SECTION 9
RADIOACTIVE STRONTIUM IN DRINKING WATER
Method 905.0

1. Scope and Application

1.1 This method covers the measurement of total strontium and soluble strontium-89 and strontium-90 in drinking water. Some naturally insoluble (and probably suspended) forms of strontium-89 and strontium-90 would also be measured by this method when samples of such drinking water supplies are acid-preserved before analysis.

1.2 The Drinking Water Regulations under the Safe Drinking Water Act set maximum contaminant concentrations for radionuclides in drinking water based on a 2 liter per day drinking water intake using the 168 hour data listed in Handbook 69, National Bureau of Standards. The maximum contaminant concentration for strontium-89 and strontium-90 are 80 pCi/l and 8 pCi/l, respectively, the critical organ being bone marrow. If other radionuclides are also present in the drinking water, the sum of their annual dose equivalent must not exceed 4 mrem per year. The Regulations also give a required sensitivity of measurement which is defined in terms of a detection limit. The required detection limits given for strontium-89 and strontium-90 are 10 pCi/l and 2 pCi/l, respectively. Appendix C has equations for calculating the counting time necessary to meet the required detection limit.

2. Summary of Method

2.1 Stable strontium carrier is added to the drinking water sample and strontium-89 and strontium-90 are precipitated from the solution as insoluble carbonates. Interferences from calcium and some radionuclides are removed by one or more precipitations of the strontium carrier as strontium nitrate. Barium and radium are removed as the chromate. The yttrium-90 daughter of strontium-90 is removed by a hydroxide precipitation step and the separated combined strontium-89 and strontium-90 are counted for beta particle activity. The counting result; immediately ascertained, represents the total strontium activity (strontium-90 + strontium-89) plus an insignificant fraction of the yttrium-90 that has grown into the separated strontium-90. The yttrium-90 daughter grows in again and is then separated with stable yttrium carrier as hydroxide and finally precipitated as oxalate and beta counted. The strontium-90 concentration is determined by the yttrium-90 activity and the strontium-89 concentration is then determined by difference.

2.2 Counting efficiency data must be obtained with standard strontium-89, strontium-90, and yttrium-90 activities. These data are used to make corrections since strontium-89, strontium-90, and yttrium-90 emit beta particles with different energies.

3. Sample Handling and Preservation

3.1 It is recommended that samples be preserved with acid at the time of collection. For preservation, sufficient acid should be added to make the sample pH < 2.

3.2 The Drinking Water Regulations allow for the option of quarterly compositing for an annual analysis or averaging the analyses of four quarterly samples. It is especially recommended to preserve composited samples.

3.3 It is recommended that no less than one liter size samples be collected for analysis.

4. Interferences

4.1 Radioactive barium and radium will be carried down with radioactive strontium as carbonate. This method includes steps to separate strontium from barium and radium.

4.2 Samples that naturally contain significant amounts of stable strontium will cause errors in the recovery of the added strontium carrier. Blank samples to which no strontium carrier is added should be run to determine natural strontium content. Hard waters contain calcium which precipitates with the strontium in the initial carbonate precipitation. If not separated, the calcium will cause errors in the recovery of the strontium carrier. Repeated precipitations with 16N HNO_3 (conc.) will eliminate this interference.

5. Apparatus - See Appendix D for details and specifications.

5.1 Low background beta counting system (< 3 cpm background on the beta voltage plateau is recommended).

5.2 Centrifuge and 50 ml centrifuge tubes

5.3 Drying oven

5.4 Hot water bath

5.5 Electric hot plate

5.6 Analytical balance

5.7 pH meter

5.8 Desiccator, aluminum and/or glass

5.9 Stainless steel planchets, 2-inch diameter by 1/4-inch deep

5. 10 Sintered-glass (fine). crucibles

5.11 Plastic ring and disc mounts

5.12 Mylar film

5.13 Teflon filter holder

5. 14 Drying lamps

5.15 Glassware

6. Reagents

Distilled or deionized water is to be used, and all chemicals should be of "reagent-grade" or equivalent whenever they are commercially available.

6.2 Strontium carrier (10 mg/ml): Dissolve 24.16g $Sr(NO_3)_2$ in water and dilute to 1 liter in a volumetric flask with water. Mix thoroughly.

Standardization: (In triplicate).

