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Nuclear Techniques for the Chemical Analysis of Environmental Materials

University of California

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NUCLEAR TECHNIQUES FOR THE CHEMICAL ANALYSIS OF ENVIRONMENTAL MATERIALS

by

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ABSTRACT

The specific nuclear methods used by the Environmental Surveillance Group for elemental analysis of water, geological, and biological samples are described in detail. Reactor facilities, thermal and epithermal neutron activation, capture γ-ray spectrometry, and delayed neutron assay are covered. Detailed tabulations of γ-ray emitting species by both isotope and energy are included.

INTRODUCTION

Environmental science is increasingly dependent upon chemical analysis to provide information for investigation, management, and monitoring of man's impact on the natural system. Most classical analytical methods are unable to handle the wide variety of matrix types and the complexity of the individual matrices, or to provide the sensitivity needed for sub parts per million (ppm) measurements in environmental samples. Nuclear techniques have a number of advantages that place them among the primary methods for environmental analysis. The projectiles used for activation (neutrons and high energy γ-rays) and the radiations induced have long ranges in the sample materials so the chances of matrix effects are substantially reduced. Furthermore, the use of purely instrumental methods involve no chemical manipulations that might add contaminants, fail to dissolve some portions of the samples, or cause loss of volatile species during sample dissolution. Care must be taken, however, to prevent loss of some of the most volatile elements during the irradiation themselves (1, 2).

The errors involved with nuclear procedures are largely reduced to those caused by statistical fluctuations in counting rates, by pipetting of elemental standard solutions, by variations of the flux within the sample container during irradiation, and by variations in positioning of the sample during counting (geometry).

The information in this manual has been compiled with several users in mind. It is intended to document some of our analytical procedures so that those involved in the environmental monitoring effort will better understand the quality and limitations of their chemical data. It is further intended to provide a general introduction to environmental analysis for new professional staff and technicians. Hence, this manual includes literature references for an in-depth review of nuclear analytical methods as well as highly specific information on equipment and procedures in use by the Analytical Chemistry section of the Environmental Surveillance Group.

Certain terms will be used extensively in this document. "Instrumental" will refer to any analysis that involves no chemical manipulations. Samples are irradiated as received and counted directly on nuclear radiation detectors. "Radiochemistry" involves some degree of chemical processing. Generally, the sample is irradiated as received and all chemical processing is done after irradiation. The advantage of post-irradiation chemistry is that contamination control is not a problem; indeed, milligram amounts of the element of interest (in a nonradioactive form) will probably be added as a carrier to minimize loss during chemistry. The essence of a radiochemical separation is to partially or completely isolate the elements of interest from interfering radioactive species in the sample. Separations may be as simple as a single precipitation step, or as complex as multiple precipitation, distillation, and successive ion exchange stages.

There are seven interactions of interest here between an incident particle and a target nucleus. If the incident particle is charged, it may interact only with a charge field of the electrons (atomic ionization) or it may interact with the nuclear charge field (coulomb scattering or excitation). Since neutrons have no charge, they do not participate in these reactions. Both charged and uncharged particles may be scattered off the nucleus and leave the target in the ground state (elastic scattering) or in an excited state (inelastic scattering). Finally, the incident particle may react directly with the nucleus to produce a compound nucleus. This is a genuine nuclear transformation resulting in a chemical change in identity. One mode of nuclear de-excitation is the instantaneous emission of nuclear γ-rays (capture radiation). These remove some or all of the extra energy present in the compound nucleus. The new nucleus may be either stable or radioactive. In the latter case, radioactive decay γs are emitted with a characteristic half-life. It is this type of nuclear-interaction that is of most interest and analytical utility here. There is also a direct interaction mechanism, but this theory applies largely to charged particle nuclear interactions and will not be pursued here.

The incident particles referred to above may be produced from a variety of sources. Particle accelerators (linear and cyclotronic) produce beams of charged particles and high energy γ-rays, the latter through conversion of the charged particle beam to bremsstrahlung radiation. These sources are available at Los Alamos Scientific Laboratory (LASL) but are not currently being used for environmental analysis. The Environmental Surveillance Group uses neutrons almost exclusively as incident particles to produce nuclear reactions that have analytical utility. Either isotopic (^{252}Cf, Pu-Be, Po-Be, Ra-Be, Am-Be) sources or nuclear reactors may be used as neutron sources to activate samples. Because of limited neutron fluxes from isotopic sources (typically less than 10^8 n/cm^2/s), reactor neutrons are most commonly used in activation analysis. Neutron fluxes are usually characterized by their energy spectrum, i.e., the distribution of neutron energies. The unmodified fission neutron spectrum, available directly in the reactor core, contains a high proportion of fast neutrons (Kinetic energy >1 MeV) and relatively few thermal neutrons (KE <0.1 eV). The thermal flux, available in the thermal column outside the reactor core, is a highly modified fission neutron spectrum with a very high proportion of thermal neutrons and relatively few fast neutrons. The epithermal flux is another modified fission neutron spectrum in which most of the thermal neutrons have been completely excluded and many of the fast neutrons have been slowed down somewhat. An epithermal neutron flux commonly contains neutrons with kinetic energies in the range of 0.4 eV to 1 MeV. The lower energy boundary is determined by the material used as a thermal neutron absorber (3).

NEUTRON IRRADIATION FACILITIES

The Omega West Reactor (OWR) is a thermal, heterogeneous, tank-type research reactor operated by Group P-2 in support of research and testing activities at the Los Alamos Scientific Laboratory. The reactor is light-water moderated and cooled, utilizing Al-clad fuel elements of the Materials Testing Reactor type. It provides neutron fluxes of up to 9 x 10^{13} n/cm^2/s (fission spectrum). The facility originally went critical in 1956 and has operated at a maximum power level of 8-MW since 1968. The operational schedule presently calls for five 8-hr days per week, although 120-hr/wk schedules have been maintained in the past. Construction details of the reactor itself may be found in Reference 4.

In addition to neutron beam ports, the OWR provides a variety of irradiation locations summarized in Table I. The Cd (Au) ratio given in the table is defined by:

$$R_{Cd} = \frac{\sigma_{Th}\phi_{Th} + I\phi_E}{I\phi_E}$$

Where σ_{Th} is the thermal neutron cross section of Cd,

I is the resonance integral of Cd and

ϕ_{Th} and ϕ_E are the thermal and epithermal neutron fluxes, respectively. Thermal Column Rabbits 1-5, 8, 10, and 11 will accomodate only a 4 cm^3 screw-cap polyethylene rabbit. The Thermal Column Rabbits 6, 7, and 9 will accomodate either a 25 cm^3 or 40 cm^3 screw-cap bottle or double screw-cap ended rabbit, respectively. The Epithermal Rabbit will take either the 4 cm^3 polyethylene or a 4 cm^3 sealable Al rabbit. The latter is desirable for irradiations of longer than eight hours because the polyethylene becomes extremely brittle from fast neutron damage. All thermal and epithermal facilities have pneumatic rapid transfer capability. The Hydraulic Rabbit has a specially designed Al can (which must be sealed) for use in this nonpneumatic facility. With the high heating rates encountered in this facility, any potentially thermally unstable samples must be encapsulated in quartz.

The epithermal irradiation port is surrounded by a permanently installed natural boron filter to shield the sample from essentially all of the thermal

TABLE I

OWR NEUTRON IRRADIATION FACILITIES (4,5)

Facility	Reactor Face Location	Maximum Sample Size	Thermal Neutron Flux at 8 MW	Cd (Au) Ratio	Comments
End-Port Rabbit	South	9 mm x 57 mm	4×10^{13}		Sample terminal water cooled Rad. heating = 0.5 w/g
Epithermal Rabbit*	South	9 mm x 57 mm	$\sim 2 \times 10^{12}$(?)		
Thermal Column Rabbits -1*	"	"	3.4×10^{12}	9.0	
-2*	"	"			
-3*	"	"			
-4*	"	"	9.7×10^{12}	2.75	
Hydraulic Rabbit	Top	19 mm x 40 mm	9×10^{13}		Sample water cooled. Rad. heating = 5 w/g
In Core Samples	Top	Up to 53 mm diam, length not restricted	$6\text{-}9 \times 10^{13}$		Four positions available.
North and South Vertical Ports	Top	88 mm x 300 mm	1.6×10^{13}		No cooling, rad. heating = 0.3 w/g
Upper and Lower through Ports	North or South	150 mm diam, length not restricted	2.5×10^{13}		Ports accessible from each end.
Capture Gamma Ray Port	North	25 mm x 75 mm	$\sim 3 \times 10^{11}$(?)		No cooling, requires lowering of Boran Curtain to change sample.
Thermal Column Rabbits -5	North	9 mm x 57 mm	9.7×10^{12}	2.75	Dedicated DNA sediments.
-6	North	20 mm x 120 mm	5×10^{12}		
-7	North	20 mm x 120 mm	1×10^{13}	2.7	
-8	North	9 mm x 57 mm	1×10^{13}	2.7	Dedicated DNA for CNC-11
-9	North	20 mm x 120 mm	1×10^{13}		Dedicated DNA water
-10	North	9 mm x 57 mm	6×10^{12}	4.5	Dedicated Multi-element Activation Sediments (-10 and -11)
-11*	North	9 mm x 57 mm	5×10^{12}	6.4	

*Samples may be pneumatically transferred outside Reactor Room.

neutrons in the unmodified fission neutron spectrum. The filter material is a 50-50 volume percent mixture of powdered crystalline boron and aluminum, hot pressed into aluminum sleeves. The boral powder is pressed to 95% of theoretical density and the shield wall is 2.5 cm thick. This provides about 2.3 g/cm^2 of boron, with an estimated filter cutoff energy of 280 eV (3,6).

Flux gradients in the thermal and epithermal irradiation locations have been investigated in some detail. No radial gradients have been observed over the short rabbit diameters. The results for linear (axial) gradients are summarized in Tables II and III. For the thermal neutron fluxes, 50 µg of Co were pipetted onto 4.25 cm Whatman No. 2 filter paper and air dried. These circles were then folded to fit the 200 mg capacity BEEM snap-cap polyethylene vials used almost exclusively as sample containers for our thermal irradiations. Four of these vials fit end to end in each 4 cm^3 polyethylene rabbit, resulting in eight irradiation positions, since two rabbits are normally irradiated simultaneously (see Fig. 1). All monitors were counted in the same geometry on the same detector within 30 days after irradiation so that no decay corrections were needed. The results in Table II have been normalized to the first irradiation position by dividing the net counts in each position by those from the first position. The uncertainty shown in the Table represents that from counting statistics alone. The relative standard deviation among several replicates in each position is 2-3%.

Two different methods of sample encapsulation were examined for the epithermal irradiation port. Either whole vials (rabbits) or the 200 mg BEEM snap-cap vials are commonly employed for irradiations in this facility. Ten microgram amounts of Au were pipetted onto 7.0 cm Whatman 41 filter paper for whole vials or onto the 4.25 cm Whatman No. 2 paper mentioned above for the BEEM vials. These were again folded to fit their respective sample containers. The data shown in Table III are normalized in the fashion described above. Four rabbits were irradiated simultaneously to investigate the axial gradient shown in the first entry in Table III. The relative standard deviations for ten measurements in the four positions were 3, 2, 16, and 2% respectively. The strong flux gradient beyond the second rabbit limits the usefulness of this facility to no more than two simultaneous irradiations, and the detailed gradient for the BEEM vials was examined for only eight postions (two 4 cm^3) irradiation vials. As before, the uncertainty shown in this table represents counting statistics alone.

TABLE II

FLUX DISTRIBUTIONS IN THERMAL NEUTRON IRRADIATION FACILITIES AT OWR

Facility	Irradiation Position*								Error
	1	2	3	4	5	6	7	8	
TCR-1	1.00	1.01	0.96	1.04	1.03	0.99	0.97	0.96	0.01
2	1.000	0.962	0.945	0.948	0.900	0.931	0.895	0.900	0.008
3	1.000	1.001	1.003	0.936	0.978	0.949	0.919	0.943	0.027
4	1.000	0.993	1.018	1.020	0.999	0.987	0.989	0.991	0.006
5	1.00	0.99	1.00	1.00	0.97	0.94	0.97	0.91	0.01
11	1.00	0.99	0.99	0.98	0.93	0.93	0.97	0.97	0.01

*Successive positions are 1.5 cm increments from the deepest point of the pneumatic tubes in the thermal column.

TABLE III

FLUX DISTRIBUTIONS IN THE EPITHERMAL NEUTRON IRRADIATION FACILITY AT OWR

Sample Size	Position*								Error
	1	2	3	4	5	6	7	8	
Whole Vial	1.000	0.935	0.634	0.444					0.034
BEEM Capsule									
Sb	1.00	1.08	1.02	0.99	1.01	0.99	0.96	0.93	0.03
Mo	1.00	0.97	0.93	0.90	0.89	0.96	0.88	0.86	0.03

*Successive positions are 6 cm and 1.5 cm increments for the whole vial and BEEM Capsules, respectively from the deepest point of the pneumatic tube in the epithermal facility.

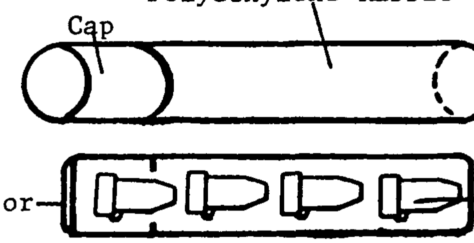

Fig. 1. Side view of small (9 mm x 57 mm) polyethylene rabbit for neutron irradiations.

The Capture Gamma Ray port accepts a rabbit approximately 2.5 x 7.5 cm. A hollow graphite tube is ususally used for a framework to support the irradiation container, although this can be replaced by metallic containers for special experiments. The experimental arrangement of the target, collimator, and detector is shown in Fig. 2. The target is placed in a graphite holder, which is inside an evacuated Bi channel. This Bi channel traverses the entire width of the thermal column and is embedded in the concrete shielding in the far side of the reactor. Thus no thermal column graphite is located directly behind the target and this important source of background is eliminated. Gamma rays from the reactor core are attenuated in entering the thermal column by a 7.6 cm lead shield located adjacent to the core tank and a 12.7 cm bismuth shield just inside the thermal column. The neutron capture γ-ray beam is extracted through a collimator, the viewing area of which does not include the bismuth channel. Hence any capture γ-rays from the thermal column, the bismuth channel, or any core γ-rays which penetrate the thermal column shielding must be scattered through a large angle in order to pass through the collimator. Thermal neutrons accompanying the γ-ray beam are highly attenuated by a ^{6}Li absorber.

The detector is a 3 mm deep by 1.8 cm diam. Li-drifted Ge crystal placed at the center of a cylindrical NaI (T1) annulus which is 30 cm long by 20 cm outside diameter and which has a 6.5 cm bore along its axis. The γ-ray beam is 1.2 cm in diam. at the position of the detector, approximately 6 m from the target.

The detector can be operated as a total energy spectrometer at low energies (anticoincidence mode) or as a two-quantum escape pair spectrometer at

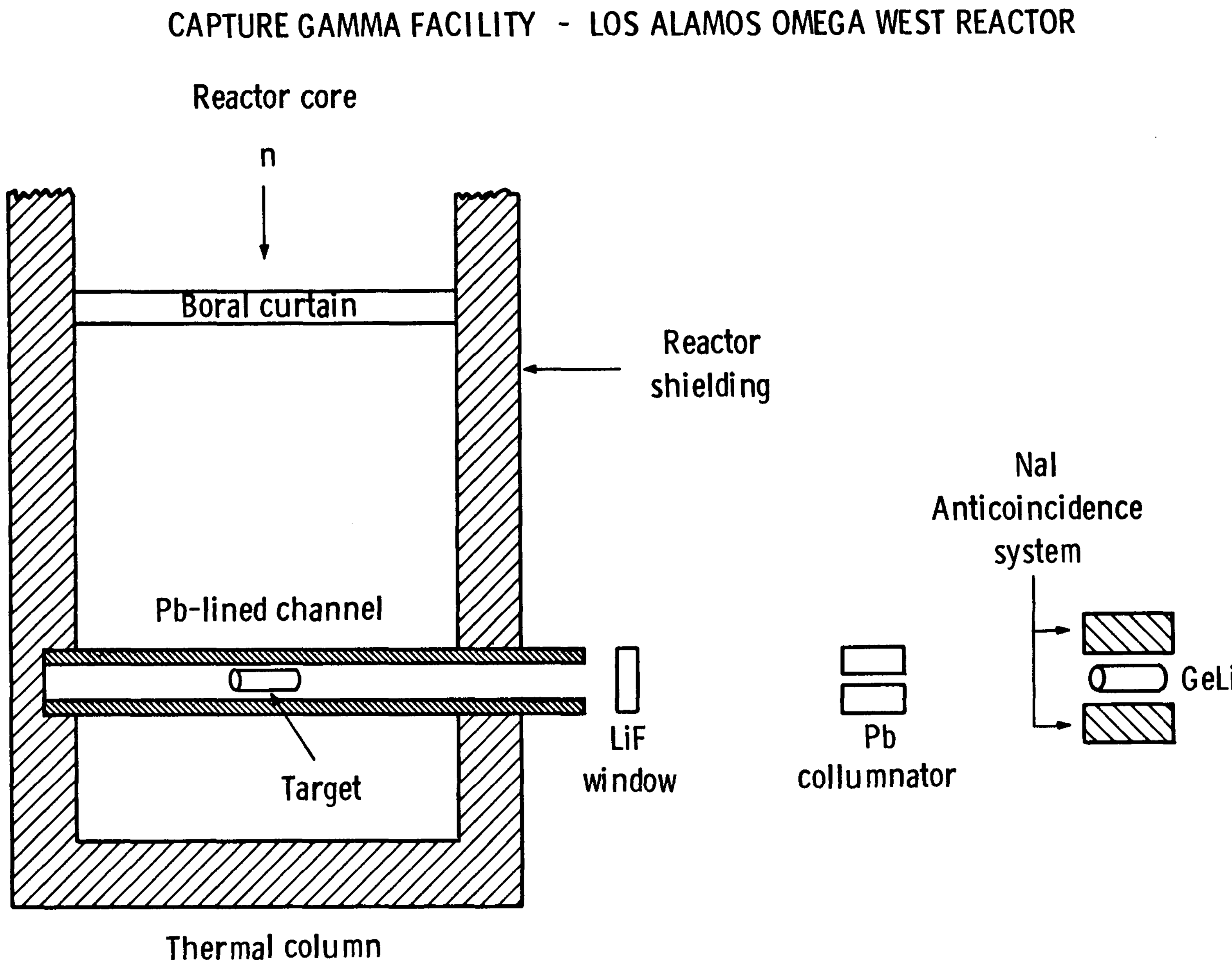

Fig. 2. Thermal column target assembly for capture gamma-ray spectrometry.

energies >2 MeV (coincidence mode). In this latter mode of operation, pulses corresponding to 1022 ± 100 keV from the annulus are used to gate pulses from the Ge detector into a Geosciences 4096-channel analyzer. At high energies, segments of the γ-ray spectrum 2 to 3 MeV in width are selected with a biased amplifier. Resolution varies from 5 keV (FWHM) at 1 MeV to ∿6.5 keV at 5 MeV. The sensitivity of the system is such that transitions corresponding to as little as 0.15 mb· mol of capture generally stand clearly above background except in the energy region between 1.5 and 2.5 MeV where the sensitivity is limited by the full energy efficiency of the rather small detector (7).

