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NEUTRON ACTIVATION ANALYSIS AT THE LIVERMORE POOL-TYPE REACTOR FOR THE ENVIRONMENTAL RESEARCH PROGRAM

MASTER

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NEUTRON ACTIVATION ANALYSIS AT THE LIVERMORE POOL-TYPE REACTOR FOR THE ENVIRONMENTAL RESEARCH PROGRAM

Abstract

Instrumental neutron activation analysis is a technique of trace analysis using measurements of radioactivity induced in the sample by exposure to a source of neutrons. The induced activity is measured by the emitted gamma radiation. Each gamma emitter can then be identified by the energy of the photopeaks produced as the nuclide decays and by the half-life of the neutron-induced activity. A complex computer program GAMANAL has been used to accomplish the major

tasks of nuclide identification and quantification. The nuclide data output from GAMANAL is processed by a second computer code NADAC, which develops elemental abundance data from disintegration rates observed. The methods are those employed at the Livermore Pool-Type Reactor in support of the Environmental Research Program. Among the procedures described and discussed are sample preparation, irradiation, analysis, and application of the technique.

Introduction

The purpose of this report is to describe the capabilities for trace element analysis at the Livermore Pool-type Reactor (LPTR) using Instrumental Neutron Activation Analysis (INAA). The technology and methods employed are

discussed. Applications of the INAA technique in past and current projects are described. This procedure was described earlier in UCRL-51855,¹ but the present report reflects significant changes in our method of data analysis.

Scope of Trace Element Analysis

Trace-element analysis at the LPTR has been primarily concerned with environmental research programs.

Involvement occurs at various levels of interaction, from definition of problems through finished reports.

In addition, a service is provided within the Laboratory for trace-element analysis. Users of the service are given as much assistance as desired. Applied research and development contracts are also carried out with groups outside the Laboratory.

Some areas of investigation are:

- Trace elements in emissions from fossil fuel power generating plant.
- Trace elements in the environment of geothermal wells of the Imperial Valley.

- Trace elements in milk.
- Trace elements in aerosols.
 - Air sampling in the vicinity of smelting operations in Kellogg, Idaho.
 - ACHEX (California Aerosol Characterization Experiment).
- Trace elements in environmental samples.
 - Soils and sediments.
 - Vegetation.
 - Water - fresh and marine.

Some of these projects are described in the section on applications.

Description of the Technique

The INAA method of trace element identification has become increasingly important with progressive improvement in sensitivity. This improved sensitivity has been made possible by high-resolution, solid-state radiation detectors, improved data-collection and data-reduction techniques, and increased experience in sample-preparation and collection methods.

One of the chief advantages of INAA is that it is usually a nondestructive analytical technique that requires little or no chemical pretreatment. It also permits measurement of isotopic concentrations as well as elemental concentrations for some isotopes. The word instrumental in this context means that element or

isotope identification is accomplished by instruments without the need for chemical separation.

Most INAA is done with thermal neutrons from a nuclear reactor. Neutron fluxes of 10^{12} to 10^{15} n/cm² sec are easily obtained at most reactor facilities. Those with fluxes of 10^{16} n/cm² sec can be obtained at some of the pulsed research reactor facilities. However, pulsed reactor fluxes are useful only when analyzing elements with induced activities having half-lives on the order of tenths of seconds.

BASIC PRINCIPLES

Instrumental neutron activation analysis is based on the measurement

Fig. 1. Schematic diagram of instrumental neutron activation analysis procedure.

of radioactivity induced in the sample after exposure to a source of neutrons. This induced activity is determined most easily by detecting the emitted gamma radiation with a gamma spectrometer that characterizes the emissions. This characterization gives the energy and absolute intensity of each gamma ray. Figure 1 is a schematic representation of the method.

The mixture of nuclides that makes up the complex gamma spectrum must then be identified. Each gamma emitter can be identified by the energy (or energies) of the photopeaks produced as the nuclide decays towards its ground state and by the half-life of the neutron-induced activity. Most elements that have a useful cross-section for neutron capture produce at least one isotope that can be used for a unique identification based on

half-life and gamma peaks. A complex computer program, GAMANAL, developed by Gunnink and Niday,² accomplishes the major tasks of nuclide identification and quantitation. This program GAMANAL² is discussed later.

The identification of the nuclide in an activated sample does not immediately yield an elemental analysis in a useful form. Information such as disintegrations per minute or atoms present at zero time must be translated into parts per million, total nanograms, etc. This can be accomplished in two ways. The first method is based on the application of known cross-section and radioactive decay relationships to calculate the disintegrations per minute per microgram that would be observed under the given irradiation, cooling, and counting conditions. The second method is the simultaneous irradiation of a mixture

of known amounts of the elements in question and determination of the unknown by direct ratio of activities. The procedure we use is primarily based on the first method given above. However in all cases one or more samples containing known amounts of specific elements are included in the irradiation package. These samples are subjected to the same counting and analysis procedure as the unknown samples to ensure the accuracy of the derived results. The program NADAC,³ which converts disintegration-rate data to elemental abundance data, is discussed below.

In most, if not all, samples competing activities must be considered. The samples usually contain many trace elements. The activation and counting scheme must be chosen to optimize the activity of as many elements as reasonably possible. This usually requires two or more separate irradiations for each sample and various counting schedules depending on the type of sample and elements to be analyzed. This is an effective method of utilizing the half-lives to separate elements into groups, thereby reducing the complexity of the spectra and producing less ambiguous identification. In addition, strong interference produced by a major component such as sodium can be allowed to decay, leaving the longer-lived trace elements sufficiently active for analysis.

SAMPLE PREPARATION AND HANDLING

General

Sample preparation and handling are of great importance in trace element work. Clean techniques must be employed at every step prior to irradiation. After the sample is activated, care can be relaxed since the sample is easily differentiated from any contamination other than radioactivity that might be introduced. The insensitivity to handling procedures after irradiation is one of the most attractive features of activation analysis. To maximize this advantage, preirradiation handling should be minimized.

If possible, the sample should be transferred from its irradiation container into a counting container to eliminate the problem of subtracting the trace-element content of the irradiation container. If the sample is to be counted in its irradiation container or with a binder, the trace-element content must be determined from a statistically significant number of control containers or binder samples. The same clean handling techniques must be applied to the container or binder.

Samples may be either in solid or liquid form, solid being preferred. In general, liquid samples may require a concentration step before irradiation. Liquids such as milk are freeze-dried.