Carefully pipet 10.0-ml portions of the strontium carrier solution into separate 50-ml centrifuge tubes. Add 1 ml 6N NaOH and heat in a water bath. Slowly, and with stirring, add 15 ml of 2N Na_2C0_3 solution (see sodium carbonate solution below) and continue digesting for 15 to 20 minutes. Allow to cool and filter the $SrC0_3$ precipitate through a tared sintered-glass (fine) crucible. Wash the precipitate and the crucible walls with three 5-ml portions of distilled water adjusted to pH 8 with 6N NH_4OH, and with three 5-ml portions of acetone. Dry the crucible for 30 minutes in a 105°C oven. Cool the crucibles in a desiccator and weigh.

$$\text{Strontium, mg/ml} = \frac{\text{mg of } SrCO_3 * 0.5935}{10\text{ml}}$$

6.3 Yttrium carrier (10 mg/ml): Dissolve 43g $Y(NO_3)_3.6H_20$ in water plus 5 ml 16N HNO_3 (conc.) and dilute to 1 liter in a volumetric flask with water. Mix thoroughly

Standardization: (In triplicate).

Carefully pipet 10.0-ml portions of the yttrium carrier solution into separate 50-ml centrifuge tubes. Add 30 ml saturated $(NH_4)_2C_2O_4 \cdot H_2O$ to each centrifuge tube and stir. Digest in a hot water bath (near boiling) for

30 minutes. Cool in an ice bath. Filter the precipitate onto a Whatman #42 filter paper, then ignite in a tared crucible at 800°C for 1 hour to convert the oxalate to the oxide. Cool and weigh the crucible and calculate the yttrium concentration from the following equations.

$$\frac{Y}{Y_2O_3} = \frac{2*88.92}{225.84} = 0.7875$$

$$\text{yttrium, mg/ml} = \frac{\text{mg of } Y_2O_3 * 0.7875}{10\text{ml}}$$

6.4 Acetic acid, 5.8N: Mix 1 volume 17.4N CH_3COOH (glacial) with 2 volumes of water.

6.5 Acetone, $(CH_3)_2CO$: anhydrous.

6.6 Ammonium acetate buffer: Dissolve 154g $NH_4C_2H_3O_2$ in 800 ml of water, add 57 ml 17.4N CH_3COOH (glacial), adjust the mixture to pH 5.5 using CH_3COOH or NH_4OH. Dilute to 1 liter.

6.7 Ammonium hydroxide, 15N: NH_4OH (conc.), sp. gr. 0.90, 56.6%.

6.8 Ammonium hydroxide, 6N: Mix 2 volumes 15N NH_4OH (conc.) with 3 volumes of water.

6.9 Ammonium hydroxide, 0.1N: Mix 1 volume 15N NH_4OH (conc.) with 150 volumes of water.

6.10 Ammonium oxalate, saturated: Into 100 ml boiling water, dissolve 10g $(NH_4)_2C_2O_4 \cdot H_20$. Cool.

6.11 Barium carrier, (10 mg/ml): Dissolve 19.0g $Ba(NO_3)_2$ in water and dilute to 1 liter with water.

6.12 Hydrochloric acid, 6N: Mix 1 volume 12N HCl (conc.) with 1 volume of water.

6.13 Methyl red indicator, 0.1%: Dissolve 0.lg of methyl red in 100 ml ethanol.

6.14 Nitric acid, 16N: HNO_3 (conc.) sp. gr. 1.42, 70.4%.

6.15 Nitric acid, 6N: Mix 3 volumes 16N HNO_3 (conc.) with 5 volumes of water.

6.16 Nitric acid, 1N: Mix 1 volume 6N HNO_3 with 5 volumes of water.

6.17 Phenolphthalein indicator, 1%: Dissolve lg phenolphthalein in 50 ml ethanol and

add 50 ml water.

6.18 Sodium carbonate, 2N: Dissolve 124g $Na_2CO_3 \cdot H_20$ (or 106g Na_2CO_3) in water and dilute to 1 liter with water.

6.19 Sodium chromate, 0.5M: Dissolve 117g $Na_2CrO_4 \cdot 4H_20$ in water and dilute to 1 liter with water.

6.20 Sodium hydroxide, 6N: Dissolve 240g NaOH in water and dilute to 1 liter with water.

6.21 Wetting agent solution: e.g. Photo-Flo, Eastman Kodak Co.

7. Calibrations

7.1 Counting Efficiencies - Separate counting efficiencies should be determined for strontium-89 and strontium-90 using known amounts of the respective radioactive standards and 20.0 mg of strontium carrier, precipitated as carbonate and counted. A strontium-90 precipitate is prepared after separation of the yttrium-90 daughter by the following procedure. Add a known amount of strontium-90 standard, in the order of 1000 disintegrations per minute (dpm), and 20 mg of strontium carrier to a 50-ml centrifuge tube, add 20 ml of water and proceed as in steps 8.9 through 8.11. Then for the yttrium-90 counting efficiency, continue with steps 8.12 through 8.16.