The thermal neutron flux distribution in the capture facility has been studied as a function of distance from the center of the thermal column. An empty polyethylene vial in the standard graphite rabbit was moved along the channel and the intensity of the 2223 keV capture γ-ray from $^{1}H(n,\gamma)^{2}H$ in the plastic was monitored at constant reactor power. This relative flux distribution is shown in Table IV. The maximum thermal flux in the channel is approximately 2×10^{11} n/cm^2/s (7).

TABLE IV

RELATIVE THERMAL NEUTRON FLUX IN OWR CAPTURE GAMMA-RAY SYSTEM

Distance from Center of Thermal Column (ft)	Relative Flux
0	1.0
0.5	1.0
1.0	0.93
1.5	0.78
2.0	0.53
2.5	0.36

INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS

Quantitative analysis by means of neutron activation is the determination of the elemental composition of unknown materials by measurement and characterization of radioactivity induced in the samples by artificial means. It is important to recognize that this procedure yields no chemical information about the oxidation state of the elements measured--only the bulk composition of the sample irradiated.

The radioactivity used for elemental measurements is artificially produced in the samples and is in addition to the naturally occurring radioactive isotopes (e.g., ^{40}K, ^{226}Ra, ^{235}U, etc.). This artificial radioactivity is induced through nuclear reactions on elements in the sample. These reactions are usually expressed in a short hand form:

$$^{i}A(x,y)^{j}B$$

where isotope _i_ of element _A_ reacts with an incident particle _x_, gives off excess energy _y_, and becomes isotope _j_ of element _B_. The incident particles may be charged particles (protons, deutrons, tritons, alphas) produced from linear or cyclotronic accelerators, photons from bremsstrahlung radiation from particle accelerators or neutrons from reactors and neutron generators. The Environmental Surveillance Group uses reactor neutrons exclusively for activation analysis, so only neutron-induced nuclear reactions will be considered in this document.

An excellent, detailed review of the basic principles of activation analysis, including the calculations required, is given in Hoste et al. (8), so only our specific analytical scheme will be given here, divided into thermal and epithermal sections.

INSTRUMENTAL THERMAL NEUTRON ACTIVATION ANALYSIS (ITNA)

By utilizing various combinations of irradiation lengths, decay times, and counting times, up to 49 elements can be measured in environmental samples by completely instrumental techniques, which avoid problems associated with sample dissolutions. These elements, their nuclear properties, most useful γ-rays, irradiation length, and preferred neutron flux are shown in Table V. In the cases where epithermal neutrons are the preferred flux, the measurement can still be made using a thermal neutron irradiation, but with less sensitivity.

TABLE V

PROPERTIES OF ELEMENTS DETERMINED BY INSTRUMENTAL NEUTRON ACTIVATION

Element	Target Isotope	Isotope Abundance (%)	Cross Section (barns)[a]	Radioactive product[b] Half-life	Radioactive product[b] Isotope	Gamma-rays Used (keV)	Major Interferences	Irradiation Length[e]	Preferred Flux Type[f]
Ag	109	48.17	4.5	252 d	110 m	658, 884		L	E - T
Al	27	100	0.232	2.3 m	28	1779		S	T
As	75	100	4.3	26 h	76	559, 657	554 ^{82}Br	L	E
Au	197	100	99	65 h	198	411		L	E - T
Ba	130	0.1	8	12 d	131	216, 496	216 ^{160}Tb	L	T
	138	71.9	0.35	83 m	139	166		S	T
Br	79	50.56	11.1	18 m	80	616, 666	620 ^{38}Cl(DE)	S - M	E - T
	81	49.44	2.69	35 h	82	554, 777	559 ^{76}As	M - L	E - T
Ca	48	0.19	1.1	8.7 m	49	3084		S	T
Ce	140	88.5	0.57	33 d	141	145	143 ^{59}Fe	L	T
Cl	37	24.47	0.43	37 m	38	1642, 2168		S	T
Co	59	100	37.2	5.3 y	60	1173, 1332		L	T
Cr	50	4.3	15.9	28 d	51	320		L	T
Cs	133	100	29	2.1 y	134	796		L	E - T
Cu	63	69.1	4.5	13 h	64	511	511 ^{24}Na	M	T
	65	30.9	2.17	5.1 m	66	1039	1044 ^{82}Br	S	T
Dy	164	28.2	2700	2.4 h	165	362		M	T
Eu	151	47.8	5900	12 y	152	1408		L	T
F	19	100	0.0095	11 s	20	1633		S	T
	19	100	0.0014	27 s	^{19}O[c]	200		S	E
Fe	54	5.8	0.082	312 d	^{54}Mn[c]	835		L	E - T
	58	0.31	1.15	45 d	59	1099, 1292		L	T
Ga	71	39.6	4.9	14 h	72	834, 2202	835 ^{54}Mn	L	E
Hf	180	35.2	12.6	42 d	181	482		L	T
I	127	100	6.2	25 m	128	443		S - M	E - T
In	115	95.7	65	54 m	116 m	417, 1097	1099 ^{59}Fe	S - M	T
Ir	191	37.4	624	74 d	192	308, 468		L	T
K	41	6.9	1.46	12 h	42	1525		S - M	T
La	139	99.9	9.0	40 h	140	487, 1596		L	T
Lu	176	2.6	2050	6.7 d	177 m	208		L	T
Mg	26	11.2	0.038	9.5 m	27	844, 1014	847 ^{56}Mn	S	T
Mn	55	100	13.3	2.6 h	56	847, 1811	844 ^{27}Mn	S	T
Mo	98	24.4	0.13	66 h	99	140	143 ^{59}Fe	L	E
Na	23	100	0.53	15 h	24	1368, 2754		S - M	T
	23	100	0.0015	38 s	^{23}Ne[c]	439		S	E
Nd	146	17.2	1.3	11 d	147	91, 531		L	T
Ni	58	68.3	0.113	71 d	^{58}Co[c]	811		L	E
Rb	85	72.3	0.46	19 d	86	1077		L	T
S	36	0.014	0.15	5.1 m	37	3101		S	T
Sb	121	57.25	6.25	2.8 d	122	564	562 ^{76}As	L	E - T
	123	42.75	4.28	60 d	124	1691		L	E - T
Sc	45	100	26.5	84 d	46	889, 1121	1115 ^{65}Zn	L	T
Se	74	0.87	58.2	120 d	75	265, 280	264 ^{182}Ta	L	T
	76	9.0	21	17 s	77 m	162		S	E - T
Si	29	4.67	0.56	6.5 m	^{29}Al[c]	1273	1268 ^{28}Al(SE)	S	E
Sm	152	26.6	206	47 h	153	103	104 ^{233}Pa, ^{239}Np	L	E - T
Sr	86	9.9	0.84	2.8 h	87 m	388		M - L	E

TABLE V (cont.)

Element	Target Isotope	Isotope Abundance (%)	Cross Section (barns)[a]	Radioactive product[b] Half-life	Isotope	Gamma-rays Used (keV)	Major Interferences	Irradiation Length[e]	Preferred Flux Type[f]
Ta	181	100	21	115 d	182	1189, 1221		L	T
Tb	159	100	25.5	72 d	160	966, 1178, 1272	1173 ^{60}Co	L	T
Th	232	100	7.4	22 m	233	86.9	87.6 ^{239}U	S	E
	232	100	7.4	27 d	^{233}Pa[d]	312		L	E - T
Ti	47	7.5	0.016	3.4 d	^{47}Sc[c]	159		L	E
	48	73.7	0.00027	44 h	^{48}Sc[c]	983, 1040		L	E
	50	5.5	0.179	5.8 m	51	320		S	T
U	238	99.3	2.7	24 m	239	74.7		S	E
	238	99.3	2.7	2.4 d	^{239}Np[d]	228, 278		M - L	E - T
V	51	99.8	4.88	3.8 m	52	1434		S	T
W	186	28.6	37.8	24 h	187	479, 686		L	E
Yb	168	0.14	3470	32 d	169	177, 198		L	T
Zn	64	48.9	0.78	245 d	65	1116	1121 ^{46}Sc	L	T
	68	18.6	0.072	14 h	69 m	439		M - L	E - T
	70	0.62	0.0087	4.0 h	71 m	385		M - L	E - T
Zr	94	17.4	0.056	64 d	95	757		L	E

[a] Erdtmann, 1976 (9).
[b] Product is from (n,γ) reaction unless otherwise indicated.
[c] Product is from (n,p) reaction.
[d] Daughter from β^- decay of (n,γ) reaction product.
[e] S = short, M = medium, L = long.
[f] E = epithermal, T = thermal.

A number of irradiation/decay schemes have been described in the literature (8, 10-15). Our basic irradiation technique is as follows, although specific matrices require slight modifications. If F and/or Se are sufficiently abundant in the sample, they may be measured on a very short (30 s) irradiation followed by a 10 s count after 10 s decay. If additional short-lived elements are to be determined on these samples, they are permitted to decay 24 h before reirradiation. Then a short (<5 min) irradiation followed by two or three different counts is employed. The first count normally begins about 3 min after irradiation and lasts 60 s or less. This is intended for only the shortest lived radionuclides (e.g., ^{28}Al, ^{52}V). After a few minutes additional decay, a second, longer count (∿5 min) is taken to observe the remaining short-lived nuclides (Table VI) with γ energies below 2 MeV. If Ca or S is desired, a third 5-10 min count at a reduced gain is taken to measure their high energy γs. All counts of short-lived isotopes must be done at the reactor, since their rapid decay does not allow time for their transport to counting equipment at other locations. All longer-lived isotopes are usually returned to the Occupational Health Laboratory for counting.

A medium length irradiation (5-30 min) may be employed for the determination of isotopes with half-lives of 1-15 hours (Table VI). The samples are usually counted for 10-60 min after one hour's decay and they may be recounted again for 30-60 min after a further 24 hours decay if especially precise data for Br, Na, and K are required.

If sufficient sample is available, a new unirradiated aliquot is used for further analyses. A long irradiation lasts 1-7 hours. Longer irradiations might be employed; however, the OWR operates only 7 h/day, 5 days/wk, and sample decay during the 17 intervening hours complicates the analysis. The elements typically observed from the irradiation are also shown in Table VI. Usually two separate counts are sufficient to measure all the elements of interest. The first count is normally 15-60 min long after about 2-4 days decay, followed by a 1-24 h count after 2-4 weeks additional decay.

Flux monitoring of each irradiation is essential. This may be accomplished by running a multielement solution, pipetted onto filter paper, and folded to approximate sample geometry with each irradiation. Single element monitors may also be employed. We use Ni and Co with our short and long irradiations, respectively. At least one irradiation facility at the OWR has a fission-ion chamber neutron monitor very near it with output to a scaler. The neutron flux in the vicinity of this pneumatic tube may be monitored directly, eliminating the need to run our own monitors. This is particularly convenient when doing large numbers of short irradiations. All data are corrected for flux differences observed by one of these methods. Our experience at the OWR has been that day to day variations in the thermal flux are slight over long irradiations at constant power level. There is a definite drift of the flux level during the day and differences of as much as 10% have been observed on short irradiations done on the same day.

INSTRUMENTAL EPITHERMAL NEUTRON ACTIVATION ANALYSIS (IENA)

Epithermal neutrons are those with kinetic energies of roughly 0.4eV→1 MeV. The lower energy boundary is usually determined by the type of "filter" used to remove thermal neutrons from the flux. Although epithermal neutrons are available in all reactors, activation analysis utilizing these

TABLE VI

IRRADIATION/COUNTING TIMES FOR INSTRUMENTAL THERMAL NEUTRON ACTIVATION

Irradiation Time (min)	Decay Time (min)	Count Time (min)	Typical Isotopes Observed
0.5	0.2	0.2	^{20}F, ^{77m}Se
<5	3	1	^{28}Al, ^{52}V
<5	5-7	5	^{38}Cl, ^{66}Cu, ^{27}Mg, ^{56}Mn, ^{24}Na, ^{51}Ti
<5	12	5-10	^{49}Ca, ^{37}S, ^{80}Br, ^{56}Mn, ^{24}Na
5-30	60	10-15	^{139}Ba, ^{82}Br, ^{165}Dy, ^{72}Ga, ^{128}I, ^{116m}In, ^{42}K, ^{56}Mn, ^{24}Na, ^{87m}Sr, ^{69m}Zn, ^{71m}Zn
60-400	2800-5700	15-60	^{76}As, ^{198}Au, ^{82}Br, ^{72}Ga, ^{42}K, ^{140}La, ^{99}Mo, ^{24}Na, ^{122}Sb, ^{153}Sm, ^{239}Np, ^{187}W
60-400	30 000	60-1000	^{110m}Ag, ^{131}Ba, ^{141}Ce, ^{60}Co, ^{51}Cr, ^{134}Cs, ^{152}Eu, ^{59}Fe, ^{54}Mn, ^{181}Hf, ^{192}Ir, ^{177m}Lu, ^{147}Nd, ^{58}Co, ^{86}Rb, ^{124}Sb, ^{46}Sc, ^{75}Se, ^{182}Ta, ^{160}Tb, ^{233}Pa, ^{169}Yb, ^{65}Zn, ^{95}Zr

more energetic neutrons has not been widespread. A major disadvantage in their use is the need for a thermal neutron filter, usually Cd, in which samples usually have to be wrapped. Short-lived nuclides cannot be readily studied. A further problem is that the epithermal flux is typically one to two orders of magnitude lower than the corresponding thermal fluxes of a given reactor.

The Los Alamos OWR has a unique facility for epithermal irradiations which makes their use as convenient as thermal neutrons. This special pneumatic irradiation tube was described in detail in the section on the OWR. Although Cd has been the material of choice for epithermal filters, its melting point is too low to permit a Cd-lined facility to be permanently installed in most reactors. The B-Al alloy developed at LASL for this application has ideal temperature stability but does sacrifice some flux as the neutron cutoff energy is 280 eV, much higher than the 0.4 eV of Cd.

The lower epithermal neutron fluxes are compensated for by the fact that certain elements have strong neutron capture cross sectional resonances in this neutron energy region. The most common crustal elements that produce high levels of activity in most samples irradiated with thermal neutrons (e.g., Al, Na, K, Mn, P, Mg, Cl) do not have these resonances. Their cross sections follow the 1/v law for neutron velocity. Therefore, the induced activity of the elements with high cross sections in the epithermal region is enhanced relative to the more common activation products. Even with reduced flux, this change in relative activation decreases the instrumental detection limit for certain elements dramatically.

The concept of the "Advantage Factor" (AF) for elements irradiated in a Cd-filtered epithermal neutron flux has been exhaustively developed and tabulated by Brime and Jirlow (16) and Steinnes (17). The AF is developed by calculation comparing the actual epithermal cross section of a given element of its theoretical 1/v cross section. A condensed version of Steinnes' AF table is shown in Table VII. These calculations may be checked by irradiating elements with and without Cd covers in the same location in the reactor. A number have been experimentally evaluated and found to be accurate (18). Since the exact neutron cutoff energy in our facility is not known and since a simple covered/uncovered irradiation cannot be done in a permanently filtered system, an experiemental method had to be devised to compare a boron filtered to the Cd-filtered system of Steinnes (17). Since Na and Sc provide the principal interferent activities in samples irradiated with thermal neutrons, we decided to develop an Enhancement Factor (EF) by a double normalization procedure defined as follows:

$$EF = \frac{(X)_E/(SC)_E}{(X)_T/(SC)_T}$$

Where $(X)_E$ and $(X)_T$ are the induced activities per gram per unit irradiation time of element X in our epithermal facility and a thermal irradiation position respectively, and $(Sc)_E$ and $(Sc)_T$ represent similar activities of Sc per gram per unit irradiation time. Sodium may be used for the reference element instead of Sc. Our EF data may be conveniently compared with those of Steinnes by noting that the Steinnes AF for both Na and Sc is 1.2 and 1.0 respectively. This means that at the Cd cutoff energy AF = EF. Any net gain in relative activation of an element as a result of further suppressing the 1/v activation of Na or Sc by using the higher neutron energy cutoff of B will be reflected by EF > AF. Such a result indicates a lowering in detection limits in the boron-filtered system. The reverse result, EF < AF, indicates that there is a neutron resonance in that element for neutrons of energy $0.4 \rightarrow 300$ eV and that the use of the boron-filtered system increases the detection limits for that element in our system relative to a Cd-covered irradiaton.

Another extremely useful attribute of epithermal neutrons is the greatly reduced ^{235}U (n,f) cross section. Elements which have neutron capture isotopes at the peaks of the fission yield curve (e.g., Mo, Zr) can be seriously interfered with in thermal neutron activation. Since the (n,f) cross section follows the 1/v law (19), epithermal neutron activation minimizes this interference for nuclides that have favorable advantage factors. The improvement for Mo analysis in rocks has been documented (20). The (n,f) cross section for ^{232}Th has a resonance in the fast neutron region, so interference contributions from this reaction become more important in epithermal neutron work. In practice, the correction to Mo results for 20 ppm Th and 100 ppm Th concentrations is about 14% and 21% respectively for Mo concentrations of approximately 0.2 ppm (20). Increases in the Mo/Th ratio would also minimize this correction.