Sample Geometry

Geometry must be considered in two aspects: irradiation and counting. In some cases, the same geometry will apply to both, namely when a disk shape, which is ideal for counting, can be irradiated. When the sample cannot be irradiated in disk form, it may be possible to approximate such a configuration during counting by placing a powdered sample in a flat polyethylene envelope, or a liquid in a cylindrical vial.

Techniques have been developed for preparing most dry samples in a disk shape for irradiation with a hydraulic press and appropriate dies. Some samples, such as freeze-dried skim milk, will maintain their shape after pressing while others require some binder material. Binders must be treated as any other trace-element content introduced into the sample.

Liquid Samples

When a sample must be irradiated in liquid form, several precautions must be observed. Basically the problem is leakage of the sample from its container. There will be an increase in pressure in the container resulting from heating and radiolysis. Therefore space must be provided in the container for such a release of gas. About one-half to two-thirds of the volume of the container should be available for expansion. Samples in

plastic vials must be sealed by welding; those in quartz containers are sealed by heat. The heat-sealed primary container must then be placed in a leak-proof outer container. The LPTR User's Guide⁴ provides physical dimensions of most available outer containers.

After irradiation the container is opened, and the liquid is transferred to a counting vial. The sample can be counted in the irradiation container if counting geometry and container blank are taken into consideration.

Solid Samples

Solid samples have several advantages over liquid. The most important of these is the absence of leakage problems and the consequent relaxation of sealing requirements. These samples must still be held in a primary container that is closed tightly, but not necessarily sealed. There must be a secondary container as with liquids.

Another advantage is the ease of handling and the consequent reduced exposure of personnel to radiation. As stated before, the solid sample may be pressed into a disk shape. The disks are made in a variety of diameters, ranging from a quarter-inch to one inch. If binder is necessary, a known amount is added to the weighed sample. Powdered polyethylene and

Avicel^{*} are two commercially available binders. Polyethylene requires heating to form a wafer but does not require much pressure. Avicel requires no heat, but more pressure. Both materials have acceptable blanks for most analyses.

Solid samples include particles suspended in air or other gases. Such particles are generally irradiated on the collection media. The blank for the collection media must be determined as for other materials.

Sample Size

The size of sample varies with the type of sample, the matrix, and information desired. Experimental conditions often determine sample size. For example, air sampling is limited by low concentrations of aerosol, sampling time, and capacity of the collection medium. In other cases, such as with milk, coal, soil, etc, enough sample might be available to provide any size desired. The limiting factors are then the amount of radiation from the major constituents that can be handled and counted, and the mixture of major and trace elements.

The range of sample sizes for ana-

lyzing most solids is from 1.0 mg to 1.0 g. Liquids can be handled in amounts close to 30 ml.

IRRADIATION AND COUNTING PROCEDURE

The neutron source for activation of samples is the LPTR, which is moderated and cooled by light water and consists of plate-type fuel elements and boron-containing control rods located in a tank 7.9 m (26 ft) deep and 1.98 m (6.5 ft) in diameter. Various beam tubes and irradiation facilities allow access to neutron fluxes ranging as high as 7×10^{13} n/cm²sec, and gamma-dose rates above 10^{10} rad/hr. The reactor is used for basic and applied research in support of Laboratory programs. It is operated on a schedule that permits a routine maintenance period, standard safety system checks, and maximum operation for experiments and irradiations. The LPTR's User's Guide⁴ describes the experimental irradiation facilities and services that are available.

Counting Schedule

The counting schedules shown in Table 1 are typical for short and long irradiations. The 10-min cooling time shown for the short irradiation is necessary since the detector systems used in the short analysis are not located at the reactor itself. Following irradiation, samples are

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Table 1. Neutron irradiation and counting schedule.

Irradiation time	Neutron flux (n/cm ² -sec)	Cooling time	Counting time	Elements detected
1 min	$2.1 \cdot 10^{13}$	min	10, 20, 40 min consecutive counts	Al, V, Cu, Ti, Ca, Na, Mg, Cl, Mn, Br, I, Ba, In, Dy, As, Ga, Sm, V, Mo
70 min*	$2.6 \cdot 10^{13}$ *	3 days	8 000 sec	Na, As, W, Ca, K, Cd, Mo, V, Sm, Au, Hg, La, Sb, Mo, Zn
		15 days	20 000 sec	Fe, Cr, Co, Zn, Hg, Se Ag, Sb, Ce, Cs, Eu, Sc, Th, Ni, Ta, Hf, Ba, Rb

* For bulky sample: an alternative radiation position with a flux of 5×10^{12} n/cm² sec may be used. The irradiation time is increased accordingly.

packed for counting and transported to the counting facility within the 10-min cooling period. The irradiation scheme shown in Table 1 is only an example of various schemes that may be used depending on the nature of the elemental information desired. This scheme provides a relatively complete analysis with a minimum amount of detector time.

The number of detector systems available for the neutron-activation program varies but usually is in the range of 10 to 12 systems. All systems are calibrated to operate under the GAMANAL resolution and analysis method. Five of the systems are automated. The automated systems, interfaced to a PDP-8 computer, can handle 16 samples/system thus allowing 24-hr/da counter use. The remainder

of the systems can analyze one sample at a time, and the data are transferred to the PDP-8 system by a manual dump. All data are subsequently transferred to magnetic tape and analyzed on a CDC-6600 computer (described below).

Figure 2 shows a typical sample changer with a Ge(Li) detector system. The cryostat and detector are seen to the left of upper center, the sample holders in the changer are in the lower half, and the mechanism for raising a sample into counting position is at the center of the photograph. The whole system is automated under control of the PDP-8 system.

The data obtained from the counting scheme shown in Table 1 are recorded on computer-compatible magnetic tape

for permanent reference and for subsequent reduction and analysis.

Two libraries of photopeak abundances and half-lives are used. The library for short-irradiation analyses contains nuclides whose half-lives range from 2 min to about 1 da. The 75 nuclides in this library include all candidates for activation having cross-sections greater than about 0.05 b. The library for analysis of long irradiation spectra consists of 108 nuclides whose half-

lives exceed about 1 hr. The criteria for inclusion are again based on cross-section. The total library listing of nuclide half-lives and photopeak abundances is too long to include in this report. A partial listing, giving only the major abundance photons for the more commonly found nuclides is given in Table 2. The table shows that ^{65}Zn has a gamma ray with an energy of 1115.4 keV. Thus, if there are large amounts of both Zn and Sc in a sample it may not

Fig. 2. Radiochemistry Division automatic sample changing system utilizing a Ge(Li) detector.