7.2 Sources of supply: For strontium-90-yttrium-90, the National Bureau of Standards, Washington, DC offers a standard solution (SRM 4234) as listed in their latest catalog #260.

For strontium-89. Amersham Radiochemicals, Arlington Heights, Illinois, offers a standardized aqueous solution essentially free from strontium-90. This item is listed as SMZ.64 in their latest catalog.

Standard sources of strontium-89 and strontium-90 are also available from the Quality Assurance Division, U.S. Environmental Protection, EMSL-Las Vegas.

8. Procedure

8.1 Transfer 1-liter water sample aliquots to 2-liter beakers. Add 2.0 ml each of strontium and barium carrier solutions to each sample and blank beakers. Heat the samples to boiling and add 6N NaOH while stirring, to the phenolphthalein end point (red color), and add 50 ml 2N Na_2CO_3 solution. Continue heating to near boiling for 1 hour with occasional stirring. Then set the beakers aside for at least 2 hours, allowing the carbonate precipitate to settle.

8.2 Decant most of the clear supernate and discard it. With the remainder of the

supernate and necessary water washes (adjusted to ph 8 with 6N NH_4OH), quantitatively transfer the precipitate to a 50-ml centrifuge tube. Centrifuge and discard the supernate. This precipitate will contain the strontium and barium carriers.

8.3 Dissolve the precipitate by the dropwise addition of 4 ml 16N HNO_3.

8.4 Add 20 ml 16N HNO_3 to the centrifuge tube, cool in an ice bath and stir. Centrifuge and discard the supernate which will contain a significant fraction of the calcium present in the sample.

8.5 Add 20 ml 16N HNO_3 to the centrifuge tube, cool in an ice bath and stir. Centrifuge and discard supernate.

Note: If drinking water samples contain much calcium (hardness), it will be necessary to repeat step 8.5.

8.6 Dissolve the strontium and barium nitrate precipitate in 25 ml water, add 2 drops methyl red indicator, neutralize to yellow color with 6N NH_4OH, then adjust the pH back to red color by adding 5.8N CH_3COOH dropwise.

8.7 Add 5 ml ammonium acetate buffer solution, and heat in a hot water bath. Add, with stirring, 2 ml 0.5M Na_2CrO_4 and digest in the hot water bath for 15 minutes. Cool the reaction mixture and centrifuge. Transfer the supernate to a clean 50-ml centrifuge tube, and discard the barium chromate residue.

Note: This residue can be saved if radioactive barium, radium, or lead analysis is desired.

8.8 To the buffered chromate supernate add 2 ml 15N NH_4OH and heat in a hot water bath. Add 5 ml 2N Na_2CO_3 solution-and digest for 15 minutes. Cool, centrifuge, and discard the supernate.

Note: In the next step, the strontium-89 and strontium-90 are separated from yttrium-90 with a yttrium carrier scavenge to start a specific ingrowth period and to get a separate radiostrontium count in the following steps.

8.9 Add a few drops 16N HNO_3 to the carbonate precipitate, then add 25 ml water and 1 ml yttrium carrier. Add 1 drop of wetting agent solution (such as "Photo-Flo," an Eastman Kodak Company film processing product) and 5 ml 15N NH_4OH. Heat in a hot water bath for 15 minutes with occasional stirring. Centrifuge and transfer the supernate to a clean 50-ml centrifuge tube. Wash the yttrium hydroxide precipitate with 5 ml water, centrifuge and add this wash to the supernate. Note the time of this yttrium hydroxide precipitation which marks the beginning of the yttrium-90 ingrowth period. From this point on it is important to proceed without delay to the final separation and count of the strontium-89 and

strontium-90 activity to minimize ingrowth of yttrium-90.

Note: Concentrated NH_4OH sometimes contains CO_2 in solution which will cause precipitation of some of the strontium carrier in this step. If low carrier recoveries are obtained in step 8.11, then for subsequent strontium analyses, anhydrous NH_3 gas may be substituted for concentrated NH_4OH in step 8.9 by bubbling NH_3 gas in the sample solution until the phenolphthalein end point is reached, and then 5 minutes more. The same precaution might be taken in step 8.14 to prevent carrydown of the strontium-90 as the carbonate precipitate in that step.

