RECEIVED BY OTIF SEP 20 1971

BNWL-SA-3993

CONF-710818--1

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MEASUREMENTS IN NATURAL WATERS

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July 1971

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- (a) This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

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NUCLEAR TECHNIQUES FOR TRACE ELEMENT AND RADIONUCLIDE^(a)MEASUREMENTS IN NATURAL WATERS

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P.O. Box 999
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Many of the pollutants which are generated by man enter our natural waters. Liquid effluents from numerous industrial processes and municipal waste treatment plants are discharged directly into rivers, lakes, and the ocean. Precipitation scavenging provides a mechanism for removing aerosol material from the atmosphere and thus serves to deposit airborne pollutants along with rain, or in snow packs which subsequently feed the natural waters. The trace elements which are nondestructible, and must therefore be regarded as potentially permanent pollutants, are concentrated by aquatic organisms by several orders of magnitude relative to concentrations in the water. This occurs for both biologically essential elements and those which may be detrimental. It has been recognized that several elements are toxic to aquatic organisms at very low concentrations, while others move through the food chain and thus enter the diet of man. The documented cases of heavy metal pollution of natural water are numerous and many of these have recently been documented by Margaret Merlini, "Heavy-Metal Contamination," Impingement of Man on the Oceans, John Wiley and Sons, 1971.

There is also a wide spectrum of radionuclides in natural waters. These radionuclides enter the waters from both natural and man-made sources and include the primordial radionuclides and their decay products, the cosmic ray produced radionuclides, and those from nuclear weapons testing and nuclear plant operations. While the trace elements of anthropogenic origin together with man-made radionuclides may be considered as pollutants, these substances together with naturally occurring radionuclides can be extremely useful as tracers in defining biogeochemical processes. Trace elements in natural waters are therefore of interest from their potential danger to the aquatic environments and also because of their usefulness in defining natural processes. It is well-known that the behavior of a trace element or radionuclide depends on the chemical makeup of the matrix of which it is a part. A pollutant element which enters the hydrosphere in a chemical form which is different from that already present may be taken up at a much faster rate and therefore its potential hazard is much greater. For example, available data indicate that the specific activity of ^{55}Fe , $t_{1/2} = 2.4$ yr. (^{55}Fe per gram of iron) is 100 to 1000-fold higher in Pacific salmon than in seawater (Palmer 1968). These observations have been confirmed by Preston (1970) with measurements in Atlantic cod. One concludes from this that fallout ^{55}Fe is in a chemical or physical form which is far more available for biological uptake than the natural iron in the oceans. It is therefore possible for a pollutant element to be taken up preferentially by the aquatic biosphere before it is completely "diluted" to the natural concentration of that element in the water. For example, the chemical and biological uptake of an element may be entirely different in ocean water than in fresh water. Also, the behavior of an element may be affected by other trace elements present in the matrix. For this reason

it is very important that the behavior of an element in an aqueous system be considered relative to that of a wide spectrum of other elements. This can be conveniently accomplished using analytical techniques which permit simultaneous multielement analysis. Neutron activation analysis has provided a vehicle for this type of multielement analysis and the number of elements which can be easily observed is now being extended through application of other multielement techniques including X-ray fluorescence and absorption spectrometry. The natural and man-made radionuclides which are present in fresh and salt water systems can be used to define many of the rates and mechanisms of the biogeochemical processes of interest if they can be precisely measured. The concentrations of most of these radionuclides are such that they must be separated from hundreds to thousands of liters of samples in order to be measured. This requirement need not be a serious constraint to measurement and practical methods for concentrating and measuring radionuclides at these very low concentrations have been developed.