Table 2. Parent, daughter, half-life, and energy of observed gamma rays for elements analyzed by INAA at the LPTR.

Parent element exposed	Daughter isotope observed	Half-life	Gamma-ray energy observed ^a (keV)
Ti	⁵¹ ₂₂ Ti	5.79 min	320.0(100)
Mg	²⁷ ₁₂ Mg	9.46 min	843.8(100), 1014.5(37.5)
Cu	⁶⁶ ₂₉ Cu	5.10 min	1039.2(100)
V	⁵² ₂₃ V	3.75 min	1434.3(100)
Al	²⁸ ₁₃ Al	2.32 min	1778.7(100)
Ca	⁴⁹ ₂₀ Ca	8.80 min	3084.4(100)
Ba	¹³⁹ ₅₆ Ba	82.9 min	165.8(100)
I	¹²⁸ ₅₃ I	25.0 min	443.3(100), 526.4(9.9)
Br	⁸⁰ ₃₅ Br	16.8 min	616.2(100), 665.6(17.2)
In	¹¹⁶ ₄₉ In	53.7 min	417.0(40.2), 1097.1(59.8), 1293.4(100)
Na	²⁴ ₁₁ Na	15.0 hr	1368.4(100), 2754.1(100)
Cl	³⁸ ₁₇ Cl	37.3 min	1642.7(74.5), 2167.6(100)
Mn	⁵⁶ ₂₅ Mn	155.0 min	846.7(100), 1811.2(29.4)
As	⁷⁶ ₃₃ As	26.4 hr	559.1(100), 657.1(100)
W	¹⁸⁷ ₇₄ W	23.9 hr	134.2(32.6), 479.5(83.1), 618.2(23.1), 685.7(100)
Ga	⁷² ₃₁ Ga	14.1 hr	629.9(25.5), 834.0(100), 2201.6(27.3)
K	⁴² ₁₉ K	12.4 hr	1524.7(100)

Table 2. (Continued)

Parent element exposed	Daughter isotope observed	Half-life	Gamma-ray energy observed ^a (keV)
Cd	¹¹⁵ ₄₈ Cd	53.5 hr	492.3(29.5), 527.9(100)
Sm	¹³³ ₆₂ Sm	46.8 hr	103.2(100)
Au	¹⁹⁸ ₇₉ Au	64.7 hr	411.8(100)
La	¹⁴⁰ ₅₇ La	40.2 hr	328.8(21.4), 487.0(49.4), 1596.6(100)
Fe	⁵⁹ ₂₆ Fe	45.6 da	1099.3(100), 1291.5(77.0)
Cr	⁵¹ ₂₄ Cr	27.8 da	320.1(100)
Co	⁶⁰ ₂₇ Co	5.26 yr	1173.2(100) 1332.5(100)
Zn	⁶⁵ ₃₀ Zn	24.3 da	1115.5(100)
Hg	²⁰³ ₈₀ Hg	46.9 da	279.2(100)
Sc	⁷⁵ ₃₄ Sc	120. da	136.0(96.0), 264.7(100)
Ag	^{108m} ₄₇ Ag	5.00 yr	434.0(100), 614.4(100), 723.0(100)
Ag	^{110m} ₄₇ Ag	255. da	657.7(100), 884.7(79.6), 937.5(36.5), 1384.2(27.7)
Sb	¹²⁴ ₅₁ Sb	60.3 da	602.7(100), 1691.1(53.2)
Ce	¹⁴¹ ₅₈ Ce	32.5 da	145.5(100)
Eu	¹⁵² ₆₃ Eu	12.7 yr	121.8(100), 344.2(85.6), 1408.1(65.0)
Sc	⁴⁶ ₂₁ Sc	83.9 da	889.3(100), 1120.5(100)
Th	²³³ ₉₁ Pa	27.0 da	311.9(100)

Table 2. (Continued)

Parent element exposed	Daughter isotope observed	Half-life	Gamma-ray energy observed ^a (keV)
Ni	⁵⁸ ₂₇ Co	71.3 da	811.1(100)
Hf	¹⁷⁵ ₇₂ Hf	70.0 da	343.4(100)
Hf	¹⁸¹ ₇₂ Hf	42.3 da	133.1(49.4), 482.2(100)
U	²³⁹ ₉₂ U	23.5 min	76.67(59.3)
U	²³⁹ ₉₃ Np	2.353 da	99.4(12.3), 103.6(19.6), 106.1(25.2), 228.1(11.0)

^aNumbers given in parentheses following the gamma ray energy are the relative intensities (%) of the gamma rays. Only higher abundance gammas are included in this table.

be possible to separate the gamma-ray peaks because of overlap. Detectors that are currently available do not have adequate resolutions to separate these peaks. Scandium has another gamma ray with an energy of 889.4 keV, and the only appreciable interference with this peak is the ^{110m}Ag gamma ray at 884.7 keV. By the use of the GAMANAL program, it is possible to resolve large amounts of ^{110m}Ag, ⁴⁶Sc, and ⁶⁵Zn in the same sample. A close examination of Table 2 reveals several other interferences of the type discussed above that occur in a typical sample.

Typical Output from Instrumental Neutron Activation Analysis Sample

A typical high-volume, air-filter, aerosol sample is shown as an example of gamma spectra obtained after activation. Figures 3 through 7 are plots of the data for our filter sample 21A resulting from the irradiation and counting periods for the analyses of these particular samples.

DATA REDUCTION

The gamma-spectrometric data produced by the detector systems are processed first by GAMANAL. The output

Fig. 3. INAA spectrum Q1 for high-volume air filter sample IAS-21A. Sample data: total airflow through filter 958 m^3 ; mass loading of air as indicated by material trapped in filter, $226 \text{ }\mu\text{g}/\text{m}^3$. SEP = single escape peak, DEP = double escape peak, AP = annihilation peak.

Fig. 5. INAA spectrum L1 for high-volume air filter sample IAS-21A. (Sample data and abbreviations same as Fig. 3.)

Fig. 6. INAA spectrum L2 for high-volume air filter sample IAS-21A. (Sample data and abbreviations same as Fig. 3.)

Fig. 7. INAA spectrum L3 for high-volume air filter sample IAS-21A. (Sample data and abbreviations same as Fig. 3.)

of GAMANAL (consisting of one card per nuclide for each spectrometric analysis) serves as input to NADAC. The NADAC program reduces these data to micrograms of element for each element on a sample-by-sample basis.

