Standard Practice for
Analysis of Aqueous Leachates from Nuclear Waste Materials Using Inductively Coupled Plasma-Atomic Emission Spectroscopy[1]

1. Scope

1.1 This practice is applicable to the determination of low concentration and trace elements in aqueous leachate solutions produced by the leaching of nuclear waste materials, using inductively coupled plasma-atomic emission spectroscopy (ICP-AES).

1.2 The nuclear waste material may be a simulated (non-radioactive) solid waste form or an actual solid radioactive waste material.

1.3 The leachate may be deionized water or any natural or simulated leachate solution containing less than 1 % total dissolved solids.

1.4 This practice should be used by analysts experienced in the use of ICP-AES, the interpretation of spectral and non-spectral interferences, and procedures for their correction.

1.5 No detailed operating instructions are provided because of differences among various makes and models of suitable ICP-AES instruments. Instead, the analyst shall follow the instructions provided by the manufacturer of the particular instrument. This test method does not address comparative accuracy of different devices or the precision between instruments of the same make and model.

1.6 This practice contains notes that are explanatory and are not part of the mandatory requirements of the method.

1.7 The values stated in SI units are to be regarded as the standard.

1.8 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C859 Terminology Relating to Nuclear Materials

C1009 Guide for Establishing and Maintaining a Quality Assurance Program for Analytical Laboratories Within the Nuclear Industry

C1220 Test Method for Static Leaching of Monolithic Waste Forms for Disposal of Radioactive Waste

D1193 Specification for Reagent Water

D7035 Test Method for Determination of Metals and Metalloids in Airborne Particulate Matter by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)

E135 Terminology Relating to Analytical Chemistry for Metals, Ores, and Related Materials

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

2.2 *ISO and European Standards:*[3]

ISO 1042 Laboratory Glassware—One-mark Volumetric Flasks

ISO 3585 Borosilicate Glass 3.3—Properties

ISO 8655 Piston-Operated Volumetric Instruments (6 parts)

3. Terminology

3.1 For definitions of pertinent terms not listed here, see Terminology C859.

3.2 *Definitions:*

3.2.1 *atomic emission*—characteristic radiation emitted by an electronically excited atomic species. **D7035**

3.2.1.1 *Discussion*—In atomic (or optical) emission spectrometry, a very high-temperature environment, such as a plasma, is used to create excited state atoms. For analytical purposes, characteristic emission signals from elements in their excited states are then measured at specific wavelengths.

5.3 This practice can be used to analyze leachates from static leach testing of waste forms using Test Method C1220.

6. Apparatus

6.1 Ordinary laboratory apparatus are not listed, but are assumed to be present.

6.2 *Glassware,* volumetric flasks complying with the requirements of ISO 1042, made of borosilicate glass complying with the requirements of ISO 3585. Glassware should be cleaned before use by soaking in nitric acid and then rinsing thoroughly with water.

6.3 *Filters,* inert membrane, having pore size of 0.45 μm or smaller.

6.4 *Piston-operated Volumetric Pipettors and Dispensers,* complying with the requirements of ISO 8655, for pipetting and dispensing of solutions, acids, and so forth.

6.5 *Bottles,* tetrafluoroethylene or polyethylene, for storage of calibration and check solutions.

6.6 *Disposable Gloves,* impermeable, for protection from corrosive substances. Polyvinyl chloride (PVC) gloves are suitable.

6.7 *Inductively Coupled Plasma-Atomic Emission Spectrometer,* computer controlled, with a spectral bandpass of 0.05 nm or less, is required to provide the necessary spectral resolution.

NOTE 1—The spectrometer may be of the simultaneous multielement or sequential scanning type. The spectrometer may be of the air-path, inert gas-path, or vacuum type, with spectral lines selected appropriately for use with the specific instrument.
NOTE 2—An autosampler having a flowing rinse is recommended.

7. Reagents and Materials

7.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society where such specifications are available.[5] Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

7.2 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean reagent water as defined by Type I of Specification D1193 or water exceeding these specifications.

7.3 *Nitric Acid (specific gravity 1.42)*—Concentrated nitric acid (HNO_3).