There are two different neutron reactions which are important to consider when using epithermal neutrons. The primary reaction is still (n,γ), just as with thermal neutrons. The (n,p) reaction, which generally has an energy

TABLE VII

EPITHERMAL ACTIVATION POSSIBILITIES FOR ELEMENTS WHICH CAN BE DETERMINED BY REACTOR NEUTRON ACTIVATION ANALYSIS. THE CALCULATED ADVANTAGE FACTORS ARE BASED ON R_{Cd}^{Au}=3.00, CORRESPONDING TO R_{Cd}=72 FOR A NUCLIDE FOLLOWING THE 1/v LAW - MODIFIED FROM STEINNES (17)

Element	Stable Isotope	Half-life of Radioisotope	Advantage Factor*	Enhancement Factor
Na	^{23}Na	15.0 h	1.2	3.0
Mg	^{26}Mg	9.5 min		2.5
Al	^{27}Al	2.3 min	1.8	4.7
Cl	^{37}Cl	37.2 min		1.2
K	^{41}K	12.4 h	2.0	9.2
Ca	^{48}Ca	8.8 min		2.9
Sc	^{45}Sc	84 d	1.0	1.0
Ti	^{50}Ti	5.8 min		8.6
V	^{51}V	3.8 min	1.0	1.9
Mn	^{55}Mn	2.57 h	2.3	8.0
Fe	^{58}Fe	45 d	2.3	8.9 (?)
Co	^{59}Co	5.3 y	4.4	6.2
Cu	^{63}Cu	12.8 h	2.4	12
	^{65}Cu	5.1 min	2.5	7.1
Zn	^{64}Zn	245 d	3.8	83
	^{68}Zn	13.9 h	5.9	49
Ga	^{71}Ga	14.1 h	8.8	40
Ge	^{74}Ge	83 min		26
	^{76}Ge	54 s		152
As	^{75}As	26.4 h	16	92
Se	^{74}Se	120 d	15	20
Br	^{79}Br	17.6 min	27	63
	^{81}Br	35.4 h	21	126
Rb	^{85}Rb	18.7 d	24	240
Sr	^{86}Sr	2.8 h		74
Zr	^{94}Zr	65 d $\rightarrow$ 35 d		121
	^{96}Zr	17 h		475
Mo	^{98}Mo	67 h $\rightarrow$ 6.0 h	44	424
	^{100}Mo	14.6 min	28	664

TABLE VII (cont.)

Element	Stable Isotope	Half-life of Radioisotope	Advantage Factor*	Enhancement Factor
Ru	^{96}Ru	2.9 d	33	394
	^{102}Ru	39.5 d	6.1	54
Pd	^{108}Pd	13.5 h	13	64
Ag	^{107}Ag	2.4 min	5.3	9.9
In	^{115}In	54 min	30	3.9
Sb	^{121}Sb	2.7 d	34	62
	^{123}Sb	60 d	46	68
Te	^{130}Te	25 min	2.7	57
I	^{127}I	25 min	30	257
Cs	^{133}Cs	2.05 y	22	24
Ba	^{138}Ba	82.9 min	1.3	8.4
La	^{139}La	40.2 h	2.9	5.1
Ce	^{140}Ce	32.5 d	1.8	9.6
Sm	^{152}Sm	46.8 h	20	12
Eu	^{151}Eu	9.3 h	8.1	1.5
		12.4 y	1.9	0.7
Tb	^{159}Tb	72 d	25	5.2
Dy	^{164}Dy	2.35 h	<1	<1
Tm	^{169}Tm	130 d	22	96
Yb	^{168}Yb	32 d	9.2	1.3
	^{174}Yb	4.2 d	10	1.5
Hf	^{180}Hf	42.5 d	5.4	12
Ta	^{181}Ta	115 d	37	70
W	^{186}W	23.8 h	22	16
Re	^{185}Re	90 h	18	16
	^{187}Re	16.8 h	7.9	22
Os	^{190}Os	13 h		19
	^{192}Os	31 h		31
Ir	^{191}Ir	74 d	7.8	2.8
	^{193}Ir	17.4 h	1.9	12

TABLE VII (cont.)

Element	Stable Isotope	Half-life of Radioisotope	Advantage Factor*	Enhancement Factor
Pt	^{196}Pt	18 h		165
	^{198}Pt	31 min → 3.15 d	22	82
Au	^{197}Au	2.70 d	24	13
Th	^{232}Th	22.1 min → 27.4 d	19	74
U	^{238}U	23.5 min → 2.35 d	55	130

*Relative to nuclides following the 1/v law (R_{Cd}=72).

threshold, occurs with equal probability in both thermal and epithermal fluxes from the same reactor. However, the reduction in gross induced activity from isotopes such as ^{28}Al, ^{24}Na, ^{46}Sc, and ^{59}Fe makes the (n,p) products much easier to observe instrumentally on epithermal irradiations. The nuclear properties, most useful γ-rays, irradiation length, and preferred flux are given in Table V.

Table VIII gives a listing of (n,p) reactions that are being investigated at this laboratory. The quantitative use of ^{58}Ni (n,p) ^{58}Co has been carefully documented (21). Thus far, we have proven that the use of ^{54}Mn, ^{47}Sc, ^{29}Al, ^{23}Ne, and ^{19}O for the quantitative determination of Fe, Ti, Si, Na, and F, respectively are possible. All six of these reactions produce unique products which have no important interferences from (n,γ) or (n,α) reactions (22).

The situation for using the (n,p) products of ^{28}Si, ^{27}Al, and ^{26}Mg is not as straightforward. These three reactions have strong competition from the corresponding (n,γ) reaction on ^{27}Al, ^{26}Mg, and ^{23}Na respectively. In epithermal irradiations of common silicate materials the (n,p) products account for approximately 20-50% of the induced ^{28}Al activity, about 90% of the induced ^{27}Mg activity, and 10-20% of the induced ^{24}Na activity. In principal, it is possible to resolve the two contributions through the careful irradiation of very pure standards. In practice, the overall accuracy of this

TABLE VIII

EPITHERMAL NEUTRON (n,p) REACTIONS

Target Nuclide	Isotopic Abundance (%)	Activation Product	(n,p) Cross Section (mb)	Energy Threshold MeV	Half-life	Prominent Gamma-rays (keV)	Interfering Reactions and Gamma Rays (keV)	Epithermal Cross Sections of Interfering Reactions (mb)
^{19}F	100	^{19}O	1.35	E*	27 s	193	$^{18}O(n,\gamma)^{19}O$	0.070
							$^{22}Ne(n,\alpha)^{19}O$	0.056
^{23}Na	100	^{23}Ne	1.5	3.76	38 s	439	$^{26}Mg(n,\alpha)^{23}Ne$	0.027
^{24}Mg	79	^{24}Na	1.53	4.93	15 h	1368,2754	$^{23}Na(n,\gamma)^{24}Na$	290
^{27}Al	100	^{27}Mg	4.0	1.90	9.4 m	844,1013	$^{26}Mg(n,\gamma)^{27}Mg$	13
							$^{30}Si(n,\alpha)^{27}Mg$	0.155
							847 keV ^{56}Mn	--
^{28}Si	92.2	^{28}Al	6.4	3.99	2.2 m	1779	$^{27}Al(n,\gamma)^{28}Al$	180
							$^{31}P(n,\alpha)^{28}Al$	0.118
^{29}Si	4.7	^{29}Al	560	3.00	6.5 m	1273	1268 keV ^{28}Al Single Escape	--
^{31}P	100	^{31}Si	36	0.72	2.6 h	1266	$^{30}Si(n,\gamma)^{31}Si$	47
							$^{34}S(n,\alpha)^{31}Si$	22
							1268 keV ^{28}Al Single Escape	--
^{46}Ti	8.0	^{46}Sc	10.5	1.62	84 d	889,1021	$^{45}Sc(n,\gamma)^{46}Sc$	10 700
^{47}Ti	7.5	^{47}Sc	16.3	E	3.4 d	160	$^{50}V(n,\alpha)^{47}Sc$	1.5
							$^{46}Ca(n,\gamma)^{47}Ca(\beta^{+})^{47}Se$	320
^{48}Ti	73.7	^{48}Sc	0.27	3.27	43.7 h	983,1037 1312	$^{51}V(n,\alpha)^{48}Sc$	0.022
^{54}Fe	5.8	^{54}Mn	82.5	E	312 d	835	834 keV^{72}Ga	--
							$^{55}Mn(n,2n)^{54}Mn$	0.258
^{58}Ni	68.3	^{58}Co	113	E	71 d	811	$^{59}Co(n,2n)^{58}Co$	0.72

*Exothermic

approach is no better than ±25% (22). Thermal neutron activation or non-nuclear methods provide more quantitative data, and we have been unable to perfect the (n,p) reaction. The use of (n,p) reactions on Ca and P has thus far shown no sensitivity whatsoever (22).

Epithermal neutrons have also proven to be extremely useful in the determination of U in environmental materials where the U concentration is

>10 ppm, or where the 235/238 isotope ratio is perturbed from 0.072. The details of the determination of U in ores and of depleted U in soils have been previously published (23, 24).

Analysis

A stepwise series of irradiation/decay/count sequences similar to that used for ITNA is the approach used. These are summarized along with the elements determined on each irradiation/count in Table IX. A number of other activities are observed in various matrices, but only the isotopes shown in the table are routinely used for quantitative measurements. Flux variations in our irradiation facility are such that all irradiatons of 1 min or longer have a gold flux monitor included with the samples. The monitors are prepared by pipetting an Au solution onto punched filter discs and inserting them into the caps of the 4 cm^3 polyethylene rabbit (see Fig. 1). Other monitoring procedures have been described in the literature (25, 26), but we have not yet

TABLE IX

IRRADIATION/COUNTING TIMES FOR INSTRUMENTAL EPITHERMAL NEUTRON ACTIVATION

Irradiation Time (min)	Decay Time (min)	Count Time (min)	Typical Isotopes
0.2	0.3	0.2 - 0.5	^{19}O, ^{23}Ne
1.0	2.0 - 10	1.0 - 5.0	^{28}Al, ^{29}Al, ^{27}Mg. ^{56}Mn, ^{80}Br, ^{233}Th, ^{239}U
10	100-2000	10 - 100	^{87m}Sr, ^{82}Br, ^{135m}Ba, ^{139}Ba, ^{72}Ga, ^{76}As, ^{122}Sb, ^{153}Sm, ^{99}Mo, ^{140}La, ^{24}Na, ^{42}K, ^{239}Np, ^{47}Sc, ^{48}Sc
100	1000-100 000	100 - 1000	^{75}Se, ^{233}Pa, ^{99}Mo, ^{47}Sc, ^{58}Co, ^{54}Mn, ^{131}Ba, ^{95}Zr, ^{51}Cr, ^{65}Zn, ^{124}Sb, ^{59}Fe, ^{60}Co

investigated them. Other details on the use of epithermal neutrons in activation analysis may be found in the literature (27-34).

<u>Sample Preparation for ITNA and IENA</u>

Five different matrix types are routinely handled by the Environmental Surveillance Analytical Chemistry Section: solutions, air particulates, geologicals, vegetations, and tissues.

Solutions may be irradiated directly in the OWR for short periods. TCR-11 has a 42° bend at the end so that the standard 4 cm^3 screw-cap rabbit can only be filled 2/3 full of a liquid. The seal is water tight for only a few minutes. Twenty-five or forty-ml volume rabbits may also be run in TCR 6, 7, and 9, but they also leak after a few minutes. Solutions irradiated in this fashion must have their containers changed before counting as significant Al, Mn, and Cl contamination from the rabbit tubes has been observed. Solutions may not be directly irradiated in the epithermal facility.

Longer irradiations of liquids require that they be dried or encapsulated in quartz . Freeze drying can be employed, and trace element losses during it have been carefully studied (35). For most routine measurements, we air dry 10-100 ml of solution onto 10 cm square polyethylene films. These are then folded to fit the 4 cm^3 vials. Standards and flux monitors are prepared similarly. The spectrum of elements which can be determined in natural waters has been discussed in detail by Salbu et al. (24).

Trace element determination in air particulates by neutron activation has received considerable attention (10, 11). We employ essentially the same methods as discussed in these references. The filters are folded "face in" to minimize the loss of collected particulate, individually sealed in polyethylene bags, inserted directly into 4 cm^3 rabbits, and irradiated along with standards.

Geological materials are first ground to -325 mesh in an alumina ceramic-lined Shatterbox grinder. The pulverized samples are then weighed into small snap-cap polyethylene vials (BEEM vials--Ladd Research, VT), which hold 100-300 mg of the sample. Four vials fit into one 4 cm^3 rabbit (see Fig. 1). Since radial flux gradients are very small and the linear flux gradient characterized, normally two rabbits are irradiated at a time during long irradiations. The BEEM vials have been shown to have such low levels of trace metal contaminants that the samples need not be transferred after irradiation. These vials also provide a convenient "constant" geometry for the samples.

Standards are prepared by pipetting 50 μℓ of solution onto a 2 cm diameter Whatman No. 2 or No. 41 filter paper. After air drying, it can be folded so that it just fits the small BEEM vials. Nadkarni and Morrison have demonstrated that NBS Standard Reference Materials (SRM) may be used as multielement irradiation standards (36). We prefer to reserve these SRMs for use as quality assurance materials.

Vegetation samples are handled in much the same manner as geologicals. They are first dried (air or freeze drying), ground in the Shatterbox, and weighed into snap-cap vials for irradiation.

Tissue and high water content biologicals require more careful sample preparation. These materials must normally be freeze dried. When dry, they are normally weighed directly into snap-cap vials without grinding and handled like the vegetations.

If certain highly volatile elements, e.g., Hg, are to be measured, the samples must be sealed in quartz ampoules to prevent loss during irradiation (1, 2). Although we have this capability, we have chosen to measure these elements by other techniques (37, 38) and seldom use quartz encapsulation.

Data Reduction

One of the cornerstones of any form of γ- or x-ray analysis is a good table of energies, relative intensities, and, where appropriate, half lives. Extensive tabulations of radioactive decay γ-rays (39, 40) and capture γ-rays (41-43) exist. Appendixes I and II represent a condensation of the tables for radioactive decay γ-rays concentrating only upon isotopes observed in environmental materials. Appendix I is ordered by element and Appendix II is arranged in order of increasing energy.

A number of large machine computer codes have been written for the reduction and identification of γ-ray spectral data. The best example of these codes is probably GAMANAL written by R. Gunnick at the Lawrence Livermore Laboratory (44). This program is available at LASL, but we have elected to develop a small machine capability in addition. Considerable simplification of our needs has been achieved by our approach to short-lived analysis (described above). When counting at high dead times (>10%) with rapidly decaying sources (i.e., the half lives of the principal isotopes are less than five times the count length), the data require complex special corrections to compensate for the response time of the measurement electronics to the changing dead time (45-47).

Spectral data from the Analytical Section's γ-counting procedures may originate from several different counting systems. Seven-track magnetic tape recorders are available at each counting system and are used as the storage medium for the accumulated counting data. A set of data reduction programs has been developed in the analytical section to enable the analyst to retrieve the data from magnetic tape and analyze it on either of two PDP-11 minicomputers which are available in the Environmental Surveillance Group.

The magnetic tapes written during counting sessions are transported to the Occupational Health Laboratory for analysis. A PDP 11-20 computer equipped with two Kennedy Model 9100 7 track tape drives is used to read the tapes. Programs have been developed to translate each of the specific formats in which the tapes may be written into a common disk file format that is compatible with the data analysis program GAMSPEC (48).

The γ-ray spectra generated by our analyses are usually simple, with only a small portion of the spectrum of interest in which the γ peaks are generally well defined. Program GAMSPEC was developed in group H-8 to suit this application. GAMSPEC is written in FORTRAN for use under this RT-11 operating system with a PDP-11 computer equipped with at least 20K words of memory. The program interactively queries the user for pertinent sample information and counting parameters, and then the appropriate spectral data are read from a disk file and plotted on the console terminal for visual examination. Integration limits for the γ-peaks of interest are supplied by typing an "x" under the plot at the points that are desired as the low and high limits of each peak. A baseline background correction is then performed by the program, and the previously entered counting parameters are included to calculate a final result.

Program GAMSPEC was designed for use with computers having a CRT device as the console terminal and some type of hard copy device installed as a line printer. The program features optional disk storage of hard copy images as they appear on the CRT, so that the speed of program execution is not slowed by a printing device. The disk files containing the hard copy images may subsequently be listed under the control of another program: LISTER (48). LISTER can run simultaneously with GAMSPEC under the RT-11 Foreground/ Background monitor with 28K words of memory, or after the termination of GAMSPEC under the RT-11 Single Job monitor with the $\geq$20K words of memory mentioned previously.

The use of an automatic peak search and integrate type routine has been considered, but has not yet been implemented in our section due to the relatively simple needs we have for spectral analysis. The program described above has been found both fast and simple to operate, and it has an added advantage over most peak searching routines in that it is able to analyze portions of the spectrum in which very small peaks exist.

THERMAL NEUTRON CAPTURE GAMMA RAY SPECTROSCOPY

In-situ spectroscopy of prompt γ-rays produced by irradiating materials in a thermal neutron flux provides a means of elemental analysis that can have advantages over alternative analytical methods. Two primary factors govern the detection limit for elemental analysis using the (n,γ) reaction: the partial capture cross section for producing a useful transition and the elemental composition of the matrix material being examined. Limitations of the first type are fundamental and can be assessed from known nuclear properties of the elements (41-43). Figure 3 illustrates these considerations. Plotted is the partial thermal (n,γ) cross section per unit mass of the most intense transition (regardless of energy) emitted by most of the elements. In most cases, the intensity of the characteristic γs vary over about 2-1/2 orders of magnitude. It is only in those cases where elements have most of their transitions into one γ that prompt (n,γ) spectroscopy can be considered a practical tool for trace analysis. An earlier paper from this Laboratory demonstrated the utility of the technique for measuring submicrogram quantities of B and Cd in complex materials (49). With these exceptions, the main analytical usefulness of prompt γ-rays spectroscopy lies in its ability to give fairly rapid, nondestructive determinations of many elements having moderately high concentrations, generally without chemical separations or other complicated sample preparation. Subsequent work at this Laboratory has been concerned with applications where more conventional analytical techniques are difficult or manpower intensive. We did a detailed study of the analysis of S in complex matrices (50) and analyzed standard lithic materials for most of their major and minor constituents (51). The feasibility of analyzing C, N, and H by prompt γ-ray spectroscopy in environmental materials has also been demonstrated (52). Carbon, N, H, and S have traditionally been measured by destructive combustion methods (53) or, in the case of N, by the classic Kjeldahl determination (54).