Description of GAMANAL

The GAMANAL code is a general purpose computer program for data reduction and interpretation of gamma spectra. It examines the pulse-height data for background and peak regions, fits these peaks with the proper shape functions, and corrects for the effects of geometry, attenuation, and detector efficiency in evaluating the photon-emission rate. The program then searches a library of decay-scheme information and makes tentative assignments for each of the observed peaks. A matrix of equations is formed so that the intensity of each peak is described as a linear addition of the identified nuclides. The quantitative value, as well as the degree of interference, is the result of a least-squares solution of this set of equations. Unlikely components are also eliminated in this process. A more complete description is given by Gunnink and Niday.²

Description of NADAC

For each nuclide in a sample, NADAC calculates the expected disintegration rate per microgram of element at

counting time. The total micrograms of element for each nuclide detected is calculated by dividing the disintegration rate found by GAMANAL by the expected rate calculated by NADAC for the irradiation, cooling, and counting times for the sample. When the sample is counted more than once, the total micrograms calculated for each count are combined according to a weighting factor that corresponds to the inverse square of the standard deviations for the separate counts. The weighted mean for the total micrograms of each element is corrected first for interfering production of the measured nuclide by an alternate reaction (e.g. $^{27}\text{Al} (n,p) ^{27}\text{Mg}$ interferes with $^{26}\text{Mg} (n,\gamma) ^{27}\text{Mg}$) and second for contribution to the observed total micrograms by mounting or sample containment materials that were irradiated and counted with the sample. In addition to providing for interference and blank correction, NADAC also provides for correctly calculating total micrograms when:

- Counting time is long compared to half-life of nuclide.
- Sample was subjected to multiple or interrupted irradiations.
- Nuclide counted is daughter of nuclide produced, including the case where the daughter nuclide has some independent production.

The physical parameters used in the NADAC calculation are the half-lives

of the parent and daughter, the correction for blanks, the rate of production of nuclide per microgram of element, and the rate of production of nuclide per microgram of element, giving the interfering reaction. The half-life data are the same as those used in GAMANAL and represent best values either measured at LLL or taken from the literature. The elemental abundances in the blank are determined from separate irradiations of multiple samples. The rate of production of nuclide by reactions yielding n,p interferences is determined by irradiating a known quantity of the element producing the interference in each region of the reactor used. The rate of production of those nuclides by n, γ or n fission reactions can be calculated if the following are known:

- Thermal neutron cross-section $\sigma_{th}(b)$.
- Resonance integral RI (b).
- Thermal neutron flux ϕ_{TH} ($n/cm^2 sec$).
- Epithermal neutron flux ϕ_{EPI} ($n/cm^2 sec$).
- Atomic mass of the element M (g).
- Isotope abundance of the nuclide G(%).

Where the production rate of the nuclide R is expressed in units of atoms/min $\cdot\mu g$ the following relationship is used:

$$R = \frac{3.614 \times 10^6 G (\phi_{TH} \sigma_{TH} + \phi_{EPI} RI)}{M} \quad (1)$$

The constant factor 3.614×10^6 includes a flux factor of $1 \times 10^{13} n/cm^2 sec$. Hence ϕ_{TH} and ϕ_{EPI} in the above expression are fluxes expressed in units of $10^{13} n/cm^2 sec$. Thus if the thermal flux were 2.5×10^{13} the numerical value of ϕ_{TH} would be 2.5.

$$R = \frac{(3.614 \times 10^6) (G \phi_{TH} \sigma_{TH}) \left[1 + \left(\frac{\phi_{EPI}}{\phi_{TH}} \right) \left(\frac{RI}{\sigma_{TH}} \right) \right]}{M} \quad (2)$$

The ratio of epithermal to thermal flux can be determined for a particular reactor region either from the cadmium ratio for the region or by simultaneous irradiation of two nuclides having widely different RI/σ_{TH} values and well-known thermal cross-sections. For the LPTR reactor, the flux ratio in the S-2 irradiation facility is 0.0208; and in both the E-1 facility and the slow rabbit it is 0.0450. While these may seem to be small correction terms in themselves, when taken with the ratio of the resonance integral to thermal cross-section, they may produce a very significant deviation from pure thermal neutron production rates. Values of RI/σ_{TH} for the nuclides in the GAMANAL libraries range from 0.46 for ^{46}Sc to 102.9 for ^{239}U . Thus for ^{239}U (and ^{239}Np) the actual rate of production is higher than that for a pure thermal neutron flux by a factor of 3.14 in the S-2 facility and by a factor of 5.63 in E-1 and slow rabbit facilities.

Tabulations of σ_{TH} and RI values are given by R. Sher⁵ and H. Albinsson⁶ in the IAEA *Handbook of Nuclear Activation Cross-Sections*. A discussion of multielement determination of ϕ_{EPI}/ϕ_{TH} as well as a compilation of RI/ σ_{TH} values is given by Van Der Linden, De Corte, and Hoste⁷ in Vol. II of *Nuclear Data in Science and Technology*. Further data on RI and σ_{TH} measurement that postdate those cited by Sher and Albinsson are reported by G. Gleason.⁸

Equation (2) above may be expressed as a product of two terms:

$$R = \phi_{TH} R_0 \quad (3)$$

where

$$R_0 = 3.614 \times 10^4 \text{ G } \sigma_{TH} \left[1 + \left(\frac{\phi_{EPI}}{\phi_{TH}} \right) \left(\frac{RI}{\sigma_{TH}} \right) \right] \quad (4)$$

is the rate of production of a thermal neutron flux of 1×10^{13} n/cm² sec. Values of R_0 for the individual nuclides are entered into NADAC as a table of stored constants for each of the reactor irradiation facilities. The value of ϕ_{TH} , which is the thermal neutron flux expressed in units of 10^{13} n/cm² sec, is determined for individual samples by concurrent irradiation of flux monitors. A flux monitor can be any element for which a known number of micrograms is irradiated. The value for ϕ_{TH} is simply the ratio of micrograms calculated

assuming a flux of 1×10^{13} to micrograms actually present in the monitor. A detailed description of the NADAC code and its mathematical basis is given by Heft and Martin.³

Standardization

The foregoing discussion of the determination of micrograms of an element by NADAC was given in terms of theoretical application of the literature values of thermal cross-sections and resonance integral. The actual application modifies these values based on the results obtained by irradiation of standard samples containing known amounts of the elements. Where the calculated amount of element differs from the standards, the rate constant R is adjusted to give the correct answer. For most nuclides whose literature values for σ_{TH} and RI appear to be adequately determined, the calculated R value and the literature value are within a few percent. For a few nuclides (e.g., ¹¹⁵Cd, ¹⁶⁹Yb, ¹⁷⁵Yb) a significant difference exists between calculated and literature values. For some of the less common elements (e.g., Er, Ho, Ir) where suitable standard solutions of the elements are not available, the literature values for the cross-sections are used. An ongoing program of standardization based on the assay of elemental standards is being carried out. The results of

this program will be published upon its completion.