7.4 *Nitric Acid, High-Purity*—Nitric acid of higher purity than reagent grade, specially prepared to be low in metallic

contaminants. The acid may be prepared by sub-boiling distillation (4), or purchased from commercial sources.

7.5 *Stock Solutions*—May be purchased or prepared from metals or metal salts of known purity. Stock solutions should contain known concentrations of the element of interest ranging from 100 to 10 000 mg/L.

7.6 *Calibration Blank Solution,* 1 % (v/v) HNO_3.

7.7 *Calibration Reference Solutions, Instrument Check Solutions, and Linearity Check Solutions:*

7.7.1 Prepare single-element or multielement calibration reference solutions by combining appropriate volumes of the stock solutions in acid-rinsed volumetric flasks. To establish the calibration slope accurately, provide at least one solution with element concentration that is a minimum of 100 times the L_D for each element. Add sufficient nitric acid to bring the final solution to 1 % HNO_3. Prior to preparing the multielement solutions, analyze each stock solution separately to check for strong spectral interference and the presence of impurities (5). Take care when preparing the multielement solutions to verify that the components are compatible and stable (they do not interact to cause precipitation) and that none of the elements present exhibit mutual spectral interference. Transfer the calibration reference solutions to acid-leached FEP TFE-fluorocarbon or polyethylene bottles for storage. Calibration reference solutions must be verified initially using a quality control sample and monitored periodically for stability.

NOTE 3—Solutions in polyethylene bottles are subject to transpiration losses that may affect the assigned concentration values.

7.7.2 Prepare the instrument check solution(s) and linearity check solutions in a similar manner.

7.7.3 Fresh solutions should be prepared as needed with the realization that concentrations can change over time. The recommended maximum shelf life for calibration reference solutions, instrument check solutions, and linearity check solutions is one month.

8. Sample Preparation

8.1 If necessary to remove solids or suspended colloids, filter the leachate through a clean filter, using an inert filter support (avoid the use of fritted glass supports). Examine the filtered leachate to verify the absence of visible solids or suspended colloids. The deposit on the filter may be analyzed separately if required.

8.2 Prepare filtered and unfiltered aliquots of a calibration blank solution, and compare the results of these aliquots to determine whether the filter membrane contributes to the blank level of the filtered solution.

NOTE 4—Step 8.2 may be omitted if none of the samples requires filtration.

8.3 Add sufficient high-purity concentrated nitric acid to bring the leachate sample solution to volume 1 % HNO_3. If the leachate is known to be a chloride solution, or nitric acid is undesirable for other experimental reasons, concentrated hydrochloric or other mineral acid may be used instead. The acid conditions of the calibration and check solutions used in the analytical procedure must match those of the leachate sample.

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[5] *Reagent Chemicals, American Chemical Society Specifications, American Chemical Society,* Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see *Analar Standards for Laboratory Chemicals,* BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary,* U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.

NOTE 5—It is necessary that quantities of acid and sample be carefully measured during acidification to allow correction of results to account for dilution.

9. Analytical Conditions

9.1 *Analytical Lines*—Suggested analytical lines for typical elements are given in Table 1. Additional lines for these and other elements of interest, and information about possible interfering lines, can be found in compilations of analytical lines for ICP-AES (6-14).

9.2 *Selection of Analytical Conditions*—Select an optimum combination of analytical lines, background correction methods, plasma viewing position, and plasma/spectrometer operating conditions to obtain the following for each element:

9.2.1 The lowest attainable L_D,

9.2.2 The acceptable linear dynamic range,

9.2.3 Avoidance or minimization of spectral and non-spectral interference, and

TABLE 1 Suggested Analytical Wavelengths of Typical Elements for ICP-AES[A]

