8	Nb-95	34.97 d	——	——	——
768.4	U-238	4.5E+09 y	351.9	295.1	186.1
773.7	Te-131m	30.0 h	852.2	793.8	1125.5
776.5	Br-82	35.3 h	554.4	619.1	698.4
778.0	Mo-99	65.94 h	140.5	181.1	739.6
778.9	Eu-152	13.33 y	1408.0	344.3	964.1
785.5	Th-232	1.4E+10 y	2614.5	583.2	238.6
793.8	Te-131m	30.0 h	773.7	852.2	1125.5
794.9	Th-232	1.4E+10 y	2614.5	583.2	238.6
795.8	Cs-134	2.06 y	604.7	569.3	563.2
801.9	Cs-134	2.06 y	795.8	604.7	569.3
807.9	Ca-47	4.54 d	1297.1	489.2	——
810.3	Ho-166m	1200. y	711.7	184.4	280.5
810.8	Co-58	70.82 d	——	——	——
815.8	La-140	40.27 h	1596.2	487.0	328.8
818.5	Cs-136	13.16 d	1048.1	340.6	1235.4
822.5	Sn-125	9.64 d	1067.1	1089.2	915.6
827.8	Br-82	35.3 h	776.5	554.4	619.1
830.6	Ho-166m	1200. y	711.7	184.1	810.3
834.8	Mn-54	312.12 d	——	——	——
846.8	Co-56	77.7 d	1238.3	1037.8	1771.4
852.2	Te-131m	30.0 h	773.7	793.8	1125.5
860.6	Th-232	1.4E+10 y	2614.5	583.2	238.6
867.4	Eu-152	13.33 y	1408.0	344.3	778.9
867.8	La-140	40.27 h	1596.2	487.0	328.8
873.2	Eu-154	8.59 y	1274.8	1004.8	723.3
879.4	Tb-160	72.3 d	298.6	966.2	1178.0
884.7	Ag-110m	249.76 d	657.8	937.5	1384.3
889.3	Sc-46	83.81 d	1120.5	——	——
898.1	Y-88	106.61 d	1836.1	——	——
909.2	Sr-89	50.55 d	——	——	——
911.2	Th-232	1.4E+10 y	2614.5	583.2	238.6

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
915.6	Sn-125	9.64 d	1067.1	1089.2	822.5
919.6	La-140	40.27 h	1596.2	487.0	328.8
925.2	La-140	40.27 h	1596.2	487.0	328.8
933.8	Cd-115m	44.6 d	1290.6	484.4	-----
934.0	U-238	4.5E+09 y	351.9	295.1	186.1
937.5	Ag-110m	249.76 d	657.8	884.7	1384.3
962.3	Tb-160	72.3 d	879.4	298.6	966.2
964.1	Eu-152	13.33 y	1408.0	344.3	778.9
964.8	Th-232	1.4E+10 y	2614.5	583.2	238.6
966.2	Tb-160	72.3 d	879.4	298.6	1178.0
969.0	Th-232	1.4E+10 y	2614.5	583.2	238.6
983.5	Sc-48	43.7 h	1037.5	1312.1	-----
996.3	Eu-154	8.59 y	1274.5	1004.8	723.3
1004.8	Eu-154	8.59 y	1274.5	723.3	123.1
1037.5	Sc-48	43.7 h	983.5	1312.1	-----
1037.8	Co-56	77.7 d	1238.3	846.8	1771.4
1044.1	Br-82	35.3 h	776.5	554.4	619.1
1048.1	Cs-136	13.16 d	818.5	340.6	1235.4
1067.1	Sn-125	9.64 d	1089.2	915.6	822.5
1076.6	Rb-86	18.66 d	-----	-----	-----
1085.9	Eu-152	13.33 y	1408.0	344.3	778.9
1089.2	Sn-125	9.64 d	1067.1	915.6	822.5
1093.7	Tm-172	63.6 h	1387.2	1466.0	1529.8
1099.3	Fe-59	44.5 d	1291.6	192.4	142.7
1112.1	Eu-152	13.33 y	1408.0	344.3	778.9
1115.6	Zn-65	243.9 d	-----	-----	-----
1120.3	U-238	4.5E+09 y	351.9	295.1	186.1
1120.5	Sc-46	83.81 d	889.3	-----	-----
1121.3	Ta-182	114.5 d	1221.4	1189.1	100.1
1125.5	Te-131m	30.0 h	773.7	852.2	793.8
1173.2	Co-60	5.27 y	1332.5	-----	-----
1178.0	Tb-160	72.3 d	879.4	298.6	966.2
1189.1	Ta-182	114.5 d	1221.4	100.1	1121.3
1212.9	As-76	26.32 h	559.1	657.1	1216.1
1216.1	As-76	26.32 h	559.1	657.1	563.2
1221.4	Ta-182	114.5 d	1189.1	100.1	1121.3
1228.5	As-76	26.32 h	559.1	657.1	1216.1
1231.0	Ta-182	114.5 d	1221.4	1189.1	100.1
1235.4	Cs-136	13.16 d	1048.1	818.5	340.6
1238.1	U-238	4.5E+09 y	351.9	295.1	186.1