8.10 Add 5 ml 2N Na_2CO_3 to the supernate from step 8.9, heat in a hot water 6ath for about 10 minutes, centrifuge and discard the supernate.

8.11 Slurry the strontium carbonate precipitate with a few ml water and transfer quantitatively to a tared glass fiber filter. Wash the precipitate with three 10-mi portions of water adjusted to pH 8 with NH_4OH, then with three 10-ml portions of acetone. During filtration and washes of the strontium carbonate, minimize the time of air flow through the filter to avoid collection of radon daughters. Dry the filter at 105°C for 10 minutes, then weigh, mount and count (within 2 hours). This count gives the total of strontium-89 and strontium-90 activities, plus the ingrown yttrium-90. Note the time of this count as it must be corrected for yttrium-90 ingrowth (time between steps 8.9 and 8.11).

Note A: An alternative to step 8.11 involves the collection and counting of the strontium carbonate precipitate on a tared stainless steel planchet. For this, the approach is as follows:

1. Slurry the strontium carbonate precipitate with a few mi water and transfer quantitatively to a tared stainless steel planchet. Dry under infrared lamp.

2. Cool, weigh, and beta count (within 2 hours).

Note B: The calculation of the total strontium activity D, in the sample at this point in time can be made as follows:

$$D = \frac{C}{2.22 * EVR}$$

where:

C = net count rate, cpm,
E = counter efficiency, for strontium-90
V = liters of sample used,

R = fractional chemical yield, and
2.22 = conversion factor from dpm/pCi.

Strontium-90 (By Yttrium-90)

8.12 After counting the strontium carbonate for strontium-89 and strontium-90 activity, store the filter or the planchet for a measured period of ingrowth, then proceed with the following steps for yttrium-90 separation. A 2-week or longer ingrowth period is recommended for samples with very low strontium-90 activity. Step 8.9 was the beginning of this ingrowth period.

8.13 Undo the mylar covering from the nylon ring and disc, and transfer the filter to a small funnel which has been placed to drain into a 50 ml centrifuge tube. Dissolve the strontium precipitate by carefully wetting the filter with 5 ml of 6N HNO_3. Wet the filter with 2.0 ml yttrium carrier. Rinse the strontium and yttrium into the centrifuge tube by washing the filter with four 5-ml portions of 1N HNO_3. Remove the funnel from the centrifuge tube, discard the filter, and add 1 drop of wetting agent solution to the centrifuge tube. Swirl the tube to mix the contents thoroughly.

Note: In the case of the stainless steel planchet:

1. After the period for yttrium-90 ingrowth, slurry the precipitate on the planchet with 2 ml water and transfer to a centrifuge tube with the aid of a rubber policeman. To make the transfer quantitative, wash the residue from the planchet with a small amount of 1N HNO_3. Dissolve the precipitate in the tube with sufficient 1N HNO_3, and dilute with water to 10 ml.

2. Add 2.0 ml yttrium carrier and stir.

3. Boil to expel dissolved carbon dioxide; cool to room temperature.

8.14 Precipitate the yttrium as hydroxide by adding 10 ml 15N NH_4OH to the centrifuge tube, stirring and heating for 10 minutes in a hot water bath. Cool, centrifuge and decant supernate into a 100-ml beaker. Note time of last precipitation; this is the end of yttrium-90 ingrowth and the beginning of yttrium-90 decay.

8.15 Dissolve precipitate in 1 ml 1N HNO_3 and dilute with water to 10 ml.

8.16 Reprecipitate yttrium by dropwise addition of 15N NH_4OH.

8.17 Centrifuge and combine supernate with solution in the 100-ml beaker (step 8.14).

8.18 Repeat steps 8.15, and 8.16. Save the combined supernates in the beaker for strontium gravimetric yield determination, step 8.22.

Note: Steps 8.22 to 8.25 are a repeat of the strontium carbonate precipitation to determine chemical yield after the yttrium has been removed.

8.19 Dissolve the precipitate in 15 ml water containing 2 ml 6N HCl. Precipitate the yttrium as oxalate by adding 20 ml saturated $(NH_4)_2C_2O_4$ and heating for 30 minutes in a hot water bath (near boiling). Cool in an ice bath and then filter the yttrium oxalate onto a Whatman #42 filter (4.25 cm diameter). Wash the precipitate with three 5-ml portions of water, then with three 5-ml portions of acetone. Air dry the filter for about 1 hour.

