

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/231188334>

Simultaneous determination of uranium, thorium, molybdenum, tungsten, arsenic, and antimony in granitic rocks by epithermal neutron activation analysis

ARTICLE *in* ANALYTICAL CHEMISTRY · SEPTEMBER 1976

Impact Factor: 5.64 · DOI: 10.1021/ac50005a008

CITATIONS

23

READS

7

1 AUTHOR:



Eiliv Steinnes

Norwegian University of Science and Technol...

529 PUBLICATIONS 10,775 CITATIONS

SEE PROFILE

tions with reactor fast neutrons, this technique has only limited applications, mainly because of high activities and interferences produced via (n,γ) reactions. The thermal neutrons may be completely cut off, but considerable (n,γ) activation due to epithermal neutrons still remains.

The problem of primary interfering reactions is somewhat more complicated in activations with cyclotron-produced neutrons than in activation with 14-MeV neutrons. In general, the number of interfering elements increases with increasing deuteron energy. This can be explained by the fact that with increasing deuteron energy the average neutron energy gets larger, so additional interfering reactions become energetically possible. In Table III, the extent of primary interfering reactions for cyclotron-produced neutrons obtained by using three different deuteron energies is compared with that for 14-MeV neutrons and reactor fast neutrons. From Table III, one can see that the extent of the following interferences is at about the same level for both the cyclotron-produced neutrons and the 14-MeV neutrons: the interference of sodium and aluminum in the determination of magnesium in counting ^{24}Na ; of sodium for $E_d \geq 30$ MeV and of magnesium in counting ^{24}Na and of silicon in counting ^{27}Mg for the determination of aluminum; of aluminum and phosphorus in counting ^{28}Al for the detection of silicon; and of aluminum and silicon in the detection of phosphorus. The extent of interference is somewhat higher for cyclotron-produced neutrons than for 14-MeV neutrons in the following cases: for lower deuteron energies, the interference of sodium in counting ^{24}Na to detect aluminum; the interference of magnesium in counting ^{27}Mg to detect aluminum (by a factor of 3 to 4) though this interference still remains extremely weak; and the interference of molybdenum in the detection of zirconium by counting ^{89m}Zr (by a factor of 2 to 9). However, in activations with cyclotron-produced neutrons, the interference of some few additional elements must be considered: the interference of silicon in the detection of magnesium; of phosphorus, sulfur, and chlorine in the determination of silicon and phosphorus; and of ruthenium in the determination of molybdenum. In most cases, these additional interferences occur only at high deuteron energies, and to a very low extent.

From Table III, it is evident that in activations with reactor fast neutrons considerable interference can occur via (n,γ) reaction from Na in the determination of Mg; from Mg, in the determination of Al; and from Al, in the determination of Si and P.

LITERATURE CITED

- (1) H. P. Yule, H. R. Lukens, Jr., and V. P. Guinn, in "Utilization of Reactor Fast Neutrons for Activation Analysis", GA-5075, March 1964.
- (2) K. G. Broadhead and D. E. Shanks, *Int. J. Appl. Radiat. Isot.*, **18**, 279 (1967).
- (3) E. A. Uken, J. I. W. Watterson, A. Knight, and J. P. T. Sellschop, *Int. J. Appl. Radiat. Isot.*, **19**, 615 (1968).
- (4) R. Henkelmann, E. Pfeiffermann, H.-J. Born, and D. C. Aumann, *Radiochem. Radioanal. Lett.*, **6**, 21 (1971).
- (5) J. Janczyszyn, L. Loska, and L. Gorski, *Radiochem. Radioanal. Lett.*, **8**, 363 (1971).
- (6) D. E. Wood, "Activation Analysis with 14 MeV Neutron Generators", *Adv. Act. Anal.*, **2**, 265-337, (1972).
- (7) S. S. Nargolwalla and E. P. Przybylowicz, "Activation Analysis with Neutron Generators", Wiley, New York, 1973.
- (8) V. Krivan and H. Münzel, *J. Radioanal. Chem.*, **15**, 575 (1973).
- (9) E. L. Steele, *Proc. 1965 Int. Conf. Modern Trends in Act. Anal.*, 102-106 (1965).
- (10) E. Bruninx, *Nat. Bur. Stand. (U.S.) Spec. Publ.* **312**, "Vol II, Modern Trends in Activation Analysis", 860-867 (1969).
- (11) G. J. Batra and D. K. Bewley, *J. Radioanal. Chem.*, **16**, 275 (1973).
- (12) R. O. Allen, Jr., and G. W. Reed, Jr., *J. Radioanal. Chem.*, **22**, 63 (1974).
- (13) W. Seelmann-Eggebert, G. Pfennig, and H. Münzel, "Chart of the Nuclides", 4th ed., Kernforschungszentrum, Karlsruhe, 1974.
- (14) K. A. Keller, H. Münzel, and H. Lange, "Q-values for Nuclear Reactions", Landolt-Börnstein, New Series, Group I, Vol. 5, Part a, Springer, Berlin, 1973.
- (15) G. Erdtmann and W. Soyka, "Die Gamma-Linien der Radionuklide", Jül-1003-AC, Jülich, W. Germany, September 1973.
- (16) "Handbook on Nuclear Activation Cross-Sections", Technical Report No. 156, IAEA, Vienna, 1974.
- (17) H. Münzel, J. Buschmann, G. Christaller, D. Hartmann, D. Hartwig, F. Michel, R. Schneider, and E. Schwarzbach, *Nucl. Instrum. Methods*, **73**, 103 (1969).
- (18) G. W. Schweimer, *Nucl. Phys.*, **A100**, 537 (1967).
- (19) K. Schmidt and H. Münzel, KFK-Report 1288, September 1970.
- (20) V. Krivan and K. Krivan, *J. Radioanal. Chem.*, **29**, 145 (1976).