TABLE V. (cont.)

Energy1 (keV)	Isotope	Halflife	Energy2 (keV)	Energy3 (keV)	Energy4 (keV)
1238.3	Co-56	77.7 d	846.8	1037.8	1771.4
1257.4	Ta-182	114.5 d	1221.4	1189.1	100.1
1271.9	Tb-160	72.3 d	879.4	298.6	966.2
1274.5	Na-22	2.60 y	———	———	———
1274.5	Eu-154	8.59 y	1004.8	723.3	123.1
1289.2	Ta-182	114.5 d	1221.4	1189.1	100.1
1290.6	Cd-115m	44.6 d	933.8	484.4	———
1291.6	Fe-59	44.5 d	1099.3	192.4	142.7
1297.1	Ca-47	4.54 d	489.2	807.9	———
1312.1	Sc-48	43.7 h	983.5	1037.5	———
1317.5	Br-82	35.3 h	776.5	554.4	619.1
1332.5	Co-60	5.27 y	1173.2	———	———
1365.2	Cs-134	2.06 y	795.8	604.7	569.3
1368.2	Sb-124	60.2 d	1691.0	602.7	722.8
1377.7	U-238	4.5E+09 y	351.9	295.1	186.1
1379.3	Ho-166	26.8 h	80.6	———	———
1384.3	Ag-110m	249.76 d	657.8	884.7	937.5
1387.2	Tm-172	63.6 h	1093.7	1466.0	1529.8
1408.0	Eu-152	13.33 y	344.3	778.9	964.1
1460.8	K-40	1.28E+09 y	———	———	———
1466.0	Tm-172	63.6 h	1093.7	1387.2	1529.8
1474.9	Br-82	35.3 h	776.5	554.4	619.1
1505.0	Ag-110m	249.76 d	657.8	884.7	937.5
1529.8	Tm-172	63.6 h	1093.7	1387.2	1466.0
1588.2	Th-232	1.4E+10 y	2614.5	583.2	238.6
1596.2	La-140	40.27 h	487.0	328.8	815.8
1608.6	Tm-172	63.6 h	1093.7	1387.2	1466.0
1620.7	Th-232	1.4E+10 y	2614.5	583.2	238.6
1691.0	Sb-124	60.2 d	602.7	722.8	645.9
1729.6	U-238	4.5E+09 y	351.9	295.1	186.1
1764.5	U-238	4.5E+09 y	351.9	295.1	186.1
1771.4	Co-56	77.7 d	1238.3	846.8	1037.8
1836.1	Y-88	106.61 d	898.1	———	———
2034.8	Co-56	77.7 d	1238.3	846.8	1037.8
2090.9	Sb-124	60.2 d	1691.0	602.7	722.8
2204.1	U-238	4.5E+09 y	351.9	295.1	186.1
2598.5	Co-56	77.7 d	1238.3	846.8	1037.8
2614.5	Th-232	1.4E+10 y	583.2	860.6	238.6
3253.4	Co-56	77.7 d	1238.3	846.8	1037.8