Element	Suggested Wavelength, nm	Estimated Detection Limit, mg/L	Alternative Wavelength, nm	Estimated Detection Limit, mg/L
Aluminum	308.22	0.04	237.32	0.03
Americium	283.23	0.01	292.06	>0.01
Arsenic	193.70	0.05	189.04	0.01[B]
Barium	493.41	0.002	455.40	0.001
Beryllium	234.86	0.0003	313.04	0.0003
Boron	249.77	0.005	249.68	0.005
Cadmium	214.44	0.002	...	...
Calcium	317.93	0.01	393.37	0.0002
Cerium	418.66	0.05	413.76	0.05
Chromium	267.72	0.007	205.55	0.006
Dysprosium	353.17	0.01	205.50	...
Gadolinium	342.25	0.01	...	...
Iron	259.94	0.006	273.96	0.02
Lanthanum	408.67	0.01	379.48	0.01
Lead	217.00	0.09	220.35	0.04
Lithium	670.78	0.002	...	...
Magnesium	279.55	0.0001	279.08	0.03
Manganese	257.61	0.001	294.92	0.008
Molybdenum	202.03	0.008	203.84	0.01
Neodymium	406.11	0.1	401.22	0.05
Neptunium	382.91	0.09	456.04	0.13
Nickel	231.60	0.02	221.65	0.01
Phosphorus	214.91	0.08	178.29	[B]
Plutonium	300.06	0.03	297.25	0.03
Potassium	766.49	0.04	...	...
Rhodium	343.49	0.06	233.48	0.04
Ruthenium	240.27	0.03	...	...
Samarium	442.43	0.05	...	...
Selenium	203.99	0.1	196.03	0.08[B]
Silicon	288.16	0.03	212.41	0.02
Sodium	589.00	0.03	330.24	1.9
Strontium	421.55	0.0008	407.77	0.0004
Sulfur	180.73	[B]	...	...
Technetium	254.32	0.002	261.00	0.002
Tellurium	214.28	0.04	214.72	0.2
Thorium	401.91	0.08	...	...
Titanium	337.28	0.007	334.94	0.004
Uranium	385.96	0.25	367.01	0.3
Vanadium	292.40	0.008	...	...
Zinc	213.86	0.002	206.20	0.006
Zirconium	343.82	0.008	339.20	0.008

[A] See Refs (6-14) for a more complete list. Check those references also to identify any possible interfering spectral lines from components such as rare earths, actinides, or high-concentration components.
[B] Vacuum spectrometer.

9.2.4 Best attainable precision.

9.3 Follow the spectrometer manufacturer's recommendation wherever possible in establishing operating conditions. For simultaneous multielement systems, the optimum plasma viewing position and set of operating conditions is usually a compromise (15). The combination of conditions selected must be used in all subsequent ICP operations, including determination of L_D, calibrations, sample analyses, and performance checks. Systematic use of an appropriate method such as reference to an atom-to-ion emission intensity ratio (5) to ensure reproducible conditions is recommended.

9.4 Perform at least ten consecutive measurements of a matrix blank and calculate L_D as described in 3.2.12.1.

9.5 Perform experiments to determine the linear dynamic range for each element of interest. Use L_D and the linear dynamic range as a guide in the preparation of calibration reference solutions and linearity check solutions.

9.6 Estimate the standard deviation for use in establishing control limits for each element through repetitive analysis of the instrument check solution(s). For a particular element, these control limits are the known elemental concentration plus or minus a multiple of the standard deviation, based on the required confidence limit. For example, a multiple of two times the standard deviation would provide a confidence limit of 95 %. Different control limits may be used for individual samples, or sets of samples, as required by the laboratory. It is recommended that at least ten independent analyses, distributed randomly with respect to time and laboratory operating conditions, be used to estimate the standard deviation.

10. Calibration

10.1 *Calibration of the Spectrometer System:*

10.1.1 Follow the spectrometer manufacturer's instructions for forming and stabilizing the plasma. Allow sufficient time for plasma stabilization before making measurements.

10.1.2 Calibrate the spectrometer system using the calibration blank and the appropriate calibration reference solutions, following the same procedure as for sample analysis (see Section 11). Obtain separate intensity measurements at the analytical line peak position while introducing the calibration blank and the calibration reference solution. Subtract the analytical line peak intensity determined during analysis of the calibration blank from that of the calibration reference solution analysis to determine the net intensity related to concentration. Then check the accuracy of the calibration by analyzing the instrument check solution(s). The values obtained must fall within the previously determined control limits (see 9.6) or the instrument must be recalibrated. Finally, check calibration linearity by analyzing the linearity check solutions. The values obtained must be accurate to within 5 % of the known solution concentration for all elements. It is not necessary to check for calibration linearity every time the spectrometer is calibrated provided that the analysis conditions have not been altered.