Trace Elements

Both the ocean and fresh water systems contain several major trace elements including magnesium, calcium, phosphorus, sulfur, sodium and chlorine, but also contain a spectrum of trace elements of both natural and anthropogenic origin. The concentrations of these range from a few parts per million to less than one part per trillion, thus characterization of the trace elements in natural waters is truly a micro-chemical analytical problem. Neutron activation analysis has become synonymous with trace element analysis because of the high sensitivity, precision and accuracy which it affords. With the advent of Ge(Li) diode spectrometry, the utility of neutron activation analysis

for simultaneous multielement measurements has been greatly improved. Multi-element analysis using Ge(Li) diode gamma-ray spectrometry has been employed for the measurement of trace elements in a variety of environmental materials and has been shown to be particularly useful for the measurement of trace element pollutants in the atmosphere. In this connection it has been possible to measure some 20 to 35 trace elements on air filters taken from various industrial metropolitan areas. Where one is concerned with the measurement of trace elements in natural waters, it must be recognized that the number of elements which can be measured by instrumental neutron activation without chemical separation is limited. This is because of the fact that even fresh waters contain sufficient amounts of sodium chloride so that the contribution from the activation products masks many of the short-lived radionuclides which must be identified if certain trace elements are to be measured. For example, the gamma-ray radiation from ^{24}Na often masks that from ^{64}Cu , ^{76}As , ^{56}Mn and ^{42}K . If a simple chemical separation which removes sodium and chlorine from an irradiated water sample is employed, then the majority of the neutron activation products can be measured by instrumental techniques. A method which provides this separation and is currently being used at our laboratory is shown in Figure 1. The details of this method are covered in a separate report. (Tanner et al, 1971)

Basically the procedure involves collecting a sample in a specially cleaned polyethylene container and immediately freezing it to minimize absorption of colloidal or ionic material on to the walls of the container, or the possible leaching of contaminants from the walls into the sample. The sample is then irradiated to an integral neutron exposure of about 2×10^{16} neutrons/cm². After irradiation, the frozen sample is etched to remove any surface contamination, then weighed to determine the amount of material removed, and is

melted and filtered. The particulate material collected on the filter can be analyzed by direct counting on a Ge(Li) spectrometer. The liquid portion is passed through a specially prepared ion exchange column which removes essentially all of the anions and cations except for the alkali and alkaline earth metal groups. This ion exchange column consists of three sections of anion exchange resin which are activated in the hydroxide, sulfide and carbonate forms. As the water passes through the column, anions are removed by normal exchange processes, while cations other than the alkali and alkaline earth metals are removed by precipitation on the activated ion exchange resins. If it is important to measure the potassium content which is in the column effluent, then the potassium along with rubidium and cesium can be separated from the sodium by precipitating it as the tetraphenyl-boron. The need for separating ^{24}Na from other activation products is illustrated by the gamma-ray spectra of neutron irradiated Columbia River water in Figure 2. The top spectra is that obtained from the whole sample three hours after irradiation. It is evident that the only radionuclides which can be observed at this time are ^{24}Na and ^{56}Mn . In many instances the ^{56}Mn is also marked by ^{24}Na . When the sample is passed through the ion exchange column, essentially all of the sodium and other alkali metals are removed in the column effluent, and from the gamma-ray spectrum of the resin bed essentially all of the short-lived radionuclides can be measured. Subsequent measurements of this resin bed fraction allow a total of some 20 to 30 trace elements to be quantitatively determined. The bottom spectrum is simply the tetraphenyl-boron fraction which contains ^{42}K , ^{56}Rb and ^{134}Cs and from their activities the stable element concentrations can be quantitatively measured.

While many of the trace elements in natural waters can be measured directly by Ge(Li) diode gamma-ray spectrometry after separation of the alkali metals, the sensitivity and absolute accuracy for the measurement of each element is a function of its concentration and the matrix composition of the sample. By

combining sophisticated Ge(Li) diode gamma-ray spectrometry and sodium iodide coincidence spectrometry, the sensitivities and accuracies for the measurement of most trace elements can be considerably improved.