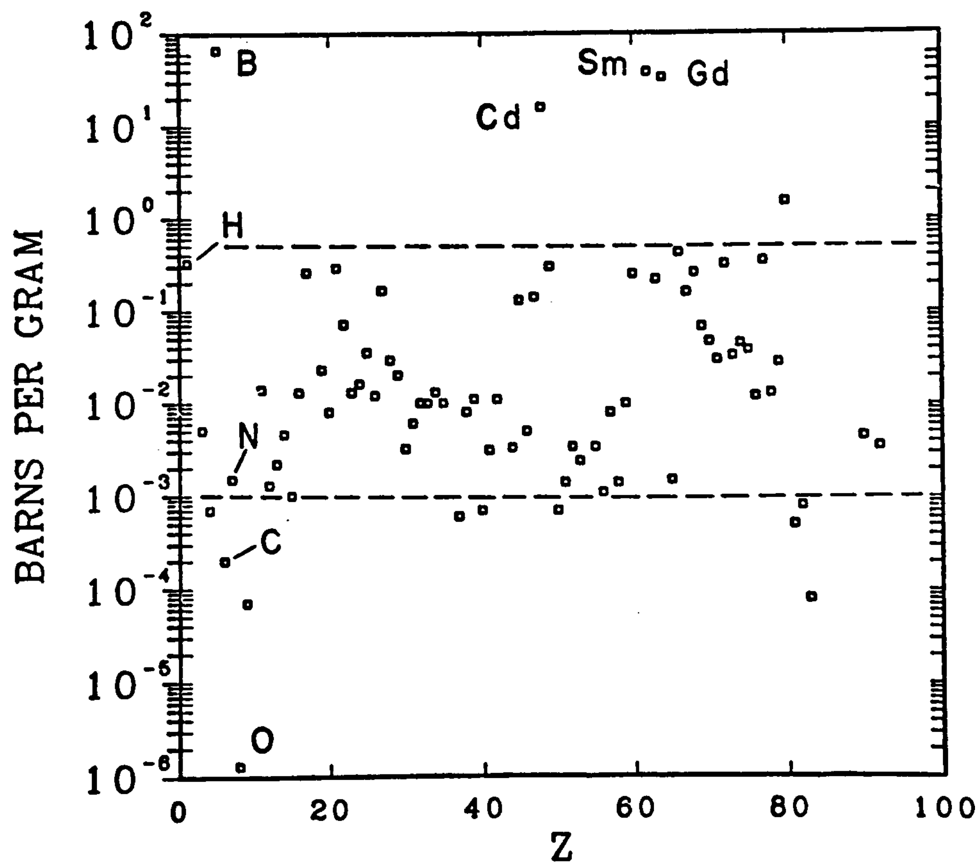

Fig. 3. Plot of the single most intense prompt gamma-ray emitted by the elements after thermal neutron capture. Points for the noble gases and for radioactive elements are not included.

The basic layout of the capture-γ facility at the OWR has been described above. The list of principal capture γs used for our analytical determinations is presented in Table X. These lines have proven to be the most useful. Note that the most intense line is not always the best from the standpoint of interferences. The data behind the various choices and trade-offs has been presented in the literature (49-52). Another excellent compilation of useful γ-rays is presented in Failey et al. (55) as well as a different approach to multielement analysis.

External neutron beams and irradiation of the samples outside the reactor are more frequently used for the generation of capture γ-ray data. The

TABLE X

ENERGIES OF CAPTURE GAMMA RAYS USED FOR ANALYTICAL DETERMINATIONS (46)

Element	Preferred Gamma Ray (keV)	Alternative Gamma Ray (keV)
Al	1779 (100)*	984 (21)
		2960 (28)
		3034 (24)
		3465 (20)
		4133 (23)
		4259 (19)
		7695 (20)
		7724 (100)
B	478 (100)	None
C	4945 (100)	1261 (44)
		3684 (47)
Ca	1942 (100)	520 (11)
		4419 (21)
		6420 (54)
Cd	559 (100)	651 (19)
		806 (6)
		1364 (7)
Fe	352 (40)	5920 (30)
		6018 (30)
		7632 (100)
		7646 (81)
H	2223 (100)	None
K	771 (100)	1159 (19)
		1618 (25)
		2073 (33)
		5380 (23)
Mg	1808 (62)	585 (53)
		2828 (87)
		3054 (27)
		3917 (100)
N	5267 (93)	1888 (100)
		3675 (57)
		4507 (58)
		5297 (68)
		10828 (55)

TABLE X (cont.)

Element	Preferred Gamma Ray (keV)	Alternative Gamma Ray (keV)
Na	871 (99)	2027 (77) 2518 (67) 3588 (67) 3982 (84) 6395 (100)
P	636 (76)	1413 (88) 2154 (95) 3900 (100) 6785 (81)
S	841 (100)	2380 (59) 3220 (36) 5420 (78)
Si	3539 (100)	2093 (34) 4934 (89) 6380 (16)
Ti	1381 (100)	342 (47) 6418 (56) 6760 (83)

*Relative intensity (%).

literature on this technique as well as capture-γ analysis in general has been surveyed recently (56).

Two different containment schemes are used for sample irradiation. Approximately 500 mg of a geological or biological sample may be weighed into a BEEM snap-cap polyethylene vial. This vial is then mounted in the center of the cylindrical graphite rabbit using a polyethylene disc with a hole in the center to receive the sample. Water samples may be similarly handled after air drying 10 ml onto a 7.5 cm x 7.5 cm polyethylene sheet. This method works for 12 elements--all except C, H, and N. A specially designed Be sample holder is used in the place of the BEEM vial and polyethylene holder ring and the capture γ-ray channel inside the reactor is evacuated when C, H, and N are to be determined. This configuration eliminates interference to C and H from the polyethylene and to N from the air.

By comparison with primary elemental standards, the concentrations of the elements of interest are determined and compared to the certified values. The results of these comparisons are published in Ref. 49-52. These data demonstrate quantitative capability for B, Cd, S, Fe, Si, Al, Na, K, Ti, N, and H in a wide variety of environmental matrices. The data are inconclusive for C, Mg, and P, and further investigation is required to determine the usefulness of capture γ-ray spectrometry for these analyses.

DELAYED NEUTRON ASSAY

The determination of U in environmental materials has been dominated by fluorometric methods for over 20 years. Before 1977, almost all U measurements made by the Environmental Surveillance Group utilized standard fluorometric methods (57-58). Several deficiencies in the procedure prompted us to search for alternate techniques. A decision by Safety that our bottled gas for the fusion burner must be located outside in an unheated area resulted in considerable instability in our burner performance due to wide fluctuations in the gas temperature. We have never been entirely satisfied with the QA data for environmental materials. The ethyl acetate extraction proved to be particularly tempermental with the wide matrix types encountered in environmental research. First, instrumental epithermal activation was applied to the determination of U and depleted U in rocks and soils (23, 24). When a delayed neutron system was constructed by the Research Reactor Experiments Group (P-2), we decided to investigate the application of this method to environmental U measurement.

One of the least common decay modes encountered in nuclear activation is the emission of a neutron in preference to α, b, or γ decay. This phenomenon is found exclusively in the decay of very light nuclei (^{9}Li, ^{17}N) or in the decay of fission products of very heavy nuclei (^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu) (59). When a nucleus undergoes fission, only a small fraction of the fission products decay by neutron emission, and these neutrons are distinct from the prompt neutrons emitted during the fission process. Fission can be induced in ^{233}U, ^{235}U, and ^{239}Pu with thermal neutrons, while fast neutrons induce fission in ^{232}Th and ^{238}U. By judicious use of the neutron spectrum, ^{235}U fission can be favored over other products, provided the sample does not contain significant amounts of Pu. With natural materials, this is not a problem (60-62).

Delayed neutron yields from fission are detailed in Keepin et al. (63) and thermal fission yields are summarized in Table XI. Groups of neutron emitters with similar half lives have been identified. By manipulating the irradiation and decay times of the sample, different decay groups become the primary contributors to the neutrons observed. From Table XI, groups 2, 3, and 4 constitute 80% of the total delayed neutrons emitted from the thermal neutron fission of ^{235}U. Since ^{17}N, produced from $^{17}O(n,p)^{17}N$ reaction, is also a delayed neutron emitter ($t_{1/2}$ = 4.1 s), this source of interference can be removed by waiting until the shorter-lived products have decayed before counting the neutrons. A 60 s irradiation with a 20 s decay preceding a 60 s neutron count observes 44% of all neutrons emitted. The 20 s decay permits 97% of the ^{17}N to decay, effectively eliminating this source of interference.

Two detection media are commonly used with delayed neutron measurement--BF_3 and ^3He. Two specially designed ^3He neutron detectors, one for water samples and one for geologicals, were developed for use in the DNA system at the OWR (64). Basically, the water detector consists of two concentric rings of ^3He-filled tubes imbedded in a moderator to slow down the emitted neutrons and increase the counting efficiency. A 2.5-cm thick Pb absorber separates the sample from the ^3He tubes in the water detector to reduce γ-ray pile up in the counting electronics. For geologicals, only one ring of ^3He counters is used because higher levels of U are encountered, and the Pb absorber thickness is increased to 4.5 cm in order to control the higher levels of induced γ activity in rock samples. Both detectors are located at the bottom of a 3.25-m deep water pool. This amount of shielding reduces the neutron background in the counter by at least an order of magnitude.

The analysis scheme is shown in block diagram form in Fig. 4. Samples in polyethylene rabbits are individually weighed and loaded sequentially into a clip which holds up to 50 samples. The clip fits directly into the pneumatic loader which injects the sample into the thermal flux of the reactor through two switches, S_1 and S_2. During the short irradiations, S_1 is repositioned and the rabbit, when ejected from the reactor, drops directly into the neutron counter. After the decay period, the counter is activated and switch S_2 is changed so that when the sample is removed from the counter at the end of the count, it is shot into a storage pig. The entire operation after the clip loading is computer controlled.

TABLE XI

DELAYED NEUTRON YIELDS FROM THERMAL FISSION (63)

Isotope	No. of Delayed Neutrons/Fission	Group Index	Group Half-life (sec)	Relative Group Yield (%)
		Thermal Fission		
^{235}U	0.0158	1	55.7	3.3
		2	22.7	21.9
		3	6.2	19.6
		4	2.3	39.5
		5	0.61	11.5
		6	0.23	4.2
^{239}Pu	0.0061	1	54.3	3.4
		2	23.0	29.8
		3	5.6	21.2
		4	2.1	32.7
		5	0.62	8.5
		6	0.26	4.4

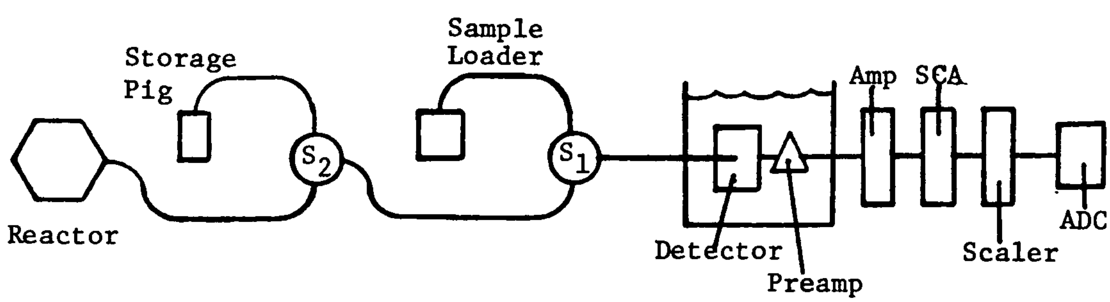

Fig. 4. Block diagram of the delayed neutron assay system at the OWR.

The output of the detector is passed through a preamplifier (located underwater in the detector can) through a linear amp and into a single channel analyzer (SCA). The output of the SCA goes to a scaler where the neutron counts within the window set on the SCA are recorded. A typical neutron spectrum taken on a 100-channel analyzer is shown in Fig. 5. The closed dots show the detector response to a pure neutron flux from a Ra-Be source lowered into it to check detector response. No γ-ray pile up is seen since the neutron source emits few γ-rays. When a spectrum is taken of an irradiated sample of granodiorite rock (open circles), the neutron peak clearly remains, but γ-ray pile up below channel 50 is strong. Experience has shown that the γ pile-up peak does not invade the neutron peak region for geologicals thus far encountered, so only a single SCA window is set directly over the neutron count peak (65). For waters, where less shielding is available in the counter and lower levels of U are encountered, the γ pile-up pulse has been seen to invade the neutron peak area. To detect this, two SCAs are used in the water system, one set on the neutron peak as before and the second with its window in the valley region between channels 50 and 60 in Fig. 5. Both outputs are sent to separate scalers and the data from the sample are discarded if the peak/valley ratio is less than 10. The designers feel that this should provide sufficient protection against γ pile up being misinterpreted as neutron counts (65).

The water and geological DNA systems operate simultaneously and independently, using two different thermal column irradiation ports. For geologicals, where the U/O ratio is much higher than in water samples (which are mostly H_2O), an abbreviated irradiation-decay-count scheme has been developed. A 20s-10s-20s arrangement is used instead of the 60s-20s-60s used for water samples. Neutron counts from the $^{17}O(n,p)^{17}N$ reaction have not been detected in geologicals above the cosmic ray-reactor neutron background. The shorter sequence enables a sample to be analyzed every 36 s instead of the 90 s interval required for the water system (65).

Standardization is accomplished by irradiating samples with known ^{235}U content, similar to the comparator technique used by most activation analysts. Either artificially doped solids and liquids or certified standards can be used. The water analyses are standardized against a 150 parts per billion solution prepared by diluting an aliquot of NBS SRM 950a (U_3O_8) dissolved in HNO_3. The geological system is standardized by irradiating a known

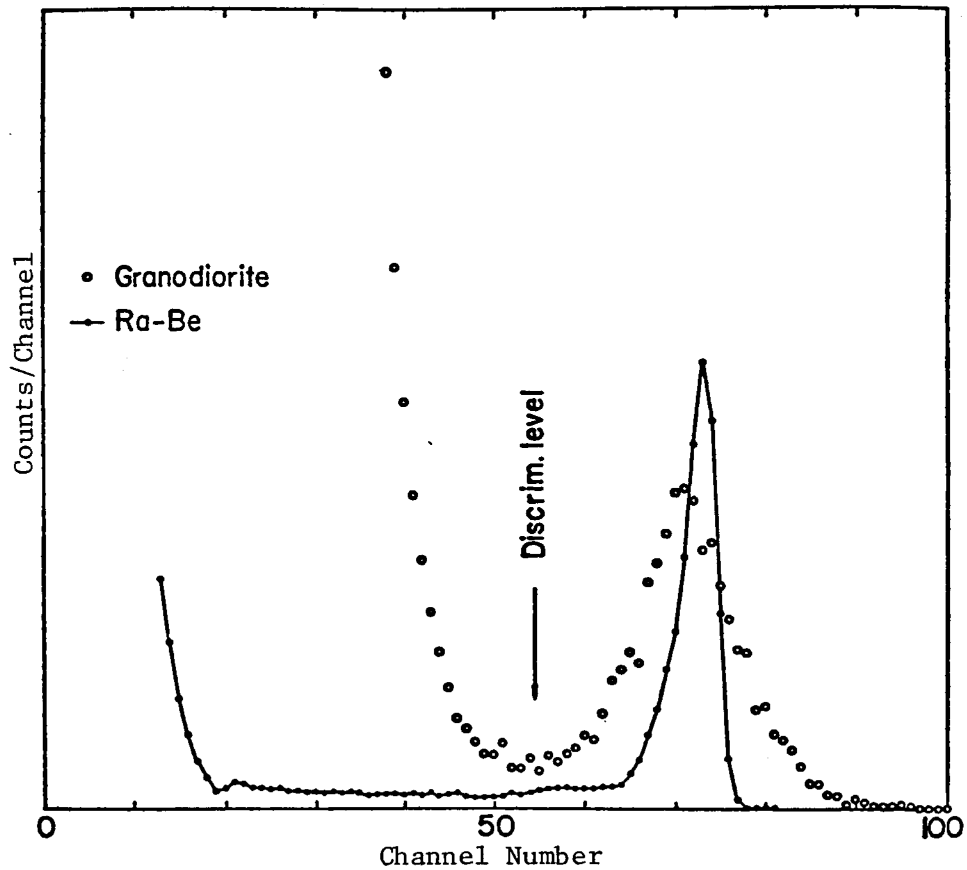

Fig. 5. Superimposed neutron spectrum pulse-height analysis from a low intensity Ra - Be source and from an irradiated rock sample showing gamma-ray pile-up effect and the ideal placement of the discrimination level (reprinted from Nuclear Instruments and Methods by permission).

amount of NBS SRM 1633 (Fly Ash - 11.6 ppm U). One limitation of this standardization procedure must be appreciated. Since thermal DNA measures neutrons from only ^{235}U fission, the $^{235/238}U$ isotopic ratio must be known in order to translate the signal into total U at the natural isotopic abundance of 0.72% ^{235}U. Since the U in both calibration standards has the crustal isotopic ratio, the data translate directly. The analyst must beware of samples which might have this ratio perturbed, whether enriched or depleted. Our studies have shown that DNA will grossly underestimate the total U content of depleted U samples and strongly overestimate the total U concentration in samples containing enriched U (24). It is imperative that the sample also be analyzed by a technique sensitive to ^{238}U only (such as epithermal neutron activation) if the U isotope ratio is suspect. Only in this manner can meaningful interpretation of the DNA results be made. A bonus of this double analysis is that a value for the isotope ratio can be determined, and both enriched and depleted U samples may be analyzed for total U. The isotope ratio thus determined does not compete with mass spectrometry (MS) for precision, but is sufficient for most environmental monitoring purposes and considerably less expensive than MS measurements. For samples known to contain depleted U, analysis by epithermal activation alone gives excellent results (24).

Our operating experience with the OWR DNA systems is summarized in our quality assurance data published in Gladney et al. (23, 66). These QA samples were run in conjunction with our monitoring effort and represent average performance of the DNA systems.

It is not possible to accomodate the wide range of uranium concentrations encountered in environmental materials with the same irradiation scheme. Normally, 1- to 2-g samples are used in the geological counter. The sample size can be reduced to 50 mg without noticeable loss in precision. The next device is to cut reactor power back from 8 Mw to as little as 10 Kw, nearly three orders of magnitude reduction in the neutron flux (flux scales linearly with reactor power). These methods are necessary to keep the neutron counting rate below the saturation point for the detectors. Geologicals with U concentrations above 100 ppm should not be run at full sample weight and full reactor power. Detector saturation begins to be a problem with water above 1.0 ppm U.

DNA and epithermal activation have provided methods that are instrumental, cost effective, manpower efficient, and matrix independent. The QA data are also very reliable. We have switched our U analyses almost exclusively to those two nuclear procedures. The use of the delayed neutron facility is arranged by contacting Group P-2.

RADIOCHEMICAL SEPARATIONS

When an element of interest cannot be detected in an irradiated environmental sample by instrumental methods, the final appeal is to a chemical separation. The purpose is to eliminate interfering gross activities and need not entail complete isolation of the element. A vast array of separation procedures has been published over the past 30 years and no attempt will be made to review this literature. Rather, only separations in routine use in this laboratory for environmental monitoring will be mentioned.