DETECTION LIMITS

Theoretical detection limits for 75 elements given in Table 3 are based on a maximum irradiation time of 1 hr, a thermal neutron flux of 10^{13} n/cm²sec, and no appreciable interferences.⁹ These detection limits can therefore be considered as theoretical limits within the state-of-the-art for analysis of the pure element.

For samples containing a mixture of elements, the detection limits vary greatly depending on the nature of the principal constituents and on the contribution to the blank by other materials contained in the sample. An extreme case of limited detection would occur if one attempted to measure short-lived trace contaminants in a sample of dysprosium oxide. An example of detection limits including limitations imposed by matrix and mounting materials is shown in Table 4.¹⁰

Table 3. Theoretical detection limits of the INAA technique to 75 elements, assuming a 1-hr irradiation with a thermal neutron flux of 10^{13} n/cm²sec and no appreciable interferences.

Limit of detection (μ g)	Elements
1.3×10^{-7}	Dy
4.9×10^{-7}	Eu
1.3×10^{-6}	—
4.9×10^{-6}	Mn, In, Lu
1.3×10^{-5}	Co, Rh, Ir
4.9×10^{-5}	Br, Sm, Ho, Re, Au
1.3×10^{-4}	Ar, V, Cr, Ga, As, Pd, Ag, I, Pr, W
4.9×10^{-4}	Na, Ge, Sr, Nb, Sb, Cs, La, Er, Yb, U
1.3×10^{-3}	Al, Cl, K, Sc, Se, Kr, Y, Ru, Gd, Tm, Hg
4.9×10^{-3}	Si, Ni, Rb, Cd, Te, Ba, Tb, Hf, Ta, Os, Pt, Th
1.3×10^{-2}	P, Ti, Zn, Mo, Sn, Xe, Ce, Nd
4.9×10^{-2}	Mg, Ca, Tl, Bi
1.3×10^{-1}	F, Cr, Zr
4.9×10^{-1}	Ne
1.3	S, Pb
4.9	Fe

VALIDATION

To verify the accuracy of the INAA procedure that is described above, duplicate samples of the National Bureau of Standards standard reference materials Coal (SRM 1632) and Flyash (SRM 1633) were analyzed and the results compared with elemental concentration for those materials reported by NBS and by Ondov *et al.*¹¹ The data of Ondov *et al.* are based on multiple analyses of these standard reference materials by a group of independent laboratories. (The group included LLL; however, the earlier LLL results were obtained by an INAA procedure based on concurrent irradiation of elemental standards with the sample to be analyzed.)

The counting schedule in the current analysis of both coal and flyash standard reference materials was exactly that shown in Table 1. Irradiation times and sample sizes for the two materials were as follows:

Material	<u>Short Irradiation</u>			<u>Long Irradiation</u>		
	Amount	Time	Flux	Amount	Time	Flux
Coal (SRM 1632)	100 mg	2 min	2.1×10^{13}	200 mg	60 min	2.6×10^{13}
Flyash (SM 1633)	100 mg	15 sec	2.1×10^{13}	100 mg	60 min	2.6×10^{13}

The results of these analyses are compared with those reported by Ondov *et al.*¹¹ and by NBS in Table 5. Elemental concentration data were

Table 4. Limits of detection (ng/m³ above blank for trace elements in aerosols with instrumental neutron activation.

Element	Detection limit (ng/m ³ above blank)	
	Gelman GA-1	Impactor film ^a
Na	300	200
Mg	100	10
Al	0.3	100
Cl	1	1
Ca	1	10
Ti	10	1
V		0.1
Mn	0.6	
Cu	0.1	1
Br		0.0003
In	0.002	0.0004
I		0.02
Ba	2	0.5

^a Average results for 0.0006 cm Mylar, 0.0025 cm Teflon, and 0.0025 cm polyethylene covered with 0.004 cm sticky resin.

obtained in the current analyses for Mo, Nd, and Dy, but for these elements no data were available for comparison.

Table 5. Comparison of LLL INAA results for NBS standard reference material coal and flyash to results reported by NBS and by Ondov et al.¹¹ ($\mu\text{g/g} \pm 2\sigma$ unless % indicated).