Note: A pH of 1.7-1.9 in the solution from which yttrium oxalate is being precipitated is necessary to get a uniform $9H_20$ hydrate precipitate. This is necessary if the analyst prefers and is going to weigh the yttrium oxalate for chemical yield. Also, the analyst may then prefer to use a tared glass fiber filter instead of a Whatman #42 paper filter. The filter plus oxalate precipitate is weighed to determine chemical yield (recovery). See note following 9.1 for calculations. If this procedure is followed, step 8.21 can be eliminated.

8.20 Mount filter on a plastic ring and disc, and count for yttrium-90 activity. Record the time of the counting for decay correction (time between 8.14 and count time).

8.21 Undo the mylar covering, and transfer the filter to a tared crucible. Ignite at 800°C for 1 hour in a muffle furnace to convert the oxalate to the oxide. Cool and weigh the crucible. Determine the yttrium recovery (see Section 9.1).

8.22 Warm the combined supernates from step 8.14, add 5 ml 2N Na_2CO_3, and digest for 10 minutes. Cool, centrifuge, and discard supernate.

8.23 Wash the $SrCO_3$ with 15 ml water and discard wash solution.

8.24 Slurry with a few ml water and transfer quantitatively to a tared stainless-steel planchet. Dry under infrared lamps.

8.25 Cool and weigh the planchet. Determine the strontium recovery (see Section 9.1).

9. Calculations

9.1 Chemical yields for strontium and yttrium

$$a = \text{Yield factor for Sr} = \frac{\text{mg } SrCO_3 \text{ recovered}}{\text{mg Sr carrier added (as carbonate)}}$$

20.0 mg of strontium is equivalent to 33.7 mg $SrCO_3$

b = Yield factor for Y = $\frac{\text{mg } Y_2O_3 \text{ Recovered}}{\text{mgY carrier added (as oxide)}}$

20.0 mg of yttrium is equivalent to 25.4 mg of Y_2O_3.

Note: If chemical yield is to be determined from the yttrium oxalate precipitate the following calculations are used.

b = yield factor for Y = $\frac{\text{mg } Y_2(C_2O_4)_3CH_2O}{\text{mg Y carrier added (as oxalate)}}$

20.0 mg of yttrium is equivalent to 67.9 mg of yttrium oxalate, $Y_2(C_2O_4)_3 \bullet H_2O$.

9.2 Calculations for Activities at Equilibrium Conditions:

Indicated cpm values are net cpm (reagent blank, including background, subtracted).

$$Y^{90} \text{ dpm} = \frac{Y^{90} \text{ dpm}}{abefi} = Sr^{90} \text{ dpm}$$

$$Sr^{90} \text{ cpm} = Y^{90} \text{ dpm} * c$$

Total $Sr^{89,90}$ cpm = total cpm ($SrCO_3$) - ingrown Y^{90} cpm

$$\text{Ingrown } Y^{90} \text{ cpm} = Sr^{90} \text{ cpm} * e * g$$

$$Sr^{89} \text{ cpm} = \frac{\text{total Sr cpm}}{a} - Sr^{90} \text{ cpm} - Sr^{90} \text{ dpm} * e * g$$

$$Sr^{89} \text{ dpm} = \frac{Sr^{89} \text{ cpm}}{d}$$

$$Sr^{90} \text{ pCi/liter} = \frac{Sr^{90} \text{ dpm}}{2.22 * V}$$

$$Sr89 \text{ pCi/liter} = \frac{Sr^{89} \text{ dpm}}{2.22 * V}$$

where:

c = strontium-90 counting efficiency,
d = strontium-89 counting efficiency,
e = yttrium-90 counting efficiency,

f	=	yttrium-90 decay factor,
g	=	yttrium-90 ingrowth factor, for unwanted yttrium-90 in total strontium-89, strontium-90 count,
h	=	strontium-89 decay factor,
V	=	volume of sample analyzed, in liters,
i	=	yttrium-90 ingrowth factor for strontium-90 by yttrium-90 determination, and
2.22	=	conversion factor from dpm/pCi.

Error associated with the results of the analysis should also be reported. See Section 10 for error and statistical calculations, for yttrium-90 decay and ingrowth factors, and for strontium-89 decay factors.