Philosophically, separations can be approached in two ways. One may add a tracer (radioactive or stable) at the outset of a procedure and determine the "chemical yield" at the end of the chemistry by counting or reactivating the tracer. Alternatively, separations can be developed that have essentially quantitative yields (>98%) and no tracer is required. Although the second approach requires more development work initially, it does not depend upon any isotopic equilibrium between the sample and added tracer.

Several monographs and a number of research papers have been published concerning the use of inorganic ion exchange media (67-83). The media investigated include hydrated antimony pentoxide, hydrated manganese dioxide, anhydrous manganese dioxide, tin dioxide, zirconium phosphate, cupric sulfate, cupric sulfide, cuperous chloride, and cerous oxalate in addition to aluminum oxide. Nevertheless, the mechanism of the exchange reactions is poorly understood. Insufficient theory makes it difficult to tailor separations as neatly as can be done with organic exchange resins. Another problem is that ions retained on the inorganic media generally cannot be eluted. The routine use of Al_2O_3 for separation of As, W, and Sb from waters (78); As, W, Sb, Mo, and Th from rocks (79); and Se from rocks, vegetations, biologicals, and coals (80) have all been documented in previous publications.

We also utilize the noble metal specific srafion NMRR ion exchange resin for the separation of Mo (81), the noble metals (82), and Cu (83) from geological samples.

STANDARDS

All nuclear methods of analysis must be standardized in one of two fashions: (1) either through the use of nuclear cross sections or (2) by comparison to elemental monitors of known composition. For the former, only a limited number of elements have carefully measured nuclear cross sections (e.g., Au, H). An example of this standardization technique is given in Gladney et al. (49). By far, the latter is the more common procedure, since no assumptions about the quality of the cross sectional data need be made. One must, however, be aware that some elements (U, Li) in "off-the-shelf" chemicals may have altered (non-natural) isotopic abundances. In these cases a standard with certified isotopic abundance as well as certified chemical content must be obtained.

For nuclear analysis, elemental monitors may either be used as solids or they may be dissolved, diluted, and pipetted onto another matrix. One must be cautious when using solids directly, due to possible neutron self-shielding effects which will yield high results for the unknown. Self shielding typically occurs for elements which have moderate to high cross sections (e.g., Au, Cu). The mass of an element required to yield various self-shielding effects is shown in Table XII. Gross activity must also be kept to the same levels as that of the samples being analyzed, or dead-time differences may make the results less accurate. Solid elemental standards work best for elements which are in major abundance in the matrix being analyzed and have small cross sections (e.g., Mg, Ca, Fe, Si).

Standards for elements which are present at trace levels and/or have high cross sections must be prepared by dissolving a known amount of the element of interest, diluting the stock solution to the appropriate concentration, and pipetting a known amount of the diluted stock onto some kind of substrate (e.g., filter paper). This standard is then folded to approximate the size and shape of the sample to be analyzed. For greater accuracy, one should prepare his own solutions from among the elements and compounds suggested in Table XIII. This list, which is an expanded form of that prepared by Smith and Parsons (85), has been developed from experience and incorporates the following criteria:

1. Stability

   The element/compound should not be deliquescent, efflorescent, or hygroscopic. If it does absorb water, it should be readily dryable and not undergo any chemical change upon drying. The solution should not undergo chemical change (e.g., precipitation) upon aging or dilution.

2. Purity

   The element/compound should be readily available in reasonable (>99%) purity. The exact degree of purity required is influenced by whether single element or multielement solutions will be prepared.

3. Ease of Preparation

   The element/compound should be soluble in water, common mineral

TABLE XII

MAXIMUM SAMPLE SIZE (grams) FOR VARIOUS DEGREES OF SELF SHIELDING (84)

Element	Magnitude of Self-Shielding 10%	1%	0.1%
Gd	2.61×10^{-11}	--	--
Sm	4.00×10^{-8}	--	--
Cd	1.91×10^{-7}	--	--
Eu	2.76×10^{-7}	--	--
Dy	1.04×10^{-5}	--	--
Ir	2.44×10^{-5}	--	--
Hg	1.17×10^{-4}	--	--
Mn	2.18×10^{-4}	--	--
Rh	2.96×10^{-4}	--	--
Li	4.87×10^{-4}	--	--
In	5.22×10^{-4}	--	--
Pa	8.71×10^{-4}	--	--
Au	2.96×10^{-3}	--	--
Re	3.48×10^{-3}	--	--
Hf	3.83×10^{-3}	--	--
Lu	6.09×10^{-3}	--	--
Ag	6.09×10^{-3}	--	--
Er	6.96×10^{-3}	--	--
Co	7.13×10^{-3}	--	--
Ho	0.0278	2.30×10^{-5}	--
Nd	0.0836	6.91×10^{-5}	--
Tb	0.0871	7.20×10^{-5}	--
Sc	0.0888	7.34×10^{-5}	--
Yb	0.278	2.30×10^{-4}	--
Ta	0.313	2.59×10^{-4}	--
W	0.365	3.02×10^{-4}	--
Os	0.522	4.32×10^{-4}	--
Zn	0.591	4.89×10^{-4}	--
Se	--	1.58×10^{-3}	--
Pd	--	1.80×10^{-3}	--

TABLE XII (cont.)

Element	Magnitude of Self-Shielding 10%	1%	0.1%
Ti	--	2.70×10^{-3}	--
Pt	--	2.74×10^{-3}	--
Ni	--	2.88×10^{-3}	--
Cs	--	3.16×10^{-3}	--
V	--	3.31×10^{-3}	--
Cu	--	6.91×10^{-3}	--
U	--	0.0101	--
Cr	--	0.0104	--
La	--	0.0115	--
Br	--	0.0187	--
Fe	--	0.0202	--
Sb	--	0.0245	--
Th	--	0.0288	2.96×10^{-5}
Ru	--	0.0446	4.51×10^{-5}
Ga	--	0.0504	5.34×10^{-5}
Te	--	0.0576	5.64×10^{-5}
Mo	--	0.0648	6.06×10^{-5}
Ge	--	0.101	9.87×10^{-5}
As	--	0.158	1.55×10^{-4}
K	--	0.994	9.72×10^{-4}
Y	--	--	2.39×10^{-3}
Sr	--	--	6.06×10^{-3}
S	--	--	7.05×10^{-3}
Na	--	--	9.59×10^{-3}
Ba	--	--	0.0141
Ce	--	--	0.0176
Sr	--	--	0.0176
Al	--	--	0.0240
Ca	--	--	0.0352
P	--	--	0.0700
Rb	--	--	0.0747

TABLE XII (cont.)

Element	Magnitude of Self-Shielding 10%	1%	0.1%
Si	--	--	0.127
Zr	--	--	0.296
Pb	--	--	1.69
Mg	--	--	2.12
Be	--	--	21.2
Bi	--	--	282
C	--	--	987

TABLE XIII

ELEMENTS AND COMPOUNDS FOR STANDARD SOLUTION PREPARATION

Element	Compound	Formula Weight (g)	Weight Required to Make 1000 ppm (g/ℓ)	Dissolution Method
Al	metal	26.98	1.000	hot, dil. HCl
	Al_2O_3	101.96	1.890	NH_4OH
Sb	$KSbOC_4H_4O_6 \cdot 1/2H_2O$	333.9	2.743	water
As	As_2O_3	197.8	2.641	dil. HCl
Ba	$BaCO_3$	197.4	1.437	dil. HCl
Bi	Bi_2O_3	466.0	1.115	HNO_3
B	H_3BO_3	61.84	5.720	water
Br	KBr	119.0	1.489	water
Cd	metal	112.40	1.000	dil. HNO_3
	CdO	128.4	1.142	HNO_3
Ca	$CaCO_3$	100.1	2.497	dil. HCl
Ce	Ce_2O_3	328.24	1.171	dil HNO_3
	$(NH_4)_2Ce(NO_3)_6$	548.2	3.913	water
Cs	$CsNO_3$	194.91	1.467	water
	Cs_2SO_4	361.9	1.361	water
Cr	metal	52.00	1.000	HCl
	$K_2Cr_2O_7$	294.2	2.829	water
Co	metal	58.93	1.000	HNO_3
Cu	metal	63.55	1.000	dil HNO_3
	CuO	79.54	1.252	hot HCl
Dy	Dy_2O_3	373.0	1.148	hot HCl
Er	Er_2O_3	382.6	1.144	hot HCl
Eu	Eu_2O_3	351.9	1.158	hot HCl
Gd	Gd_2O_3	362.5	1.153	hot HCl
Ga	metal	69.72	1.000	hot HNO_3
	Ga_2O_3	187.4	1.344	NH_4OH (?)
Ge	GeO_2	104.6	1.441	hot NaOH
Au	metal	197.0	1.000	hot Aqua Regia
	NH_4AuCl_4	356.82	1.812	water
Hf	metal	178.5	1.000	HF
Ho	Ho_2O_3	377.9	1.146	hot HCl

TABLE XIII (cont.)

Element	Compound	Formula Weight (g)	Weight Required to Make 1000 ppm (g/ℓ)	Dissolution Method
In	metal	114.82	1.000	HNO_3
	In_2O_3	277.6	1.209	hot HCl
I	KIO_3	214.0	1.686	water
Ir	$(NH_4)_2IrCl_6$	441	2.30	water
Fe	metal	55.47	1.000	hot HCl
La	La_2O_3	325.8	1.173	hot HCl
Lu	Lu_2O_3	397.9	1.137	hot HCl
Mg	metal	24.31	1.000	HNO_3
	MgO	40.31	1.658	HCl
Mn	metal	54.94	1.000	HNO_3
	metal	94.94	1.000	HNO_3
Mo	MoO_3	143.9	1.500	NH_4OH
	$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$	1235.9	1.840	water
Nd	Nd_2O_3	336.5	1.166	HCl
Ni	metal	58.71	1.000	hot HNO_3
Nb	Nb_2O_3	265.8	1.430	HF
Os	$(NH_4)_2Os\ Cl_6\cdot 2H_2O$	475	2.50	water
Pd	metal	106.4	1.000	hot HNO_3
	$K_2Pd\ Cl_4$	284.29	2.672	water
	$K_2Pd\ Cl_6$	355.20	3.338	water
P	$NH_4H_2PO_4$	115.03	3.714	water
Pt	metal	195.09	1.000	aqua Regia
	$K_2Pt\ Cl_4$	415.1	2.128	water
	$(NH_4)_2\ Pt\ Cl_6$	443.89	2.275	water
K	KCl	74.55	1.907	water
	$K_2\ Cr_2\ O_7$	294.2	3.761	water
Pr	$Pr_6\ O_{11}$	1021.44	1.208	HCl
Re	metal	186.2	1.000	HNO_3
	$K\ ReO_4$	289.3	1.554	water
Rh	metal	102.9	1.000	hot H_2SO_4
	$(NH_4)_3\ RhCl_6\cdot 3H_2O$	423.79	4.118	water

TABLE XIII (cont.)

Element	Compound	Formula Weight (g)	Weight Required to Make 1000 ppm (g/ℓ)	Dissolution Method
Rb	Rb_2CO_3	230.95	1.351	HNO_3
	Rb_2SO_4	267.0	1.563	water
Ru	$(NH_4)_2$ Ru Cl_6	349.87	3.462	water
	RuO_4	165.1	1.633	water
Sm	Sm_2O_3	348.7	2.319	hot HCl
Sc	Sc_2O_3	137.9	1.534	hot HCl
Se	metal	78.96	1.000	hot HNO_3
	SeO_2	110.96	1.405	water
Si	metal	28.09	1.000	conc. NH_4OH
	SiO_2	60.08	2.139	HF
Ag	metal	107.9	1.000	HNO_3
	$AgNO_3$	169.9	1.575	water
Na	Na_2CO_3	105.99	2.305	water
	$Na_2C_2O_4$	134.0	2.915	water
Sr	$SrCO_3$	147.6	1.685	HCl
S	elemental	--	--	not used in solution
Ta	metal	180.95	1.000	HF
	Ta_2O_5	441.9	1.221	HF
Te	TeO_2	159.6	1.251	HCl
Tb	Tb_2O_3	365.8	1.151	hot HCl
Tm	Tm_2O_3	385.9	1.142	hot HCl
Sn	metal	118.7	1.000	HCl
	SnO	134.7	1.135	HCl
Ti	metal	47.90	1.000	HF + HNO_3
	TiO_2	79.90	1.668	H_2SO_4, NH_4OH
W	metal	183.85	1.000	HF
U	U_3O_8	842.1	1.179	HNO_3
V	metal	50.94	1.000	HNO_3, aqua regia
Yb	Yb_2O_3	394.1	1.139	hot HCl
Zn	metal	65.37	1.000	dil. HNO_3
Zr	metal	91.22	1.000	HF + HNO_3

acids, or bases. Choice of solvent must take into consideration activation of the solvent (e.g., ^{38}Cl from HCl).

4. <u>High Molecular Weight</u>

   The higher the molecular weight of the element/compound, the greater the degree of accuracy that can be achieved when weighing.

5. <u>Toxicity</u>

   Compounds of the lowest toxicity possible should be used.

Two recent papers also offer some insight into dissolution of refractory elements (86, 87).

As alluded to above, elements/compounds of lesser purity may be employed if single element standards are to be irradiated. Only materials of the highest purity should be used if mixed elemental standards are contemplated. Preparation of iron, manganese, and cobalt standards provides an example of problems which may be encountered. Metallic iron of 99% purity typically contains several thousand ppm Co and Mn as impurities. Since Co and Mn are usually prepared in great dilution, the mixing of a concentrated iron standard and dilute Co and Mn standards can introduce large errors in the Co and Mn content calculated from their standard solutions alone.

Several firms prepare commercial liquid elemental standards for use in atomic absorption spectrophotometry. These solutions are frequently prepared exclusively from water-soluble compounds, which fail to meet the criteria for good standards mentioned above. These should be used only with the greatest caution. Experience at this laboratory has shown that Fe, Se, As, Pb, and Ag solutions from commercial suppliers are amongst the least stable and most poorly prepared of the commercial offerings.

A number of Standard Reference Materials are available from agencies such as the National Bureau of Standards, the US Geological Survey, and the Canadian Geological Survey. The philosophy behind the preparation and intended use of these materials is discussed in an excellent paper by Uriano and Gravatt (88). The use of these materials in a Quality Assurance program is the subject of another report (89).

SOURCES OF ERROR

Basic to any analytical procedure is an understanding of the sources of error. Adequate quality assurance samples, typically 10-20% of the total, will alert the investigator to errors which may have crept into the procedure, but then he must know where to begin looking for the problem. For neutron activation analysis, some common sources are error due to:

1) Sample weighing,
2) Sample inhomogeneity,
3) Imprecise measurement of the length of irradiation, decay, or count. These factors are especially significant in measurement of short-lived nuclides.
4) Improperly prepared standards. In general, standards should be of the same physical size and shape and have somewhat similar activities as the samples to "look the same" to the Ge (Li) detector. Potential sources of error in filter paper standards include pipetting error; contaminated, oxidized, or unstable standard solutions; and constituents of the filter paper itself that can be activated.
5) Flux variation. Neutron flux at the OWR has been observed to vary as much as 10-20% during daily operations. At present, 50 μℓ pipetted flux monitor caps of Au for epithermal irradiations and Co for thermal irradiations are used to monitor flux with each sample.
6) Measurement of radioactivity. This would include sample self-shielding as well as detector problems such as loss of efficiency in counting high energy γs due to "screening" by lower energy γs of high activity, poor resolution, excess dead-time, improper crystal bias voltage, and various electronic nuances.
7) Sample counting geometry. Several per cent errors can be obtained if sample positioning and size are not consistently maintained. This becomes extremely critical as sample proximity to the detector increases.
8) Interferences. These are likely the investigators' most subtle nemeses due to their unpredictability. Each sample matrix has its own particular interferences for a given element, and these include other nearby γs, single- and double-escape peaks, (n,p) and (n,α) reactions.
9) Inadequate counting statistics. These may often be improved by increasing irradiation or counting times or choosing another γ to observe altogether.

A recent paper by Greenberg (90) contains a very useful discussion of error analysis for neutron activation.