10.1.3 The calibration range for each element should be limited to a linear ratio of the net signal intensity and concentration.

10.1.4 Frequency of calibration required depends on instrument stability. Common practice is to verify correct calibration daily at start-up and to recalibrate whenever the check solutions analysis indicates the need (see Section 11).

11. Procedure

11.1 *Leachate Solution Analysis:*

11.1.1 Follow the spectrometer manufacturer's instructions for forming and stabilizing the plasma. Allow sufficient time for plasma stabilization before making measurements.

11.1.2 Analyze samples using the instrument operating procedure recommended by the manufacturer. A minimum of three sequential spectral integrations is recommended for determining the average (reported) concentration for a single sample analysis. Provide a dilute acid rinse between samples, with sufficient rinse time to ensure analyte signals return to blank concentrations. The calibration blank may be used for this purpose. If a high concentration of any element is observed in the sample, the calibration blank should be analyzed to verify that no carryover memory effect has occurred. If carryover is observed, repeat rinsing until the correct blank value is obtained. After introducing each sample or blank, allow sufficient time for complete equilibration before initiating data collection. Analysis for elemental concentrations beyond the linear calibration range should be conducted by reducing the sample concentration to the linear range by appropriate dilution and acidification of the sample.

11.1.3 Analyze the instrument check solution(s) after every group of ten samples has been analyzed. Precede the analysis of the instrument check solution(s) by analysis of the calibration blank to verify that the routine rinse procedure prevents memory effects from previous sample analyses. Analyze the instrument check solution(s) more frequently if nonroutine leachate samples or analytical conditions are suspected. The concentrations obtained should fall within the control limits (see 9.6). If not, the spectrometer must be recalibrated and all samples analyzed since the last satisfactory check solution analysis must be reanalyzed. If serious instrumental drift occurs, the analysis of samples should be halted and cause of the instability sought and eliminated. Concentrations must fall within the linear range of each element. Otherwise, samples must be diluted and reanalyzed.

11.1.4 The stability of the baseline for each element is determined by comparison of successive analyses of the calibration blank. The baseline stability should be monitored by periodic analysis of instrument check solution(s). Analysis for baseline drift is recommended after every group of ten samples.

12. Corrections

12.1 *Spectral Interference*—Spectral interference can usually be avoided by judicious choice of analytical wavelengths (16). When spectral interference cannot be avoided, the necessary corrections should be made using the empirical method of spectral interference correction, using either the operating computer software supplied by the spectrometer manufacturer or the manual method detailed below. The empirical correction method cannot be used with scanning spectrometer systems if both the analytical and interfering lines cannot be located

precisely and reproducibly. With any instrument, the analyst must always be alert to the possible presence of unexpected elements producing interfering spectral lines.

12.1.1 The empirical method of spectral interference correction uses interference correction factors (17). Interference correction factors are determined by analyzing the single-element, high-purity stock solutions under conditions matching as closely as possible those used for sample analysis. Unless plasma conditions can be accurately reproduced from day to day, or for longer periods, interference correction factors found to affect the results significantly must be redetermined each time samples are analyzed (5, 18, 19).

12.1.2 Interference correction factors, K_{ij}, are calculated from apparent concentrations observed in the analysis of the high-purity stock solutions.

$$K_{ij} = (A_i - C_i)/B_j \qquad (1)$$

where:

K_{ij} = interference correction factors,
A_i = apparent concentration observed for element i,
C_i = concentration of i observed for the blank, and
B_j = actual concentration of interfering element j.

12.1.3 Sample concentrations observed for element i (already corrected for baseline drift) are corrected for spectral interferences from elements j, k, and l, for example:

$$S_i = \left[A_i - \left((B_j \cdot K_{ij}) + (B_k \cdot K_{ik}) + (B_l \cdot K_{il}) \right) \right] \qquad (2)$$

where:

S_I = concentration of element i corrected for spectral interference,
A_i = observed concentration of i,
B_j = observed concentration of interfering element j,
B_k = observed concentration of interfering element k,
B_l = observed concentration of interfering element l,
K_{ij} = interference correction factor for element j,
K_{ik} = interference correction factor for element k, and
K_{il} = interference correction factor for element l.