TABLE VI. RECOMMENDED GAMMA RAYS FOR ANALYSIS AND THEIR INTERFERENCES ($t_{1/2} < 5$ hours)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Aluminum	Al-28	2.24 m	1779.0					
Barium	Ba-139	84.63 m	165.8					
Bromine	Br-80	17.68 m	616.3					
Calcium	Ca-49	8.72 m	3084.5					
Chlorine	Cl-38	37.24 m	1642.7					
	Cl-38	37.24 m	2167.7					
Copper	Cu-66	5.10 m	1039.2					
Dysprosium	Dy-165	2.33 h	94.7	Th-233	22.3 m	94.7	86.5	0.3460
Fluorine	F-20	11.03 s	1633.6					
Indium	In-116m	54.15 m	1097.3					
Iodine	I-128	24.99 m	442.9					
Magnesium	Mg-27	9.46 m	843.8	Mn-56	2.58 h	846.8	1810.7	3.6360
	Mg-27	9.46 m	1014.4					
Manganese	Mn-56	2.58 h	846.8	Mg-27	9.46 m	843.8	1014.4	2.4960
	Mn-56	2.58 h	1810.7					

TABLE VI. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Nickel	Ni-65	2.52 h	1481.8					
Oxygen	O-19	26.91 s	197.1					
Selenium	Se-77m	17.45 s	161.9					
Silicon	Al-29	6.56 m	1273.4					
Silver	Ag-110	24.6 s	657.8					
Strontium	Sr-87m	2.81 h	388.4					
Sulfur	S-37	5.05 m	3104.0					
Titanium	Ti-51	5.76 m	320.1					
Uranium	U-239	23.47 m	74.7					
Vanadium	V-52	3.75 m	1434.1					

TABLE VII. RECOMMENDED GAMMA RAYS FOR ANALYSIS AND THEIR INTERFERENCES (5 hours $< t_{1/2} <$ 7 days)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Antimony	Sb-122	2.70 d	564.2	As-76	26.32 h	563.2	559.1	0.0267
				& Cs-134	2.06 y	563.2	795.8	0.0981
Arsenic	As-76	26.32 h	559.1	In-114m	49.51 d	558.4	190.3	0.0649
Bromine	Br-82	35.3 h	554.4					
	Br-82	35.3 h	619.1	W-187	23.9 h	618.3	685.7	0.2300
	Br-82	35.3 h	776.5	Mo-99	65.94 h	778.0	739.6	0.3578
Cadmium	In-115m	53.46 h	336.3					
	Cd-115	53.46 h	527.9					
Calcium	Ca-47	4.54 d	1297.1	Eu-152	13.33 y	1299.1	1408.1	0.0784
Copper	Cu-64	12.7 h	1345.8					
Gallium	Ga-72	14.1 h	630.0					
	Ga-72	14.1 h	834.1	Mn-54	312.12 d	834.8	——	——
Germanium	Ge-77	11.3 h	264.4	Se-75	119.77 d	264.7	400.7	5.1210
Gold	Au-198	2.70 d	411.8	Eu-152	13.33 y	411.1	344.3	0.0839
Holmium	Ho-166	26.8 h	80.6	I-131	8.04 d	80.2	364.5	0.0323

TABLE VII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Lanthanum	La-140	40.27 h	328.8					
	La-140	40.27 h	487.0	Ba-131	11.8 d	486.5	496.3	0.0430
	La-140	40.27 h	815.8					
	La-140	40.27 h	1596.2					
Lutetium	Lu-177	6.71 d	208.4	Np-239	2.36 d	209.8	277.6	0.2303
Molybdenum	Mo-99	65.94 h	140.5					
Platinum	Pt-191	2.96 d	538.9					
Potassium	K-42	12.36 h	1524.6					
Rhenium	Re-188	16.98 h	155.1	Ta-182	114.5 d	156.4	100.1	0.1929
Samarium	Sm-153	46.27 h	69.7	Gd-153	241.6 d	69.7	97.4	0.0841
	Sm-153	46.27 h	103.2	Gd-153 & Np-239	241.6 d 2.36 d	103.2 {103.7 X-ray}	97.4 106.1	0.7101 1.0529
Sodium	Na-24	14.96 h	1368.6	Sb-124	60.2 d	1368.2	1691.0	0.0553
	Na-24	14.96 h	2754.0					