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APPENDIX I

GAMMA RADIATION EMITTED BY RADIOACTIVE SPECIES
ARRANGED BY ELEMENT

APPENDIX I

GAMMA RADIATION EMITTED BY RADIOACTIVE SPECIES ARRANGED BY ELEMENT

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{7}Be	53.28 d	477.4	100
^{19}O	26.8 s	112	2.8
		200	100
		1370	60
		1440	2.8
^{20}F	11.0 s	1633.1	100
^{22}Na	2.60 y	1274.6	100
^{23}Ne	37.5 s	438	100
		1630	2.8
		2060	.25
		2200	.14
		2420	.03
^{24}Na	15.02 h	1368.5	100
		1732.1	DE
		2243.1	SE
		2754.1	100
^{27}Mg	9.45 m	170.8	1.2
		843.8	100
		1014.4	37
^{28}Al	2.24 m	757	DE
		1268	SE
		1778.9	100
^{29}Al	6.5 m	1273.3	100
		2425.8	6.4
^{31}Si	2.62 h	1266.2	100
^{37}S	5.05 m	2080	DE
		2591.4	SE
		3102.4	100
^{38}Cl	37.2 m	620.7	DE
		1131.7	SE
		1145.6	DE
		1642.7	85
		1656.6	SE
		2167	100

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{41}Ar	1.83 h	1293.6	100
^{40}K	1.28×10^9 y	1460.7	100
^{42}K	12.36 h	312.9	1.1
		1524.7	100
^{47}Ca	4.54 d	489.5	8.8
		1296.9	100
^{49}Ca	8.72 m	2061.0	DE
		2572.0	SE
		3083.0	100
		4071.0	11.2
^{46m}Sc	18.7 s	142.5	100
^{46}Sc	83.8 d	889.3	100
		1120.5	100
^{47}Sc	3.41 d	159.8	100
^{48}Sc	43.7 h	983.5	100
		1037.4	100
		1311.6	100
^{51}Ti	5.75 m	320.0	100
		608.4	1.5
		928.5	4.4
^{52}V	3.76 m	1434.4	100
^{51}Cr	27.71 d	320.1	100
^{54}Mn	312.5 d	834.8	100
^{56}Mn	2.580 h	789.2	DE
		846.6	100
		1090.6	DE
		1300	SE
		1601	SE
		1811.2	30
		2112.2	15.3
^{59}Fe	44.6 d	142.6	.014
		192.3	.045
		334.9	.005
		1099.3	100
		1291.6	77

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{58}Co	70.8 d	511.0	29
		810.5	100
		863.5	1.2
^{60m}Co	10.48 m	1332.4	100
^{60}Co	5.27 y	1173.2	100
		1332.5	100
^{65}Ni	2.520 h	366.5	14.6
		1115.4	61.5
		1481.7	100
^{64}Cu	12.71 h	511.0	100
		1345.8	2.6
^{66}Cu	5.10 m	1039.0	100
^{65}Zn	243.8 d	511.0	--
		1115.5	100
^{69m}Zn	13.8 h	438.7	100
^{70}Ga	21.1 m	175.3	100
		1039.4	100
		1215.0	0.4
^{72}Ga	14.1 h	601.1	8
		630.1	24
		834.1	11
		1894	11
		2201	27
		2508	14
^{75}Ge	82.8 m	198.6	12
		264.6	100
^{77m}Ge	53 s	159.8	55
		215.5	100
^{77}Ge	11.30 h	211.4	57
		215.5	52
		264.5	100
		367.3	24
		416.4	41
		558.1	31
		1085.8	13

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{74}As	17.8 d	511.0	--
		596.0	100
		608.3	0.8
		634.9	30
		1203.5	0.4
^{76}As	26.3 h	559.1	100
		562.8	1.6
		657.0	15
		1216.3	10.6
		1228.6	2.8
		2096.6	1.2
^{75}Se	120 d	96.7	--
		121.1	28
		135.9	96
		264.5	100
		279.4	42
		400.4	20
^{77m}Se	17.4 s	161.9	100
^{79m}Se	3.89 m	95.9	100
^{81m}Se	57.3 m	103.0	100
^{81}Se	18.5 m	275.8	100
		565.8	57
		828.0	51
^{83}Se	22.3 m	224.9	64
		356.6	100
		510.0	86
		717.8	36
		833	59
		1310	36
^{80}Br	17.7 m	617.0	100
		640.4	3.5
		665.7	15
		704.3	3
		1256.7	1.3
^{82}Br	35.3 h	273.4	8.7
		554.3	83
		619.1	52
		698.4	32
		776.5	100

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
		827.8	30
		1044.0	37
		1317.4	38
		1474.9	24
		1650.2	1.2
^{85m}Kr	4.4 h	151.2	100
		304.9	18
^{87}Kr	76 m	402.6	100
		845.5	19
		2556.0	42
^{88}Kr	2.80 h	196.3	75.1
		834.8	37.5
		2195.8	38.1
		2392.1	100
^{86m}Rb	1.018 m	555.8	100
^{86}Rb	18.65 d	1078.8	100
^{88}Rb	17.7 m	898	63
		1836	100
		2118.6	4.5
		2677.6	11
^{85}Sr	65.2 d	514.0	100
^{87m}Sr	2.81 h	388.5	100
^{89}Sr	50.52 d	909.0	100
^{88}Y	106.6 d	814.1	DE
		898.0	91
		1325.1	SE
		1836.1	100
^{90m}Y	3.19 h	202.4	100
		756.7	100
		479.3	95.7
^{95}Zr	64.0 d	724.2	79
		756.7	100
^{97}Zr	16.8 h	254.3	1.6
		355.7	3.0
		602.5	1.7
		743.4	100
		1148.0	3.1

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{94m}Nb	6.26 m	871.1	100
^{94}Nb	2.0×10^4 y	702.5	0.6
		871.1	100
^{99}Mo	66.02 h	140.6	13
		181.0	40
		366.3	12
		739.4	100
		777.8	27
^{101}Mo	14.6 m	192.0	100
		506.0	63
		590.8	87
		877.4	16
		1012.4	68
		1532.7	32
^{99m}Tc	6.02 h	140.4	100
^{97}Ru	2.89 d	215.8	100
		325.1	8
^{103}Ru	39.4 d	497.1	100
		557.1	1
		610.3	6.8
^{105}Ru	4.44 h	262.8	13
		316.5	27
		469.4	43
		676.3	27
		724.2	100
^{104m}Rh	4.35 m	97.2	100
^{104}Rh	42 s	555.8	100
^{109m}Pd	4.67 m	188.9	100
^{109}Pd	13.43 h	88	100
		311.5	10
^{111m}Pd	5.5 h	172.1	100
^{111}Pd	22 m	376.5	75
		580.0	100
		1388.1	60
		1458.9	60
		1488.9	60

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{108}Ag	2.41 m	433.8	100
		632.9	58
^{110m}Ag	252 d	657.6	100
		677.5	10
		706.6	20
		763.8	24
		884.5	74
		937.3	33
		1384.3	22
^{109}Cd	453 d	88.0	100
^{111m}Cd	48.7 m	150.8	29
		245.4	100
^{115m}Cd	44.6 d	484.9	16
		934.1	100
		1289.9	45
^{115}Cd	53.5 h	231.4	2.5
		260.9	7.1
		492.3	54
		527.9	100
^{114m}In	49.5 d	189.9	100
		558.3	26
		725.2	26
^{114}In	71.9 s	1300.0	100
^{116m}In	54.2 m	417.0	45
		818.8	21
		1097.1	66
		1293.4	100
		1507.7	14
		2112.0	25
^{113}Sn	115 d	255.2	100
^{117m}Sn	14 d	158.4	100
^{123}Sn	129 d	160.2	100
^{125m}Sn	9.6 m	332.0	100
^{122}Sb	2.72 d	564.1	100
		692.8	5

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{124}Sb	60.20 d	602.7	100
		645.8	7.5
		669.0	DE
		713.4	4
		722.8	10
		1069.2	DE
		1180	SE
		1368.3	4.7
		1580	SE
		1691.0	51
		2091.2	7
^{121m}Te	150 d	212.3	100
^{121}Te	17 d	507.5	23
		572.9	100
^{123m}Te	119.7 d	158.8	100
^{125m}Te	58 d	109.3	100
^{127m}Te	109 d	361.0	15
		417.4	100
^{129m}Te	33.4 d	106	3
		556.7	3
		696	100
		730	6
		833.5	.01
^{129}Te	69 m	459.5	100
^{131}Te	25.0 m	149.7	100
		452.4	24
		492.7	7
		602.1	6
		997.2	5.1
		1147.8	9.4
^{128}I	25.0 m	442.9	100
		526.6	9
		743.3	0.9
		969.5	1.8
^{131}I	8.05 d	364.5	100
		637.0	12
^{133m}Xe	2.19 d	233.2	100

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{138}Xe	14.2 m	258.3	100
		434.5	65.9
		1768.3	63.5
		2015.8	46.6
^{134m}Cs	2.90 h	127.4	100
^{134}Cs	2.062 y	563.2	7
		569.3	13
		604.7	100
		795.8	87
		801.9	8
^{136}Cs	13.1 d	340.6	46.9
		818.5	100
		1048.1	80.0
		1235.3	19.8
^{137}Cs	30.17 y	661.6	100
^{138}Cs	32.2 m	462.8	35.7
		1009.8	37.9
		1435.9	100
		2218.0	21.4
^{131m}Ba	14.6 m	108.2	100
^{131}Ba	11.7 d	124.2	66
		133.7	4.5
		216.1	51
		373.1	31
		496.3	100
		585.0	2.6
		620.0	3.0
^{133m}Ba	38.9 h	275.9	100
^{133}Ba	10.7 y	160.6	1.2
		276.3	11
		302.7	30
		355.9	100
		383.7	14
^{135m}Ba	28.7 h	268.1	100
^{137m}Ba	2.552 m	661.6	100
^{139}Ba	83.2 m	165.9	100

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{140}La	40.23 h	328.8	36
		432.5	4
		487.0	46
		574.2	DE
		751.7	2
		815.8	42
		1085	SE
		1596.2	100
		2521.8	1
^{139m}Ce	56 s	754.0	100
^{139}Ce	137.6 d	165.9	100
^{141}Ce	32.5 d	145.4	100
^{143}Ce	33.0 h	231.6	7
		293.2	100
		350.6	9
		490.4	5.3
		664.6	15
		722.0	17
^{142}Pr	19.13 h	1575.5	100
^{147}Nd	10.99 d	91.0	100
		319.4	11
		439.8	7
		531.0	43
^{149}Nd	1.73 h	114.6	68
		156.0	23
		211.4	100
		269.6	78
		326.3	19
		423.5	31
		542	33
^{151}Nd	12.4 m	116.4	100
		139.0	16
		255.6	28
		1180.7	22
^{153}Sm	46.7 h	97.5	2.6
		103.2	100
^{155}Sm	22.2 m	104.2	100
		141.2	1.9
		245.6	5.5

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{152m}Eu	9.3 h	121.8	50
		344.2	17
		841.6	100
		963.5	83
		1388.9	5.5
^{152}Eu	13.4 y	121.8	100
		344.3	100
		778.9	56
		964.0	60
		1085.8	48
		1112.1	56
		1407.9	88
^{154}Eu	8.2 y	123.1	100
		723.3	56
		873.2	31
		996.3	31
		1004.8	50
		1274.8	100
^{153}Gd	241.6 d	97.5	100
		103.2	73
^{159}Gd	18.6 h	225.8	1.9
		305.3	0.8
		347.5	2.4
		363.5	100
^{161}Gd	3.7 m	102.2	17
		164.9	7
		283.3	12
		314.6	37
		360.4	100
		480.1	3.2
		529.5	2.6
^{160}Tb	72.4 d	879.3	100
		962.5	27
		966.2	66
		1178.0	45
		1271.9	21
^{159}Dy	144 d	58.2	100
^{165}Dy	139.2 m	279.6	57
		361.5	100
		545	17
		566	14
		716	64

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{166}Ho	26.9 h	1378.1	100
		1580.5	23
171 Er	7.52 h	111.6	39
		116.7	4
		124.0	12
		295.8	40
		308.1	100
^{170}Tm	129 d	84.4	100
^{169}Yb	32.0 d	109.8	50
		130.5	31
		177.2	62
		198.0	100
		307.7	28
^{175}Yb	4.19 d	113.5	31
		144.7	5.9
		282.6	62
		396.1	100
^{177}Yb	1.9 h	121.6	17
		138.3	6.3
		150.3	100
		1079.8	28
		1240.9	17
^{177m}Lu	161 d	112.9	41
		128.5	20
		153.3	22
		208.3	100
		228.4	56
		281.8	20
		327.7	24
		378.5	37
		413.6	27
		418.5	30
^{177}Lu	6.71 d	112.9	58
		208.3	100
		250.1	2
^{175}Hf	70 d	229.5	1.0
		343.6	100
		432.8	2.0
^{179m}Hf	18.7 s	160.6	--
		214.3	100

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{180m}Hf	5.5 h	215.3	88
		332.2	100
		443.1	86
^{181}Hf	42.4 d	133.1	49
		136.3	7.4
		346.0	16
		482.2	100
^{182m}Ta	15.9 m	146.7	95
		171.7	100
		184.9	55
		318.3	13
^{182}Ta	115 d	100.1	40
		152.4	35
		222.1	35
		264.1	18
		1121.2	100
		1189.0	45
		1221.3	95
		1230.9	50
^{181}W	121.0 d	136.3	100
		152.3	42
^{185}W	75.1 d	125.4	100
^{187}W	23.9 h	134.3	34
		479.4	86
		552	18
		618	22
		686	100
		773	14
^{186}Re	90.6 h	122.6	6.4
		137.0	100
^{188}Re	16.95 h	155.0	100
		478.0	6.4
		633.0	9.1
^{185}Os	94 d	645.8	100
^{190m}Os	9.9 m	503	100
^{191}Os	15.3 d	129.4	100
^{193}Os	30.5 h	139.0	100

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{192}Ir	74.2 d	295.9	36
		308.4	37
		316.5	100
		468.1	60
^{194}Ir	19.15 h	293.6	20
		328.0	100
		644.6	8.2
		938.4	4.5
^{191}Pt	2.8 d	129.4	100
		172.3	58
		360.3	15
^{195m}Pt	4.02 d	129.7	100
^{197m}Pt	80 m	346.3	100
^{197}Pt	18.3 h	191.3	100
^{198}Au	2.696 d	411.8	100
		675.9	0.8
		1087.6	0.2
^{197}Hg	64.1 h	191.4	100
^{203}Hg	46.6 d	279.2	100
^{205}Hg	5.2 m	203.8	100
^{208}Tl	3.10 m	583.1	86
		2614.5	100
^{212}Pb	10.64 h	238.6	100
		300.00	--
^{214}Pb	26.8 m	295.2	60
		352.0	100
^{212}Bi	60.6 m	727.2	100
^{214}Bi	19.7 m	609.4	100
		1120.3	30
		1764.0	34

APPENDIX I (cont.)

Nuclide	Half-Life	Energy (keV)	Relative Intensity (%)
^{226}Ra	1600 y	186.1	9
		242.0	--
		295.2	--
		351.9	--
		609.3	100
		1120.3	--
		1238.1	--
^{228}Ac	6.13 h	338.4	41.4
		794.8	16.7
		911.1	100
^{233}Pa	27.0 d	300.1	17
		312.4	100
		340.5	12
^{235}U	7.1×10^8 y	110	5
		143	20
		163	10
		185	100
		204	10
^{239}Np	2.35 d	209.8	24
		228.2	84
		277.6	100
		315.9	11
		334.3	15

APPENDIX II

GAMMA RADIATION EMITTED BY RADIOACTIVE SPECIES ARRANGED BY ENERGY

APPENDIX II

GAMMA RADIATION EMITTED BY RADIOACTIVE SPECIES ARRANGED BY ENERGY

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
84.4	^{170}Tm	129 d	100	--	ACT
88.0	^{109}Cd	453 d	100	--	ACT
88.0	^{109}Pd	13.43 h	100	311.5	ACT
91.0	^{147}Nd	10.99 d	100	531.0, 319.4	ACT
95.9	^{79m}Se	3.89 m	100	--	ACT
96.7	^{75}Se	120 d	5.7	264.5, 135.9, 279.4	ACT
97.5	^{153}Sm	46.7 h	2.6	103.2	ACT
97.5	^{153}Gd	241.6 d	100	103.2	ACT
100.1	^{182}Ta	115 d	40	1121.2, 1221.3	ACT
102.2	^{161}Gd	3.7 m	17	360.4, 314.6	ACT
103.2	^{153}Gd	241.6 d	73	97.5	ACT
103.2	^{153}Sm	46.7 h	100	--	ACT
104.2	^{155}Sm	22.2 m	100	--	ACT
106.0	^{129m}Te	33.4 d	3	696.0	ACT
108.7	^{131m}Ba	14.6 m	100	--	ACT
109.3	^{235}U	7.1×10^{8} y	5	185, 143	NAT
109.3	^{125m}Te	58 d	100	--	ACT
109.8	^{169}Yb	32.0 d	50	198.0, 177.2, 130.5	ACT
111.6	^{171}Er	7.52 h	39	308.1, 295.8	ACT
112.0	^{19}O	26.8 s	2.8	200.0, 1370.0	ACT
112.9	^{177m}Lu	161 d	41	208.3, 228.4, 378.5	ACT
112.9	^{177}Lu	6.71 d	58	208.3	ACT
113.5	^{175}Yb	4.19 d	31	396.1, 282.6	ACT
114.6	^{149}Nd	1.73 h	68	211.4, 269.6, 542	ACT
116.4	^{151}Nd	12.4 m	100	255.6, 1180.7	ACT
116.7	^{171}Er	7.52 h	4	308.1, 295.8	ACT
121.1	^{75}Se	120 d	28	264.5, 135.9	ACT
121.6	^{177}Yb	1.9 h	17	150.3, 1079.8	ACT
121.8	^{152m}Eu	9.3 h	50	841.6, 963.5	ACT
121.8	^{152}Eu	13.4 y	100	344.3, 1407.9, 964.0	ACT
122.6	^{186}Re	90.6 h	6.4	137.0	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
123.1	^{154}Eu	8.2 y	100	1274.8, 723.3, 1004.8	ACT
124.0	^{171}Er	7.52 h	12	308.1, 295.8	ACT
124.2	^{131}Ba	11.7 d	66	496.3, 216.1, 373.1	ACT
125.4	^{185}W	75.1 d	100	--	ACT
127.4	^{134m}Cs	2.90 h	100	--	ACT
128.5	^{177m}Lu	161 d	20	208.3, 228.4, 378.5	ACT
129.4	^{191}Os	15.3 d	100	--	ACT
129.4	^{191}Pt	2.8 d	100	172.3, 360.3	ACT
129.7	^{195m}Pt	4.02 d	100	--	ACT
130.5	^{169}Yb	32.0 d	31	198.0, 177.2, 109.8	ACT
133.1	^{181}Hf	42.4 d	49	482.2, 346.0	ACT
133.7	^{131}Ba	11.7 d	4.5	496.3, 216.1, 124.2	ACT
134.3	^{187}W	23.9 h	34	686.0, 497.4, 552	ACT
135.9	^{75}Se	120 d	96	264.5, 279.4, 121.8	ACT
136.3	^{181}Hf	42.4 d	7.4	482.2, 133.1	ACT
136.3	^{181}W	121.0 d	100	152.3	ACT
137.0	^{186}Re	90.6 h	100	--	ACT
138.3	^{177}Yb	1.9 h	6.3	150.3, 1079.8, 1240.9	ACT
139.0	^{151}Nd	12.4 m	16	116.4, 255.6, 1180.7	ACT
139.0	^{193}Os	30.5 h	100	--	ACT
140.4	^{99m}Tc	6.02 h	100	--	ACT
140.6	^{99}Mo	66.02 h	13	739.4, 181.0, 777.8	ACT
141.2	^{155}Sm	22.2 m	1.9	245.6	ACT
142.5	^{46m}Sc	18.7 s	100	--	ACT
142.6	^{59}Fe	44.6 d	1.4	1099.3, 1291.6	ACT
143.8	^{235}U	7.1×10^8 y	20	185, 163, 204	NAT
144.7	^{175}Yb	4.19 d	5.9	396.1, 282.6, 113.5	ACT
145.4	^{141}Ce	32.5 d	100	--	ACT
146.7	^{182m}Ta	15.9 m	95	171.7, 184.9	ACT
149.7	^{131}Te	25.0 m	100	452.4	ACT
150.3	^{177}Yb	1.9 h	100	1079.8, 1240.9, 121.6	ACT

APPENDIX II (cont.)