An anticoincidence shielded Ge(Li) diode gamma-ray spectrometer which provides a major improvement in sensitivity and is presently being used for water sample analysis is shown in Figure 3. The Ge(Li) diode is a 65 cc closed end coaxial unit. Its resolution is 1.4 keV at 120 keV, and 2.4 keV at 1332 keV. The anticoincidence shield consists of a 15" long by 11-1/2" diameter sodium iodide annulus together with a 5-1/2" diameter by 4" sodium iodide crystal which serves as an end plug. Both coincidence and anticoincidence spectra from a given sample are simultaneously collected. The instrument provides a 10-fold reduction in the smooth portion of the natural background and provides a Compton / ^{reduction of} as much as 85 times in the anticoincidence spectrum over that which would be obtained without anticoincidence shielding techniques. In the recommended mode of operation, several coincidence spectra together with one anticoincidence spectrum are accumulated simultaneously. This mode of operation, which is described in detail in a separate report (Cooper 1971), improves the sensitivity for the measurement of many radio-nuclides by several-fold. An example of the Compton suppression provided by simple anticoincidence shielding is shown in Figure 4 where the coincidence and anticoincidence spectra of ⁶⁰Co are given. The normal gamma-ray spectrum would, of course, be the sum of these two spectra and it is evident that the Compton in the anticoincidence spectra is reduced by as much as 85 times. When elements are present in samples of extremely low concentrations, a vast improvement in measurement sensitivity can be obtained by using large sodium iodide crystals and coincidence gamma-ray spectrometry. The use of this

technology, which is called multidimensional gamma-ray spectrometry at our laboratory, is developed to a very high degree. Some of the long-lived radio-nuclides including ^{60}Co and ^{46}Sc can be measured by counting on these instruments, while they are not detectable by even the most sensitive Ge(Li) diode spectrometers.

In studying the behavior of trace element pollutants, it is important to know their origin and their transport behavior to the hydrosphere. The degree of transport of trace element pollutants can be better appreciated by comparing the relative concentrations of trace elements in rainwater with those in the earth's crust. When this is done, it is evident that the atmosphere transports trace elements from industrial and metropolitan areas over greater distances. In Table 1 the concentrations of trace elements in rainwater have been normalized to that of scandium in the earth's crust and are then compared with the earth's crust composition. It is evident that several of these elements, including Ag, Se, Sb, As and Zn could not have come from the earth's crust. The trace elements Cl and Br could not have come from the earth's crust, but could have come from seawater. Since this rainwater was collected near the ocean on the Olympic Peninsula of the State of Washington and came from air which had a trajectory across the Pacific Ocean, it can be said that the pollutant trace elements must have been transported a great distance prior to their removal from the atmosphere. The degree to which trace elements of anthropogenic origin have entered natural waters can be recognized by comparing trace element concentrations in river water, rainwater, air, and in a major earth's crust component, diabase. (see Table 2) For this comparison, all of the concentrations have been normalized to the scandium content of the diabase, W-1 (Mason 1966). Scandium has been shown to be a conservative element and is mainly of natural

origin both in the atmosphere and in natural waters. The most striking point of this comparison is that the trace element concentrations in rainwater, Columbia River water, and in air from the City of Cleveland are in similar ratios. From this one concludes that many of the trace elements in the atmosphere and in natural fresh waters are the result of pollution.

The measurement of trace elements in ocean water is a much greater challenge than the measurement in fresh waters. The ocean water concentrations of many of the trace elements are far lower than those in natural waters, particularly in the open ocean where pollution is at a minimum. Also, where activation analysis is employed, the interference from ^{24}Na is a serious matter and efforts to remove the radio-sodium from the trace elements either by the technique described in this paper, or by other techniques, have not been satisfactory to date. The separation of trace elements from seawater prior to neutron activation analysis is a very difficult task, since contamination or loss of the element being separated can occur. Some of the most accurate measurements of trace elements in the ocean have been made by neutron activation of seawater followed by direct counting after a delayed period, which permits the decay of ^{24}Na and ^{82}Br . Figure 5 shows the gamma-ray spectrum of a 30 ml. neutron activated seawater sample measured 54 days after its exposure to an integrated neutron flux of 2×10^{18} neutrons per square centimeter. From this spectrum several trace elements, including iron, cobalt, zinc, strontium, rubidium, cesium, antimony and uranium, can be measured. A more precise analysis of the cobalt together with the measurement of the scandium content can be made by direct counting on a multidimensional gamma-ray spectrometer. The precision which can be achieved in neutron activation of seawater is illustrated in Table 3. Eight seawater samples were irradiated

along with appropriate standards and the strontium content of the samples determined by subsequent measurements of the induced ^{85}Sr . These analyses showed a standard deviation of 1.1% (Robertson et al, 1968.)