TABLE VII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Tungsten	W-187	23.9 h	72.0					
	W-187	23.9 h	134.2	Ba-131	11.8 d	133.6	216.0	0.1095
				& Hf-181	42.39 d	133.0	345.9	2.3800
	W-187	23.9 h	479.6					
	W-187	23.9 h	685.7	Ag-110m	249.76 d	687.0	657.8	0.0681
Uranium	Np-239	2.36 d	106.1					
	Np-239	2.36 d	228.2	Te-132	78.2 h	228.3	49.8	6.1250
				& Ta-182	114.5 d	229.3	222.1	0.4790
	Np-239	2.36 d	277.6	Th-232	1.4E+10 y	277.4	583.2	0.0747
				& Nd-147	10.98 d	275.4	531.0	0.0611
				& Eu-152	13.33 y	275.4	344.3	0.0013
Ytterbium	Yb-175	4.19 d	282.5	Lu-177m	160.9 d	281.8	208.4	0.2315
	Yb-175	4.19 d	396.3					
Zinc	Zn-69m	13.76 h	438.6					

TABLE VIII. RECOMMENDED GAMMA RAYS FOR ANALYSIS AND THEIR INTERFERENCES ($t_{1/2}$ > 7 days)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Antimony	Sb-124	60.2 d	602.7	Cs-134	2.06 y	604.7	795.8	1.1418
	Sb-124	60.2 d	1691.0					
Barium	Ba-131	11.8 d	216.0	Tb-160	72.3 d	215.6	298.6	0.1526
	Ba-131	11.8 d	373.2					
	Ba-131	11.8 d	496.3	Ru-103	39.26 d	497.1	610.3	15.8640
Cerium	Ce-139	137.66 d	165.8					
	Ce-141	32.5 d	145.4	Ta-183	5.10 d	144.1	246.1	0.0954
				& Yb-175	4.19 d	144.9	396.3	0.0511
Cesium	Cs-134	2.06 y	604.7	Sb-124	60.2 d	602.7	1691.0	2.0660
	Cs-134	2.06 y	795.8	Th-232	1.4E+10 y	795.0	911.2	0.1632
Chromium	Cr-51	27.7 d	320.1	Nd-147	10.98 d	319.4	531.0	0.1488
				& Lu-177m	160.9 d	319.0	378.5	0.3971
Cobalt	Co-60	5.27 y	1173.2					
	Co-60	5.27 y	1332.5					
Erbium	Er-171	7.52 d	308.3					

TABLE VIII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Europium	Eu-152	13.33 y	344.3					
	Eu-152	13.33 y	778.9					
	Eu-152	13.33 y	1408.0					
Gadolinium	Gd-153	241.6 d	97.4					
	Gd-153	241.6 d	103.2					
Hafnium	Hf-181	42.39 d	133.0	Ba-131	11.8 d	133.6	216.0	0.1095
				& Ce-144	284.9 d	133.5	———	———
	Hf-181	42.39 d	345.9					
	Hf-181	42.39 d	482.2	Ir-194m	171. d	482.7	338.8	1.7586
Indium	In-114m	49.51 d	190.3	Fe-59	44.5 d	192.4	1099.2	0.0545
Iridium	Ir-192	73.83 d	296.0	Lu-177m	160.9 d	296.4	378.5	0.1949
				& U-238	4.5E+09 y	295.2	351.9	0.5175
	Ir-192	73.83 d	316.5					
	Ir-192	73.83 d	468.1	Eu-154	8.59 y	468.1	478.3	0.2627