10. Calculation Factors

10.1 Error and Statistical Calculations - Because of the random nature of radioactivity disintegrations, there is an error associated with any measured count of these disintegrations. The variabi1ity of any measurement is indicated by the standard deviation. The standard deviation in the counting rate, (R). is determined by the following equation:

$$\sigma (R) = \left[\frac{R_0}{t_1} + \frac{B}{t_2} \right]^{\frac{1}{2}}$$

where:	R_0	=	Gross count rate
	T_1	=	counting time for the gross count
	B	=	background count rate
	T_2	=	counting time for the background count
Let σ(R1)	$= D_1$	=	standard deviation for the count of total strontium-89 and strontium-90 (from $SrCO_3$ precipitate, which includes the unwanted ingrown yttrium-90).
Let σ(R2)	$= D_2$	=	Standard deviation for the yttrium-90 count for the strontium-90 determination.

The counting errors, E, for a given sample for the strontium-89 and strontium-90 determinations expressed in pCi/liter are shown as follows:

For 90Sr, E = $$\frac{1.96 D_2 * 1000}{2.22 * abefiV}$$

For 89Sp, E = $$\frac{1.96*1000}{2.22*adV}\left[\left(D_1\right)^2+\left(\frac{c+e*g}{befi}\right)^2\left(D_2\right)^2\right]^{\frac{1}{2}}$$

where:

1.96 = 95% confidence factor
1000 = ml/liter
2.22 = conversion factor from disintegrations/minute to picocuries
a = strontium recovery factor
b = yttrium recovery factor
c = strontium-90 counting efficiency
d = strontium-89 counting efficiency
e = yttrium-90 counting efficiency
f = yttrium-90 decay factor
g = ingrowth factor for unwanted yttrium-90 in total radiostrontium count
i = ingrowth factor for yttrium-90 for strontium-90 determination

These were derived by applying propagation of error theory to the expressions in Section 9.3.

The standard deviations of a number of experimental analyses or observations is determined by:

$$S = \left[\sum_{i=1}^{n}\frac{\left(x_i-\bar{x}\right)^2}{n-1}\right]^{\frac{1}{2}}$$

where:

x_i = activity (pCi/liter) of a given sample
$\bar{x}$ = mean activity (pCi/liter) of a series of analyses
n = the number of replicate analyses

10.2 Yttrium-90 Decay and Ingrowth Factors (0-71 Hours)

t(hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$	t(hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$	t(hr)	$e^{-\lambda t}$	$1-e^{-\lambda t}$
0.0	1.0000	.0000	22.5	.7843	.2157	45.0	.6151	.3849
0.5	.9940	.0054	23.0	.7801	.2199	45.5	.6118	.3882
1.0	.9893	.0107	23.5	.7759	.2241	46.0	.6085	.3915
1.5	.9839	.0161	24.0	.7717	.2283	46.5	.6053	.3947
2.0	.9786	.0214	24.5	.7676	.2324	47.0	.6020	.3980
2.5	.9734	.0266	25.0	.7634	.2366	47.5	.5988	.4012
3.0	.9681	.0319	25.5	.7593	.2407	48.0	.5955	.4045
3.5	.9629	.0371	26.0	.7552	.2448	48.5	.5923	.4077
4.0	.9577	.0423	26.5	.7512	.2488	49.0	.5891	.4109
4.5	.9526	.0474	27.0	.7471	.2529	49.5	.5860	.4140
5.0	.9474	.0526	27.5	.7431	.2569	50.0	.5828	.4172
5.5	.9423	.0577	28.0	.7391	.2609	50.5	.5797	.4203
6.0	.9373	.0627	28.5	.7351	.2549	51.0	.5766	.4234
6.5	.9322	.0678	29.0	.7311	.2689	51.5	.5735	.4265
7.0	.9272	.0728	29.5	.7272	.2728	52.0	.5704	.4296
7.5	.9222	.0778	30.0	.7233	.2767	52.5	.5673	.4327
8.0	.9172	.0828	30.5	.7194	.2806	53.0	.5642	.4358
8.5	.9123	.0877	31.0	.7155	.2845	53.5	.5612	.4388
9.0	.9074	.0926	31.5	.7117	.2883	54.0	.5582	.4418
9.5	.9025	.0975	32.0	.7078	.2922	54.5	.5552	.4448
10.0	.8976	.1024	32.5	.7040	.2960	55.0	.5522	.4478
10.5	.8928	.1072	33.0	.7002	.2998	55.5	.5492	.4508
11.0	.8880	.1120	33.5	.6965	.3035	56.0	.5462	.4538
11.5	.8832	.1168	34.0	.6927	.3073	56.5	.5433	.4567
12.0	.8785	.1215	34.5	.6890	.3110	57.0	.5404	.4596
12.5	.8737	.1263	35.0	.6853	.3147	57.5	.5375	.4625
13.0	.8690	.1310	35.5	.6816	.3184	58.0	.5346	.4654
13.5	.8644	.1356	36.0	.6779	.3221	58.5	.5317	.4683
14.0	.8597	.1403	36.5	.6743	.3257	59.0	.5288	.4712
14.5	.8551	.1449	37.0	.6706	.3294	59.5	.5260	.4740
15.0	.8505	.1495	37.5	.6670	.3330	60.0	.5232	.4768
15.5	.8459	.1541	38.0	.6634	.3366	60.5	.5203	.4797
16.0	.8413	.1587	38.5	.6599	.3401	61.0	.5175	.4825
16.5	.8468	.1632	39.0	.6563	.3437	61.5	.5148	.4852
17.0	.8323	.1677	39.5	.5428	.3472	62.0	.5092	.4880
17.5	.8278	.1722	40.0	.6493	.3507	62.5	.5092	.4908
18.0	.8234	.1766	40.5	.6458	.3542	63.0	.5065	.4935
18.5	.8189	.1811	41.0	.6423	.3577	64.0	.5010	.4990
19.0	.8145	.1855	41.5	.6388	.3612	65.0	.4957	.5043
19.5	.8101	.1899	42.0	.6354	.3646	66.0	.4903	.5097
20.0	.8058	.1942	42.5	.6320	.3680	67.0	.4851	.5149
20.5	.8014	.1986	43.0	.6286	.3714	68.0	.4799	.5201
21.0	.7971	.2029	43.5	.6252	.3748	69.0	.4747	.5253
21.5	.7928	.2072	44.0	.6219	.3781	70.0	.4696	.5304
22.0	.7885	.2115	44.5	.6185	.3815	71.0	.4646	.5354