RECEIVED for review March 30, 1976. Accepted May 24, 1976.

Simultaneous Determination of Uranium, Thorium, Molybdenum, Tungsten, Arsenic, and Antimony in Granitic Rocks by Epithermal Neutron Activation Analysis

Eiliv Steinnes

Institutt for Atomenergi, Isotope Laboratories, Kjeller, Norway

Activation with epithermal neutrons and subsequent Ge(Li) γ -spectrometry measurements after 6 days' delay facilitates the simultaneous determination of U, Th, Mo, W, As, and Sb in granitic rocks. A gain in sensitivity of a factor of 20 or more is obtained as compared with instrumental activation analysis using thermal neutrons. The limit of detection is about 0.1 ppm for U and Th and 0.5-1 ppm for the other elements. Neutron shielding effects are estimated to be of minor importance, and the fission product interference in the case of Mo is very substantially reduced by using the epi-cadmium irradiation technique. Possible errors due to interfering γ rays are discussed.

The simultaneous determination of uranium and thorium in rocks is of interest in prospecting analyses as well as in more

fundamental geochemical studies. Nuclear methods offer several possibilities to perform this determination without the need of sample decomposition. Neutron activation followed by delayed neutron counting (1) is a rapid and sensitive technique, but requires immediate access to a reactor and special experimental facilities. Thermal neutron activation analysis based on Ge(Li) γ -spectrometry provides adequate sensitivity for thorium in most cases, provided that the activity measurements are performed 2 weeks or more after the end of the irradiation. The sensitivity of uranium determination by this technique is, however, less satisfactory. Activation with epithermal neutrons (2), using a cadmium cover to eliminate the thermal neutrons, gives rise to a considerable improvement in sensitivity for both elements, and should be a useful alternative when the delayed-neutron method is not easily accessible.

During a prospecting program involving a series of granitic rocks, it was found that measurements by γ spectrometry carried out about 6 days after the end of an epithermal irradiation facilitated the determination of molybdenum, tungsten, arsenic, and antimony in addition to uranium and thorium. Antimony has been determined previously by this technique (2) while the determination of molybdenum, tungsten, and arsenic in silicate rocks by instrumental activation analysis with epithermal neutrons has not been reported before.

EXPERIMENTAL

Irradiations were carried out for 20 h in the JEEP-II reactor (Kjeller, Norway) in a position close to the edge of the reactor core with a thermal neutron flux of $1.5 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$ and a cadmium ratio of 3.0 for ^{197}Au . Rock samples of about 100 mg were wrapped in $3 \times 3 \text{ cm}$ sheets of aluminium foil and irradiated in a cadmium box (20-mm i.d., 15-mm internal height, 1.0-mm thickness) along with standards prepared by evaporating 100- μl aliquots of appropriate standard solution carefully to dryness on the same sort of aluminium sheets. Twenty samples were irradiated in each batch.