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
150.8	^{111m}Cd	48.7 m	29	245.4	ACT
151.2	^{85m}Kr	4.4 h	100	305.0	FIS
152.3	^{181}W	121.0 d	42	--	ACT
152.9	^{182}Ta	115 d	35	1121.2, 1221.3, 1189.0	ACT
153.3	^{177m}Lu	161 d	22	208.3, 228.4, 328.5	ACT
155.0	^{188}Re	16.95 h	100	--	ACT
156.0	^{149}Nd	1.73 h	23	211.4, 269.6, 114.6	ACT
158.4	^{117m}Sn	14 d	100	--	ACT
158.8	^{123m}Te	17 d	100	--	ACT
159.8	^{47}Sc	3.41 d	100	--	ACT
159.8	^{77m}Ge	53 s	55	215.5	ACT
160.2	^{123}Sn	129 d	100	--	ACT
161.9	^{77m}Se	17.4 s	100	--	ACT
163.4	^{235}U	7.1×10^8 y	10	185, 143	NAT
164.9	^{161}Gd	3.7 m	100	360.4, 314.6	ACT
165.9	^{139}Ce	137.6 d	100	--	ACT
165.9	^{139}Ba	83.2 m	100	--	ACT
170.8	^{27}Mg	9.45 m	1.2	843.8, 1014.4	ACT
171.7	^{182m}Ta	15.9 m	100	146.7, 184.9	ACT
172.1	^{111m}Pd	5.5 h	100	--	ACT
172.3	^{191}Pt	2.8 d	58	129.4, 360.3	ACT
175.3	^{70}Ga	21.1 m	100	1039.4	ACT
177.2	^{169}Yb	32.0 d	62	198.0, 109.8, 130.5	ACT
181.0	^{99}Mo	66.02 h	40	739.4, 777.8	ACT
184.9	^{182m}Ta	15.9 m	55	171.7, 146.7	ACT
185.7	^{235}U	7.1×10^8 y	100	143, 163, 204	NAT
186.1	^{226}Ra	1600 y	9	609.3	NAT
188.9	^{109m}Pd	4.67 m	100	--	ACT
189.9	^{114m}In	49.5 d	100	558.3, 725.2	ACT
191.3	^{197}Pt	18.3 h	100	--	ACT
191.4	^{197}Hg	64.1 h	100	--	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
192.0	^{101}Mo	14.6 m	100	590.8, 1012.4, 506.0	ACT
192.3	^{59}Fe	44.6 d	4.5	1099.3, 1291.6	ACT
196.3	^{88}Kr	2.80 h	75.1	2392.1, 2195.8	FIS
198.0	^{169}Yb	32.0 d	100	177.2, 109.8, 130.5	ACT
198.6	^{75}Ge	82.8 m	12	264.6	ACT
200.0	^{19}O	26.8 s	100	1370.0	ACT
202.4	^{90m}Y	3.19 h	100	479.3	ACT
203.8	^{205}Hg	5.2 m	100	--	ACT
205.3	^{235}U	7.1 x 10^8 y	10	185, 143	NAT
208.3	^{177}Lu	6.71 d	100	112.9	ACT
208.3	^{177m}Lu	161 d	100	228.4, 112.9, 378.5	ACT
209.8	^{239}Np	2.35 d	24	277.6, 228.2, 334.3	ACT
211.4	^{149}Nd	1.73 h	100	269.6, 114.6, 423.5	ACT
211.4	^{77}Ge	11.30 h	57	264.5, 215.5, 558.1	ACT
212.3	^{121m}Te	150 d	100	--	ACT
214.3	^{179m}Hf	18.7 s	100	160.6	ACT
215.3	^{180m}Hf	5.5 h	88	332.2, 443.1	ACT
215.5	^{77}Ge	11.30 h	52	264.5, 211.4, 558.1	ACT
215.5	^{77m}Ge	53 s	100	159.8	ACT
215.8	^{97}Ru	2.89 d	100	--	ACT
216.1	^{131}Ba	11.7 d	51	496.3, 124.2, 373.1	ACT
222.1	^{182}Ta	115 d	35	1121.2, 1221.3, 1230.9	ACT
224.9	^{83}Se	22.3 m	64	356.6, 510.0, 833.0	ACT
225.8	^{159}Gd	18.6 h	1.9	363.5	ACT
228.2	^{239}Np	2.35 d	84	277.6, 209.8, 334.3	ACT
228.4	^{177m}Lu	161 d	56	208.3, 112.9, 378.5	ACT
229.5	^{175}Hf	70 d	1.0	343.6	ACT
231.4	^{115}Cd	53.5 h	2.5	527.9, 492.3	ACT
231.6	^{143}Ce	33.0 h	7	293.2, 722.0, 664.6	ACT
233.2	^{133m}Xe	2.19 d	100	--	FIS
238.6	^{212}Pb	10.64 h	100	300.0	NAT-^{232}Th

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
241.0	^{224}Ra	3.64 d	100	--	NAT-^{232}Th
242.0	^{226}Ra	1600 y	--	609.3	NAT
245.4	^{111m}Cd	48.7 m	100	150.8	ACT
245.6	^{155}Sm	22.2 m	5.5	104.2	ACT
249.8	^{135}Xe	9.09 h	100	--	FIS
250.1	^{177}Lu	6.71 d	2	208.3, 112.9	ACT
254.3	^{97}Zr	16.8 h	1.6	743.4	ACT
255.2	^{113}Sn	115 d	100	--	ACT
255.6	^{151}Nd	12.4 m	28	116.4, 1180.7	ACT
258.3	^{138}Xe	14.2 m	100	434.5, 1768.3, 2015.5	FIS
260.9	^{115}Cd	53.5 h	7.1	527.9, 492.3	ACT
262.8	^{105}Ru	4.44 h	13	724.2, 469.4, 676.3	ACT
264.1	^{182}Ta	115 d	18	222.1, 1221.3	ACT
264.5	^{75}Se	120 d	100	135.9, 279.4, 121.1	ACT
264.5	^{77}Ge	11.30 h	100	211.4, 215.5, 416.4	ACT
264.6	^{75}Ge	82.8 m	100	198.6	ACT
268.1	^{135m}Ba	28.7 h	100	--	ACT
269.6	^{149}Nd	1.73 h	78	211.4, 114.6, 423.5	ACT
273.4	^{82}Br	35.3 h	8.7	776.5, 554.3, 619.1	ACT
275.8	^{81}Se	18.5 m	100	565.8, 828.0	ACT
275.9	^{133m}Ba	38.9 h	100	--	ACT
276.3	^{133}Ba	10.7 y	11	355.9, 302.7, 383.7	ACT
277.6	^{239}Np	2.35 d	100	228.2, 209.8, 334.3	ACT
279.2	^{203}Hg	46.6 d	100	--	ACT
279.4	^{75}Se	120 d	42	264.5, 135.9, 121.1	ACT
279.6	^{165}Dy	139.2 m	57	361.5, 716.0	ACT
281.8	^{177m}Lu	161 d	20	208.3, 228.4, 378.5	ACT
282.6	^{175}Yb	4.19 d	62	396.1, 113.5	ACT
283.3	^{161}Gd	3.7 m	12	360.4, 314.6, 102.2	ACT
293.2	^{143}Ce	33.0 h	100	722.0, 664.6	ACT
293.6	^{194}Ir	19.15 h	20	328.0, 664.6	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
295.2	^{214}Pb	26.8 m	60	352.0	NAT-^{238}U
295.2	^{226}Ra	1600 y	--	609.3	NAT
295.8	^{171}Er	7.52 h	40	308.1, 111.6	ACT
295.9	^{192}Ir	74.2 d	36	316.5, 308.4, 468.1	ACT
300.1	^{233}Pa	27.0 d	17	312.4, 340.5	ACT
300.6	^{212}Pb	10.64 h	--	238.6	NAT-^{232}Th
302.7	^{133}Ba	10.7 y	30	355.9, 383.7	ACT
304.9	^{85m}Kr	4.4 h	18	151.2	FIS
307.7	^{169}Yb	32.0 d	28	198.0, 177.2, 109.8	ACT
308.1	^{171}Er	7.52 h	100	295.8, 111.6	ACT
308.4	^{192}Ir	74.2 d	37	316.5, 468.1, 295.9	ACT
311.5	^{109}Pd	13.43 h	10	88	ACT
312.4	^{233}Pa	27.0 d	100	300.1, 340.5	ACT
312.9	^{42}K	12.36 h	1.1	1524.7	ACT
314.6	^{161}Gd	3.7 m	37	360.4, 102.2, 283.3	ACT
315.9	^{239}Np	2.35 d	11	277.6, 228.2, 334.3	ACT
316.5	^{105}Ru	4.44 h	27	724.2, 469.4, 676.3	ACT
316.5	^{192}Ir	74.2 d	100	468.1, 308.4, 295.9	ACT
318.3	^{182m}Ta	15.9 m	13	171.7, 146.7, 184.9	ACT
319.4	^{147}Nd	10.99 d	11	91.0, 531.0	ACT
320.0	^{51}Ti	5.75 m	100	--	ACT
320.1	^{51}Cr	27.71 d	100	--	ACT
325.1	^{97}Ru	2.89 d	8	215.8	ACT
326.3	^{149}Nd	1.73 h	19	211.4, 269.6, 423.5	ACT
327.7	^{177m}Lu	161 d	24	208.3, 228.4, 378.5	ACT
328.0	^{194}Ir	19.15 h	100	293.6	ACT
328.8	^{140}La	40.23 h	36	1596.1, 487.0, 815.8	ACT
332.0	^{125m}Sn	9.6 m	100	--	ACT
332.2	^{180m}Hf	5.5 h	100	215.3, 443.1	ACT
334.3	^{239}Np	2.35 d	15	277.6, 228.2, 209.8	ACT
334.9	^{59}Fe	44.6 d	1	1099.3, 1291.6	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
338.5	^{228}Ac	6.13 h	41.4	911.1, 794.8	NAT-^{232}Th
340.5	^{233}Pa	27.0 d	12	312.4, 300.1	ACT
340.6	^{136}Cs	13.1 d	46.9	818.5, 1048.1	FIS
343.6	^{175}Hf	70 d	100	--	ACT
344.2	^{152m}Eu	9.3 h	17	841.6, 963.5, 121.8	ACT
344.3	^{152}Eu	13.4 y	100	121.8, 1407.9, 964.0	ACT
346.0	^{181}Hf	42.4 d	16	482.2, 133.1	ACT
346.3	^{197m}Pt	80 m	100	--	ACT
347.5	^{159}Gd	18.6 h	2.4	363.5	ACT
350.6	^{143}Ce	33.0 h	9	293.2, 722.0, 664.6	ACT
351.9	^{226}Ra	1600 y	--	609.3	NAT
352.0	^{214}Pb	26.8 m	100	295.2	NAT-^{238}U
355.7	^{97}Zr	16.8 h	3.0	743.4	ACT
355.9	^{133}Ba	10.7 y	100	302.7, 383.7	ACT
356.6	^{83}Se	22.3 m	100	224.9, 833.0	ACT
360.3	^{191}Pt	2.8 d	15	129.4, 172.3	ACT
360.4	^{161}Gd	3.7 m	100	314.6, 102.2, 283.3	ACT
361.0	^{127m}Te	109 d	15	417.4	ACT
361.5	^{165}Dy	139.2 m	100	716, 279.6, 545	ACT
363.5	^{159}Gd	18.6 h	100	--	ACT
364.5	^{131}I	8.05 d	100	637.0	FIS
366.3	^{99}Mo	66.02 h	12	739.4, 181.0, 777.8	ACT
366.5	^{65}Ni	2.520 h	14.6	1481.7, 1115.4	ACT
367.3	^{77}Ge	11.30 h	24	264.5, 211.4, 215.5	ACT
373.1	^{131}Ba	11.7 d	31	496.3, 216.1, 124.2	ACT
376.5	^{111}Pd	22 m	75	580.0, 1388.1, 1458.9	ACT
378.5	^{177m}Lu	161 d	37	208.3, 228.4, 112.9	ACT
383.7	^{133}Ba	10.7 y	14	355.9, 302.7	ACT
388.5	^{87m}Sr	2.81 h	100	--	ACT
396.1	^{175}Yb	4.19 d	100	282.6, 113.5	ACT
400.4	^{75}Se	120 d	20	264.5, 135.9, 279.4	ACT

APPENDIX II (cont.)

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
402.6	^{87}Kr	76 m	100	2556.0	FIS
411.8	^{198}Au	2.696 d	100	675.9	ACT
413.6	^{177m}Lu	161 d	27	208.3, 228.4, 378.5	ACT
416.4	^{77}Ge	11.30 h	41	264.5, 211.4, 215.5	ACT
417.0	^{116m}In	54 m	45	1293.4, 1097.1, 2112.0	ACT
417.4	^{127m}Te	109 d	100	361.0	ACT
418.5	^{177m}Lu	161 d	30	208.3, 228.4, 378.5	ACT
423.5	^{149}Nd	1.73 h	31	211.4, 296.6, 114.6	ACT
432.5	^{140}La	40.23 h	4	1596.2, 487.0, 815.8	ACT
432.8	^{175}Hf	70 d	2.0	343.6	ACT
433.8	^{108}Ag	2.41 m	100	632.9	ACT
434.5	^{138}Xe	14.2 m	65.9	258.3, 1768.3, 2015.8	FIS
439.8	^{147}Nd	10.99 d	7	91.0, 531.0	ACT
442.9	^{128}I	25.0 m	100	526.6	ACT
443.1	^{180m}Hf	5.5 h	86	332.2, 215.3	ACT
452.4	^{131}Te	25.0 m	24	149.7	ACT
459.5	^{129}Te	69 m	100	--	ACT
462.8	^{138}Cs	32.2 m	35.7	1435.9, 1009.8	FIS
468.1	^{192}Ir	74.2 d	60	316.5, 308.4, 295.9	ACT
469.4	^{105}Ru	4.44 h	43	724.2, 676.3, 316.5	ACT
477.4	^{7}Be	53.28 d	100	--	NAT
478.0	^{188}Re	16.95 h	6.4	155.0	ACT
479.3	^{90m}Y	3.19 h	95.7	202.4	ACT
479.4	^{187}W	23.9 h	86	686, 134.3	ACT
480.1	^{161}Gd	3.7 m	3.2	360.4, 314.6	ACT
482.2	^{181}Hf	42.4 d	100	133.1, 346.0	ACT
484.9	^{115m}Cd	44.6 d	16	934.1, 1289.9	ACT
487.0	^{140}La	40.23 d	46	1596.2, 815.8, 328.8	ACT
489.5	^{47}Ca	4.54 d	8.8	1296.9	ACT
490.4	^{143}Ce	33.0 h	5.3	293.2, 722.0	ACT
492.3	^{115}Cd	53.5 h	54	527.9	ACT

APPENDIX II (cont.)