10.3 Yttrium-90 Ingrowth Factors (0-27 days)

t(days)	$1-e^{-\lambda t}$	t(days)	$1-e^{-\lambda t}$	t(days)	$1-e^{-\lambda t}$
0.00	.0000	9.00	.9029	18.00	.9906
0.25	.0627	9.25	.9090	18.25	.9912
0.50	.1215	9.50	.9147	18.50	.9917
0.75	.1766	9.75	.9201	18.75	.9922
1.00	.2283	10.00	.9251	19.00	.9927
1.25	.2767	10.25	.9298	19.25	.9932
1.50	.3221	10.50	.9342	19.50	.9936
1.75	.3646	10.75	.9384	19.75	.9940
2.00	.4045	11.00	.9422	20.00	.9944
2.25	.4418	11.25	.9458	20.25	.9948
2.50	.4768	11.50	.9492	20.50	.9951
2.75	.5097	11.75	.9524	20.75	.9954
3.00	.5404	12.00	.9554	21.00	.9957
3.25	.5692	12.25	.9582	21.25	.9959
3.50	.5963	12.50	.9608	21.50	.9962
3.75	.6216	12.75	.9633	21.75	.9964
4.00	.6453	13.00	.9656	22.00	.9967
4.25	.6676	13.25	.9678	22.25	.9969
4.50	.6884	13.50	.9697	22.50	.9971
4.75	.7080	13.75	.9716	22.75	.9973
5.00	.7263	14.00	.9734	23.00	.9974
5.25	.7435	14.25	.9751	23.25	.9976
5.50	.7596	14.50	.9766	23.50	.9977
5.75	.7746	14.75	.9781	23.75	.9979
6.00	.7888	15.00	.9795	24.00	.9980
6.25	.8020	15.25	.9808	24.25	.9981
6.50	.8145	15.50	.9820	24.50	.9982
6.75	.8261	15.75	.9831	24.75	.9984
7.00	.8370	16.00	.9842	25.00	.9985
7.25	.8472	16.25	.9852	25.25	.9986
7.50	.8568	16.50	.9861	25.50	.9987
7.75	.8658	16.75	.9870	25.75	.9987
8.00	.8742	17.00	.9878	26.00	.9988
8.25	.8820	17.25	.9886	26.25	.9989
8.50	.8896	17.50	.9893	26.50	.9990
8.75	.8864	17.75	.9900	26.75	.9990
				27.00	.9991