Because of the difficulty of measuring trace elements in seawater which has activation products with half-lives comparable to ^{24}Na , it appears that their analyses will of necessity be performed by pre-irradiation separations of the elements of interest. While such methods have several inherent sources of error, this approach will probably be the method of choice.

Radionuclides

The oceans and large freshwater bodies of the world contain wide spectra of radionuclides which originate from several sources and are potential tracers in defining transport, mixing, and a variety of biogeochemical processes in these water masses. These radionuclides include those which are formed during decay of the natural uranium and thorium chain members in sea-water, those formed by decay of an insoluble parent radionuclide in the sediments, the radon daughter products which are formed in the air and subsequently deposited on ocean or freshwater surfaces, the radionuclides which are produced by cosmic-ray reactions in the atmosphere, and the activation and fission products injected into the atmosphere during nuclear-weapons testing. When they enter the ocean, these radionuclides participate in the natural ocean processes and are thus tracers of the mixing rates and of various physical, chemical and biological processes of the ocean. While measurements of these radionuclides at various depths and locations in the ocean could provide a great deal of information about dynamic ocean processes, relatively few analyses of this type have been made. This is because of the extremely low concentrations of the radionuclides and the accompanying great difficulty in making the measurements. For the measurement of many of these radionuclides, sample sizes ranging from hundreds to thousands of liters are required even where extremely sensitive counting instrumentation is employed. Because of the serious technical difficulties of performing large volume separations at sea, sorption bed concentration techniques have been developed. The feasibility of using a sorption technique in which radionuclides were concentrated from sea-water on passage of sea-water through a sorption bed which resulted in the retention of radionuclides of

interest, was demonstrated by Lal, Arnold and Somayajulu (1964). Also, specific sorption of radiocesium on various media has been used extensively (Mohanrao and Folsom, 1962; Boni, 1966). Our laboratory studies have shown that chromatographic grade Al_2O_3 † is a reasonably good sorption medium for removal of a wide spectrum of radionuclides from sea-water and that by activating it with appropriate chemicals it can be made to be an efficient collector for additional radionuclides.

The Battelle Large Volume Water Sampler (BLVWS), which was developed to permit the separation of radionuclides from sample volumes up to tens of thousands of liters is shown assembled and schematically in Figure 6. Except for supporting components, the sampler is constructed entirely of polyvinyl chloride (PVC) and water flowing through the unit is exposed only to PVC surfaces. The bottom portion of the unit comprises the filtration section and normally accommodates eight 30.5 cm diameter filters, although the modular design is such that more or fewer filters can be used. The alternate inlet frames of the unit, which receive raw water through an inlet manifold, direct the water through filters and into alternate filter frames. The water then enters a common (outlet) manifold which leads to the sorption bed section in the upper portion of the unit. The water is then discharged through a water meter, which provides a record of the total volume processed. Complete details of its design have been reported by Silker, Perkins and Rieck (1971). The sorption beds are 0.64 cm deep by 29.0 cm in diameter. Filter papers (sharkskin* and/or fiber glass**) on the top and bottom of each sorption bed retain the bed material, while the modular design permits the use of as many different beds as required by the particular experiment.

† Noehlm Neutral, available from Alupharn Chemicals, New Orleans, La.

* Available from Carl Schleicher and Schuell, Co., Keene, New Hampshire.

**Number AP-2030500, available from Millipore Corp., Bedford, Mass.

A BLVWS and auxiliary equipment are shown in shipboard operation in Figure 7. In this case, the ocean water was drawn through a 2.5 cm diameter polyethylene hose which was lowered to the desired depth from the motorized reel shown on the right. The end of the hose is weighted with a 100-lb lead weight, and a depth indicator line is attached near the inlet to provide a continuous record of the depth from which the sample was obtained throughout the sampling interval. Where 110 V a.c. power is available, a self-priming centrifugal pump (Montgomery Ward Model No. SBN 25415) mounted at deck level is used to draw the sample. Where electrical power is not available, a gasoline engine-powered pump (Homolite Model No. V-65-1-1/2-1) was employed. With either of these units, water could be lifted as much as 4.4 m and provide an outlet pressure of approximately 50 psi.