12.1.4 Interference correction factors may be negative if background correction is employed for element i. A negative K_{ij} can result where an interfering line is encountered at the background correction wavelength rather than at the peak wavelength. The concentrations of interfering elements j, k, and l must have been determined within their respective linear ranges to approximate the actual concentrations as closely as possible. Mutual interferences (i interferes with j and j interferes with i) require iterative or matrix methods for calculation.

12.2 *Non-spectral Interference*—Non-spectral interference is not likely to occur in ICP-AES if the matrix of the samples matches the matrix of the standards. This condition generally holds for the low-concentration leachants to which this practice applies. Further assurance of avoiding non-spectral interference can be achieved by preparing all standard solutions using the original leachant solution as the matrix (matrix matched standards) instead of simply pure water or acid.

12.2.1 If non-spectral interference correction is determined to be necessary, the method of standard additions can be used (20). The method of standard additions is applicable under the following conditions:

12.2.1.1 The chemical and physical form of the analyte in the standard addition is the same as the analyte in the sample, or the analytical source (ICP) is capable of converting the analyte in both sample and addition to the same form so that transport, atomization, and excitation processes do not differ;

12.2.1.2 The interference effect is independent of analyte concentration over the concentration range of standard additions; and

12.2.1.3 The calibration curve is linear over the concentration range of standard additions.

12.2.2 The method of standard additions involves the addition of a known concentration of analyte to the sample. The concentration of the addition should be not less than 50 % nor more than 100 % of the analyte concentration in the sample so that measurement precision will not be degraded and so that interferences which exhibit a dependence on analyte/ interfering element ratios will not cause erroneous results. The method must be applied to all elements in the sample set individually. Multielement standard addition **(21)** can be used if it has been determined that added elements do not produce interferences.

13. Precision and Bias

13.1 The precision of this practice will depend on the choice of instrumentation, analytical wavelengths, operating conditions, etc. Typical values for short-term precision (based on replicate measurements performed at concentrations at least 100 times the L_D) range from 0.3 to 2 % relative standard deviation. Precision degrades with decreasing concentration.

TABLE 2 Standard Deviation of ICP-AES Analysis of Simulated Leachate Solutions SL-1[A]

Element	Concentration, mg/L	Standard[B] Deviation, mg/L	Relative Standard Deviation,%
Boron	47.1	0.5	1.06
Calcium	0.021	0.0053	24.8[C]
Cerium	2.01	0.04	1.99
Iron	0.014	0.003	21.4[C]
Molybdenum	1.92	0.03	1.56
Neodymium	1.60	0.03	1.88
Silicon	18.9	0.18	0.95
Sodium	79.6	1.4	1.76
Strontium	5.13	0.03	0.58

[A] Analytical data from twelve analyses conducted at random times on each of 4 successive days. Each analysis consisted of the average of triplicate contiguous burns of the solution (routine procedure).
[B] Standard deviation of individual analysis: $n = 12$ (See Ref. **(21)**, Table 6.11).
[C] Concentration of Ca and Fe is approaching the L_D.

13.2 The bias of this practice is dependent on the reliability of the calibration reference solutions, the amount of spectral and non-spectral interference, the accuracy of interference corrections, and the adherence to the calibration drift specifications **(22)**. Using accurate calibration reference solutions, and with all necessary corrections applied correctly, the relative analytical bias for element concentrations that are at least ten times the detection limit will be approximately equal to the calibration drift.

13.3 Table 2 gives typical data for ICP-AES analyses of a simulated leachate used to evaluate analytical precision. **(23)**.

REFERENCES

(1) Currie, L. A., "Nomenclature in Evaluation of Analytical Methods Including Detection and Quantification Capabilities," *Pure and Applied Chemistry*, 1995, Vol, 67, pp. 1699-1723.

(2) Gibbons, R. D., and Coleman, D. E., *Statistical Methods for Detection and Quantification of Environmental Contamination*, John Wiley and Sons, New York, 2001.

(3) *ASTM Methods for Emission Spectrochemical Analysis*, ASTM International, 1967.