	NBS coal SRM #1632			NBS flyash SRM #1633		
	LLL (INAA)	Ondov <u>et al.</u>	NBS	LLL (INAA)	Ondov <u>et al.</u>	NBS
Al%	1.59 $\pm$ 0.20	1.85 $\pm$ 0.13		12.1 $\pm$ 0.5	12.7 $\pm$ 0.5	
Sb	3.4 $\pm$ 0.1	3.9 $\pm$ 1.3		6.9 $\pm$ 0.6	6.9 $\pm$ 6	
As	5.8 $\pm$ 0.3	6.5 $\pm$ 1.4	5.9 $\pm$ 0.6	64 $\pm$ 4	64 $\pm$ 4	61 $\pm$ 6
Ba	302 $\pm$ 8	352 $\pm$ 30		2510 $\pm$ 160	2700 $\pm$ 200	
Br	17.2 $\pm$	19.3 $\pm$ 1.9		6.7 $\pm$ 0.6	12 $\pm$ 4	
Ca	0.42 $\pm$ 0.06	0.43 $\pm$ 0.05		4.2 $\pm$ 0.2	4.7 $\pm$ 0.6	
Ce	18.8 $\pm$ 1.0	19.5 $\pm$ 0.1		148 $\pm$ 6	146 $\pm$ 15	
Cl	828 $\pm$ 22	890 $\pm$ 125		—	42 $\pm$ 10	
Cs	1.40 $\pm$ 0.08	1.4 $\pm$ 0.1		8.6 $\pm$ 0.8	8.6 $\pm$ 1.1	
Cr	17.6 $\pm$ 1.0	19.7 $\pm$ 0.9	20.2 $\pm$ 0.5	117 $\pm$ 7	127 $\pm$ 6	131 $\pm$ 2
Co	5.51 $\pm$ 16	5.7 $\pm$ 0.4		39.4 $\pm$ 1.2	41.5 $\pm$ 1.2	
Eu	0.27 $\pm$ 0.02	0.33 $\pm$ 0.04		2.39 $\pm$ 0.11	2.5 $\pm$ 0.4	
Hf	1.00 $\pm$ 0.07	0.96 $\pm$ 0.05		7.2 $\pm$ 0.6	7.9 $\pm$ 0.4	
In	0.03 $\pm$ 0.02	0.20 $\pm$ 0.12		0.27 $\pm$ 0.14	0.32 $\pm$ 0.10	
Fe	0.84 $\pm$ 0.02	0.84 $\pm$ 0.04	0.87 $\pm$ 0.03	6.8 $\pm$ 0.03	6.2 $\pm$ 0.3	
La	9.5 $\pm$ 0.2	10.7 $\pm$ 1.2		81 $\pm$ 2	82 $\pm$ 2	
Mg	0.25 $\pm$ 0.08	0.20 $\pm$ 0.05		2.0 $\pm$ 0.4	1.8 $\pm$ 0.4	
Mn	39.5 $\pm$ 0.7	43 $\pm$ 4	40 $\pm$ 3	505 $\pm$ 14	496 $\pm$ 49	493 $\pm$ 7
K	0.27 $\pm$ 0.02	0.28 $\pm$ 0.03		1.75 $\pm$ 0.18	1.61 $\pm$ 0.15	
Rb	19.0 $\pm$ 1.5	21 $\pm$ 2		105 $\pm$ 10	125 $\pm$ 10	
Sm	1.72 $\pm$ 0.08	1.7 $\pm$ 0.2		13.0 $\pm$ 0.7	12.4 $\pm$ 0.9	
Sc	3.68 $\pm$ 0.08	3.7 $\pm$ 0.3		27.0 $\pm$ 0.6	27 $\pm$ 1	
Si	2.9 $\pm$ 0.4	3.4 $\pm$ 0.2	2.9 $\pm$ 0.3	9.0 $\pm$ 1.4	10.2 $\pm$ 1.4	9.4 $\pm$ 0.5
Na	380 $\pm$ 12	414 $\pm$ 20		3240 $\pm$ 100	3200 $\pm$ 400	
Sr	112 $\pm$ 26	161 $\pm$ 16		1250 $\pm$ 230	1700 $\pm$ 300	
Ta	0.23 $\pm$ 0.02	0.24 $\pm$ 0.04		2.0 $\pm$ 0.2	1.8 $\pm$ 0.3	
Tb	0.20 $\pm$ 0.02	0.23 $\pm$ 0.05		1.87 $\pm$ 0.15	1.9 $\pm$ 0.3	
Th	2.9 $\pm$ 0.1	3.2 $\pm$ 0.2		23.6 $\pm$ 0.8	248 $\pm$ 2.2	
Ti	1000 $\pm$ 260	1040 $\pm$ 110		7150 $\pm$ 1200	7400 $\pm$ 300	
W	0.65 $\pm$ 0.15	0.75 $\pm$ 0.17		5.5 $\pm$ 1.5	4.6 $\pm$ 1.6	
U	1.24 $\pm$ 0.05	1.41 $\pm$ 0.07	1.4 $\pm$ 0.1	10.5 $\pm$ 1.0	12.0 $\pm$ 0.5	11.6 $\pm$ 0.2
V	41 $\pm$ 10	36 $\pm$ 3	35 $\pm$ 3	290 $\pm$ 80	235 $\pm$ 13	214 $\pm$ 0.8
Yb	0.76 $\pm$ 0.03	0.7 $\pm$ 0.1		5.9 $\pm$ 0.3	7 $\pm$ 3	
Zn	43 $\pm$ 2	30 $\pm$ 10	37 $\pm$ 4	230 $\pm$ 40	216 $\pm$ 25	210 $\pm$ 20
Zr	28 $\pm$ 24	—		182 $\pm$ 76*	301 $\pm$ 20	

*Zr value 182 $\pm$ 76 $\mu\text{g/g}$ was corrected for $^{235}\text{U}_{(n,f)}\ ^{95}\text{Zr}$ contribution. Uncorrected value was 295 $\mu\text{g/g}$.

Applications

The major area of application of the LLL instrumental neutron activation capability is in the multielement analysis of samples derived from large scale environmental studies. In the Environmental Research Programs the analytical capability of INAA is supplemented by nondispersive x-ray fluorescence analyses (XRFA), which also provides multielement analysis but for a different group of elements than INAA. Elements of particular interest that are not measurable either by INAA or by XRFA are analyzed by atomic absorption analysis. The overall analytical program provides an appropriate combination of the analytical methods that depends on the elemental abundance information that is required. This section describes the major programs for which elemental analysis data have been provided. The programs are grouped according to whether they are completed or are continuing. In addition to the major programmatic analyses described below, analyses are performed in response to particular individual or one-time problems.

COMPLETED ENVIRONMENTAL STUDIES

The California Aerosol Characterization Experiment (ACHEX) 1972-1974

Some of the more pressing ques-

tions of air pollution requiring improved knowledge are those dealing with aerosols. Although airborne particles represent a small fraction of the load of trace-constituents in air, they contribute significantly to environmental degradation as a potential hazard to health, a visibility reducer, and a possible agent of weather modification. Despite many years of investigation, the origins and evolution of atmospheric aerosols remain poorly understood compared with trace gases. Recognizing this, the California Air Resources Board (ARB) sponsored a major survey of aerosols in urban and remote sites of California.¹²

The project was designed to study primary particle sources, atmospheric formation, and their relationship to changes in visibility. In California, the secondary production of aerosols by chemical and physical processes in the atmosphere is believed to be especially important.

The objectives of the study to which INAA were applied were:

- To characterize the aerosol in the basins of the Southern California Coast, the San Francisco Bay Area, and the San Joaquin Valley in terms of its interaction in the atmosphere

and its natural and anthropogenic origins.

- To evaluate the amount of the atmospheric aerosol in these three major air basins that can be related to primary emissions such as from auto exhausts or smokestacks and secondary production resulting from physical and chemical processes in the atmosphere.
- To identify those major sources of particles that can be related to aerosol pollution and reduction in visibility.
- To evaluate the applicability of the aerosol analysis instrumentation employed in this study for use in present monitoring networks.

The results of the experiment revealed extremely complicated behavior of atmospheric aerosols, as they are influenced by local sources, gas-particle interaction, and meteorological factors. However, they were found to have certain important common features. For example, the effort showed clearly that man's activities and atmospheric transformations of gaseous pollutants contribute primarily to the submicron particle size range, while natural sources influence chiefly the range $>1\text{-}\mu\text{m}$ diameter.