After 6 days' delay, the samples, after weighing into inactive counting vials, were subjected to γ spectrometry using a $35 \text{ cm}^3 \text{ Ge(Li)}$ detector with associated electronics connected to a 2000-channel analyzer based on a NORD-I digital computer (12K, 16 bit). The resolution of the system for the 1332-keV peak of ^{60}Co was 2.5 keV (FWHM). The distance between sample and detector was so selected that the total activity of no sample exceeded 10^4 counts/s. Normally the samples from one irradiated batch were divided into two groups according to activity, each group being measured at an appropriate distance. Spectrum stability and dead-time correction was determined by means of a precision pulse generator (3). The spectra were recorded at 1 keV/channel, and the pulse height of the generator was adjusted to appear approximately in channel 1650. If a pulser peak shift of more than 1 channel occurred, an error message was printed. A counting time of 8 min was used, permitting the counting, print-out of concentrations, and manual change of samples to be carried out within 10 min. Peak area calculations were performed according to the method of Covell (4), the selection of the number of channels to be included in the calculation depending on the distance to interfering adjacent peaks in the spectrum. Detection limits were established on the basis of the criterion $A < 3\sqrt{B}$, where A is the net peak area and B is the area subtracted in the peak calculation.

RESULTS AND DISCUSSION

The main aim of this work was to develop a procedure suitable for routine application. It was therefore required that all elements concerned were to be determined in one single counting, and that this operation should take no more than 10 min. It was found by preliminary experiments that counting 6 days after the end of the irradiation gave the best results, all elements being considered as a whole. The method has been used for the analysis of a great number of granitic rock samples in connection with a prospecting program. Results obtained by duplicate analysis of some typical samples under routine conditions are given in Table I. At concentrations above 5 ppm for U and Th and above 10 ppm for W, a precision of $\pm 5\%$ or better is obtained. In the case of As, Sb, and Mo, the concentrations observed were closer to the limit of detection, and the precision was consequently less satisfactory.

The capacity of the method would be improved by using a larger cadmium box. In that case, however, errors due to epithermal flux gradients, which were apparently small in the present work, could become more important. Moreover, the maximum permissible surface area of a cadmium container used for irradiation may not be the same in all reactors.

In Table II, some nuclear data relevant to the determination of the above elements by epithermal activation are listed. The main reason why this irradiation technique may be worthwhile in the instrumental activation analysis of silicate rocks (2), is that a number of isotopes of trace elements in these rocks show considerably higher I_0/σ_0 ratios (resonance activation

Table I. Simultaneous Determination of U, Th, Mo, W, As, and Sb (ppm) in Granitic Rocks by Instrumental Activation Analysis Using Epithermal Neutrons

Element	U		Th	Mo ^a	W	As	Sb
Radio-nuclide used	²³⁹ Np	²³⁹ Np	²³³ Pa	^{99m} Tc	¹⁸⁷ W	⁷⁶ As	¹²² Sb
Peak location	228	277	312	140	685	559	564
No. of channels included	5	5	3	3	5	3	3
Samples							
1A	24.9	26.7	5.9	0.7	8.0	3.5	0.24
1B	25.3	25.7	6.3	1.0	9.2	2.3	0.15
2A	18.7	19.4	7.3	<0.5	21.3	1.4	<0.10
2B	19.4	19.4	6.8	0.5	20.7	2.1	0.11
3A	29.7	29.2	19.8	0.4	9.0	1.8	0.62
3B	28.3	28.7	20.0	0.7	8.8	1.5	0.61
4A	8.4	8.9	233	<0.5	4.0	0.5	<0.10
4B	9.0	9.2	237	<0.5	6.2	0.9	<0.10
5A	17.9	18.4	6.2	2.9	71.3	3.7	<0.10
5B	18.9	18.9	7.5	3.1	70.9	4.5	<0.10
6A	18.6	19.0	7.0	0.4	16.6	2.5	0.11
6B	19.0	19.3	6.2	0.6	19.7	1.9	0.13
7A	9.1	9.2	8.9	1.2	34.5	6.5	<0.10
7B	9.5	9.8	9.4	1.0	33.9	6.2	0.16
8A	9.6	9.2	257	2.2	7.0	0.6	<0.10
8B	9.5	9.8	250	1.9	9.4	0.7	<0.10
9A	18.0	18.2	7.7	3.3	75.0	4.9	<0.10
9B	17.9	17.8	7.2	2.4	74.0	3.9	<0.10
Approximate limit of detection, ppm	0.1	0.1	0.1 ^b	0.5 ^b	1	0.5	0.1