The efficiencies of aluminum oxide for retention of several radionuclides of interest has been determined both in the laboratory and in-situ in the Pacific Ocean.

Laboratory investigations were conducted with a small column system where prefiltered sea-water was passed through a 1 cm² diameter by 0.63 cm deep bed of aluminum oxide absorbent. Sea-water samples containing known amounts of one or more radionuclides of interest were passed through this system at flow rates of 50 ml/min. This is equivalent to the operational flow rate of 37.85 l./min for the BLVWS. The retention efficiencies for the various radionuclides measured by this method are included in Table 4. Retention efficiencies for most of the radionuclides were nearly constant at flow rates up to 50 ml/min/cm², but decreased by about 10 per cent at 100 ml/min/cm² and 25-30 per cent at 150 ml/min/cm². The retention efficiencies remained constant even after passage of the equivalent of approximately 6000 liters through the ocean system.

Utilizing the facilities aboard the Oregon State University R/V Yaquina for in situ chemical separations, the retention efficiencies of the radionuclides with the BLVWS were determined. A large reaction vessel on the ship allowed the separation of trace elements and radionuclides from about 600 l. of ocean water by precipitation scavenging reactions (Silker, Perkins, Rieck (1971)), while a concurrent water sample was passing through the ocean sampling system.

As is indicated in Table 4, good agreement was obtained between the laboratory and in situ ocean measurements for the retention efficiency of all of the radioisotopes. The initial laboratory retention efficiency for ^{51}Cr was much higher than that observed in the in situ measurements. This was subsequently shown to be due to the fact that while ^{51}Cr is in the Cr^{+6} state in the ocean, a part of the ^{51}Cr used in the initial laboratory tests was in the Cr^{+3} state. Subsequent laboratory measurements of the retention of Cr^{+6} confirmed the retention efficiencies obtained in the in situ ocean measurements.

The precision of this method was determined from the analysis of four surface water samples collected at a station in the North Equatorial Atlantic Ocean. Two of the surface water samples were simultaneously pumped through two BLVWS. The BLVWS were then reloaded and the sampling repeated. The analytical results obtained from these four replicate samples showing both particulate and dissolved radionuclide concentrations are given in Table 5. The plus or minus values for the individual measurements represent the 1σ statistical variations due to the counting measurements. The average total concentrations of dissolved plus particulate material are also included. The range of the replicate measurements is in reasonably

good agreement with that which would be expected from statistical considerations, indicating a good precision for the method. This would indicate that the ocean water was reasonably homogeneous with regard to these radionuclides at the sampling station.

The wide variations in the observed ^{226}Ra concentrations are probably due to the fact that ^{226}Ra is only retained with an efficiency of about 4 per cent and its absolute retention is therefore quite variable.

The air-to-sea transport rate of the atmospheric aerosols together with the mixing of ocean water can be defined from measurements of ^7Be . After its formation by cosmic-ray reactions with the atmosphere, ^7Be becomes attached to the natural aerosol and enters the ocean surface. The mixing rate of the ocean's surface waters, which depend to a considerable extent on the thermal structure of the top 100-200 meters, can be defined from measured concentration gradients of the types shown in Figure 8. These measurements have shown vertical eddy diffusion coefficients of 0.5 to $0.7 \text{ cm}^2/\text{sec}$ within the upper boundary of the main thermocline (Silker, 1971).

Sorption beds of the inorganic ion exchanger KCF-1 are frequently used for collection of ^{137}Cs from sea-water. In this application, ^{137}Cs is retained on 0.65 cm thick beds with an efficiency of about 70 per cent. The absolute efficiency has been observed to vary somewhat with particle size of the bed material.

Sorption beds composed of aluminum oxide impregnated with SnCl_2 are used for the quantitative reduction and collection of hexavalent ^{51}Cr from both fresh and salt waters (Perkins, 1969a). The use of these sorption beds has provided a very practical method for defining the vertical and horizontal

mixing of Columbia River water, which contained $^{51}\text{Cr}^{+6}$ introduced by the Hanford reactors, and also of the river estuary and of its subsequent mixing for several hundred kilometers at sea. (See Fig. 9').