(4) Moody, J. R., and Beary, E. S., "Purified Reagents for Trace Metal Analysis," *Talanta*, Vol. 29, pp. 1003-1010.

(5) Botto, R. K., "Quality Assurance in Operating a Multielement ICP Emission Spectrometer," *Spectrochimica Acta*, 1984, Vol 39B, pp. 95–113.

(6) Boumans, P. W. J. M., *Line Coincidence Tables for Inductively Coupled Plasma Atomic Emission Spectrometry*, Pergamon Press, New York, 1980.

(7) Winge, R. K., Fassel, V. A., Peterson, V. J., and Floyd, M. A., *Inductively Coupled Plasma-Atomic Emission Spectroscopy: An Atlas of Spectral Information*, Elsevier, New York, 1985.

(8) Winge, R. K., Peterson, V. J., and Fassel, V. A., *Applied Spectroscopy*, 1979, Vol 33, p. 207.

(9) Boumans, P. W. J. M., and Vrakking, J. J. A. M., *Spectrochimica Acta*, 1987, Vol 42B, pp. 553–579.

(10) Edelson, M. C., DeKalb, E. L., Winge, R. K., and Fassel, V. A., *Spectrochimica Acta*, 1986, Vol 41B, pp. 475–486.

(11) Mainka, E., Muller, H. G., and Geyer, F., Versuche zur PuBestimmung mit Hilfe der ICP-Methode, KFK-3578, Kernforschungszentrum-Karlsruhe, Karlsruhe, FRG, July 1983.

(12) Claudon, X., Birolleau, J. C., Lavergne, M., Miche, B., and Bergey, C., *Spectrochimica Acta*, 1987, Vol 42B, pp. 407–411.

(13) DeKalb, E. L., and Edelson, M. C., "Atlas of Atomic Spectral Lines of Neptunium Emitted by an Inductively Coupled Plasma," IS-4953, Ames Laboratory, Iowa State University, Ames, Iowa, August 1987.

(14) Huff, E. A., and Bowers, D. L., Argonne National Laboratory, private communication.

(15) Berman, S. S., and McLaren, J. W., "Establishment of Compromise Conditions for Multielement Analysis by Inductively Coupled Plasma Emission Spectrometry: A Preliminary Report," *Applied Spectroscopy*, 1978, Vol 32, pp. 273–377.

(16) Larson, G. F., Fassel, V. A., Winge, R. K., and Kniseley, R. N., "Ultra-trace Analysis by Optical Emission Spectroscopy: The Stray Light Problem," *Applied Spectroscopy*, 1976, Vol 30, pp. 384–391.

(17) Boumans, P. W. J. M., "Corrections for Spectral Interferences in Optical Emission Spectrometry with Special Reference to the RF Inductively Coupled Plasma," *Spectrochimica Acta*, 1976, Vol 31B, pp. 147–152.

(18) Botto, R. I., "Long-Term Stability of Spectral Interference Calibrations for Inductively Coupled Plasma Atomic Emission Spectrometry," *Analytical Chemistry*, 1982, Vol 54, pp. 1654–1659.

(19) McLaren, J. W., Berman, S. S., Boyko, V. J., and Russel, D. S., "Simultaneous Determination of Major, Minor, and Trace Elements in Marine Sediments by Inductively Coupled Plasma Atomic Emission Spectrometry," *Analytical Chemistry*, 1981, Vol 53, pp. 1802–1806.

(20) Willard, H. H., Merritt, L. L., Jr., Dean, J. A., and Settle, F. A., Jr., *Instrumental Methods of Analysis*, Sixth Edition, D. Van Nostrand, New York, 1981.

(21) Lorber, A., "Unbiased Generalized Standard Addition Method," *Analytical Chemistry*, 1985, Vol 57, pp. 952–954.

(22) Waters, R. L., "Practical Limits of Precision in Inductively Coupled Plasma Spectrometry," *American Laboratory*, March 1983.

(23) "Comprehensive Report MCC-D1: One-Year Leach Test Data for PNL 76-68 (Batch 4) Glass," September 1983, Materials Characterization Center, Pacific Northwest Laboratory, Richland, Washington.