^a Corrected for contribution from the ^{235}U (n,f) reaction with thermal neutrons and the ^{232}Th (n,f) reaction with reactor fast neutrons. ^b Depending on the uranium content of the sample.

integral/thermal neutron cross section) than most of the nuclides giving rise to major activities (^{23}Na , ^{41}K , ^{45}Sc , ^{58}Fe). In granitic rocks, ^{24}Na is a major interfering nuclide in instrumental activation analysis even one week after the irradiation. The main benefit obtained in the present work is therefore connected with the elimination of a major part of the ^{24}Na activity. This benefit can be quantitatively expressed by means of a so-called "advantage" factor (8):

$$Fa = \frac{(R_{Cd})_d}{(R_{Cd})_D}$$

where d and D denote the interfering nuclide and the nuclide under question, respectively. This factor refers to an epithermal irradiation relative to an irradiation with the entire reactor neutron spectrum in the same irradiation position (or another position with the same cadmium ratio). It may also be useful to define an "advantage" factor relative to irradiation in a thermal neutron flux with negligible epithermal contribution (9):

$$Fa = \frac{(\sigma_0)_d(I_0)_D}{(\sigma_0)_D(I_0)_d}$$

Advantage factors for the nuclides of interest in this work, relative to ^{23}Na , are calculated in Table II. It is obvious that the advantage obtained by epithermal activation for the elements concerned is considerable, in terms of improving the sensitivity of instrumental activation analysis. Taking uranium as an example, the limit of detection by irradiation in a well thermalized flux would be about 20 ppm for granitic rocks with the measuring equipment used in the present work. A straightforward irradiation in a flux with $R_{Cd}^A = 3.0$ yields

Table II. Some Data of Interest in Epithermal Activation Analysis Applied to the Elements Included in the Present Work

Element	U	Th	Mo	W	As	Sb
Stable isotope concerned	^{238}U	^{232}Th	^{98}Mo	^{186}W	^{75}As	^{121}Sb
Thermal neutron activation cross section, barns (5)	2.72	7.4	0.14	37	4.4	6.2
Resonance activation integral, barns (6)	280	82	7.5	420	63	180
Main resonance energies, eV (7)	6.7 21.0 36.7 66.2	21.8 23.4 59.5 69.1	429 467	18.8	47.0 92.4	6.2 15.4 29.7
"Advantage factor" with respect to ^{23}Na :						
A. Relative to irradiation without Cd cover with the flux distribution used in the present work ($R_{\text{Cd}} = 3.0$)	45	15.3	37	15.6	18.4	28.2
B. Relative to irradiation in a thermal neutron flux with negligible epithermal contribution	189	20.4	99	20.9	26.3	53.4

an improvement in the detection limit to about 5 ppm because of the influence of the epithermal neutrons. Exclusion of the thermal neutron component by a cadmium cover brings the limit of detection down to about 0.1 ppm, which is adequate for the determination of uranium in a wide variety of rocks.

Interfering γ Rays. In most cases, the most significant source of systematic error in instrumental activation analysis is the interference of adjacent γ rays in the spectrum. The most probable interferences is discussed below for the six elements concerned.

Uranium. For the determination of uranium via ^{239}Np , the 228.1-keV and 277.9-keV peaks are both suitable. The 277.9-keV peak is probably least subject to interference. Interference from ^{203}Hg (279.2 keV) and ^{75}Se (279.5 keV) is very unlikely in silicate rocks. The 282.6-keV peak of ^{175}Yb , which may be a serious problem if thermal neutrons are used, is strongly depressed relative to ^{239}Np in epithermal activation. For the 228.1-keV peak, the 229.3-keV line of ^{182}Ta may be a significant interference. The good agreement between results based on the two ^{239}Np peaks indicates that ^{182}Ta interference was insignificant in the present work.

Thorium. The most likely interferences to the 311.9-keV peak of ^{233}Pa seem to be ^{169}Yb (307.5 keV), ^{192}Ir (308.4 keV), and ^{239}Np (316.2 keV). In the present samples, with relatively high U/Th ratios, the latter interference was found by far to be most significant. At a U/Th ratio of 1, the 316.2 keV/311.9 keV activity ratio was about 0.2 in the present work. The interference was kept to a minimum by using only 3 channels (one channel on each side of centroid channel) in the peak area calculation. The baseline is thus drawn on the basis of the counts in channels 310 and 314, in which case the influence from the 316.2-keV peak is fairly small unless a very high U/Th ratio is present.