Aluminum oxide beds impregnated with barium sulfate remove greater than 90 per cent of the natural radium isotopes from sea-water (Perkins, 1969b), as compared with less than 5 per cent for the untreated alumina. This fact permits studies of ocean mixing processes that occur on times scales comparable to the half-lives of these radioisotopes which range from 3.64 days for ^{224}Ra and 1620 years for ^{226}Ra .

In fresh water applications, large volume sampling has been employed for the continuous separation of three short-lived cosmic-ray-produced radionuclides: ^{24}Na , ^{38}Cl , and ^{39}Cl from rainwater (Perkins, Thomas and Young, 1970). The ^{24}Na is retained on a 0.65 cm thick cation exchange resin bed and the ^{38}Cl and ^{39}Cl are retained on a 0.65 cm thick anion exchange resin bed. In atmospheric precipitation scavenging studies, these radionuclides are quantitatively removed from rain volumes up to 1000 l. at flow rates of 30 l./min.

Since these rather short lived radionuclides are attached to the natural aerosol, their measurements help define the rates and mechanisms of the in-cloud process which is involved in their scavenging. Figure 10 illustrates the impact of precipitation scavenging on the normal ^{24}Na concentration profile in the atmosphere. Ion exchange resins are also employed for studies of artificial and natural radionuclides in freshwater bodies, but due to the higher salt concentrations, the bed thicknesses of 2.54 cm are usually required to insure near quantitative retention where 1000 to 4000 l. samples are processed.

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FLOW DIAGRAM FOR THE MULTIELEMENT ANALYSIS OF TRACE
CONSTITUENTS IN NATURAL WATER BY NEUTRON ACTIVATION, TWO-
GROUP CHEMICAL SEPARATIONS AND GAMMA-RAY ANALYSIS

FIGURE 1

GAMMA-RAY SPECTRUM OF NEUTRON ACTIVATED RIVER WATER

FIGURE 2

FIGURE 3

FIGURE 4

Gamma-ray spectrum of neutron activated sea water

FIGURE 5

FIGURE 6

FIGURE 7. MULTIPLE DEPTH SAMPLING

FIGURE 8

Neg 0690697

FIGURE 9. ^{51}Cr Concentrations on 11 Sampling Legs off the West Coast During November 13-16, 1968 (d/m/1000 liters)

FIGURE 10. COSMOGENIC RADIONUCLIDE TAGGED AEROSOLS PROVIDE TRACERS OF ATMOSPHERIC PRECIPITATION PROCESSES

TABLE 1
COMPARISON OF ELEMENTAL ABUNDANCES
IN RAINWATER* AND THE EARTH'S CRUST

<u>Element</u>	<u>Earth's Crust (ppm)</u>	<u>Rainwater</u>	<u>Ratio of Rainwater to Earth</u>	
Ag	0.07	1400	20,000	20,0.
Cl	130	1,400,000	11,000	11,0
Se	0.05	100	2,000	2,0
Br	2.5	3,900	1,600	1,6
Sb	0.2	230	1,200	1,2
As	1.8	1,900	1,100	1,1
Zn	70	28,600	4.10	4
Mn	950	3,700	3.90	3.
Co	25	64	2.60	2.
Sc	22	4	0.20	0.

* Normalized to Fe = 50,000 ppm.

Comparison of Chemical Abundance in
 River Water, ~~SEA~~ OCEAN AIR, & Geological Material
 (normalized to Se content)

	Rain Water *	Sea Water **	Air ***	DIAGRAM 0.002
Ag	300	< 5	100	
As	400	1000	3000	0.00
Br	1000	3000	300	0.015
Table 2				
G	10	10	6	1.5
Cr	< 600	200	60	3.5
Cs	20	40	5	0.032
Cu	1000	400	—	3.2
Fe	1000	6000	3000	2000
Hg	< 400	< 100	1	0.006
K	200,000	300,000	40,000	1.60
Mn	1000	1000	70.0	39
Na	2. x 10 ⁵	10 x 10 ⁵	.02 x 10 ⁵	450
Rb	< 700	2000	200	0.65
Sb	600	100	3000	0.032
Se	200	100	70	0.001
Zn	6000	4000	800	2.4