Approximately 700 filter and impactor samples were analyzed during the study. Total aerosol specimens were collected on $5\text{-}\mu\text{m}$ cellulose acetate

membrane filters in low-volume air samplers. Multistage, rotating-drum, cascade impactors were used to collect size-segregated aerosols. The particle-size distributions obtained had 50% cut points of 8.0, 4.0, 1.5, and $0.5\text{ }\mu\text{m}$. Cellulose acetate after-filters collected particles $<0.5\text{ }\mu\text{m}$.

The aerosol specimens were routinely analyzed for Na, Mg, Al, Cl, Ca, Ti, V, Mn, Cu, Br, In, I, and Ba with a 2-min irradiation at 3 MW in the LPTR followed by 9- and 20-min counts. Sensitivities obtained for 10 of the elements were routinely less than 10 ng/cm^3 . Selected samples were further analyzed for Eu, Ce, Se, Th, Cr, Hf, Ag, Ni, Sc, Fe, Zn, and Co, using a 12-hr irradiation followed by an 800-min count after a 3-wk decay.

The California Aerosol Characterization Experiment data on the distribution of aerosol constituents with size confirm the hypothesis that constituents originating from certain sources dominate the mass in particular size ranges. Material from combustion, chemical, and metal refining sources appear largely in the submicron (or anthropogenic) fraction. Examples include Br, Cl, and V. In the supermicron fraction appear the natural or quasinatural elements such as Na, Cl, Al, Fe, Ca, and Sc. In this study the natural background aerosol consisted of a mixture of sea

salt, soil dust, and a residue of aged aerosol transported from a distant urban area.

Aluminum was found principally in the larger particles (8 to 15 μm) at all urban, inland, and coastal sites. Since large particles are usually a result of windblown eroded soil, the Al concentration was used as an indicator of the amount of soil component in the aerosols. Other elements with Al-like distributions were Ca, Mg, Mn, Sc, Th, Fe, and Co, implying they were also derived from soil. The vanadium distributions were bimodal with maxima at submicron ranges ($<0.5 \mu\text{m}$) and large particle sizes ($<8.0 \mu\text{m}$). These data suggest two sources of vanadium, soil dust and combustion (probably the burning of residual fuel oil) processes.

The sodium at coastal sites was from sea salt and present in the 1.5 to 4.0 μm particle size range. The sodium at inland sites was derived from soil erosion and found in the large-particle range, 8 to 15 μm . At coastal sites the chlorine distribution followed the sodium distribution. At inland sites the submicron Cl (as well as Br) that resulted from automotive emissions increased significantly.

A secondary but important role of INAA was the validation of other analytical techniques utilized in the chemical analysis of aerosols. Supplemental experiments were also per-

formed using INAA to validate the collection efficiencies of rotating-stage cascade impactors.

As a result of these studies, it was concluded that techniques using INAA were useful operational methods for chemical analysis of aerosol samples taken over 2-hr periods in urban air in an active monitoring program. These techniques have been summarized in Ref. 9.

Air Sampling in the Vicinity of Smelting Operations

An example of what can be accomplished in aerosol characterization is shown by a study of air filter samples collected at Kellogg, Idaho,¹³ in the Coeur d'Alene mining district. Samples were analyzed to determine the concentrations of trace metallic elements in the air, and to look for indications of their sources. For example, some elements are in the air as a result of the mining and smelting operations, others have been picked up from soil surfaces by the winds.

Samples were analyzed for 34 elements with INAA, and for 6 elements with XRFA. Elements were divided into three main groups according to their enrichment factors (defined as enrichment of concentration relative to the local average in the Kellogg Valley soils). Elements with low enrichment factors (<100) were considered to originate primarily from

the soil. Those with an intermediate enrichment factor (100 to 1000) were considered to be of uncertain origin (soil and/or mining and smelting). Those with a high enrichment factor (>1000), were considered to be clearly from mining or smelting.

The relationship between the

results of XRFA and INAA is shown in Fig. 8 for Cu, Br, Fe, and Zn. The solid line represents a correlation coefficient of 1.0, or perfect correlation. The linear correlation coefficients of these four elements are 0.98, 0.96, 0.93, and 0.97, respectively, for Cu, Br, Fe, and Zn.

Fig. 8. Correlation of INAA and XRFA results for Cu, Br, Fe, and Zn. Linear correlation coefficient (LCC) values are shown: a value of 0.35 or higher indicates a positive correlation.

For these samples a linear correlation coefficient of 0.15 is the minimum acceptable value.

SOIL AND VEGETATION TRACE METAL CONTAMINATION NEAR ZINC AND LEAD SMELTERS

Soil cores and vegetation samples were taken at 12 sites in the vicinity of Zn and Pb smelters in Kellogg, Idaho.¹¹ Thirteen elements were analyzed by INAA and XRF. The soil and vegetation were highly contaminated with Pb, Zn, Cd, As, Hg, Se, Sb, Ag, and In. These same elements had been found at high concentrations in ambient air aerosols collected in Kellogg 2 m from the smelters. In the surface soil fraction the concentrations were 170 to 7900 ppm Pb, 220 to 11 000 ppm Zn, and 18 to 140 ppm Cd. In the vegetation the concentrations were 220 to 10 000 ppm Pb, 450 to 12 000 ppm Zn, and 16 to 950 ppm Cd. The aerosol enrichment factors relative to the mean concentrations in the surface soil were 4100 for Cd, 180 for As, 110 for Pb, and 60 for Zn.

CONTINUING ENVIRONMENTAL STUDIES

Trace Elements in Milk

The role of trace elements in the environment both as toxic materials and as essential nutrients for plants, animals, and man is well recognized.

However, except for a few notable examples, very little information is available on the presence of these elements in the biosphere or their flux through it and into human food chains. With the presently increasing concern over energy-related trace element pollution, it becomes most appropriate to undertake a comprehensive study of trace elements in major food chains by modern instrumental methods of multielemental analysis. This documentation is of value both in itself and in improving the understanding of radionuclide behavior in the environment.

The results of the first pilot phase of this study, which is a survey of trace elements in market milk collected in California and Colorado, have been reported in Ref. 14. Analytical results are summarized in Tables 6 and 7. This survey served as a focus for developing procedures for the assay of trace elements by INAA and XRF. Comparisons between the two techniques were carried out

Table 6. Minor constituents in market milk - g/l.