Molybdenum. The measurement of molybdenum via the 140.4-keV peak of ^{99m}Tc is likely to be interfered with by ^{59}Fe (142.5 keV), ^{187}W (134.2 keV), and minor peaks of ^{181}Hf (136.3, 136.9). The ^{59}Fe peak, which is in most cases a very serious interference in thermal neutron investigations, was found to be of moderate importance in this work because of a high "advantage" factor of ^{99}Mo relative to ^{59}Fe , leading to a 140.4 keV/142.5 keV activity ratio of 1.2×10^5 at equal amounts of the elements. This means that with an iron content of 2%, which is typical of granitic rocks, the iron interference is low even at the 1-ppm Mo level. Interference from the 134.2-keV ^{187}W peak, which was present at high intensities in the present

samples, was kept at a low level in a similar way as for thorium, using only 3 channels in the peak integration.

Tungsten. Several γ rays might be used for the measurement of tungsten via ^{187}W . Of these the one at 685.7 keV is least subject to interference in a granitic rock matrix. The most probable interference seems to be the 692.8-keV peak of ^{122}Sb , which is easily avoided. The 479.5-keV γ ray is unsuitable because of interference from the 482.2-keV peak of ^{181}Hf .

Arsenic, Antimony. The simultaneous measurement of ^{76}As and ^{122}Sb by the 559.1- and 564.1-keV peaks, respectively, was made possible by using three channels in the integration of each peak. With a counting system having a resolution of better than 2 keV (FWHM) in this energy range, the influence from the 564.1-keV peak on the content of channel 561 used to draw the baseline of the ^{76}As peak, and the corresponding influence from the 559.1-keV peak on the content of channel 562, is moderate if the peaks are of the same order of magnitude. If one peak is substantially higher, the results for the other element would tend to be low. In samples of high As content, the determination of Sb via the 564.1-keV peak is further disturbed by the minor 562.8-keV peak of ^{76}As . In samples with a low As/Sb ratio, the 657.1-keV peak may be a better choice for As, provided that interference from the 657.1-keV peak of ^{110m}Ag can be neglected.

Neutron Shielding Effects. Another source of error which may sometimes interfere with activation analysis measurements, is shielding effects. Considering the low concentrations present of the elements in question, self-shielding is not likely to be of great concern. More serious errors may occur if some of the more abundant elements in the samples with appreciable resonance activation integrals have resonances overlapping the dominant ones of the elements investigated (9). The most important resonances of the six elements determined in this work are listed in Table II. It appears that none of the major elements in the rocks (Si, O, Mg, Ca, Na, K, Fe, Ti, Mn) possess resonances that would interfere. Some granitic rocks show relatively high contents of rare earths, some of which have isotopes with high resonance activation integrals. The most serious interference would seem to arise from samarium, because of the giant resonance of ^{152}Sm at 8.0 eV, which could interfere with the determination of U and Sb. According to van der Linden et al. (10), however, the epithermal self-shielding for samarium is low at concentrations below several hundred ppm. Since the effect of samarium on

the epithermal shielding effect in other elements will never exceed the self-shielding factor in samarium, and the concentrations of Sm in the samples concerned were well below the range where the self-shielding occurs, it may be concluded that shielding effects probably were of minor importance in this work.

Fission Product Interference. In the case of molybdenum, interference from ^{99}Mo produced by fission of ^{235}U present in the sample may often be serious in neutron activation analysis. In a thermal neutron flux, about 3 times more ^{99}Mo is produced from uranium than from molybdenum if equal masses of the elements were present. This means that molybdenum determination in the present samples would be virtually impossible by thermal neutron activation. By introducing a cadmium cover, the ^{99}Mo activity produced from uranium is reduced to about $\frac{1}{30}$ of that originating from the same amount of molybdenum (11), which means that the corrections to be applied are moderate even in the present samples with U/Mo ratios of 10 or higher.