TABLE VIII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Iron	Fe-59	44.5 d	1099.2					
	Fe-59	44.5 d	1291.6	Cd-115m	44.6 d	1290.6	933.8	0.4450
				& Ta-182	114.5 d	1289.2	1221.4	0.0461
Mercury	Hg-203	46.61 d	279.2	Se-75	119.77 d	279.5	264.7	0.4257
Neodymium	Nd-147	10.98 d	91.1					
	Nd-147	10.98 d	531.0					
Nickel	Co-58	70.82 d	810.8	Eu-152	13.33 y	810.8	778.9	0.0244
Osmium	Os-185	93.6 d	646.1	Sb-124	60.2 d	645.9	602.7	0.0755
Rubidium	Rb-86	18.66 d	1076.6					
Ruthenium	Ru-103	39.26 d	497.1	Ba-131	11.8 y	496.3	373.2	3.3080
Scandium	Sc-46	83.81 d	889.3					
	Sc-46	83.81 d	1120.6	Ta-182	114.5 d	1121.3	1221.4	1.2915
				& U-238	4.5E+09 y	1120.3	609.3	0.3254
Selenium	Se-75	119.77 d	136.0					
	Se-75	119.77 d	264.7	Ta-182	114.5 d	264.1	222.1	0.4789

TABLE VIII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Silver	Ag-110m	249.76 d	657.8	Eu-152	13.33 y	656.5	778.9	0.0110
	Ag-110m	249.76 d	884.7	Ir-192	73.83 d	884.5	316.5	0.0034
	Ag-110m	249.76 d	937.5					
Strontium	Sr-85	64.84 d	514.0					
Tantalum	Ta-182	114.5 d	67.8					
	Ta-182	114.5 d	100.1					
	Ta-182	114.5 d	1189.0					
	Ta-182	114.5 d	1221.4					
Tellerium	I-131	8.04 d	364.5					
Terbium	Tb-160	72.3 d	879.4					
	Tb-160	72.3 d	966.2					
	Tb-160	72.3 d	1178.0					
Thorium	Pa-233	27.0 d	300.2	Tb-160 & Th-232	72.3 d 1.4E+10 y	298.6 300.1	879.4 238.6	0.8781 0.0623
	Pa-233	27.0 d	312.0	K-42	12.36 h	312.4	1524.7	0.0186

TABLE VIII. (cont.)

Element	Isotope	Halflife	Energy (keV)	Interfering Isotope	Halflife	Interference (keV)	Reference (keV)	Abund. Ratio
Thulium	Tm-170	128.6 d	84.3	Ta-182	114.5 d	84.7	100.1	0.1943
Tin	Sn-113	115.09 d	391.7	Tb-160	72.3 d	392.5	298.6	0.0496
Ytterbium	Yb-169	32.02 d	63.1					
	Yb-169	32.02 d	177.2	Lu-177m	160.9 d	177.0	378.5	0.1235
	Yb-169	32.02 d	198.0	Tb-160	72.3 d	197.0	298.6	0.1940
				& Ta-182	114.5 d	198.4	222.1	0.1987
Zinc	Zn-65	243.9 d	1115.6	Sc-46	83.81 d	1120.6	889.3	1.0000
				& Eu-152	13.33 y	1112.1	1408.0	0.6475
				& Tb-160	72.3 d	1115.1	1178.0	0.1000
				& Ta-182	114.5 d	1113.4	1221.4	0.0160
Zirconium	Zr-95	64.02 d	724.2	Sb-124	60.2 d	722.8	602.7	0.1115
				& Eu-154	8.59 y	723.3	1274.8	0.5549
	Zr-95	64.02 d	756.7	Eu-154	8.59 y	756.9	1274.8	0.1155
	Nb-95	34.97 d	765.8	Eu-152	13.33 y	764.9	778.9	0.0139
				& Tb-160	72.3 d	765.3	879.4	0.0670