10.4 Strontium-89 Decay Factors (0-59.5 days) (t 1/2 = 51 days)

t(days)	$e^{-\lambda t}$	t(days)	$e^{-\lambda t}$	t(days)	$e^{-\lambda t}$
0.0	1.0000	20.0	.7620	40.0	.5808
0.5	.9932	20.5	.7569	40.5	.5769
1.0	.9865	21.0	.7518	41.0	.5730
1.5	.9798	21.5	.7568	41.5	.5690
2.0	.9732	22.0	.7416	42.0	.5652
2.5	.9668	22.5	.7366	42.5	.5613
3.0	.9601	23.0	.7317	43.0	.5575
3.5	.9536	23.5	.7267	43.5	.5539
4.0	.9471	24.0	.7218	44.0	.5500
4.5	.9407	24.5	.7169	44.5	.5462
5.0	.9344	25.0	.7120	45.0	.5427
5.5	.9280	25.5	.7072	45.5	.5380
6.0	.9217	26.0	.7023	46.0	.5352
6.5	.9155	26.5	.6977	46.5	.5318
7.0	.9093	27.0	.6930	47.0	.5280
7.5	.9031	27.5	.6882	47.5	.5245
8.0	.8970	28.0	.6836	48.0	.5210
8.5	.8909	28.5	.6790	48.5	.5175
9.0	.8849	29.0	.6742	49.0	.5140
9.5	.8789	29.5	.6699	49.5	.5105
10.0	.8729	30.0	.6651	50.0	.5070
10.5	.8670	30.5	.6608	50.5	.5035
11.0	.8612	31.0	.6562	51.0	.5000
11.5	.8553	31.5	.6519	51.5	.4967
12.0	.8495	32.0	.6473	52.0	.4933
12.5	.8438	32.5	.6430	52.5	.4900
13.0	.8381	33.0	.6388	53.0	.4868
13.5	.8324	33.5	.6342	53.5	.4834
14.0	.8268	34.0	.6300	54.0	.4801
14.5	.8212	34.5	.6259	54.5	.4769
15.0	.8156	35.0	.6215	55.0	.4734
15.5	.8101	35.5	.6172	55.5	.4702
16.0	.8046	36.0	.6131	56.0	.4671
16.5	.7991	36.5	.6090	56.5	.4640
17.0	.7938	37.0	.6050	57.0	.4608
17.5	.7883	37.5	.6009	57.5	.4578
18.0	.7881	38.0	.5968	58.0	.4547
18.5	.7778	38.5	.5928	58.5	.4513
19.0	.7725	39.0	.5888	59.0	.4484
19.5	.7672	39.5	.5848	59.5	.4454

11. Precision and Accuracy

11.1 In a single operator test of the method, two sets of five water samples containing known amounts of strontium-89, strontium-90, were analyzed for those radionuclides. The average recovery of added strontium-90 was 95 and 94 percent for the two sets of samples at a precision of 3 and 5 percent at the 95 percent confidence level.

11.2 In a collaborative test of the method with 13 laboratories participating, three samples containing known amounts of strontium-89 and strontium-90 were analyzed (Samples A, B and C).

11.3 The data of two laboratories for all three samples for strontium-90 were rejected because their scores in the ranked results of the laboratory averages were outside the acceptable range for 13 laboratories and 3 samples.

11.4 The coefficients of variation for the three samples ranged from 11.3% for 1000 pCi/l concentrations to 57% for 10 pCi/l concentrations.

11.5 The coefficients of variation for the combined within-laboratory precision for strontium-90 in the three samples ranged from 13.6% for 1000 pCi/l concentrations to 23% for 10 pCi/l concentrations.

11.6 The coefficients of variation for the precision of the method between laboratories for strontium-89 in the three samples ranged from 20% for 1000 pCi/l concentrations to 43% for 10 pCi/l concentrations.

11.7 The coefficients of variation for the precision of the method between laboratories for strontium-90 in the samples ranged from)5% for 1000 pCi/l concentrations to 44% for 10 pCi/l concentrations.

11.8 The coefficients of variation for the total error between laboratories based on a single analysis for strontium-89 in the three samples ranged from 23% for 1000 pCi/l concentrations to 71% for 10 pCi/l concentrations.

11.9 The coefficients of variation for the total error between laboratories based on a single analysis for strontium-90 in the three samples ranged from 17% for 1000 pCi/l concentrations to 46% for 10 pCi/l concentrations.

11.10 In the statistical test to detect method bias, no significant bias was shown in the analysis of the three samples for strontium-89. In the analysis of the three samples for strontium-90, sample C (1000 pCi/l concentration) showed a low bias but not seriously.

11.11 The strontium-89 analysis of samples A, B, and C deviated from the known values by the factor 1.49, 1.01, and 1.03, respectively. The strontium-90 analysis of

samples A, B, and C deviated from .ne known values by the factors 1.00, 0.899, and 0.820, respectively.

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