Element	This work		Ref. 15	
	Mean	Standard deviation	Range	Mean
Ca	1.17	0.09	1.04-1.45	1.23
Mg	0.110	0.026	0.04-0.17	0.12
Na	0.434	0.052	0.33-0.61	0.58
K	1.65	0.18	1.32-2.00	1.41
Cl	1.00	0.10	0.80-1.20	1.19

Table 7. Trace elements in market milk - mg/l.

Element	This work			Ref. 16
	Mean	Standard deviation	Range	Range
Al	1.64	0.38	1.1-2.8	1.4-17.0
Co	0.0126	0.0336	0.0003-1.8	0.1-0.9
Fe	0.75	0.62	0.2-2.7	0.3-1.5
Rb	1.40	0.81	0.6-4.5	0.6-3.4
Zn	3.80	0.50	2.8-5.0	1.0-5.0
Cs	0.0035	0.0025	0.001-0.012	Not given
Br	3.60	1.30	1.56-6.13	1.0-8.0
I	0.44	0.19	0.16-0.96	0.07-1.61
Se	0.0231	0.0085	0.012-0.049	0.015-0.048
Sr	1.30	1.40	0.65-9.3*	0.10-1.51

* The number 9.3 was single high value. Next highest was 1.6 mg/l.

to validate the analytical procedures. Collection procedures were also tested and validated during the course of the study.

Marine Studies of Coastal Reactors

Reactors located on the coast can use sea water for cooling and for disposing of low level radioactive wastes. The Environmental Research Division had undertaken a coastal studies program designed to investigate the fate of radionuclides released into a marine environment. One phase of the program involved the study¹⁷ of the Pacific Gas and Electric Company reactor at Humboldt Bay where over a 3-yr period all reactor releases were assayed for radionuclide composition and concentration and the

uptake of the radionuclides by sediments and biota was followed. Stable element concentrations in the various environmental compartments were determined by neutron activation analysis. The concentration of the stable element counterpart of each of the radionuclides released should be determined in each compartment to understand the observed radionuclide partitioning. Thus, if we know that in a particular aqueous pool the ratio of radioactive ⁶⁵Zn to stable Zn is 0.3 pCi/μg; and if we know that mature oysters have stable Zn concentrations of 4000 μg Zn/kg wet weight of oyster, then we expect the concentration of radioactive ⁶⁵Zn in the oysters to reach 0.3 × 4000 or 1200 pCi/kg wet weight.

Elements of interest in the coastal studies program are those having a radioactive counterpart that is released into the marine environment. Since these are all relatively long-lived species produced by neutron capture, INAA is particularly appropriate for their determination. For the Humboldt Bay study elements of interest were Cs, Ce, Mn, Zn, and Co. These were determined for three main categories of sample - seawater, sediment, and biota. Seawater samples were filtered and acidified at the point of collection. At the laboratory, the trace elements from 4-l samples were preconcentrated, first by evaporation to reduce volume by a factor of 4, and second by selectively precipitating elements of interest to eliminate the major interference of sodium in seawater. The ashed precipitates were irradiated for 8 hr, cooled for 1 wk, and counted to determine the quantity of the activation products.

Sediment samples were dried and then 100 mg aliquots were irradiated, cooled, and counted using the same schedule as above. This schedule was also followed for the biota samples. In this case, however, the original biological material was first dried and then ashed at 450°C to provide a 100-mg sample.

In all cases, additional elements (Sc, U, Th, Cr, Nd, Mo, Fe, Sm, Ag,

Rb, and Eu) were routinely determined by the analysis although not all were determined on every type of sample. A similar program in which the elemental concentrations in marine organisms are determined is being conducted of the Diablo Canyon Reactor site (San Luis Obispo, California).

Trace Contaminants From Coal Fired Power Plants

As a result of recent efforts to reduce U.S. dependency on foreign oil for power production, construction of coal-fed electrical generating stations is increasing at unprecedented rates. It is well-documented that high-temperature combustion processes, such as fossil-fuel power production, are responsible for mobilizing vast quantities of toxic substances by injection of both vapor-phase (metallic) species and submicron particles into the atmosphere. Submicron particles are particularly hazardous because 50% of the inhaled particles between 0.01 and 0.1 μm deposit in the alveoli of the lung where most trace elements are readily absorbed into the blood stream. The work reported here is part of an effort at the Lawrence Livermore Laboratory to assess the impact of coal-fed power plant emissions as the resulting dose increment to man. The first phase of the program is the characterization of trace-element emissions,

in terms of quantity and particle-size distribution. Particular emphasis is given to primary factors affecting the characteristics of trace-element emission such as elemental concentrations in coal, coal chemistry, vapor-phase/particulate fractionation, operation temperatures, and type and efficiency of pollution-control equipment. This information could be used in conjunction with models of atmospheric transport and lung deposition to predict increases in blood and whole body levels of toxic trace elements resulting from the operation of a proposed power installation.

The complete elemental analysis of coal, flyash, and stack effluents from two western coal-fired plants by INAA, XRFA, and atomic absorption is in progress. Several hundred samples have been analyzed thus far. Preliminary results from this program are given in Reference 18. Figure 9 shows some typical distributions of elemental particle size in flyash emitted from one of the coal-fired power plants studied. The elements emitted from the unit equipped with a wet-venturi scrubber emission-control system are concentrated on submicron particles, whereas the elemental emissions from the unit equipped with an electrostatic precipitator are concentrated on supermicron particles. These effects occur because of the signifi-

cant differences in collection efficiency as a function of particle size between the two types of emission control devices. The health implications of these data are presented elsewhere.¹⁹

Imperial Valley Environmental Project (IVEP)

The Lawrence Livermore Laboratory has been appointed by the U.S. Energy Research and Development Administration to be the lead laboratory for a long-term project to acquire complete understanding of the environmental quality in the Imperial Valley of California prior to any major developments. The purpose of this project is to ensure that the development of geothermal resources proceeds on an environmentally sound basis. Consequently, the Imperial Valley Environmental Project (IVEP) is committed to an intensive and comprehensive study designed to establish an environmental baseline for the Imperial Valley as well as to develop an understanding of environmental and other effects associated with development of geothermal resources.²⁰

The LLL elemental analysis group is responsible for the analysis of certain categories of samples resulting from IVEP for analytical quality control for data produced by other laboratories. The scope of the analysis program is being established.

Fig. 9. Typical particle size distributions for several elements determined on particles collected downstream from a wet venturi scrubber and an electrostatic precipitator.

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