REFERENCES TO TABLES

[1] Ajzenberg-Selove, F., Nucl. Phys. **A413** (1984) 50.
[2] Ajzenberg-Selove, F., Nucl. Phys. **A392** (1983) 65.
[3] Ajzenberg-Selove, F., Nucl. Phys. **A392** (1983) 120.
[4] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 38.
[5] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 67.
[6] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 96.
[7] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 183.
[8] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 208.
[9] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 243.
[10] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 296.
[11] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 450.
[12] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 474.
[13] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 529.
[14] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 563.
[15] Ajzenberg-Selove, F., Nucl. Phys. **A310** (1978) 599.
[16] Alburger, D.E., Nucl. Data Sheets **49** (1986) 237.
[17] Burrows, T.W., Nucl. Data Sheets **48** (1986) 1.
[18] Alburger, D.E., Nucl. Data Sheets **45** (1985) 557.
[19] Burrows, T.W., Nucl. Data Sheets **48** (1986) 569.
[20] Zhou Chunmei, Zhou Enchen, Lu Xiane, Huo Junde, Nucl. Data Sheets **48** (1986) 111.
[21] Beene, J.R., Nucl. Data Sheets **25** (1978) 235.
[22] Wang Gongqing, Zhu Jiabi, Zhang Jigen, Nucl. Data Sheets **50** (1987) 255.
[23] Huo Junde, Hu Dailing, Zhou Chunmei, Han Xioling, Hu Baohua, Wu Yaodong, Nucl. Data Sheets **51** (1987) 1.
[24] Burrows, T.W., Bhat, M.R., Nucl. Data Sheets **47** (1986) 1.
[25] Peker, L.K., Nucl. Data Sheets **42** (1984) 457.
[26] Andersson, P., Ekstrom, L.P., Lyttkens, J., Nucl. Data Sheets **39** (1983) 641.
[27] Andersson, P., Ekstrom, L.P., Lyttkens, J., Nucl. Data Sheets **48** (1986) 251.
[28] Halbert, M.L., Nucl. Data Sheets **28** (1979) 179.
[29] Ward, N.J., Tuli, J.K., Nucl. Data Sheets **47** (1986) 135.
[30] Ward, N.J., Kearns, F., Nucl. Data Sheets **39** (1983) 1.
[31] Mo, J.N., Sen, S., Nucl. Data Sheets **39** (1983) 741.
[32] Kearns, F., Ward, N.J., Nucl. Data Sheets **35** (1982) 101.
[33] Kearns, F., Mo, J.N., Nucl. Data Sheets **27** (1979) 517.
[34] Kearns, F., Mo, J.N., Nucl. Data Sheets **31** (1980) 103.
[35] Singh, B., Viggars, D.A., Nucl. Data Sheets **51** (1987) 255.
[36] Ekstrom, L.P., Nucl. Data Sheets **32** (1981) 211.
[37] Singh, B., Viggars, D.A., Nucl. Data Sheets **42** (1984) 233.
[38] Singh, B., Viggars, D.A., Nucl. Data Sheets **29** (1980) 75.
[39] Singh, B., Viggars, D.A., Nucl. Data Sheets **37** (1982) 393.
[40] Singh, B., Viggars, D.A., Nucl. Data Sheets **36** (1982) 127.
[41] Muller, J., Nucl. Data Sheets **46** (1985) 487.
[42] Muller, H.W., Nucl. Data Sheets **50** (1987) 1.
[43] Muller, J., Nucl. Data Sheets **49** (1986) 579.
[44] Tepel, J.W., Nucl. Data Sheets **30** (1980) 501.
[45] Tepel, J.W., Nucl. Data Sheets **25** (1978) 553.
[46] Luksch, P., Tepel, J.W., Nucl. Data Sheets **27** (1979) 389.
[47] Bunting, R.L., Kraushaar, J.J., Nucl. Data Sheets **18** (1976) 87.
[48] Kocher, D.C., Nucl. Data Sheets **16** (1975) 445.