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
492.7	^{131}Te	25.0 m	7	149.7, 452.4	ACT
496.3	^{131}Ba	11.7 d	100	124.2, 216.1, 373.1	ACT
497.1	^{103}Ru	39.4 d	100	--	ACT
503.0	^{190m}Os	9.9 m	100	--	ACT
506.0	^{101}Mo	14.6 m	63	192.0, 590.8, 1012.4	ACT
507.5	^{121}Te	17 d	23	572.9	ACT
510.0	^{83}Se	22.3 m	86	356.6, 224.9, 833	ACT
511.0	Various	--	--	--	Annihilation Radiation
514.0	^{85}Sr	65.2 d	100	--	ACT
526.6	^{135m}Xe	15.6 m	100	--	FIS
526.6	^{128}I	25.0 m	9	442.9	ACT
527.9	^{115}Cd	53.5 h	100	492.3	ACT
529.5	^{161}Gd	3.7 m	2.6	360.4, 314.6	ACT
531.0	^{147}Nd	10.99 d	43	91.0, 319.4	ACT
542.0	^{149}Nd	1.73 h	33	211.4, 269.6, 114.6	ACT
545.0	^{165}Dy	139.2 m	17	361.5, 716, 279.6	ACT
552.0	^{187}W	23.9 h	18	686, 479.4, 134.3	ACT
554.3	^{82}Br	35.3 h	83	776.5, 619.1, 1317.4, 1044.0	ACT
555.8	^{104}Rh	42 s	100	--	ACT
555.8	^{86m}Rb	1.018 m	100	--	ACT
556.7	^{129m}Te	33.4 d	3	696.0	ACT
557.1	^{103}Ru	39.4 d	1.0	497.1	ACT
558.1	^{77}Ge	11.30 h	31	264.5, 211.4, 215.5, 416.4	ACT
558.3	^{114m}In	49.5 d	26	189.9, 725.2	ACT
559.1	^{76}As	26.3 h	100	657.0	ACT
562.8	^{76}As	26.3 h	1.6	657.0	ACT
563.2	^{134}Cs	2.062 y	13	604.7, 795.8	ACT
564.1	^{122}Sb	2.72 d	100	--	ACT
565.8	^{81}Se	18.5 m	57	275.8, 828.0	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
566.0	^{165}Dy	139.2 m	14	361.5, 716, 279.6	ACT
569.3	^{134}Cs	2.062 y	13	604.7, 795.8	ACT
572.9	^{121}Te	17 d	100	507.5	ACT
574.2	^{140}La	40.23 h	DE	1596.2, 815.8, 487.0	ACT
580.0	^{111}Pd	22 m	100	376.5, 1388.1, 1458.9, 1488.9	ACT
583.1	^{208}Tl	3.01 m	86	2614.5	NAT-^{232}Th
590.8	^{101}Mo	14.6 m	87	192.0, 1012.4, 506.0, 1532.7	ACT
596.0	^{74}As	17.8 d	100	634.9	ACT
601.1	^{72}Ga	14.1 h	8	834.1, 2201, 630.1	ACT
602.1	^{131}Te	25.0 m	6	149.7, 452.4	ACT
602.5	^{97}Zr	16.8 h	1.7	734.4	ACT
602.7	^{124}Sb	60.20 d	100	1691.0	ACT
604.7	^{134}Cs	2.062 y	100	795.8	ACT
608.3	^{74}As	17.8 d	0.8	596.0, 634.9	ACT
608.4	^{51}Ti	5.75 m	1.5	320.0	ACT
609.3	^{226}Ra	1600 y	100	186.1	NAT
609.4	^{214}Bi	19.7 m	100	1764.7, 1120.2	NAT-^{238}U
610.3	^{103}Ru	39.4 d	6.8	497.1	ACT
617.0	^{80}Br	17.7 m	100	665.7	ACT
618.0	^{187}W	23.9 h	22	686, 479.4, 134.3	ACT
619.1	^{82}Br	35.3 h	52	776.5, 554.3, 1317.4, 1044	ACT
620.0	^{131}Ba	11.7 d	3.0	496.3, 124.2, 216.1	ACT
620.7	^{38}Cl	37.2 m	DE	2167, 1642.7	ACT
630.1	^{72}Ga	14.1 h	24	834.1, 2201	ACT
632.9	^{108}Ag	2.41 m	58	433.8	ACT
633.0	^{188}Re	16.95 h	9.1	155.0	ACT
634.9	^{74}As	17.8 d	30	596.0	ACT
637.0	^{131}I	8.05 d	12	364.5	FIS
640.4	^{80}Br	17.7 m	3.5	617.0, 665.7	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
644.6	^{194}Ir	19.15 h	8.2	328.0, 293.6	ACT
645.8	^{124}Sb	60.20 d	7.5	602.7	ACT
645.8	^{185}Os	94 d	100	--	ACT
657.0	^{76}As	26.3 h	15	559.1	ACT
657.6	^{110m}Ag	252 d	100	884.5, 937.3, 763.8	ACT
661.6	^{137}Cs	30.17 y	100	--	FIS
661.6	^{137m}Ba	2.552 m	100	--	ACT
664.6	^{143}Ce	33.0 h	15	293.2, 722.0	ACT
665.7	^{80}Br	17.7 m	15	617.0	ACT
669.0	^{124}Sb	60.20 d	DE	602.7, 722.8	ACT
675.9	^{198}Au	2.696 d	0.8	411.8	ACT
676.3	^{105}Ru	4.44 h	27	724.2, 469.4, 316.5	ACT
677.5	^{110m}Ag	252 d	10	657.6, 884.5, 937.3	ACT
686.0	^{187}W	23.9 h	100	479.4, 134.3, 618	ACT
692.8	^{122}Sb	2.72 d	5	564.1	ACT
696.0	^{129m}Te	33.4 d	100	--	ACT
698.4	^{82}Br	35.3 h	32	776.5, 554.3, 619.1	ACT
702.5	^{94}Nb	2.0×10^4 y	0.6	871.1	ACT
704.3	^{80}Br	17.7 m	3	617.0, 665.7	ACT
706.6	^{110m}Ag	252 d	20	657.6, 884.5, 937.3	ACT
713.4	^{124}Sb	60.20 d	4	602.7, 1691.0	ACT
716.0	^{165}Dy	139.2 m	64	361.5, 279.6	ACT
717.8	^{83}Se	22.3 m	36	356.6, 224.9, 833	ACT
722.0	^{143}Ce	33.0 h	17	293.2, 664.6	ACT
722.8	^{124}Sb	60.20 d	10	602.7, 1691.0	ACT
723.3	^{154}Eu	8.2 y	56	123.1, 1274.8, 1004.8	ACT
724.2	^{95}Zr	64.0 d	79	756.7	ACT
724.2	^{105}Ru	4.44 h	100	469.4, 676.3, 316.5	ACT
725.2	^{114m}In	49.5 d	26	189.9, 558.3	ACT
727.2	^{212}Bi	60.6 m	100	00	NAT-^{232}Th
730.0	^{129m}Te	33.4 d	6	696	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
739.4	^{99}Mo	66.02 h	100	181.0, 777.8	ACT
743.3	^{128}I	25.0 m	1.0	442.9	ACT
743.4	^{97}Zr	16.8 h	100	--	ACT
751.7	^{140}La	40.23 h	2	1596.2, 815.8, 487.0	ACT
754.0	^{139m}Ce	56 s	100	--	ACT
756.7	^{95}Zr	64.0 d	100	724.2	ACT
757.0	^{28}Al	2.24 m	DE	1778.9, 1268	ACT
763.8	^{110m}Ag	252 d	24	657.6, 884.5, 937.3	ACT
765.0	^{234m}Pa	1.17 m	60	1001.0	NAT-^{238}U
773.0	^{187}W	23.9 h	14	686.0, 479.4	ACT
776.5	^{82}Br	35.3 h	100	554.3, 619.1, 1044.0	ACT
777.8	^{99}Mo	66.02 h	27	739.4, 181.0, 140.6	ACT
778.9	^{152}Eu	13.4 y	56	344.3, 1407.9, 121.8	ACT
789.2	^{56}Mn	2.580 h	DE	846.6, 1811.2, 2112.3	ACT
794.9	^{228}Ac	6.13 h	16.7	911.1, 338.4	NAT-^{232}Th
795.8	^{134}Cs	2.062 y	87	604.7, 569.3	ACT
801.9	^{134}Cs	2.062 y	8	604.7, 795.8	ACT
810.5	^{58}Co	70.8 d	100	511.0	ACT
814.1	^{88}Y	106.6 d	DE	1836.1, 898.0	ACT
815.8	^{140}La	40.23 h	42	1596.2, 487.0, 378.8	ACT
818.5	^{136}Cs	13.1 d	100	1048.1, 340.6	FIS
818.8	^{116m}In	54 m	21	1293.4, 1097.1	ACT
827.8	^{82}Br	35.3 h	30	776.5, 554.3, 619.1	ACT
828.0	^{81}Se	18.5 m	51	275.8, 565.8	ACT
833.0	^{83}Se	22.3 m	59	356.6, 224.9, 510.0, 1310	ACT
834.1	^{72}Ga	14.1 h	100	2201, 630.1	ACT
834.8	^{88}Kr	2.80 h	37.5	2392.1, 196.3	FIS
834.8	^{54}Mn	312.5 d	100	--	ACT
841.6	^{152m}Eu	9.3 h	100	463.5, 121.8, 344.2	ACT
843.8	^{27}Mg	9.45 m	100	1014.4	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
845.5	^{87}Kr	76 m	19	402.6, 2556.0	FIS
846.6	^{56}Mn	2.580 h	100	1811.2, 2112.2	ACT
863.5	^{58}Co	70.8 d	1.2	511.0, 810.5	ACT
871.1	^{94}Nb	2.0 10^4 y	100	--	ACT
871.1	^{94m}Nb	6.26 m	100	--	ACT
873.2	^{154}Eu	8.2 y	31	1274.8, 123.1, 723.3	ACT
877.4	^{101}Mo	14.6 m	16	192.0, 590.8, 1012.4	ACT
879.3	^{160}Tb	72.4 d	100	966.2, 1178.0, 962.5	ACT
884.5	^{110m}Ag	252 d	74	657.6, 937.3	ACT
889.3	^{46}Sc	83.8 d	100	1120.5	ACT
894.0	^{72}Ga	14.1 h	11	834.1, 2201, 630.1	ACT
898.0	^{88}Rb	17.7 m	63	1836, 2677.6	ACT
898.0	^{88}Y	106.6 d	91	1836.1, 1325.1	ACT
909.0	^{89}Sr	50.52 d	100	--	ACT
911.1	^{228}Ac	6.13 h	100	338.4, 794.8	NAT-^{232}Th
928.5	^{51}Ti	5.75 m	4.4	320.0	ACT
934.1	^{115m}Cd	44.6 d	100	1289.9, 484.9	ACT
938.4	^{194}Ir	19.15 h	4.5	328.0, 293.6	ACT
937.3	^{110m}Ag	252 d	33	657.6, 884.5, 763.8	ACT
962.5	^{160}Tb	72.4 d	27	879.3, 966.2, 1178.0	ACT
963.5	^{152m}Eu	9.3 h	83	841.6, 121.8, 344.2	ACT
964.0	^{152}Eu	13.4 y	60	344.3, 121.8, 964.0, 1112.1	ACT
966.2	^{160}Tb	72.4 d	66	879.3, 1178.0, 962.5	ACT
969.5	^{128}I	25.0 m	1.8	442.9	ACT
983.5	^{48}Sc	43.7 h	100	1037.4, 1311.6	ACT
996.3	^{154}Eu	13.4 y	31	1274.8, 123.1, 723.3	ACT
997.2	^{131}Te	25.0 m	5.1	149.7, 452.4	ACT
1001.0	^{234m}Pa	1.17 m	100	765.0	NAT-^{238}U
1004.8	^{154}Eu	8.2 y	50	1274.8, 123.1, 723.3	ACT
1009.8	^{138}Cs	32.2 m	37.9	1435.9, 462.8	FIS

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
1012.4	^{101}Mo	14.6 m	68	192.0, 590.8, 506.0	ACT
1014.4	^{27}Mg	9.45 m	37	843.8	ACT
1037.4	^{48}Sc	43.7 h	100	983.5, 1311.6	ACT
1039.0	^{66}Cu	5.10 m	100	--	ACT
1039.4	^{70}Ga	21.1 m	100	175.3	ACT
1044.0	^{82}Br	35.3 h	37	776.5, 544.3, 619.1	ACT
1048.1	^{136}Cs	13.1 d	80.0	818.5, 340.6	FIS
1069.2	^{124}Sb	60.20 d	DE	602.7, 1691.0	ACT
1076.6	^{86}Rb	18.65 d	100	--	ACT
1079.8	^{177}Yb	1.9 h	28	150.3, 1240.9, 121.6	ACT
1085	^{140}La	40.23 h	SE	487.0, 1596.2	ACT
1085.8	^{77}Ge	11.30 h	13	264.5, 211.4, 215.5	ACT
1085.8	^{152}Eu	13.4 y	48	344.3, 121.8, 1407.9, 964.0	ACT
1087.6	^{198}Au	2.696 d	0.2	411.8	ACT
1090.6	^{56}Mn	2.580 h	DE	846.6, 1811.2, 2112.2	ACT
1097.1	^{116m}In	54 m	66	1293.4, 417.0	ACT
1099.3	^{59}Fe	44.6 d	100	1291.6	ACT
1112.1	^{152}Eu	13.4 y	56	344.3, 121.8, 1407.9, 964.0	ACT
1115.4	^{65}Ni	2.520 h	61.5	1481.7, 366.5	ACT
1115.5	^{65}Zn	243.8 d	100	511.0	ACT
1120.3	^{226}Ra	1600 y	--	609.3	NAT
1120.4	^{214}Bi	19.7 m	30	609.3, 1764.7	NAT-^{238}U
1120.5	^{46}Sc	83.8 d	100	889.3	ACT
1121.2	^{182}Ta	115 d	100	1221.3, 1230.9, 1189.0, 222.1	ACT
1131.7	^{38}Cl	37.2 m	SE	1642.7, 2167	ACT
1145.6	^{38}Cl	37.2 m	DE	2167, 1642.7	ACT
1147.8	^{131}Te	25.0 m	9.4	149.7, 452.4	ACT
1148.0	^{97}Zr	16.8 h	3.1	743.4	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
1173.2	^{60}Co	5.27 y	100	1332.5	ACT
1178.0	^{160}Tb	72.4 d	45	879.3, 966.2, 962.5	ACT
1180	^{124}Sb	60.20 d	SE	602.7, 1691.0	ACT
1180.7	^{151}Nd	12.4 m	22	116.4, 255.6, 139.0	ACT
1189.0	^{182}Ta	115 d	45	1121.2, 1221.3, 1230.9	ACT
1215.0	^{70}Ga	21.1 m	0.4	175.3, 1039.4	ACT
1216.3	^{76}As	26.3 h	10.6	559.1, 657.0	ACT
1221.3	^{182}Ta	115 d	95	1121.2, 1221.3, 1189.0	ACT
1228.6	^{76}As	26.3 h	2.8	559.1, 657.0	ACT
1230.9	^{182}Ta	115 d	50	1121.2, 1221.3, 1189.0	ACT
1235.3	^{136}Cs	13.1 d	19.8	818.5, 1048.1, 340.6	FIS
1238.1	^{226}Ra	1600 y	--	609.3	NAT
1240.9	^{177}Yb	1.9 h	17	150.3, 1079.8, 121.6	ACT
1256.7	^{80}Br	17.7 m	1.3	617.0, 665.7	ACT
1266.2	^{31}Si	2.62 h	100	--	ACT
1268.0	^{28}Al	2.24 m	SE	1778.9	ACT
1271.9	^{160}Tb	72.4 d	21	879.3, 966.2, 1178.0	ACT
1273.3	^{29}Al	6.5 m	100	1273.3	ACT
1274.5	^{22}Na	2.60 y	100	--	ACT
1274.8	^{154}Eu	8.2 y	100	123.1, 723.3, 1004.8	ACT
1289.9	^{115m}Cd	44.6 d	45	934.1, 484.9	ACT
1291.6	^{59}Fe	44.6 d	77	1099.3	ACT
1293.4	^{116m}In	54 m	100	1097.1, 417.0	ACT
1293.6	^{41}Ar	1.83 h	100	--	ACT
1296.9	^{47}Ca	4.54 d	100	--	ACT
1300.0	^{114}In	71.9 s	100	--	ACT
1300	^{56}Mn	2.58 h	SE	846.6, 1811.2	ACT
1310.0	^{83}Se	22.3 m	36	356.6, 510.0, 124.9	ACT
1311.6	^{48}Sc	43.7 h	100	983.5, 1037.4	ACT
1317.4	^{82}Br	35.3 h	38	776.5, 554.3, 619.1, 1044.0	ACT

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
1325.1	^{88}Y	106.6 d	SE	1836.1, 898.0	ACT
1332.4	^{60m}Co	10.48 m	100	--	ACT
1332.5	^{60}Co	5.27 y	100	1173.2	ACT
1345.8	^{64}Cu	12.71 h	100	--	ACT
1368.3	^{124}Sb	60.20 d	4.7	602.7, 1691.0	ACT
1368.5	^{24}Na	15.02 h	100	2754.1, 2243.1	ACT
1370.0	^{19}O	26.8 s	60	200	ACT
1378.1	^{166}Ho	26.9 h	100	1580.5	ACT
1384.3	^{110m}Ag	252 d	22	657.6, 884.5, 937.3	ACT
1388.1	^{111}Pd	22 m	60	580.0, 376.5	ACT
1388.9	^{152m}Eu	9.3 h	5.5	841.6, 963.5, 121.8	ACT
1407.9	^{152}Eu	13.4 y	88	121.8, 344.3, 964.0, 1112.1	ACT
1434.4	^{52}V	3.76 m	100	--	ACT
1435.9	^{138}Cs	32.2 m	100	1009.8, 462.8	FIS
1440.0	^{19}O	26.8 s	2.8	200, 1370	ACT
1458.7	^{111}Pd	22 m	60	580.0, 376.5, 1388.1	ACT
1460.7	^{40}K	1.28×10^9 y	100	--	NAT
1474.9	^{82}Br	35.3 h	24	776.5, 554.3, 619.1, 1044.0	ACT
1481.7	^{65}Ni	2.520 h	100	1115.4, 366.5	ACT
1488.9	^{111}Pd	22 m	60	580.0, 376.5, 1388.1	ACT
1507.7	^{116m}In	54 m	14	1293.4, 1097.1	ACT
1524.7	^{42}K	12.36 h	100	--	ACT
1532.7	^{101}Mo	14.6 m	32	192.0, 590.8, 1012.4	ACT
1575.5	^{142}Pr	19.13 h	100	--	ACT
1580	^{124}Sb	60.20 d	SE	602.7, 1691.0	ACT
1580.5	^{166}Ho	26.9 h	23	1378.1	ACT
1596.2	^{140}La	40.23 h	100	487.0, 815.8, 328.8	ACT
1601	^{56}Mn	2.58 h	SE	846.6, 1811.2	ACT
1630.0	^{23}Ne	37.5 s	2.8	438	ACT
1633.1	^{20}F	11.0 s	100	--	ACT

APPENDIX II (cont.)

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
1642.7	^{38}Cl	37.2 m	85	2167, 1145.6, 620.7	ACT
1650.2	^{82}Br	35.3 h	1.2	776.5, 554.3, 619.1	ACT
1656.6	^{38}Cl	37.2 m	SE	2167, 1145.6, 620.7	ACT
1691.0	^{124}Sb	60.20 d	51	602.7, 722.8	ACT
1729.9	^{214}Bi	19.7 m	2.9	1764.7, 1661.5	NAT-^{238}U
1732.1	^{24}Na	15.02 h	DE	2754.1, 1368.5	ACT
1764.7	^{214}Bi	19.7 m	34	609.3, 1120.3	NAT-^{238}U
1768.3	^{138}Xe	14.2 m	63.5	258.3, 434.5, 2015.8	FIS
1778.9	^{28}Al	2.24 m	100	1268, 757	ACT
1811.2	^{56}Mn	2.580 h	30	846.6, 2112.2	ACT
1836.0	^{88}Rb	17.7 m	100	898	ACT
1836.1	^{88}Y	106.6 d	100	898.0	ACT
2011.9	^{87}Kr	76.3 m	2.9	1740.5, 2556.0	FIS
2015.8	^{138}Xe	14.2 m	46.6	258.3, 434.5, 1768.3	FIS
2080	^{37}S	5.05 m	DE	3102.4	ACT
2091.0	^{124}Sb	60.20 d	7	602.7, 1691.0	ACT
2096.6	^{76}As	26.3 h	1.2	559.1, 657.0	ACT
2112.0	^{116m}In	54 m	25	1293.4, 1097.1, 417.0	ACT
2112.2	^{56}Mn	2.580 h	15.3	846.6, 1811.2	ACT
2118.6	^{86}Rb	17.7 m	4.5	1836, 898	ACT
2167.0	^{38}Cl	37.2 m	100	1642.7, 1656.6	ACT
2195.8	^{88}Kr	2.80 h	38.1	2392.1, 193.6	FIS
2201.0	^{72}Ga	14.1 h	27	834.1, 630.1	ACT
2218.0	^{138}Cs	32.2 m	21.4	1435.9, 1009.8, 462.8	FIS
2243.1	^{24}Na	15.02 h	SE	2754.1, 1368.5	ACT
2342.1	^{88}Kr	2.80 h	100	196.3, 834.8, 2195.8	FIS
2425.8	^{29}Al	6.5 m	6.4	1273.3	ACT
2508.0	^{72}Ga	14.1 h	14	834.1, 2201, 630.1	ACT
2521.8	^{140}La	40.23 h	1	1596.2, 487.0, 815.8	ACT
2556.0	^{87}Kr	76 m	42	402.6	FIS

Energy (keV)	Isotope	Half-life	Relative Intensity (%)	Some Associated γs (RI>10%)	Primary Origin*
2572.0	^{49}Ca	8.72 m	SE	3083.0, 4071.0	ACT
2591.0	^{37}S	5.05 m	SE	3102.4	ACT
2614.7	^{208}Ti	3.01 m	100	583.1	NAT-^{232}Th
2677.6	^{88}Rb	17.7 m	11	1836, 898	ACT
2754.1	^{24}Na	15.02 h	100	1368.5, 1732.1	ACT
3083.0	^{49}Ca	8.72 m	100	4071.0, 2572.0	ACT
3102.4	^{37}S	5.05 m	100	2591.4	ACT
4071.0	^{49}Ca	8.72 m	11.2	3083.0, 2572.0	ACT

*ACT = Activation, FIS = Fission/Fallout, NAT = Natural decay chain indicated.

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