* QUINCY, WASHINGTON
 ** COLUMBIA RIVER, WASHINGTON
 *** CLEVELAND, OHIO

TABLE 3

PRECISION FOR MEASURING STRONTIUM IN SEA WATER BY
NEUTRON ACTIVATION AND DIRECT COUNTING TECHNIQUES -
EIGHT REPLICATE ANALYSES OF A SINGLE SEA WATER SAMPLE

<u>REPLICATE SAMPLE</u>	<u>Sr CONCENTRATION FOUND (mg/l)</u>
1	7.73
2	7.81
3	7.75
4	7.78
5	7.92
6	7.79
7	7.67
8	7.95
AVERAGE CONCENTRATION	7.80
% STANDARD DEVIATION	1.1%
% STANDARD DEVIATION AT 95% C. L. (2σ)	2.2%

TABLE 4.

COMPARISON OF LABORATORY AND *in situ* RETENTION OF SOLUBLE* RADIONUCLIDES FROM SEA-WATER
BY ALUMINUM OXIDE

% Retained on 0.65 cm beds.											
Radionuclide	⁷ Be	⁴⁶ Sc	⁵¹ Cr	⁶⁰ Co	⁶⁵ Zn	⁹⁵ Zr-Nb	¹⁰⁰ Ru	¹²⁴ Sb	¹⁴⁴ Ce	²²⁶ Ra	²³⁴ Th
Laboratory	73	43	>0.5	14	45	47	18	2.5	58	2.5	56
Ocean test	66	68	0.5	10	44	59	17	3	62	4	40

(Flow = 50 ml/min/cm²)

*All material which passes through 0.3μ membrane filters is assumed to be soluble.

TABLE 5.

OBSERVED RADIONUCLIDE CONCENTRATIONS IN REPLICATE SAMPLES FROM A STATION IN THE NORTH EQUATORIAL ATLANTIC OCEAN*

Sample	^7Be	$^{90}\text{Zr-Nb}$	^{103}Ru	^{106}Ru	^{144}Ce	^{228}Th	^{226}Ra	^{232}Th
1 soluble	203.0 ± 5.5	66.1 ± 0.9	33.6 ± 2.4	65.9 ± 4.3	93 ± 34	3.2 ± 0.3	98 ± 17	6140 ± 150
particulate	19.9 ± 6.1	1.9 ± 0.5	1.8 ± 0.7	0.7 ± 1.3	—	0.1 ± 0.4	—	940 ± 140
2 soluble	207.1 ± 5.5	74.8 ± 1.0	48.4 ± 2.6	61.4 ± 5.2	122 ± 39	3.7 ± 0.4	154 ± 21	6450 ± 170
particulate	22.3 ± 6.5	2.4 ± 0.6	2.9 ± 0.7	0.5 ± 1.4	—	—	4 ± 1	950 ± 160
3 soluble	194.5 ± 4.9	65.1 ± 1.0	37.4 ± 2.4	61.6 ± 5.8	139 ± 49	2.5 ± 0.4	116 ± 34	6020 ± 145
particulate	38.8 ± 5.6	2.3 ± 0.5	1.1 ± 0.7	1.3 ± 1.6	—	0.8 ± 0.4	2 ± 2	370 ± 150
4 soluble	209.4 ± 5.9	73.1 ± 0.9	40.6 ± 2.6	70.9 ± 4.5	100 ± 33	3.3 ± 0.3	133 ± 18	6450 ± 160
particulate	47.3 ± 5.4	2.1 ± 0.5	1.3 ± 0.6	0.4 ± 1.4	—	0.4 ± 0.4	1 ± 2	820 ± 140
Average								
(Total)†	235.6	72.0	41.8	65.7	113	3.5	127	7035
Precision (%)	6.2	6.9	16.5	6.5	18.6	6.6	20.0	6.4

(dpm/1000 l.)

*Latitude $15^{\circ}00' \text{N}$, Longitude $56^{\circ}39' \text{W}$, Date: 13 May, 1969.

†Particulate plus soluble.