[49] Kocher, D.C., Nucl. Data Sheets **16** (1975) 55.
[50] Muller, H.W., Nucl. Data Sheets **44** (1985) 2.
[51] Luksch, P., Nucl. Data Sheets **38** (1983) 1.
[52] Haesner, B., Luksch, P., Nucl. Data Sheets **46** (1985) 607.
[53] Muller, H.W., Chmielewska, D., Nucl. Data Sheets **48** (1986) 663.
[54] Blachot, J., Nucl. Data Sheets **45** (1985) 701.
[55] DeFrenne, D., Jacobs, E., Verboven, M., Nucl. Data Sheets **45** (1985) 363.
[56] Blachot, J., Husson, J.P., Oms, J., Berrier, G., Nucl. Data Sheets **41** (1984) 325.
[57] DeFrenne, D., Jacobs, E., Verboven, M., DeGelder, P., Nucl. Data Sheets **47** (1986) 261.
[58] Haese, R.L., Bertrand, F.E., Harmatz, B., Martin, M.J., Nucl. Data Sheets **37** (1982) 289.
[59] Blachot, J., Nucl. Data Sheets **41** (1984) 111.
[60] DeGelder, P., Jacobs, E., DeFrenne, D., Nucl. Data Sheets **38** (1983) 545.
[61] Harmatz, B., Nucl. Data Sheets **27** (1979) 453.
[62] Lyttkens, J., Nilson, K., Ekstrom, L.P., Nucl. Data Sheets **33** (1981) 1.
[63] Blachot, J., Marguier, G., Nucl. Data Sheets **35** (1982) 375.
[64] Harmatz, B., Nucl. Data Sheets **30** (1980) 413.
[65] Blachot, J., Husson, J.P., Oms, J., Haas, F., Nucl. Data Sheets **32** (1981) 287.
[66] Blachot, J., Marguier, G., Nucl. Data Sheets **50** (1987) 63.
[67] Auble, R.L., Nucl. Data Sheets **26** (1979) 207.
[68] Tamura, T., Matumoto, Z., Hashizume, A., Tendow, Y., Miyano, K.,Ohya, S., Kitao, K., Kanbe, M., Nucl. Data Sheets **26** (1979) 385.
[69] Kitao, K., Kanbe, M., Matsumoto, Z., Seo, T., Nucl. Data Sheets **49** (1986) 315.
[70] Tamura, T., Matumoto, Z., Miyano, K., Ohya, S., Nucl. Data Sheets **29** (1980) 453.
[71] Tamura, T., Miyano, K., Ohya, S., Nucl. Data Sheets **41** (1984) 413.
[72] Tamura, T. Matumoto, Z., Ohshima, M., Nucl. Data Sheets **32** (1981) 497.
[73] Kitao, K., Kanabe, M., Matumoto, Z., Nucl. Data Sheets **38** (1983) 191.
[74] Hashizume, A., Tendow, Y., Ohshima, M., Nucl. Data Sheets **39** (1983) 551.
[75] Auble, R.L., Hiddleston, H.R., Browne, C.P., Nucl. Data Sheets **17** (1976) 573.
[76] Hiddleston, H.R., Browne, C.P., Nucl. Data Sheets **17** (1976) 225.
[77] Sergeenkov, Yu.V., Sigalov, V.M., Nucl. Data Sheets **49** (1986) 639.
[78] Sergeenkov, Yu.V., Sigalov, V.M., Nucl. Data Sheets **34** (1981) 475.
[79] Sergeenkov, Yu.V., Nucl. Data Sheets **52** (1987) 205.
[80] Burrows, T.W., Nucl. Data Sheets **52** (1987) 273.
[81] Peker, L.K., Nucl. Data Sheets **38** (1983) 87.
[82] Peker, L.K., Nucl. Data Sheets **36** (1982) 289.
[83] Peker, L.K., Nucl. Data Sheets **32** (1981) 1.
[84] Peker, L.K., Nucl. Data Sheets **51** (1987) 425.
[85] Peker, L.K., Nucl. Data Sheets **45** (1985) 1.
[86] Peker, L.K., Nucl. Data Sheets **43** (1984) 579.
[87] Peker, L.K., Nucl. Data Sheets **48** (1986) 753.
[88] Tuli, J.K., Nucl. Data Sheets **27** (1979) 97.
[89] Peker, L.K., Nucl. Data Sheets **49** (1986) 1.