LITERATURE CITED

- (1) F. F. Dyer, J. F. Emery, and G. W. Leddicotte, *U.S. At. Energy Comm. Rep., ORNL-3342* (1962).
- (2) A. O. Brunfelt and E. Steinnes, *Anal. Chim. Acta*, **48**, 13 (1969).
- (3) O. U. Anders, *Nucl. Instrum. Methods*, **68**, 205 (1969).
- (4) D. F. Covell, *Anal. Chem.*, **31**, 1785 (1959).
- (5) R. Sher, "Handbook on Nuclear Activation Cross-Sections", International Atomic Energy Agency, Vienna, 1974, pp 1-13.
- (6) H. Albinsson, "Handbook on Nuclear Activation Cross-sections", International Atomic Energy Agency, Vienna, 1974, pp 15-86.
- (7) M. D. Goldberg, S. F. Mughabghab, S. N. Purohit, B. A. Magurno, and V. M. May, *U.S. At. Energy Comm. Rep., BNL-325*, 2d ed., Suppl. no. 2 (1965-1966).
- (8) D. Brune and K. Jirlow, *Nukleonik*, **6**, 242 (1964).
- (9) E. Steinnes, in "Activation Analysis in Geochemistry and Cosmochemistry", A. O. Brunfelt and E. Steinnes, Ed., Universitetsforlaget, Oslo, 1971, pp 113-128.
- (10) R. van der Linden, F. de Corte, and J. Hoste, *J. Radioanal. Chem.*, **20**, 695 (1974).
- (11) E. Steinnes, *Anal. Chim. Acta*, **57**, 249 (1971).

RECEIVED for review February 2, 1976. Accepted June 7, 1976.

Low Flux Multielement Instrumental Neutron Activation Analysis in Archaeometry

R. G. V. Hancock

Department of Chemical Engineering and Applied Chemistry, and SLOWPOKE Reactor Facility, University of Toronto, Toronto, Ontario, Canada M5S 1A4

A routine instrumental method has been developed for the analysis of 35 elements in potsherds by means of neutron activation analysis at fluxes of $\leq 2.5 \times 10^{11} \text{ n/cm}^2 \text{ s}$. Using a SLOWPOKE reactor, each sample was bombarded 3 times with increasing neutron doses, and the resultant γ -ray emissions were analyzed following suitable decay periods. The accuracy and precision of measurement was estimated by analyzing a "standard" pottery and 2 Standard Reference Materials. For these samples, agreement with published results was within ± 5 -10% for the majority of elements, and analytical precisions were comparable. Only 3 out of 35 elements were in serious disagreement with published results for the standard pottery.

Over the past five years, considerable advances have been made in the field of archaeometry. A relatively small number of research groups has been employing either x-ray fluorescence (XRF) (1, 2) or instrumental neutron activation analysis (INAA) (3-5) for multielement analysis of ancient potsherds. As instrumentation has improved, there has been an increase in the number of elements analyzed.

Currently, 16-20 elements are being measured by INAA (3, 4) in order to establish the provenance of potsherds. The elements which have been determined are those which produce reasonably long-lived radioisotopes ($T_{1/2} > 2 \text{ h}$). This restriction was necessary because of a physical separation of the laboratory from the nuclear reactor employed in activation and/or because of the limiting of access to relatively high neutron fluxes in conventional reactors.

It is not impossible to use conventional reactors to determine elements producing short-lived radioisotopes in ceramic

materials (6), but the extra work required to produce satisfactory results appears to make the task impracticable on a routine basis.

Low flux reactors, such as the SLOWPOKE (Safe Low Power Critical Experiment) reactor at the University of Toronto (7), allow access to relatively low neutron fluxes (10^{11} - $10^{12} \text{ n/cm}^2 \text{ s}$) and can be most profitably employed for the analysis of short-lived isotope-producing elements in pottery.

The flux limitations of such a reactor are obvious, but are not sufficient to eliminate their use for the analysis of elements which produce long-lived isotopes. As an example, at the SLOWPOKE reactor, cobalt in potsherds (averages 5-30 ppm) may be determined either by the production of $^{60\text{m}}\text{Co}$ (10.5m half-life) or by the production of ^{60}Co (5.26 years half-life).

Since the number of elements previously studied has been restricted by analytical technique rather than geological or ceramic considerations, a program was instituted to develop a more comprehensive multielement analytical scheme which could be routinely applied to the analysis of potsherds.

Because of the stable nature of the neutron flux in the SLOWPOKE reactor system (8), multielement standards are not normally employed in the routine analysis of samples.

The present work described an INAA procedure in which 35 elements are quantized for each potsherd. Included are elements indicative of the provenance and the method of production of the ceramics.

EXPERIMENTAL

Samples and Standards. Two Standard Reference Materials, Coal (SRM 1632) and Fly Ash (SRM 1633), from the U.S. National Bureau of Standards, Washington, D.C., were analyzed as were samples of