[90] Harmatz, B., Ewbank, W.B., Nucl. Data Sheets **25** (1978) 113.
[91] Szucs, J.A., Johns, M.W., Singh, B., Nucl. Data Sheets **46** (1985) 1.
[92] Harmatz, B., Nucl. Data Sheets **19** (1976) 33.
[93] Baglin, C.M., Nucl. Data Sheets **30** (1980) 1.
[95] Helmer, R.G., Nucl. Data Sheets **52** (1987) 1.
[96] Lee, M.A., Nucl. Data Sheets **50** (1987) 563.
[94] Lee, M.A., Nucl. Data Sheets **37** (1982) 487.
[97] Lee, M.A., Reich, C.W., Nucl. Data Sheets **27** (1979) 155.
[98] Lee, M.A., Bunting, R.L., Nucl. Data Sheets **46** (1985) 187.
[99] Helmer, R.G., Nucl. Data Sheets **43** (1984) 1.
[100] Peker, L., Nucl. Data Sheets **50** (1987) 137.
[101] Ignatochkin, A.E., Shurshikov, E.N., Jaborov, Yu.F., Nucl. Data Sheets **52** (1987) 365.
[102] Shirley, V.S., Nucl. Data Sheets **36** (1982) 443.
[103] Zhou Chunmei, Nucl. Data Sheets **50** (1987) 351.
[104] Shirley, V.S., Nucl. Data Sheets **43** (1984) 127.
[105] Wang Gongqing, Nucl. Data Sheets **51** (1987) 577.
[106] Minor, M.M., Nucl. Data Sheets **18** (1976) 331.
[107] Ellis, Y.A., Harmatz, B., Nucl. Data Sheets **16** (1975) 135.
[108] Browne, E., Nucl. Data Sheets **52** (1987) 127.
[109] Firestone, R.B., Nucl. Data Sheets **43** (1984) 289.
[110] Schmorak, M.R., Nucl. Data Sheets **14** (1975) 559.
[111] Artna-Cohen, A., Nucl. Data Sheets **16** (1975) 267.
[112] Ellis-Akovali, Y.A., Nucl. Data Sheets **33** (1981) 557.
[113] Schmorak, M.R., Nucl. Data Sheets **13** (1974) 267.
[114] Ellis-Akovali, Y., Nucl. Data Sheets **36** (1982) 559.
[115] Singh, B., Viggars, D.A., Nucl. Data Sheets **33** (1981) 273.
[116] Lederer, C.M., Nucl. Data Sheets **35** (1982) 525.
[117] Browne, E., Nucl. Data Sheets **30** (1980) 653.
[118] Shirley, V.S., Dairiki, J.M., Nucl. Data Sheets **40** (1983) 425.
[119] Shirley, V.S., Nucl. Data Sheets **32** (1981) 593.
[120] Harmatz, B., Nucl. Data Sheets **22** (1977) 433.
[121] Harmatz, B., Nucl. Data Sheets **23** (1978) 607.
[122] Halperin, J., Nucl. Data Sheets **28** (1979) 485.
[123] Harmatz, B., Nucl. Data Sheets **34** (1981) 101.
[124] Auble, R.L., Nucl. Data Sheets **40** (1983) 301.
[125] Halperin, J., Nucl. Data Sheets **24** (1978) 57.
[126] Schmorak, M.R., Nucl. Data Sheets **46** (1985) 287.
[127] Schmorak, M.R., Nucl. Data Sheets **45** (1985) 145.
[128] Martin, M.J., Nucl. Data Sheets **47** (1986) 797.
[129] Martin, M.J., Nucl. Data Sheets **27** (1979) 637.
[130] Toth, K.S., Nucl. Data Sheets **21** (1977) 437.
[131] Ellis-Akovali, Y.A., Nucl. Data Sheets **50** (1987) 229.
[132] Martin, M.J., Nucl. Data Sheets **49** (1986) 83.
[133] Ellis, Y.A., Nucl. Data Sheets **24** (1978) 289.
[134] Schmorak, M.R., Nucl. Data Sheets **21** (1977) 117.
[135] Schmorak, M.R., Nucl. Data Sheets **40** (1983) 1.
[136] Ellis-Akovali, Y.A., Nucl. Data Sheets **44** (1985) 407.
[137] Glascock, M.D., unpublished data.
[138] Coursey, B.M., Hoppes, D.D., Schima, F.J., Unterweger, M.P.,Appl. Radiat. Isot. **38** (1987) 31.

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